SHRP-C/UFR-92-617

Freeze-Thaw Resistance in Concrete-- An Annotated Bibliography

Strategic Highway Research Program
National Research Council

Strategic Highway Research Program Executive Committee

John R. Tabb, Chairman
Mississippi Highway Department

William G. Agnew
General Motors Research (retired)

E. Dean Carlson, Ex Officio
Federal Highway Administration

A. Ray Chamberlain
Colorado Department of Highways

Raymond F. Decker
University Science Partners Inc.

Thomas B. Deen, Ex Officio
Transportation Research Board

Thomas M. Downs
New Jersey Department of Transportation

Francis B. Francois, Ex Officio
American Association of State Highway and Transportation Officials

Donald N. Geoffroy
New York Department of Transportation

William L. Giles
Ruan Transportation Management Systems

Jack S. Hodge
Virginia Department of Transportation

Boris Hryhorczuk, Ex Officio
Manitoba Department of Transportation

Thomas D. Larson, Ex Officio
Federal Highway Administration

Donald W. Lucas
Indiana Department of Transportation

Harold L. Michael
Purdue University

Wayne Muri
Missouri Highway and Transportation Department

M. Lee Powell, III
Ballenger Paving Company, Inc.

Henry A. Thomason, Jr.
Texas Department of Highways and Public Transportation

Stanley I. Warshaw
National Institute of Standards and Technology

Roger L. Yarbrough
Apcon Corporation

Key SHRP Staff

Damian J. Kulash
Executive Director

Kathryn Harrington-Hughes
Communications Director

Edward T. Harrigan
Asphalt Program Manager

Don M. Harriott
Concrete & Structures/Highway Operations Program Manager

Harry Jones
Finance & Administration Director

Guy W. Hager
Implementation Manager

K. Thirumalai
IDEA Program Manager

Acknowledgments

The research described herein was supported by the Strategic Highway Research Program (SHRP). SHRP is a unit of the National Research Council that was authorized by section 128 of the Surface Transportation and Uniform Relocation Assistance Act of 1987.

Many persons contributed to the identification and review of suitable citations for this annotated bibliography. Special thanks are given to the students and faculty colleagues at Michigan State University and the University of Washington for their assistance in compiling and reviewing this work. Thanks are also given to the members of the Strategic Highway Research Program Expert Task Group who reviewed the work in progress. Finally, this document would not have reached a completed form were it not for the editing and formatting efforts of Ron Porter, Susan Michalak, and Jennifer Nolan.

Contents

Abstract

This bibliography contains over 550 citations considered relevant to the phenomenon of freezing and thawing of concrete. Detailed abstracts of studies on the mechanism of frost action as well as case histories and laboratory investigations are provided. Peripheral topics such as autogenous healing, which helps explain the delay in appearance of D-cracking, are included. Work from the fields of Ceramics, Geology, Physics, and Soil Physics were selected for insight in the roles of moisture movement and ice crystal growth in frost heave and cracking of porous solids. Entries are alphabetical by first author (or agency when no author is given). There are author and subject indexes.

1. AASHTO T 161-86. *Resistance of Concrete to Rapid Freezing and Thawing*. The American Association of State Highway and Transportation Officials, Washington, D. C., 1986.

   This method covers the determination of the resistance of concrete specimens to rapidly repeated cycles of freezing and thawing in the laboratory by two different procedures: Procedure A, Rapid Freezing and Thawing in Water, and Procedure B, Rapid Freezing in Air and Thawing in Water. Both procedures are intended for use in determining the effects of variations in the properties of concrete on the resistance of the concrete to the freezing and thawing cycles specified in the particular procedure. Neither procedure is intended to provide a quantitative measure of the length of service that may be expected from a specific type of concrete.

2. AASHTO T 277-89. "Standard Method of Test for Rapid Determination of the Chloride Permeability of Concrete." *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, The American Association of State Highway and Transportation Officials, Washington, D. C., 1989.

   This method covers the determination of the permeability of conventional portland cement and specialized, e.g., latex-modified and polymer, concretes to chloride ions. It consists of monitoring the amount of electrical current passed through 95 mm (3.75 in.) diameter by 51 mm (2 in.) long cores when one end of the core is immersed in a sodium chloride solution and a potential difference of 60 V dc is maintained across the specimen for 6 hours. The total charge passed, in coulombs, is related to chloride permeability.

3. Abdulkarim, B. T. "The Significance of Pore Size Distribution in the Freezing and Thawing of Concrete Aggregate Particles." Ph.D. diss., Pennsylvania State University, 1971.

   This dissertation is based upon a study of quartzite, sandstone and four different limestone rock cores. The pore size distribution of each core was measured using a mercury intrusion porosimeter. The freezing and thawing of water in the pore space of the cores was studied using cold differential thermal analysis and a mercury displacement dilatometer measured core volume changes.

   The study concludes that pore size distribution influences the behavior of rocks during freezing and thawing. The test results support the operative role of the dual mechanism proposed by Cady (1967). The study recommends that the smaller size pores, which it found to intensify pressures in the pore space, be measured separately. The results of this study indicate that rocks having a higher absorption undergo a higher volume change depending on a combination of the absorption and pore size distribution.

4. Abdun-Nur, E. A., and R. C. Mielenz. "An Unusual Case of Freezing Fresh Concrete." *Journal of the American Concrete Institute* Vol. 59, No. 30 (June 1962): pp. 803-813.

   An unusual example of freezing of fresh concrete in floor slabs has been observed in the Platteville Elementary School Building, Platteville, Colo., built in the fall of 1957. Initial evidence of distress was numerous, closely spaced bumps in the finished surface of the floors. These protuberances are especially disturbing in areas of tiled floor, where they were first noted.

Detailed examination of the floor slabs, both at the site and by microscopical examination of drilled cores, showed that the upper 1/2 to 1-1/4 in. of the concrete had been frozen before hardening, causing intense fracturing of the near-surface portion and producing bumps over originally frozen lumps of sand and shale incorporated in the concrete. It is concluded that the bumps formed as a result of growth of ice lenses within and adjacent to the frozen lumps. The irregularities of the floor surfaces have increased progressively with time in areas of concentrated traffic, because of disintegration of the highly fractured near-surface concrete beneath the floor tile under the impact of heavy foot traffic.

5. Abrams, D. A. "Autogenous Healing of Concrete." *Concrete* Vol. 27 (August 1925): p. 50.

   The testing of 8-year old concrete is of itself sufficiently unusual to attract attention. Recent tests made at the Structural Materials Research Laboratory, Lewis Institute, Chicago, were unique in that the 8-year-old concrete specimens had been previously loaded to failure when 28 days old. After the original test, which did not shatter the concrete, the cylinders were thrown outdoors on the ground exposed to weather. The compressive strengths of five 6 by 12-in. cylinders, 1 part cement to 5 parts aggregate by volume are:

   28-day strength -lb. per sq/in. — 2330, 2510, 3130,2360, 1580;
   Strength of same retested after 8 years — 5070, 4200,5290,4940, 5980;
   Ratio of 2-yr. to 28-day strength, percent (average 228) — 217, 167, 169, 210, 379.

   The variation in strength was due to difference in the size and grading of the aggregates and in the consistency of the concrete. The cracks which were caused by the 28-day test closed up during 8 years' exposure to weather. This may be explained by the slight solubility of both hardened cement and aggregate in rain water. Depositing of soluble compounds in the old cracks formed a good bond. It is probably a new idea to most users of Portland cement concrete that in the presence of moisture, small cracks will heal and in fact become much stronger than before the break; it is reassuring to know that concrete possesses this remarkable property.

6. ACI Advisory Committee, Long-Time Study. "Ten-Year Report on the Long-Time Study of Cement Performance in Concrete." *Journal of the American Concrete Institute* Vol. 49 (March 1953): pp. 601-616.

   Primarily, this study was undertaken to determine whether any relationship exists between the composition, fineness, and conditions of manufacture of the test cements and the ability of the concrete in which they were used to resist disintegration when subjected to external influences such as water, sulfate solutions, temperature changes, and highway traffic with or without application of salts for ice removal; and internal changes due to instability of the hardened cement paste.

   Most of the test structures have now been exposed to weathering for 10 years and this report presents the most important facts regarding the cements and their performance. Conclusions are presented concerning the lack of correlation between the behavior of concrete exposed to freezing and thawing and the chemical content or fineness of the cement; normal differences in manufacture do not significantly affect durability of concrete; and the increase of sulfate

resistance with reduction of potential C3A content of the cement. Substantiating other studies, the evidence was strong that air entrainment greatly increases the ability of concrete to endure freezing and thawing without deterioration and was found to be particularly effective in preventing scaling when chlorides are used for ice control on concrete pavements.

7. ACI Committee 201. "Blast Furnace Slag as Concrete Aggregate." *Journal of the American Concrete Institute* Vol. 27 (October 1930): pp. 183-219.

   The article deals briefly with all characteristics of blast furnace slag for use as concrete aggregate, together with many references giving laboratory and field results obtained by the use of slag concrete. The report includes a bibliography giving about 60 references to publications, committee reports, and other data pertaining to the use of blast furnace slag as concrete aggregate. Quotations from 37 authors are also included.

8. ACI Committee 201. "Durability of Concrete in Service." *Journal of the American Concrete Institute* Vol. 59, No. 12 (1962): pp. 1771-1784.

   This report presents recommendations for materials and methods to obtain concrete with maximum resistance to deterioration, to preserve concrete against deterioration, and to restore deteriorated concrete. The report specifically excludes consideration of erosion in hydraulic structures and fire resistance of concrete that are in the province of other ACI committees. Recommendations are made with respect to freezing and thawing, the use of chemicals for ice removal, aggressive chemical agents, abrasion corrosion of steel, reactive aggregates, and the restoration of deteriorated concrete.

9. ACI Committee 201. "Guide for Making a Condition Survey of Concrete in Service." *Journal of the American Concrete Institute* Vol. 65, No. 11 (November 1968): pp. 905-918.

   This guide provides a system for reporting on the condition of concrete in service. It includes a check list of the many details to be considered in making a report, and provides standard definitions of 40 terms associated with the durability of concrete. Its purpose is to establish a uniform system for evaluating the condition of concrete.

10. ACI Committee 201. "Guide to Durable Concrete." *Journal of the American Concrete Institute* Vol. 74, No. 53 (December 1977): pp. 573-582.

    This guide is essentially an update of the committee report "Durability of Concrete in Service," which appeared in the December 1962 ACI JOURNAL. There are a number of major revisions reflecting increased knowledge of the subject.

    A separate chapter is devoted to each of the main types of concrete deterioration. Their mechanism is described and the requirements for materials, design, and construction procedures necessary to prevent damage to the concrete are given. A selected bibliography is included with each chapter.

11. ACI Committee 212. "Guide for Use of Admixtures in Concrete." *Journal of the American Concrete Institute* Vol. 68, No. 56 (September 1971): pp. 646-676.

    This guide outlines the purposes of and factors to be considered in the used of admixtures. One chapter gives information of the preparation and batching of admixtures. Other chapters give information on the properties, effects, and use of various classes of admixtures. Information is included on: (1) air-entraining admixtures; (2) accelerators; (3) water-reducing and set-controlling admixtures; (4) finely divided mineral admixtures, including relatively inert powders, cementitious materials, and pozzolans; and (5) miscellaneous admixtures, including gas-forming, grouting, expansion-producing, bonding, coloring, flocculating, fungicidal, germicidal, insecticidal, dampproofing, and permeability-reducing admixtures; admixtures to reduce alkali-aggregate reaction expansion; and corrosion inhibitors.

12. ACI Committee 226. "Silica Fume in Concrete." *American Concrete Institute Materials Journal* Vol. 84, No. 2 (1987): pp. 158-166.

    Silica fume is a by-product resulting from the reduction of high-purity quartz with coal in electric arc furnaces in the manufacture of silicon and ferrosilicon alloys. This report briefly describes the physical, chemical, and pozzolanic properties of silica fume. Methods of using silica fume in concrete are mentioned, and the properties of fresh and hardened concrete incorporating it are described. The durability of silica-fume concrete is discussed, and the limitations of its use in concrete are outlined. The report is concluded by listing research needs.

13. ACI Committee 226. *Use of Fly Ash in Concrete*, American Concrete Institute, Detroit, MI, Report 226.3R-87, 1987.

    The synthesis discusses the use of fly ash in concrete from the standpoint of its use in the construction of transportation facilities. Early developments relating to the use of fly ash from bituminous coal (Class F) are reviewed and the advantages and disadvantages as they apply to use by transportation agencies are discussed. The use of fly ash can improve workability of the fresh concrete and result in concrete of higher strength and lower permeability with consequent improved resistance to sulfate attack and ingress of corrosive liquids that might lead to corrosion of reinforcing steel. Unit costs per cubic yard of such concrete will usually be less than similar concrete without fly ash.

    A brief overview of the fly-ash marketing procedures is provided, and a summary of the amount of fly ash now being used is included. The synthesis reports the replies to a questionnaire concerning the status of the use of FAC in each state of the United States and the provinces in Canada.

14. ACI Committee 306. "Cold Weather Concreting." *Journal of the American Concrete Institute* Vol. 75, No. 18 (May 1978): pp. 161-183.

    The general requirements for producing satisfactory concrete during cold weather are discussed, as are methods for achieving these requirements. For many structural concretes, protection considerably in excess of that required to ensure freedom from damage by early freezing is required to assure safe development of strength. Accelerators, keeping of temperature records, heating of materials, subgrade preparation, protective insulating coverings, heated enclosures, curing, maturity concept, and form removal are discussed. Supplementary materials on

the effect of curing temperatures on concrete strength is referenced in authoritative sources. A list of selected references is included.

15. ACI Committee 306. "Proposed Standard Specification for Cold Weather Concreting (ACI 306.1)." *Journal of the American Concrete Institute* Vol. 83, No. 95 (November - December 1986): p. 1043.

    This Standard Specification gives the requirements for cold weather concreting. It includes cold weather requirements for preparations prior to the placement of concrete - the correct temperature of concrete and the protection of concrete.

16. ACI Committee 311. *ACI Manual of Concrete Inspection*, American Concrete Institute, Detroit, SP-2, 1975.

    The ACI Inspection Manual supplements specifications and is intended as a guide in matters not covered by specifications. It describes methods of inspecting concrete that are generally accepted as good practice and is based on information from many sources, organizations, and individuals.

17. ACI Committee 544. "Measurement of Properties of Fiber Reinforced Concrete." *Journal of the American Concrete Institute* Vol. 75, No. 30 (July 1978): p. 283.

    Laboratory and field experience in the testing of fiber reinforced concrete (FRC) has indicated the need to review existing test methods and to develop new methods where necessary to determine the properties of fiber reinforced concrete.

    This report outlines the suggested procedures for specimen preparation in general, and discusses in detail testing for modulus of rupture.

    New testing methods are suggested for (1) toughness-energy absorption, (2) impact strength, and (3) workability.

    The applicability of the following test methods to fiber reinforced concrete are reviewed: air content, yield, unit weight, compressive strength, splitting tensile strength, freeze-thaw, shrinkage, creep, modulus of elasticity, cavitation, and erosion and abrasion resistance.

18. Adkins, D. F. "Laboratory Duplication of Surface Scaling." *Concrete International* (February 1986): pp. 35-39.

    This article presents a new laboratory procedure which closely mimics the deterioration of concrete in the under moderate to severe freeze-thaw conditions. This research investigated the process which occurred and resulted in surface scaling of saturated concrete slabs subjected to complete freezing and partial thawing in such a manner that the bottoms remained frozen while the upper portion of the slabs was thawed and refrozen from the top downwards. Freezing and thawing in this manner is believed to have concentrated ice into lenses below the surface of the concrete and, in turn, caused failure by spalling the surface off in sheets, or in some cases causing popouts. The availability of this procedure should help in resolving the differences between conflicting theories on deterioration and provide insight into the relative importance of the factors and combination of factors which cause scaling.

19. Adkins, D. F., and V. T. Christiansen. "Freeze-Thaw Deterioration of Concrete Pavements." *Journal of Materials in Civil Engineering* Vol. 1, No. 2 (May 1989): pp. 97-104.

Under winter exposure conditions, solar radiation effects along with the presence of de-icing salts have a pronounced impact on the deterioration of concrete pavements. The rapid changes and differences in temperature between the pavement's dry surface and saturated subsurface can cause both thermal and hydraulic stress. As subsequent cycles of freezing and thawing occur, a subsurface plane of cracks will form in which ice lenses can grow parallel to the surface and eventually cause failure of the subsurface paste. Once the subsurface has failed, the surface will spall off in sheets. This thin, brittle layer will then crumble under traffic, and leave the aggregate exposed. By using both laboratory and field data this paper discusses concepts of how de-icers and freeze-thaw cycles limited to the upper portion of the concrete pavement contribute to scaling by setting up thermal gradients and lowering the immediate surface moisture content.

20. "Admixtures and Ground Slag for Concrete." *Transportation Research Circular* No. 365, Transportation Research Board, National Research Council, Washington, D. C., December 1990.

This report was prepared by the Transportation Research Board Committee on Chemical Additions and Admixtures for Concrete (A2E05). It is intended to provide practical information on admixtures and slag to practitioners dealing with concretes in the transportation field. The report supersedes information in Special Report 119 published in 1971 on accelerating, air-entraining, water-reducing, and pozzolanic (Type F fly ash) admixtures. In addition, it includes information concerning latex, high-range water-reducing, corrosion inhibiting, Type C fly ash, and silica fume pozzolanic admixtures and slag. The summary table in Chapter 1 provides a quick reference concerning major expected advantages and possible detrimental effects but should not be construed as being all inclusive.

21. Ainsworth, D. L., and A. M. Alexander. *Method of Test for Concrete Dilation*, U.S. Army Engineer Waterways Experiment Station, Vicksburg, miscellaneous paper no. C-69-18, November 1969.

A system has been developed to study the effects of the physical environment on concrete. This system is designed to continuously measure the total length change in a concrete specimen due to wetting and drying, temperature change, and freezing and thawing. Dilation is the increase in length of concrete as it is cooled into the freezing range of contained water. Dilation in a specimen exceeding 50 microin./in. is considered critical and may damage the specimen. The system, therefore, was designed to have a sensitivity of at least 10 microin. Numerous dilation tests were conducted on moist specimens to determine the magnitude of dilation and to proof test the system. These data are included in this report.

22. "Air Entrainment and Concrete." *Concrete Construction* (March 1976): pp. 105-110.

In the area of concrete construction, where much depends on know-how, patience and careful workmanship, it was only natural that short cuts should be offered in the form of admixtures. Of all the many products put on the market in the last few decades, one has risen head and shoulders above the others in its effectiveness. It is, of course, the air entraining agent. Even this admixture is no

wonder worker, however. It is not intended to replace correct procedures in mix design or concreting. Rather, it complements these quality concrete practices to produce a finished product that will be more durable and satisfactory to all concerned. Let's take a closer look at this pre-eminent admixture.

23. "Air Entrainment for Concrete." *Concrete Construction* (July 1970): pp. 241-244.

    Purposefully entrained air is in much of the concrete produced today. Virtually all concrete exposed to weathering should benefit from the improved durability that it provides. Many other applications where air entrainment is desirable are also being recognized. Air entrainment enhances concrete by achieving the following: improved resistance to freeze-thaw cycles and de-icing salts; increased workability; improvement in cohesiveness and reduction in likelihood of segregation; lessened permeability; minimization of bleeding; slightly better resistance to certain chemicals and increase in resistance to sulfate attack. By controlling the uniformity of such plastic concrete properties as workability, cohesiveness and bleeding, a mix designer or inspector will be able to get clues to the uniformity of the air content. (Other factors, of course, can also affect these concrete properties.)

24. Aitcin, P. C. "Freezing Behavior of Grouts Containing Granulated Slag." *Journal of the American Concrete Institute* Vol. 67, No. 26 (May 1970): pp. 413-417.

    Grouts containing granulated blast furnace slag of melilitic type present a particular behavior with respect to a succession of freezing and thawing cycles. Such grouts become surrounded with a thin film of particularly resistant finely crystallized calcite, which results from the presence of granulated slag in the grout.

    This film layer increases notably the values of tensile and compressive strengths at the rupture of these grouts.

25. Aitcin, P. C., and M. Pigeon. "Performance of Condensed Silica Fume Concrete Used in Pavements and Sidewalks." *Durability of Building Materials* Vol. 3 (1986): pp. 353-368.

    There is very little data related to long-term performance of condensed silica fume (CSF) concrete exposed to freezing and thawing cycles in the presence of deicing salts. This paper presents the results of a laboratory investigation of CSF concrete cores taken from different sidewalks and pavements around Montreal. Some of the CSF concretes are four to five years old and are still in excellent condition, while others were severely damaged after their first winter of exposure. The compressive strength, microstructure, and air-void system of these concretes are discussed. It is shown that, in order to have good freezing and thawing durability in the presence of deicing salts, condensed-silica fume concrete must contain an adequate volume of entrained air, together with the correct bubble-spacing factor.

26. Aitcin, P. C., and D. Vezina. "Resistance to Freezing and Thawing of Silica Fume Concrete." *Cement, Concrete and Aggregates - ASTM* (Summer 1984): pp. 38-42.

    The resistance to freezing and thawing of a concrete containing silica fume that was used during the construction of an experimental section of highway A25 in Montreal was done according to ASTM Test for Resistance of Concrete to Rapid

Freezing and Thawing (C666). The original mix was modified so that silica fume replaced three times its weight of cement.

The use of silica fume did not create any particular problems as far as the air content and slump were concerned except perhaps that slightly higher losses were observed during the transportation in comparison to the regular mix. The 28- and 91-day compressive strength results proved that silica fume has been more active than three times its cement weight.

The test shows that the resistance to freezing and thawing of the silica fume concrete was far superior to the plain concrete used for the completion of the project. The length increase and the absorption of the silica fume concrete were about or less than half of those observed with the regular mix. The durability factor of the silica fume concrete was 83 at the end of the test whereas the regular mix durability factor was only 68.

27. Albala, J. A. L., and S. A. Rossello. "Concrete Impermeability Study." AshTech '84: Second International Conference on Ash Technology and Marketing, London, 1984, pp. 387-389.

    A test method capable of quantifying the impermeability of concretes accurately is presented in this paper. The methodology and the apparatus for measuring impermeability are described. A comparative study is made of the impermeability of concretes with various types of cement for equal strengths, slumps, and maximum quantity of dry materials. In addition, the impermeability of concretes with a Spanish fly ash (Cercs) is investigated. The authors conclude that, with the remaining characteristics such as type of cement and consistency being the same, dry concretes are found to be the most impermeable, and concretes made with Cercs fly ash are found to be more impermeable than any other type of concrete tested.

28. Almond, D. K., and D. J. Janssen. "The Washington Hydraulic Fracture Test for Concrete Aggregates Exposed to Freezing and Thawing." Second CANMET/ACI International Conference on Durability of Concrete, Montreal, Canada, August 4-9, 1991, pp. 265-293. Ottawa, Canada: CANMET.

    A new test method for identifying concrete aggregates that are non-durable when exposed to freezing and thawing is presented. The test is rapid, requiring approximately one hour per day for five days per sample. The equipment costs less than $10,000, and the test does not require a highly skilled technician. Results in the form of percentage of fractures and percentage of mass change are presented for a durable and a non-durable aggregate.

29. Ammar, C., and M. Longuet. "Belgian Requirements About Buildings Service Life." *Durability of Building Materials and Components*, ASTM STP 691 (1980): pp. 77-90.

    The service life requirements of main dwelling components are determined through an inquiry among building specialists and among owners; this inquiry also has been extended to office buildings, schools, and hospitals. The required service life varies between 45 and 60 years for the building itself, 30 to 40 years for the external envelope and 25 to 35 years for internal partitions. The study is completed with an inquiry on actually observed service life.

30. Anderson, S. M., and R. L. Carrasquillo. *The Effects of Withholding Mixing Water and Retempering on Properties of Concrete*, Texas State Dept. of Highways and Public Transportation, Austin, Texas, FHWA/TX-88-1117-1, February 1988.

    The effects of withholding mixing water at initial batching followed by retempering of the mix at the jobsite on the properties of the concrete produced for highway applications was examined in an experimental program. Additionally, the effects of redosage with water above and beyond that called for in the specified mix design was examined. Tests were performed to determine the effects on slump, air content, unit weight, compressive strength, flexural strength, abrasion resistance, and freeze-thaw resistance.

    The effects of varying the withholding amount, withholding time, and cement content on the fresh and hardened concrete properties mentioned above were examined. The concrete examined was produced at a ready-mixed concrete facility in order to duplicate as closely as possible job-site conditions arising in typical concrete construction.

    The results of the study show that significant detrimental effects occur when mixing water is withheld and concrete is retempered at a later time. Slump, air content, abrasion resistance, and freeze-thaw resistance are all adversely affected. The effects were found to vary with variations in both withholding time and cement content. The strength was not affected when water was withheld and concrete was retempered, but a reduction in strength accompanied an increase in water-cement ratio above design values at redosage. The properties changed lead to concrete of reduced quality and questionable performance.

31. Andrews, L. E. "Recent Experiences with Air-Entraining Portland Cement Concrete in the Northeastern States." *Journal of the American Concrete Institute* Vol. 42 (June 1946): pp. 621-624.

    Describes preliminary studies and current practice in the Northeastern States in the reduction of frost action on concrete paving and other projects (roads, streets, airport pavements and hangars, bridges, and buildings); mix proportioning, methods of determining air content, and field control. Specifications tend to limit air content to 3 to 6 percent rather than fix amount of air-entraining agent used.

32. Ansari, F. "A New Method for Assessment of Air Voids in Plastic Concrete." *Cement and Concrete Research: An International Journal* Vol. 20, No. 6 (November 1990): pp. 901-909.

    Development of a new apparatus for in-situ determination of air void characteristics, particularly the distribution of entrained air system in freshly-mixed concrete during mixing, pouring, and placement is described. Air content is measured by a fiber optic probe. Reflected light intensities determine the distribution of air bubbles in fresh concrete. The system has the ability to rapidly sample air content at different locations or depths in plastic concrete improving existing quality control procedures. Air content measurements are direct, and not influenced by the type and amount of aggregates, cementitious components, and admixtures.

33. Ami, H. T. "Resistance to Weathering — Hardened Concrete." *Significance of Tests and Properties of Concrete and Concrete-Making Materials*, ASTM, Philadelphia, STP-169A, 1966. pp. 261-274.

Resistance to weathering and the somewhat synonymous term durability have been used by different authors with meanings varying from very narrow to very broad. In the paper on Resistance to Weathering — General Aspects, published in the 1955 edition of this special technical publication C. H. Scholer presented a detailed outline of the various factors that may influence concrete durability.

34. ASTM C 457-90. "Standard Test Method for Microscopical Determination of Parameters of the Air-Void in Hardened Concrete." *Annual Book of ASTM Standards*, ASTM, Philadelphia, PA.

This test method describes procedures for microscopical determinations of the air content of hardened concrete and of the specific surface, void frequency, spacing factor, and paste-air ratio of the air-void system in hardened concrete. Two methods are described:
Method A, the linear traverse method, and
Method B, the modified point-count method.

35. ASTM C 666-90. "Resistance of Concrete To Rapid Freezing and Thawing." In *Annual Book of ASTM Standards*, 1984.

This test method covers the determination of the resistance of concrete specimens to rapidly repeated cycles of freezing and thawing in the laboratory by two different procedures: Procedure A, Rapid Freezing and Thawing in Water; and Procedure B, Rapid Freezing in Air and Thawing Water. Both procedures are intended for use in determining the effects of variations in the properties of concrete on the resistance of the concrete to the freezing-and-thawing cycles specified in the particular procedure. Neither procedure is intended to provide a quantitative measure of the length of service that may be expected from a specific type of concrete.

36. ASTM C 671-86. "Standard Test Method for Critical Dilation of Concrete Specimens Subjected to Freezing." *Annual Book of ASTM Standards*, ASTM, Philadelphia, PA, 1984.

This method covers determination of the test period of frost immunity of concrete specimens as measured by the length of time of water immersion required to produce critical dilation when subjected to a prescribed slow freezing procedure. The significance of the results in terms of potential field performance will depend upon the degree to which field conditions can be expected to correlate with those employed in the laboratory.

37. ASTM C 672-91. "Scaling Resistance of Concrete Surfaces Exposed To Deicing Chemicals." In *Annual Book of ASTM Standards*, 1984.

This method covers determination of the resistance to scaling of a horizontal concrete surface subject to freezing-and-thawing cycles in the presence of deicing chemicals. It is intended for use in evaluating this surface resistance qualitatively by visual examination. The test can be used to evaluate the effect of mix design, surface treatment, curing, or other variables on resistance to scaling. It is not

intended to be used as a test method for durability of aggregates or other ingredients of the concrete.

38. ASTM STP 169B. *Significance of Test and Properties of Concrete and Concrete-Making Materials*, ASTM, Philadelphia, PA, 1978.

    This volume is an update to ASTM STP 169-A, which was published in 1966. This volume presents the point of view of the 1920s. Part I contains chapters dealing with general considerations. In Part II of Tests and Properties of Concrete, there are new chapters on accelerated strength testing and nondestructive testing of hardened concrete. In Part III, there is now an entire chapter devoted to alkali-carbonate reactions. The introduction of new chapters on admixtures is found in Part IV.

39. Backstrom, J. E., R. W. Burrows, R. C. Mielenz, and V. E. Wolkodoff. "Origin, Evolution, and Effects of the Air Void System in Concrete. Part 2 — Influence of Type and Amount of Air-Entraining Agent." *Journal of the American Concrete Institute* (August 1958): pp. 261-375.

    Air-entraining agents of differing chemical composition produce air voids of different size, distribution, and spacing. The amount of agent also has an effect on these parameters, in general, reducing the air void size and spacing when used in increasing amounts. Air, entrained by an effective agent, in the amount recommended by ACI Committee 613, or greater, will usually provide a satisfactory air void system and satisfactory resistance of concrete to freezing and thawing. In general, the factors which tend to reduce spacing also tend to increase freezing-thawing resistance of concrete.

40. Backstrom, J. E., R. W. Burrows, R. C. Mielenz, and V. E. Wolkodoff. "Origin, Evolution, and Effects of the Air Void System in Concrete. Part 3 — Influence of Water-Cement Ratio and Compaction." *Journal of the American Concrete Institute* Vol. 55, No. 22 (September 1958): pp. 359-375.

    Size distribution, frequency of air voids, spacing factor, and freezing and thawing resistance of concrete are influenced by many factors, among the most significant being water-cement ratio and degree of compaction. Increased freezing and thawing resistance generally reflects a reduction in void size and spacing factor. Such reductions are obtained, other factors being equal, through reduced water-cement ratio, increased amount of air-entraining agent, and in the case of void size through increased periods of vibration. Reduction of water-cement ratio increases the proportion of air-entraining agent necessary to produce a given air content but the air content required for maximum durability is decreased as the water-cement ratio is decreased. Increasing periods of vibration reduce the total air content and increase the specific surface of air voids, but have relatively little effect on spacing factor. For any one concrete there is an optimum air content and void spacing factor for optimum resistance to freezing and thawing. Spacing factor which obtains at optimum freezing and thawing resistance of a single concrete variously vibrated may or may not be the smallest in magnitude.

41. Bager, D. H., and E. J. Sellevold. "Ice Formation in Hardened Cement Paste, Part I — Room Temperature Cured Pastes with Variable Moisture Contents." *Cement and Concrete Research* Vol. 16 (1986): pp. 709-720.

    Ice formation in room temperature cured mature hardened Portland cement paste with different moisture contents have been measured. The measurements were carried out continuously in the temperature range from +20° C to -60° C. For moisture contents higher than that corresponding to approximately three equivalent BET-monolayers, the initial freezing temperature increases with increasing moisture contents. Moisture contents below approximately three monolayers is not freezable. For specimens containing freezable water, there is an increase in the amount of non-frozen water content with increasing moisture contents. Further, there is a slight increase in the amount of non-frozen water content with increasing moisture contents. Further, there is a slight increase in the amount of non-frozen water with increasing water/cement ratios for specimens in equilibrium with the same relative water vapor pressure. It is postulated that frost problems only can be expected in specimens containing more water than corresponding to a relative water vapor pressure of about 0.9.

42. Bager, D. H., and E. J. Sellevold. "Ice Formation in Hardened Cement Paste, Part II — Drying and Resaturation on Room Temperature Cured Pastes." *Cement and Concrete Research* Vol. 16 (June 1986): pp. 835-844.

    Ice formation in partly dried and resaturated room temperature cured mature Portland cement paste has been measured. The measurements were carried out continuously in the temperature range from +20° C to 60° C. The results demonstrate that the drying-resaturation treatment increases the volume of large pores and the continuity of the pore system. The increase in the volume of large pores occurs at the expense of small pores and necks in the pore system. As the relative water vapor pressure at which drying takes place is decreased to 0.58, the number of continuous large pores is increased. Drying at lower relative water vapor pressures does not further increase the effect. The present findings point out the importance of the moisture history of concrete before testing such properties as water permeability and frost resistance.

43. Bakr, T. A. "The Significance of Pore Size Distribution in the Freezing and Thawing of Concrete Aggregate Particles." Ph.D. diss., Pennsylvania State University, 1989.

    This study was intended to support the hypothesis that the behavior of an aggregate particle in freezing and thawing is a function of its porosity and pore size distribution, and that the freezing and thawing modes and the pore size distribution will influence the modes of dilation and relaxation of the particle.

    The scope of this study can best be summarized in four parts:

    1. Selection of test aggregate to cover a wide range of porosity and mineral composition.
    2. Determination of the pore size distribution of these study samples with a 60,000 psi mercury porosimeter.
    3. Determination of the modes and magnitude of freezing and thawing of water in the rock pore space by means of a differential thermal analysis technique.

4. Determination of the modes and magnitudes of unconfined dilation and relaxation of saturated rock samples due to freezing and thawing, using a mercury displacement dilatometer.

44. Balaguru, P., and V. Ramakrishnan. "Chloride Permeability and Air Void Characteristics of Concrete Containing High-Range Water-Reducing Admixture." *Cement and Concrete Research* Vol. 18 (1988): pp. 401-414.

This paper presents the results of an experimental investigation of chloride permeability and air void characteristics of concrete containing high-range water-reducing admixture. Two typical mixture proportions with cement contents of 611 and 799 lb/yd^3 (363 and 474 kg/m^3) were tested. The respective water reducing admixture contents by weight of cement were 1% and 1.2%. Chloride permeability tests were conducted using 6 x 12-in. (150 x 300 mm) cylinders and 8% sodium chloride solution. The chloride contents were determined at depths of 0.5, 1.0, 1.5, and 2.0 in. (12.7, 25.4, 38.1, and 50.8 mm) for time periods of 1, 3, 6, 9, and 12 months. Air void characteristics were studied using 0.75-in. (19 mm) thick slices cut from 4 x 4 x 14-in. (100 x 100 x 350 mm) prisms. Air void parameters namely: chord-intercept, average chord-intercept, spacing factor, specific surface number of voids per inch and air void content were determined using Linear Traverse (Rosiwal) Method described in ASTM C 457. Air void characteristics results obtained from three other laboratories are compared with the results of this investigation. The results show that chloride permeability of concretes made with and without high-range water-reducing admixture is about the same. The air void characteristics of concretes tested in this investigation using high-range water-reducing admixtures are satisfactory. Spacing factors, chord-intercepts and the frequency of chord-intercepts in terms of their lengths are within the normally recommended range.

45. Balaguru, P., and V. Ramakrishnan. "Freeze-Thaw Durability of Fiber Reinforced Concrete." *Journal of the American Concrete Institute* Vol. 83, No. 37 (January - February, 1986): pp. 374-382.

The results of an experimental investigation of the freeze-thaw durability of fiber reinforced concrete is presented. The primary objective of the research program was to determine whether the air content is the most significant parameter for the freeze-thaw resistance of fiber-reinforced concrete, as is the case with normal concrete. Accordingly, air content in the mixtures was varied from 1.2 percent to 10.8 percent. The results indicate that air content is the most significant factor. Based on the results, it is recommended that at least 8.0 percent air content should be specified for concrete structures exposed to severe freeze-thaw loading. Comparison of fiber-reinforced concrete specimens with plain concrete specimens indicates that their behavior under freeze-thaw loading is essentially similar. For the same air content, freeze-thaw durability is the same for both plain and fiber-reinforced concrete. An increase of cement content and a reduction of water-cement ratio improves the durability. The results also indicate that the toughness index of fiber-reinforced concrete does not change appreciably with freezing and thawing, provided the mixture is designed to prevent deterioration by incorporating sufficient air.

46. Balaguru, P., M. Ukadike, and E. Nawy. "Freeze-Thaw Resistance of Polymer Modified Concrete." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

    This paper presents the results of an experimental investigation of the freeze-thaw durability of polymer-modified concrete (PMC). Basically, prism specimens were subjected to a maximum of 900 cycles of freezing and thawing using ASTM C666 Procedure A. Five sets of specimens with various amounts of polymer content were tested. The polymer consisted of a liquid epoxy resin and a curing agent (or hardener). Weight and fundamental transverse frequency were measured at various intervals of freeze-thaw cyclic loading. The results indicate that the freeze-thaw durability of PMC is better than that of non air-entrained plain concrete. The PMC with polymer-cement ratio of 0.4 or higher can withstand 900 cycles of freezing and thawing.

47. Banthia, N., and S. Mindess. "Effect of Early Freezing on Permeability of Cement Paste." *Journal of Materials in Civil Engineering* Vol. 1, No. 3 (August 1989): pp. 119-132.

    Coefficients of permeability were obtained for cylindrical paste specimens frozen at the ages of 4, 24, 48, and 72 hours after casting. Two freezing temperatures of -5° C and -15° C were chosen. Tests are conducted at the age of 28 days after casting. Two types of cements were tested. The effects of silica fume addition were also investigated. A new technique of specimen conditioning based on cycles of flow reversal was used. With this technique, an early attainment of equilibrium flow conditions was possible. Frozen specimens were found to have permeabilities at least an order of magnitude higher than the normally cured specimens. Age at freezing is found to have a profound effect on permeability. Freezing to -15° C was found to be more severe than freezing to -5° C, up to an age of 24 hours after casting. At later ages, to two temperatures produced similar effects. An extended 22° C moist curing for 28 days after the period of freezing was found to reverse the damage to some extent.

48. Baragano, J. R., and P. Rey. "The Study of a Non Traditional Pozzolan: Copper Slags." Seventh International Congress on the Chemistry of Cement, Paris, France, 1980, pp. 37-42.

    The slags obtained in copper metallurgy are vitreous, hard, compact, abrasive, of fine granulometry, and are composed principally of fayalite and iron oxides in their crystallized phase.

    Cements prepared with these slags have similar characteristics to those of portland and pozzolanic cements with advantages in workability. The hardening curves show certain inertia in the increase in strength over short periods but with considerable later advantage, though the initial strengths improve well due to activation by alkaline sulphates. Their behavior in the presence of atmospheric agents, in freeze-thaw cycles and in alkali-silica reactions is noteworthy.

    The durability tests with solutions of $MgSO_4$, $CaSO_4$ $2H_20$ and Na_2SO_4 give results that are better than those obtained with pure portland and pozzolanic cements. They are particularly stable to effects of seawater.

49. Barbee, J. F. "What Have We Learned About Air-Entraining Concrete?" *American Concrete Institute Proceedings* Vol. 45, No. 35 (September 1948 - June 1949): p. 601.

A review of ACI published data on air-entraining concrete, this paper summarizes methods of control and the effect of air entrainment on durability, plasticity and workability, strength, resistance to abrasion and other properties of concrete. The effects of variations in cement and water content, sand-coarse aggregate ratio, mixing time and the use of calcium chloride as an admixture are described. Changes in technique necessary to successfully place, vibrate and finish air-entraining concrete are pointed out. A detailed bibliography follows.

50. Barnes, R. D., S. Diamond, and W. L. Dolch. "Micromorphology of the Interfacial Zone Around Aggregates in Portland Cement Mortar." *Journal of the American Ceramic Society* Vol. 61, No. Nos. 1-2 (January - February 1979): p. 21.

Scanning electron microscopy showed that micromorphological features of the interfacial zone, which occur next to glass slide "model aggregates," occur also in mortars made with standard Ottawa silica sand. These features included formation of a duplex film on the sand-grain surfaces, development of large well-formed $Ca(OH)_2$ crystals at intervals near the interface with their c aces roughly parallel to it, development of stacked-platelet secondary $Ca(OH)_2$ in open spaces immediately adjacent the duplex film, and hydration leading to the presence of hollow-shell hydration grains (Hadley grains) in the interfacial region.

51. Bazant, Z. P., J. Chern, A. M. Rosenberg, and J. M. Gaidis. "Mathematical Model for Freeze-Thaw Durability of Concrete." *Journal of the American Ceramic Society* Vol. 71, No. 9 (Sept. 1988): p. 776-783.

Although the equations governing the individual basic physical processes involved in freezing and thawing of concrete are known, a mathematical model for this complex phenomenon is unavailable. Its formulation is attempted in the present study. Desorption and absorption isotherms for concrete below 0° C, using pore size distribution functions. Water movement during freezing or thawing is described as a double diffusion process, involving both macroscopic diffusion through concrete and local diffusion of water into or out of air-entrained bubbles. Heat conduction is formulated taking into account the latent heat of freezing. Pore pressures are used in a two-phase material model, which makes it possible to predict the stress in the solid structure of concrete caused simultaneously by freezing and applied loads. This in principle reduces the freeze-thaw durability problem to the calculation of stresses and strains. However, development of the model to full application would require various new types of tests for calibration of the model, as well as development of a finite element code to solve the governing differential equations. Such a mathematical model could be used to assess the effect of cross-section size and shape, the effect of cooling rate, the delays due to diffusion of water and of heat, the effect of superimposed stresses due to applies loads, the role of pore size distribution, the role of permeability, and other factors which cannot be evaluated at present in a rational manner.

52. Beaudoin, J. J., and C. MacInnis. "Dimensional Changes of Hydrated Portland Cement Mortar Due to Slow Cooling and Warming." *Journal of the American Concrete Institute* SP 47-3 (April 1975).

This study is reports of the strain-temperature behavior (at various ages) of hardened portland cement mortar when subjected to a slow cycle of cooling and warming over the range 70 to 0° F. This is an extension of cement paste studies, reported earlier in order to assess the role fine aggregate plays in the transient strain behavior of mortar, during a freezing cycle. Two sands were used in mortar mixes covering a range of aggregate-cement ratios and water-cement ratios. An analysis of the measured transient strains as well as the mode of the hysteresis loops obtained, provides some insight into the nature of frost action.

53. Benda, C. C. *Preliminary Report on EMSAC F-100 Microsilica Additive for Concrete*, State of Vermont Agency of Transportation Materials and Research Division, Report No. 86-6, April 1986.

Microsilica, frequently called silica fume, is a by-product of the ferrosilicon and silicon metal manufacturing process.

Stimulated by claims of the enhanced performance of Portland Cement Concrete when microsilica is used as an additive, testing was initiated to determine if conventional Vermont Agency of Transportation concrete mixtures used in bridge deck construction could be improved with the introduction of EMSAC F-100 microsilica additive manufactured by Elken Chemicals, Inc.

Given in this preliminary report are strength test results, short-term freeze-thaw characteristics and setting times for laboratory mixed concrete containing 10 to 30 percent microsilica by weight of cement.

Initial indications are that concrete with substantially higher compressive strengths and improved durability can be produced with microsilica. The EMSAC F-100 additive accelerated setting times at the lower addition rate while retarding the setting times at the upper addition rate relative to the control mixtures.

Continued research to determine resistance to prolonged freezing and thawing and chloride ion penetration is recommended.

54. Bergstrom, S. G. "Curing Temperature, Age, and Strength of Concrete." *Magazine of Concrete Research (London)* Vol. 5, No. 14 (December 1953): pp. 61-66.

The effects of curing temperature and age on the strength of concrete can be expressed in terms of a single parameter given by the product of age and temperature, as has been suggested by Nurse and Saul. In this parameter, the temperature is reckoned from -10° C, which seems to be a reasonable value of the lowest temperature at which any appreciable increase in strength can take place. In the present paper, the correctness of this assumption is verified by means of check calculations made on previously known test series and on some new Swedish tests. It is to be noted, however, that special precautions must be taken to protect the concrete from freezing during the initial period after placing, and that the humidity of the ambient air must be taken into account. Moreover, the deterioration of concrete subjected to repeated freezing and thawing must be studied as a separate problem.

55. Bergstrom, S. G. "Influence of Frost on the Physical and Mechanical Properties of Concrete." CBI Reports 2nd International Symposium on Moisture Problems in Buildings, Rotterdam, September 10-12, 1974.

Based on the review of literature, the author found that early freezing of newly placed concrete caused permanent damage that would never be healed. This was explained by the concept of ice crystal impressions. While still workable, concrete freezes and ice crystal impressions occur leading to a strength loss of approximately 40 to 50%. It should be noted that the ice crystal impressions remain within the concrete even when thawed or hardened.

The large loss of strength, at a very early stage, is thought to be correlated with the time of set, which is in turn a function of the temperature. It is also explained by the occurrence of three other mechanisms: (1) increased porosity, due to water expansion (9%) when freezing; (2) rupture of aggregate-cement bond or adhesion, which could not be reformed, due to freezing; and (3) crack development as a result of ice-lense formation or of various changes in the concrete volume while freezing or thawing. Crack formation was believed to be a strong contributor to the large strength losses.

Other reports mentioned that factors affecting concrete strength could also affect its other properties among these are modulus of elasticity, thermal expansion and permeability. These properties are markedly changed under the influence of temperatures lower than freezing point. All the changes are connected with the volume of freezeable water in the pore system of the concrete.

56. Berke, N. S. *Microsilica and Concrete Durability*, Transportation Research Board, Washington, D. C., paper no. 870275, January 1988.

The use of silica fume (microsilica) additions to improve the compressive strength and durability of concrete is becoming widespread. In 1985 a large-scale study on the effects of silica fume additions on concrete properties was initiated. In this paper, the effects of water-to-cement ratio (w/c) and silica fume content, at a constant nominal cement factor (CF) of 600 pcy, on compressive strength, freeze-thaw resistance, chloride permeability, electrical resistivity, and corrosion resistance of embedded rebar is addressed.

57. Berwanger, C., and A. F. Sarkar. "Effect of Temperature and Age on Thermal Expansion and Modulus of Elasticity of Concrete." *Journal of the American Concrete Institute* SP 39-1 (October 1973).

The thermal coefficient of expansion and the dynamic modulus of elasticity of concrete have been determined under short-term steady state temperatures, 100 to 150° F (-73 to 66° C). Specimens were cured both saturated and air-dried in the laboratory and tested at 7, 28, 84 days, and at one year.

Thirty-five 3 x 4 x 12-in. (7.6 x 10 x 30.5-cm) concrete prisms were tested for thermal coefficient of expansion. The coefficient of expansion decreased with an increase in the water-cement ratio, increased with age, and was smaller below the freezing point of the concrete. The saturated concrete had lower coefficients of expansion than the air-dried concrete.

Thirty-six 3 x 3 x 12-in. (7.7 x 7.6 x 30.5-cm) concrete prisms were used to determine the dynamic modulus of elasticity. The dynamic modulus of the

saturated concrete increased, while that of the air-dried concrete decreased with age, under normal laboratory temperatures. The modulus also increased with a decrease in the water-cement ratio and with temperature a decrease. There were greater increases in the dynamic modulus below the freezing point, which also decreased with age.

Eighty-four 6 x 12-in. (15.2 x 30.5-cm) control cylinders were tested for compressive strength and the static modulus of elasticity of concrete.

58. Berwanger, C., and A. F. Sarkar. "Thermal Expansion of Concrete and Reinforced Concrete." *Journal of the American Concrete Institute* Vol. 73, No. 52 (November, 1976): pp. 618-621.

The thermal coefficient of expansion of concrete and reinforced concrete have been determined under short-term steady state temperatures, -100 to 150° F (-73 to 66° C). Specimens were cured both saturated and air-dried in the laboratory and tested at 7, 28, and 84 days and at 1 year.

One hundred and twenty-five 3 x 4 x 12-in. (7.6 x 10 x 30.5-cm) reinforced concrete prisms were tested for thermal coefficient of expansion. The coefficient decreased with increase in the water-cement ratio, increased with age, and was smaller below the freezing point of the concrete. The saturated concrete had lower coefficients than the air-dried concrete. Steel reinforcement ranged from 0 to about 5 percent. The coefficient for symmetrically reinforced concrete increased with the steel percentage. For unsymmetrically reinforced concrete, the coefficient for the face at the steel increased and the coefficient for the opposite face decreased with increased steel.

Eighty-four 6 x 12-in. (15.2 x 30.5-cm) concrete control cylinders were tested for compressive strength and static modulus of elasticity of concrete.

59. Biermans, M. B. G. M., K. M. Dijkema, and D. A. De Vries. "Water Movement in Porous Media Towards an Ice Front." *Nature* Vol. 264 (November 11, 1976): pp. 166-167.

In frozen soils water movement toward an ice front can occur, leading to the formation of ice lenses, frost heaving and damage to roads and other structures. During the past decades many attempts have been made to explain the transport phenomena involved, fundamental contributions being made by Everett and Takagim, among others. We present here experimental results on the influence of pressure on ice growth; they accord with thermodynamic theory.

60. Biermans, M. B. G. M., K. M. Dijkema, and D. A. De Vries. "Water Movement in Porous Media Towards an Ice Front." *Journal of Hydrology* Vol. 37 (1978): pp. 137-148.

The influence of pressure on water flow towards an ice front, located above a glass filter, was investigated experimentally at temperatures in the range from 0 to -0.05° C. At constant temperature, pressures of the ice and the water were controlled independently. The former was kept at 1 atm., whilst the latter was lowered stepwise between 1 and 0.2 atm. At a given temperature equilibrium was observed at a pressure difference between ice and water that can be found from a Kelvin-type equation. At a smaller pressure difference water flowed toward the ice, while ice accretion and frost heaving occurred. At a larger pressure

difference melting of the ice and water flow away from the ice front were observed. A simplified description is given of the phenomena occurring in the interfacial layer of water between the ice and the glass filter.

61. Bilodeau, A., G. G. Carette, and V. M. Malhotra. "Resistance of Concrete Incorporating Granulated Blast-Furnace Slags to the Action of Deicing Salts." International Workshop on Granulated Blast-Furnace Slag in Concrete, Toronto, Ontario, Canada, October 1987, pp. 459-483.

    This paper presents the results of an investigation undertaken at CANMET to determine the combined effect of de-icing salts and repeated freeze-thaw cycles on concrete incorporating granulated/pelletized BFS. Eight air-entrained concrete mixtures, each having a ratio of water to cementitious material of 0.55, were made in this investigation. Three granulated/pelletized slags from Canada and the U.S.A. were incorporated into the concrete as a partial replacement for cement. For each slag, the level of cement replacement was 25 and 50% by mass. Test cylinders and prisms were cast to determine the strength properties of concrete; test slabs were cast to determine to combined effect of the de-icing salts and the repeated freeze-thaw cycles. Sawn sections of the test prisms were used to determine the air-void parameters of the hardened concrete.

    Regardless of the percentage and the type of slag used, concrete incorporating slag exhibited considerable more surface scaling than the reference concrete. In general, for concrete containing slag, the surface condition of the slabs after the salt-scaling test corresponded to a scale rating of "moderate." The concrete incorporating 50% slag as cement replacement suffered more surface damage than that incorporating only 25% slag, despite the fact that both concretes had adequate values of the air-void spacing factor, L.

62. Bjegovic, D., D. Mikulic, and V. Ukraincik. "Theoretical Aspect and Methods of Testing Concrete Resistance To Freezing and Deicing Chemicals." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

    Theoretical aspects of concrete resistance to freezing and deicing chemicals are shown in causal terms.

    Different constituents and concreting procedures result in different concretes. Furthermore, environmental influences cause a series of physical processes that are also presented in the paper. These physical mechanisms cause stresses that may result in concrete damages. The second part of the paper contains a survey of methods for testing the resistance of concrete to freezing and deicing chemicals.

    The most common methods are presented in a flowchart showing the advantages and disadvantages of a method and its applicability for a particular structure.

63. Blachere, J. R., and J. E. Young. "Failure of Capillary Theory of Frost Damage as Applied to Ceramics." *Journal of The American Ceramic Society* Vol. 57, No. 5 (May 1974): pp. 212-216.

    The behavior of solid bars of porous ceramics saturated with water was investigated during the freezing and melting of the water. The length change, differential temperature, and temperature were monitored continuously during the experiments. The behavior of the saturated bars during the freezing of water was

analyzed in detail. It was shown that quasi-equilibrium conditions, as assumed by the capillary theory of frost damage, did not satisfactorily describe the results of these experiments because the plasticity of the ice phase is too low to permit pressure equilibriation.

64. Blanks, R. F., and W. A. Cordon. "Practices, Experiences, and Tests with Air-Entraining Agents in Making Durable Concrete." *American Concrete Institute Proceedings* Vol. 45, No. 25 (September 1948 - June 1949): p. 469.

    The authors discuss the advantages of air entrainment with regard to durability, permeability, workability, reduction in alkali expansion, time saving, reduction in water and cement, temperature rise, strength, abrasion resistance, monolithic lightweight concrete and mass concrete. U.S. Bureau of Reclamation experiences are discussed with regard to pumping, transportation and placing, grading of aggregates, factors affecting the among of air entrained. Air-entraining agents and air-entraining cements are discussed briefly. There is a brief section on the measurements of entrained air in concrete with a recommended procedure.

65. Borge, O. E., J. A. Paxton, and R. A. Kaden. "Durability of Vacuum Saturated Concrete and Grout." *Journal of the American Concrete Institute* SP 47-5 (April 1975).

    This paper presents a durability study for concretes and grout with varying air contents that were subjected to both vacuum saturation and freezing and thawing. This adverse condition might simulate years of natural weathering and thus provided the designers with useful information. The investigation proved that air-entrained concrete had better durability than non air-entrained concrete regardless of the degree of saturation. In conclusion, sufficient internal void system (air content) is essential for good durability.

66. Bowman, W. G., P. H. Bates, J. C. Pearson, R. W. Crum, F. E. Richart, and R. B. Young. "Progress with Concrete — 1923-1948." *Journal of the American Concrete Institute* Vol. 44 (April 1948): pp. 693-744.

    Five past presidents of the American Concrete Institute and an editor of engineering periodicals review and evaluate a quarter-century of progress in concrete theory design and practice. Problems of 25 years ago are recalled, and the extent to which they have been solved, discussed. Landmarks of progress are enumerated, today's problems (both new and old) are acknowledged. Difficulties encountered in formulating standards and specifications are reviewed; progressive changes in cement specifications are listed. Suggestions are made for continuing research programs and improved research techniques. Inspection practices are criticized and corrections suggested, the importance of consistency control and air entrainment effect are stressed. The history of alkali reaction studies is outlined. Important steps in structural design and theory are pointed out in some detail, there is a similar emphasis on progress of durability studies, and special mention is made of developments in highway construction.

67. Boyd, D. W. "Weather and the Deterioration of Building Materials." *Durability of Building Materials and Components - ASTM STP 691* (1980): pp. 145-156.

    Early attempts to predict the effects of the weather on the deterioration of building materials were often little more than speculation. The inadequacy of the results is discussed using freeze-thaw cycles and the annual driving rain index as examples.

More precise empirical relationships will have to be based on laboratory or test-site observations and may require special weather analyses such as the humidity tables prepared for a study of corrosion of metals. More complex relationships are being found, and the analysis of the weather often will involve the study of the coincident values of two or more elements. The research scientist should be aware of the weather data now generally available and the types of analyses that could be provided.

68. Brewer, H. W., and R. W. Burrows. "Coarse-Ground Cement Makes More Durable Concrete." *Journal of the American Concrete Institute* Vol. 47 (January 1951): pp. 353-360.

    A test procedure for mortar ring specimens is described. Rings containing coarse-ground cement shrunk less and showed greater resistance to freezing and thawing and to outdoor exposure than those containing fine-ground cement. These laboratory tests indicate that coarse-ground cement produces more durable concrete than fine-ground cement.

69. Browne, F. P., and P. D. Cady. "Deicer Scaling Mechanisms in Concrete." *Journal of the American Concrete Institute* SP 47-6 (April 1975).

    Three experiments were conducted to study the characteristics of the two primary deicer scaling mechanisms in concrete: (1) a hydraulic pressure mechanism, which is strongly dependent upon the degree of saturation and the deicer gradient, and only occurs under freeze-thaw conditions, and (2) a chemical mechanism, which operates between concrete and concentrated calcium chloride solutions. These two mechanisms are completely independent of one another.

    The experiments conducted showed: (1) the absorption of deicers by concrete is directly related to the scaling rate under freeze-thaw conditions; (2) the deicer content in freeze-thaw cycled mortar specimens decreased with increasing depth; and (3) concentrated calcium chloride solutions chemically react with concrete, causing deterioration. The mechanisms presented in the paper serve to explain most of the previous observations that have been made of deicer scaling.

70. Bruere, G. M. "The Relative Importance of Various Physical and Chemical Factors on Bubble Characteristics in Cement Pastes." *Australian Journal of Applied Science* Vol. 12, No. 1 (March 1961): pp. 78-86.

    Air contents, specific surface areas of bubbles, and spacing factors were measured in air-entrained cement pastes in which a number of physical and chemical factors were varied singly. The factors were mixing time, speed of stirrer, water/cement ratio, mixing temperature, type of cement, presence of calcium chloride and the order of adding calcium chloride and a surface-active agent to cement paste. The influence of each variable on bubble characteristics was studied using several different surface-active agents.

    The mixing time, speed of stirrer, and water/cement ratio had very important effects on the specific surface areas of bubbles. Mixing temperature, type of cement, and presence of calcium chloride had only small effects on the specific areas of bubbles. Calcium hydroxide deposits found in some bubbles reduced the effective air content in hardened cement paste but had practically no effect on the spacing factor. The relative abilities of surface-active agents to entrain high

surface area bubbles in cement pastes were not altered by the use of different mixing conditions, water/cement ratios, mixing temperatures, and cements.

71. Buck, A. D. *Investigation of Frost Resistance of Mortar and Concrete*, Concrete Laboratory, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., Technical Report C-76-4, October 1976.

Specimens from 12 mortar mixtures and one concrete mixture were tested for frost resistance by accelerated freezing-and-thawing tests and by dilation, for compressive strength, for freezable water (FW), and for weight changes after each of eight different treatments. One variable of treatment was age of continuous moist curing; the other was age together with cyclic fluctuation of water pressure to simulate the conditions that would affect concrete at a low level in the Eisenhower Lock of the St. Lawrence Seaway. The results of these tests indicated:

(a) The cyclic pressure treatment did not cause critical saturation to develop in most of the test specimens, including those most like the concrete in the Eisenhower Lock. Therefore, changing water levels presumably would not have developed critical saturation of the concrete in the lock.
(b) The concrete mixture which simulated the concrete in Eisenhower Lock with the large aggregate removed was frost resistance.
(c) The usual relationships between frost resistance and variables of age, compressive strength, water cement (w/c) ratio, and air content were apparent.
(d) The amount of air needed to obtain maximum frost resistance of the mortars increased with increasing w/c ratio to a maximum of about 9 percent air for a w/c ratio of 0.8 by weight.
(e) The data indicated that FW is not a useful index of frost resistance for air-entrained mortar or concrete mixtures.
(f) Frost resistance increases with increasing age as the w/c ratio increases.
(g) Dilation testing provides a sensitive measure of the frost resistance of mortar and concrete. Dilation testing could be a useful adjunct to accelerated freezing-and-thawing tests of concrete to provide more information on the relation of environmental influences and frost resistance.

72. Buck, A. D., B. Mather, and H. T. , Jr. Thornton. *Investigation of Concrete in Eisenhower and Snell Locks, St. Lawrence Seaway*, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, technical report no. 6-784, July 1967.

Some concrete in the filling and emptying culverts' walls and elsewhere in Eisenhower Lock has deteriorated, requiring extensive repairs. This type of deterioration has not been noted to any extent at Snell Lock, built at about the same time. The known differences regarding the concrete portions of these locks are: (a) they were built by different contractors; (b) in the Eisenhower concrete, 25% by weight of the portland cement was replaced by natural cement.

Observations were made in the field; samples were taken from both structures and subjected to a wide variety of tests and examinations; concrete varying in relevant factors was made and tested; relevant literature was studied; views of other workers in concrete technology were considered.

From these extensive explorations, it was concluded that deterioration of the Eisenhower concrete resulted from the unprecedentedly severe exposure conditions to which it was subjected before it had matured sufficiently to resist them. These severe conditions were saturation of the concrete due to submergence during the navigation season; exposure of the saturated areas to very severe freezing on termination of navigation during early winter; and continuation of these conditions, which permitted freezing to progress for several feet. The immaturity of this concrete resulted from use of natural cement which matures slower than portland cement. However, when the Eisenhower and Snell Locks were designed, there were no data indicating that a degree of maturity greater that that attained by the Eisenhower concrete was required to resist the environmental exposure.

73. Bunke, D. *Evaluation of Ohio Test Road for D-Cracking*, Ohio Dept. of Transportation, Columbus, Ohio, March 22, 1990.

D-cracking has been noted to be a serious problem in the deterioration of concrete pavements in Ohio. A plan was developed to determine the seriousness of D-cracking and to study the influence of drainage and pavement design. Field surveys and a laboratory study were conducted, and a full-scale test road was constructed, varying material combinations and drainage mechanisms in each section. Field surveys have been conducted annually, and cores have occasionally been taken for study since construction in 1974. This has resulted in a useable plan note, requiring testing for D-cracking susceptibility of larger sized aggregates if used in concrete paving. It appears that reducing the maximum aggregate particle size reduces the susceptibility to D-cracking, and therefore, increases the pavement's durability. Initially, it appeared that the various drainage mechanisms had no effect on origination of D-cracking, but this project has been continued for additional study of the drainage mechanism effects.

74. Burg, G. R. U. "Slump Loss, Air Loss, and Performance of Concrete." *Journal of the American Concrete Institute* Vol. 80, No. 4 (July-August 1983): pp. 332-339.

Field and laboratory experience demonstrates that when concrete loses slump, there is generally a loss of entrained air content. Results obtained from tests made in conjunction with a large concrete roadway and parking lot paving project may give the answer to the often asked question, "Is slump loss due to the loss of air, or is air loss due to the loss of slump?" The purpose of these tests was to study the accuracy of current recommendations for durable concrete pavement, the history of air-entrained pavement-type concrete as it matures from the time it was freshly mixed to after it has been in service for several years, and the degree of confidence that can be expected when using Standard ASTM Test Methods to obtain certain selected concrete qualities. Tests were made on randomly selected truckloads of freshly mixed concrete at three different times: 1) at the central mix plant, "as mixed," 2) at the job site, "as received," and 3) at the job site, "as retempered."

The concrete was adjusted for slump at the job site by retempering with water. Samples of hardened concrete from test cylinders and cores cut from hardened concrete pavement were microscopically analyzed. A comparison of all test data obtained from loads of freshly mixed concrete and from hardened concrete are presented, indicating the concrete's qualities as it matures over a three-year period. The coefficient of variation and standard deviation were calculated for each series of tests conducted on the concrete.

75. Burge, T. A. "Fiber Reinforced High-Strength Shotcrete with Condensed Silica Fume." Second CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Madrid, Spain, April 1986, pp. 1153-1170.

The addition of condensed silica fume increased the strengths and sharply reduced the permeability. The resistance to freezing and thawing was also greatly improved. No long-term strength loss was obtained owing to the use of a new alkali-free setting accelerator.

76. Buth, E., D. L. Ivey, and T. J. Hirsch. "Dirty Aggregate, What Difference Does It Make?" *Highway Research Record* No. 226 (1968).

The effects of clay in concrete fine aggregate on the properties of concrete are presented and discussed. The two most generally used tests, the loss by decantation and sand equivalent tests, are examined. The ability of these tests to measure the observed effects of the clay fraction of an aggregate on the properties of concrete is illustrated.

The concrete properties under study were water requirement, strength, shrinkage and freeze-thaw durability. Both the quantity and activity of the clay fraction were found to be influential. Increases in quantity and activity of clay cause both increases in water requirement and shrinkage and decreases in strength and durability. Because of the influence of the activity of the clay fraction, the sand equivalent test is the better indicator of the effect on concrete of the clay fraction of an aggregate.

77. Buth, E., and W. B. Ledbetter. "The Importance of Moisture Absorption Characteristics of Lightweight Coarse Aggregate." *Highway Research Record* No. 226 (1968).

Lightweight coarse aggregates from five sources commercially available in Texas were selected for investigation. All aggregates selected were structural lightweight aggregates produced from shale by the rotary kiln process.

The absorption characteristics of the aggregates, including total absorption and absorption rate, were studied. Concretes incorporating the five aggregates were subjected to repeated freezing and thawing (ASTM C290), and the results were compared to the aggregate absorption characteristics. The results demonstrate that the concretes that incorporated aggregates that have high absorption capacities and/or absorb water at a rapid rate are susceptible to freeze-thaw damage.

78. Buth, E., and W. B. Ledbetter. "Influence of the Degree of Saturation of Coarse Aggregate on the Resistance of Structural Lightweight Concrete to Freezing and Thawing." *Highway Research Record* No. 328 (1970): pp. 1-13.

Six commercially produced and 7 TTI kiln-produced lightweight coarse aggregates were used in 69 batches of lightweight concrete. These batches of concrete, containing the aforementioned coarse aggregates, air entrainment, Type 1 cement, and natural sand, were mixed and subjected to freezing and thawing in accordance with ASTM C 290. Absorption characteristics and porosity values were determined for each of the aggregates. Various degrees of saturation of the coarse aggregate at the time of mixing were obtained by immersing the aggregates

in water for periods ranging up to 180 days prior to mixing. The results indicate a failure envelope exists between the number of freeze-thaw cycles failure and the degree of saturation of the coarse aggregate. The "critical" degree of saturation by volume was found to be 0.25 , below which the concrete will generally withstand 300 cycles of freeze-thaw. It was also determined that some of these aggregates reached this initial saturation after only 30 minutes of immersion, while other aggregates had to be immersed for several days before becoming critically saturated. The practical implications of the test results are discussed.

79. Cabrera, J. G. "Use of Fuel Ash to Produce Durable Concrete." *Improvements in Concrete Durability* (1986): pp. 29-46.

    A review of the variations in the properties of pulverized fuel ashes (pfa) produced in the U.K. is given. Important aspects of the mix design of pfa concrete are highlighted and the properties related to the morphology of the concrete analyzed with reference to its performance. It is suggested that by controlling the porosity and pore size distribution of a pfa concrete its performance can be enhanced and thus its durability improved. Examples are given of the performance of pfa-concrete subjected to various aggressive environments.

80. Cady, P. D. "Mechanisms of Frost Destruction in Concrete." Ph.D. diss., Pennsylvania State University, 1967.

    Since considerable evidence exists to support the hydraulic pressure theory of frost action in concrete and since somewhat less, but still impressive, evidence shows the presence of a second phenomenon related to non-freezable water, the thesis proposed here is that at least two basic mechanisms are involved in the destructive process. Further, it is proposed that these mechanisms are intimately related to some basic characteristics of the rock. These characteristics will dictate which mechanism is predominant in any given case. Additionally, it is intended to probe the nature of these characteristics that are detrimental for each of the two mechanisms and to present experimental and theoretical support in each case.

81. Cady, P. D. "Mechanisms of Frost Action in Concrete Aggregates." *Journal of Materials (JMLSA)* Vol. 4, No. 2 (June 1969): pp. 294-311.

    The hydraulic pressure theory proposed by Powers and the adsorbed water theory recently advanced by Dunn and Hudec to describe the destructive mechanisms of frost action on concrete aggregates were investigated. These two theories were in direct opposition regarding the state of the water during the period in which the coarse aggregate underwent destructive volume change. Nine aggregate fractions of known and widely varying durability were subjected to adsorption tests. Differential thermal analyses were performed on concrete specimens containing the test fractions to determine the degree of freezability of the evaporable water content. Expansion (dilations) of the test specimens were also obtained during the DTA runs. Multiple correlation analyses of the test variables and detailed examination of the changes in heat evolution and specimen length during cooling revealed that Powers' hydraulic pressure mechanism was the major contributor to destructive volume change. However, the existence of the mechanism proposed by Dunn and Hudec was consistently in evidence. The latter mechanism, generally, was a minor contributor to the destructive volume change, but for one of the test aggregates it was the major effect. Thus, it was concluded that at least

two basic mechanisms were involved in the frost destruction of concrete aggregates.

82. Cady, P. D. "Soundness Testing and Durability of Coarse Aggregates in Concrete." *Cement, Concrete, and Aggregates* Vol. 6, No. 1 (Summer 1984): pp. 43-46.

Throughout its long history, sulfate soundness testing of aggregates has been frequently cited for poor reliability as a predictor of concrete durability. However, its use remains widespread, even to the point of constituting an acceptance test criterion for aggregates. Sodium sulfate soundness tests of coarse aggregates are compared in this paper with freezing and thawing tests of air-entrained concretes containing the aggregates. In one case, sodium sulfate soundness displayed a relationship to durability (freezing and thawing) test results, in a statistical sense, but the level of predictability was poor. In another test series, the level of predictability fell within the range of pure chance. The attractiveness of sulfate soundness testing is apparently derived from its simplicity and directness. However, it is shown in this paper that a combination of two aggregate property tests, specific gravity and absorption, provide a better predictor of freezing and thawing durability. Furthermore, these two tests are routinely run on aggregates and are even simpler than the sulfate soundness test.

83. Callan, E. J. "Thermal Expansion of Aggregates and Concrete Durability." *Journal of the American Concrete Institute* Vol. 48 (February 1952): pp. 485-504.

Differences in durability of concretes containing aggregates from the same source and similar concretes containing different fine and coarse aggregates are explained partially by differences in the thermal expansion of the coarse aggregate and the mortar. Methods were developed to obtain simple the thermal coefficients for numerous aggregates. Concretes were tested in accelerated freezing and thawing, yielding durability factors.

84. Campbell, L. "Aggregates and Fly Ash Concrete for Barley Lock." *ASCE* Vol. 87, No. 1 (1961): pp. 1-16.

Although the advantages of the use of a pozzolanic material, in this case fly ash, in concrete were known in 1912, the extensive use of this material for large structures is relatively new.

This paper presents an actual account of the field handling of aggregates and the mix data and test results of fly-ash concrete for Barkley Lock, Kentucky. Methods and equipment necessary for the separation of Ohio River sand into various sieve fractions, reworking of certain sieve fractions, and recombining of the fractions for the completed sand are outlined in detail. Physical and chemical tests for the fly ash are listed as well as trial and final concrete mixes and physical tests of the concrete.

85. Carette, G. G., and V. M. Malhotra. "Mechanical Properties, Durability, and Drying Shrinkage of Portland Cement Concrete Incorporating Silica Fume." *Cement, Concrete and Aggregates* Vol. 5, No. 1 (Summer 1983): pp. 3-13.

Portland cement is a highly energy-intensive material, therefore, considerable effort is being made to find substitutes for partially replacing cement in concrete. Silica fume, a byproduct in the manufacture of ferrosilicon and silicon metal is one possible substitute. Results are given of a preliminary investigation to

determine the strength, freezing and thawing characteristics, and drying shrinkage of concrete incorporating various percentages of silica fume.

Eighteen 0.06-m^3 air-entrained concrete mixes were made incorporating 0 to 30% silica fume as a partial replacement for cement. Some mixes were proportioned to have constant slump with water to cementitious materials ration (w/c + s) ranging from 0.64 to 0.84 whereas others were proportioned to have a constant w/c + s of 0.4; the latter incorporated a superplasticizer. Cylinder and prism specimens were cast for determining the mechanical properties and durability of concrete.

Test data indicate that silica fume when used in concrete as a partial replacement for cement performs as a highly efficient pozzolanic material. Notwithstanding the extreme fineness of silica fume (20,000 m^2/kg) and, hence, its high water demand, the compressive strength of constant slump concrete incorporating up to 30% silica fume is comparable with or higher than the strength of control concrete.

Superplasticized concrete mixes having a w/s + s maintained at 0.40 indicate some increase in compressive strength at all ages regardless of the percentage of silica fume.

Concrete prisms incorporating 0 to 15% silica fume (w/c + s = 0.40) perform satisfactorily when subjected to 300 cycles of freezing and thawing; however, prisms incorporating 20 to 30% silica fume and large dosages of superplasticizer show excessive expansion and relatively low dynamic moduli after 300 cycles. The drying shrinkage of concrete incorporating silica fume is generally comparable with that of control concrete regardless of the w/c + s.

86. Carles-Giberques, A., J. Grandet, and J. P. Olivier. "Contact Zone Between Cement Paste and Aggregate." *Bond in Concrete*, Applied Science Publishers, London, 1982. pp. 24-33.

The purpose of this communication is to describe some characteristics of the Portland cement paste hydration in the contact zone. The influences of additions such as fly ash, silica fume, slags, on the morphology of the aureole are analyzed.

87. Carlson, R. W. "Concrete as an Architectural Material - Remarks on Durability of Concrete." *Journal of the American Concrete Institute* Vol. 35 (April 1939): pp. 359-364.

A statement of factors affecting the durability of concrete; the fatigue action of volume changes produced by changes in temperature and moisture; the freezing of water in the pores of concrete; the phenomenon of bleeding; the thermal and elastic properties of the constituents of concrete are presented. Emphasis is placed on the need for test methods that will permit more accurate prediction of durability.

88. Carrasquillo, P. M. "Durability of Concrete Containing Fly Ash for Use in Highway Applications." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

The effect of fly ash content on the air entrainment, freeze-thaw durability, abrasion resistance, strength gain, shrinkage, and creep of concrete was studied.

Two different fly ashes were used to replace 0, 20, and 35 percent of a portland cement, by weight. A blended cement, containing 20 percent fly ash by weight, was also tested. Three different air entraining admixtures were used.

It was found that the use of fly ash in concrete could reduce the effectiveness of air-entraining admixtures depending on the properties of the fly ash such as loss on ignition (LOI). However, concrete containing fly ash exhibited freeze-thaw resistance equal to or better than that of similar concrete containing portland cement only, provided both had similar entrained air contents. Similarly, concrete containing fly ash showed equal or better resistance to abrasion when compared to concrete of equal strength containing no fly ash.

89. Carrier, R. E., D. C. Pu, and P. D. Cady. "Moisture Distribution in Concrete Bridge Decks and Pavements." *Journal of the American Concrete Institute* SP 47-8 (April 1975).

In the course of performing field surveys of bridges for a bridge deck durability study, it was noted in some instances that the type of forms used to construct the decks appeared to influence deterioration and cracks. Fewer cracks and apparent increases in mortar deterioration were observed on decks formed with stay-in-place (SIP) forms than for those with conventional removable forms. It was felt that the differences in deterioration, particularly surface mortar deterioration, were due to differences in the moisture content in the two types of deck slabs.

The stacked disc technique that had been used previously by Penn State researchers was employed to determine possible differences in twin Interstate 80 (I-80) bridge decks in central Pennsylvania (one with SIP forms, the other conventionally formed). Using this technique, moisture content and distribution were observed in each deck.

Observations indicate that the SIP formed decks have a higher moisture content than do conventionally formed decks. However, the overall moisture content of both bridges was much lower than that for a pavement slab observed in an earlier study. This is somewhat surprising if one considers that generally deterioration is much more severe on bridge decks than on pavements. Data for the entire survey period are presented as well as some data from the previous pavement study.

90. Cebeci, O. Z. "Pore Structure of Air-Entrained Hardened Cement Paste." *Cement and Concrete Research* Vol. 11 (1981): pp. 257-265.

The effect of air entrainment on the pore structure of hardened cement paste was investigated. Air-entrained and air-free samples of various water-cement ratios and ages were prepared by a well-defined procedure. The first and second-intrusion pore-sized distribution curves of the samples were determined by mercury intrusion porosimetry. It was observed that sample preparation technique affects the pore-size distributions of hardened cement pastes. The second-intrusion curves indicated a decrease in the total volume and a reduction in the size of pores that are uniform in cross section with decreasing age and water: cement ratio. The second-intrusion curves of air-entrained and air-free pastes of equal water:cement ratio and age matched with each other. It was concluded that air entrainment introduces only large air voids observable by a naked eye and does not alter the characteristic fine pore structure of hardened cement paste appreciably.

91. Chalmers, B., and K. A. Jackson. *Experimental and Theoretical Studies of the Mechanism of Frost Heaving*, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, report no. 199, October 1970.

This paper discusses the Jackson and Chalmers theory of frost heave and describes attempts to verify it experimentally. The theory takes into account the local thermal conditions in the soil and the permeability of the soil. The theory predicts (or explains) stationary ice lens formation, where there is no advance of the frost line, and also predicts a rate of heave that is independent of the rate of advance of the freezing front. The theory assumes that a soil can be represented by a single characteristic void size although in real cases soils are not as uniform and homogeneous as assumed. Several experiments to verify the theory are described. They were generally unsuccessful, neither disproving nor substantiating the theory.

92. Cheng-Yi, H., and R. F. Feldman. "Dependence of Frost Resistance on the Pore Structure of Mortar Containing Silica Fume." *Journal of the American Concrete Institute* Vol. 82, No. 5 (1985): pp. 740-743.

Mortars prepared at water to cement and silica fume [w/(c +sf)] (0, 10, and 30 percent by weight) ratios of 0.45 and 0.60 were assessed for resistance to freeze-thaw cycles. Pore size distribution was measured by mercury intrusion, and reintrusion experiments were performed after distillation of mercury. Results indicate that addition of silica fume changes the pore structure, and that pore volume in the pore size ranges of 20,000 to 2000 and 200 to 35 nm increases, whereas accessibility to the pore decreases. Frost resistance of mortars containing no entrained air and prepared at a w/(c + sf) ratio of 0.60 was improved greatly with the addition of silica fume.

93. Cheng-Yi, H., and R. F. Feldman. "Influence of Silica Fume on the Microstructural Development in Cement Mortars." *Cement and Concrete Research* Vol. 15 (1985): pp. 285-294.

Cement mortars containing 0, 10, and 30 percent silica fume were prepared at water/cement + silica fume ratios of 0.45 and 0.60. Compressive strength, $Ca(OH)_2$ and non-evaporable water contents and pore-size distribution were monitored up to 180 days. Silica fume reacts with most of the $Ca(OH)_2$ formed during hydration within 28 days and improves the compressive strength of the mortar. In addition it affects the pore-size distribution of mortars by reacting with $Ca(OH)_2$ formed around the sand grains and also with that dispersed throughout the cement paste.

94. Collins, A. R. "The Destruction of Concrete by Frost." *Journal of the Institution of Civil Engineers (London)* Vol. Paper No. 5412 (1944): pp. 29-41.

Good concrete is a durable material with a satisfactory resistance to the various forces that cause disintegration. Failure or severe damage has generally been traceable to unusual combinations of circumstances or to some chemical or physico-chemical agency. Examples of the latter are acid- and sulphate-bearing waste and salts used to remove ice from roads. The disintegration of concrete by the action of weather and alone has normally been found to be slow and is seldom of a serious nature.

Under wartime conditions, with the necessity for speed of construction and shortages of suitable labour and materials, it has not always been found possible to apply normal peacetime standards, and concrete of very low quality has sometimes been produced.

Those responsible have usually been well aware of the low quality of the concrete, but no data have been available to show how far the normal requirements for durability could be relaxed without causing trouble. Unfortunately, the winter of 1941-42 was particularly severe and in some instances serious frost failures occurred.

95. Collins, W. "Pozzo-crete." Seventh International Ash Utilization Symposium and Exposition, Orlando, FL, 1985, pp. 329-341.

ASTM-defined Class C fly ash has cementitious properties in addition to its pozzolanic properties. Pozzo-crete is the name given to concrete made with Class C fly ash as the primary cementing material together with small amounts of portland cement. This paper presents the work carried out on pozzo-cretes using several different fly ashes at high percentages of cement replacement. Trial batches of pozzo-crete with varying amounts of fly ash and cement were made to determine the properties such as strength, freeze-thaw durability, and sulphate resistance. The excellent results obtained prompted the use of pozzo-crete in pavement and parking lot constructions. It is concluded that although pozzo-crete cannot replace conventional concrete in all applications, there are instances where the use of pozzo-crete does have its place, especially from a cost-benefit relationship. It is suggested that pozzo-crete is suited for the following areas: parking lots, driveways, median interiors, exterior slabs, drainage ditches, and footings.

96. Cook, H. K. "Permeability Tests of Lean Mass Concrete." *American Society for Testing Materials — Proceedings* Vol. 51 (1951): pp. 1156-1165.

The use of air entrainment in mass concrete for large dams has made it possible to place concrete with cement factors as low as two bags per cu yd. Adequate strengths can be obtained with such concretes under relatively high hydrostatic pressures. The design and operation of permeability test equipment for testing 14 1/2-diam by 15-in. cylindrical specimens at a pressure of 200 psi is described. Permeability coefficients of specimens representing nine air-entrainment concretes containing 2 1/2-in. aggregate but with water-cement ratios equal to those for full mass mixes with 6-in. aggregate and with cement factors of from 2.00 to 3.00 bags per cu yd are reported after testing at ages of 3 months, 1 yr, and 18 months. Plans for testing at later ages and for the testing of other specimens are described.

97. Cordon, W. A. "Freezing and Thawing of Concrete — Mechanisms and Control." American Concrete Institute Monograph No. 3, Detroit, MI: American Concrete Institute, 1966.

A discussion is given on the deterioration of concrete exposed to freezing and thawing. Also the indication of freezing thawing deterioration by D-line cracking, scaling, deterioration of portland cement paste and pattern cracking is presented.

Further discussions below on the mechanism of freeze-thaw deterioration due to critical saturation, structure of portland cement paste, freezing in capillaries;

generation of hydraulic pressures, diffusion and freezing of gel water in capillaries, and osmotic pressures.

The influence of concrete aggregates on durability is also discussed under such topics as: elastic accommodation, critical size of the aggregate, accretion of water from surrounding paste, and expulsion of water from concrete aggregate into portland cement paste.

Methods for producing durable concrete include the following:

1. Produce high quality portland cement paste by limiting the amount of water in proportion to cement used in the concrete mix.
2. Use only high quality aggregates that have satisfactory performance records.
3. Use the proper amount of air-entraining agent to produce an air-bubble spacing that will relieve hydraulic pressures and reduce the growth of capillary ice.
4. Prevent rapid drying of pavement surfaces, and never give a final finish to a concrete slab until bleeding has stopped.

The following "do" and "don't" recommendations have been compiled for improved concrete construction and control methods. Perhaps only one or two of these items would apply to freezing and thawing deterioration under any given set of conditions, but all are considered good, workable practices.

1. Entrain 4 to 6 percent air in all exposed concrete that may be saturated in freezing weather.
2. Avoid concrete aggregates having high absorption.
3. Use the minimum amount of mixing water possible, commensurate with good construction practices.
4. Avoid saturation of exposed concrete in freezing weather.
5. Be sure the hydration of portland cement is well advanced before concrete is subjected to freezing and thawing.
6. Prevent rapid drying of the surface of exposed concrete before the bleeding is complete.
7. Do not finish the surface of exposed concrete until bleed water has disappeared.
8. Avoid the use of salts for ice or snow removal.
9. After curing, allow exposed concrete to dry as much as possible; then seal the surface.
10. Provide adequate drainage for all exposed concrete surfaces.

98. Cordon, W. A., and D. Merrill. "Requirements for Freezing-and-Thawing Durability for Concrete." *ASTM Proceedings* Vol. 63 (1963): p. 1026.

Specification requirements for concrete durability have not changed commensurate with increased knowledge and research developed during the past 20 years.

This paper is a short review of current thinking on the causes of concrete deterioration due to freezing-and-thawing action. Laboratory test results made with a wide variety of materials and mix proportions are reported. A method for arriving at required cement contents and air contents based on required strength and required durability is discussed.

99. Craven, M. A. "Sand Grading Influence on Air Entrainment in Concrete." *Journal of the American Concrete Institute* Vol. 20, No. 3 (November 1948): pp. 205-215.

Four series of mixes with varying air-entraining agents, cement factors, and sand grading and content were prepared in order to observe sand grading effect on concrete. A graphic record is presented of air content and w/c plotted against fineness modulus of sand; flow and compressive strength plotted against fineness modulus of sand; and air content plotted against percent of No. 30-No. 50 sand and total sand percentage. Generally the percentage of air entrained in concrete increased with a decrease in fineness modulus of sand. Quantity of air appears to be a function of the quantity of No. 30-No. 50 sand. The effect of grading and quantity of sand on other properties of fresh and hardened concrete is noted.

100. Crumpton, C. F., B. J. Smith, and G. P. Jayaprakash. "Salt Weathering of Limestone Aggregate and Concrete Without Freeze-Thaw." *Transportation Research Record* No. 1250 (1989): pp. 8-16.

Kansas aggregates are frequently alkali reactive or subject to D-cracking when used in concrete. The use of deicing salt, usually halite (NaCl) in Kansas, makes those problems worse. Salt allows the concrete to become wet and to stay wet longer, increasing the time for reactions to occur. Clays in limestone aggregates have been altered by deicing salt solutions remaining in the aggregates. Degraded illite changed to soduim montmorillonite. Quartz has been altered by electric currents induced in the concrete. Some quartz took on an optical property, undulatory extinction, that is frequently associated with potential alkali reactivity. Salt (NaCl) scaling of concrete blocks and slabs without freeze-thaw has been observed. Monitoring salt water movement through the walls of concrete cups has provided insight on how and where slat water moves in concrete. The salt water movement and deposition of salt crystals has caused considerable scaling of both the cement paste and the limestone aggregates of the concrete. The salt corrodes the limestone aggregates and cement paste, attacking the most accessible and most susceptible parts first. Particles as large as 0.6-in. have scaled from limestone aggregates. Most of the scaled flakes are oatmeal size and no larger than 0.2 in in length. A silane "sealer" did not prevent salt water from moving through the limestone aggregates in the concrete cups. All three cups treated with silane cracked on the first salt treatment cycle (five days filled with salt water, emptied, soaked in plain water, then nine days of air drying). Untreated cups did not crack even after 12 cycles. No freeze-thaw was involved.

101. Day, R. L., R. C. Joshi, B. W. Langan, and M. A. Ward. "Evaluation of a Foam Test to Assess Air-Entraining Agent Requirements in Concretes Containing Fly Ash." ACI-RILEM Symposium '85: Technology of Concrete When Pozzolans, Slags, and Chemical Admixtures Are Used, Monterrey, Mexico, 1985, pp. 89-102.

Generally, for a given target air content the air-entraining agent (AEA) requirement in concretes varies widely. The foam test was developed for provide a rapid assessment of the AEA demand for a given fly ash-cement combination. This paper presents a laboratory study undertaken to determine the efficiency of the foam test. The tests are conducted with the following parameters varied: type of fly ash and cement, replacement level, type of admixture, length and degree of agitation of the foaming solution, effect of temperature, and effect of sample size. The results show that this test method is effective in estimating the relative AZEA demand for cement-fly ash-water combinations. The foam test is also found to be relatively insensitive to factors such as speed and duration of agitation,

temperature, and sample size. Good correlation is found between the foam index and the AEA requirement to produce 6.5 percent air in laboratory concrete mixes.

102. "D-Cracking Pavements - Causes Are Understood but Treatment Choices are Few." *Materials and Technology Engineering and Science* No. 24 (October 1988).

This article describes the causes and factors influencing D-cracking of concrete pavements. It was stated that coarse aggregates causing D-cracking included sedimentary materials such as limestone, dolomite, shale, sandstone, and greywacke. The list also included aggregates with low permeability, high porosity, and small pore size.

The availability of continuous moisture within pavements containing such aggregates promote D-cracking. Saturation of the aggregate pores takes place and when freezing occurs internal pore pressure develops leading to cracks in the particles and in the mortar as well. Repeated freezing and thawing cycles contribute to more crack development.

To ameliorate the quality of poor aggregates, the following techniques were adopted:

1. Reduction of coarse aggregate particle size.
2. Separation of harmful particles by means of heavy media (liquids).
3. Blending harmful aggregates with more durable aggregates.

Size reduction method is believed to be the most promising approach. Reduction of the aggregate's maximum size is thought to significantly improve frost resistance of some materials. The author, however, sees the best approach is testing a range of maximum size from each aggregate source. This will determine the largest acceptable maximum size from each source. Yet, more information is needed in terms of maintenance and rehabilitation of D-cracked pavements.

103. Decker, E. A. "Chemical Admixtures for Concrete." *ACI Materials Journal* Vol. 86, No. 3 (May-June 1989): pp. 297-327.

This sixth report of ACI Committee 212, now named "Chemical Admixtures for Concrete," updates the previous reports of 1944, 1954, 1963, 1971 and 1981. Admixtures discussed herein are those known as chemical admixtures; finely divided mineral admixtures have been transferred to ACI Committee 226. Admixtures are classified into five groups: (1) air-entraining; (2) accelerating; (3) water-reducing and set-controlling; (4) admixtures for flowing concrete; and (5) miscellaneous. Preparation and batching, which had a separate chapter in the 1981 report, are included here in Chapter 1. Chapter 5, "Admixtures for Flowing Concrete," is new, representing technology that has matured since 1981. Any of those admixtures possessing properties identifiable with more than one group are discussed with the group that describes its most important effect on concrete.

104. Delage, P., and P. C. Aitcin. "Influence of Condensed Silica Fume on the Pore Size Distribution of Concretes." *Industrial and Engineering Research* Vol. 22 (1983): pp. 286-290.

Condensed silica fume is a quite new pozzolanic material used in concrete. It is composed of very fine spherical glassy spheres of quite pure silica, a hundred times finer than cement particles. It is known that condensed silica fume

increases the compressive strength and decreases the permeability of concrete in a very spectacular manner. This action has always been related to the pozzolanic reaction. In this paper it is shown that the action condensed silica fume results also not only in the closing of most of the pores of the concrete having a diameter between 0.05 and 0.5 μm but also in a decrease of the size of the micropores. This physical action, in addition to the chemical one previously advanced, can explain more completely the beneficial action of this very reactive pozzolan on the concrete properties.

105. Demirel, T., B. W. Gunnink, B. V. Enüstün, and K. L. Bergeson. *Development of a Conductometric Test for Frost Resistance of Concrete, Final Report*, Iowa State University, Engineering Research Institute, Iowa DOT Project HR-272, ERI Project 1775, ISU-ERI 87-410, January 31, 1988.

This report describes the research completed under the research contract entitled "Development of a Conductometric Test for Frost Resistance of Concrete" undertaken for the Iowa Highway Research Board. The objective of the project was to develop a test method which can be reasonably and rapidly performed in the laboratory and in the field to predict, with a high degree of certainty, the behavior of concrete subjected to the action of alternate freezing and thawing. The significance of the results obtained, and recommendations for use and the continued development of conductometric testing are presented in this final report.

In this project the conductometric evaluation of concrete durability was explored with three different test methods. The test methods and procedures for each type of test as well as presentation of the results obtained and their significance are included in the body of the report. The three test methods were:

1) Conductometric evaluation of the resistance of concrete to rapid freezing and thawing,
2) Conductometric evaluation of the resistance of concrete to natural freezing and thawing, and
3) Conductometric evaluation of the pore size distribution of concrete and its correlation to concrete durability.

The report also includes recommendations for the continued development of these test methods.

106. DePuy, G. W. "Freeze-Thaw and Acid Resistance of Polymer-Impregnated Concrete." *Journal of the American Concrete Institute* SP 47-11 (April 1975).

The developmental program for concrete-polymer materials has shown polymer-impregnated concrete (PIC) to have significantly improved durability and structural properties as compared with conventional concrete. Laboratory test show PIC outlasts conventional air-entrained concrete more than 10 times as long in the Bureau's freeze-thaw test and two or more times as long in exposure to acid. Acid resistance can be further increased by doubly coating the specimen with polymer to improve surface sealing. The Bureau tests are customarily evaluated on a weight loss basis, and other criteria would be helpful to evaluate durability and to shorten test times. A series of tests were performed to measure compressive and tensile strength, dynamic modulus of elasticity, length change,

ultrasonic pulse velocity, and weight loss of specimens during the course of the tests.

107. Detwiler, R. J., B. J. Dalgleish, and R. B. Williamson. "Assessing the Durability of Concrete in Freezing and Thawing." *ACI Materials Journal* Vol. 86, No. 1 (January-February 1989): pp. 29-35.

Concretes subjected to cycles of freezing and thawing can deteriorate rapidly unless they are designed properly for these conditions. Standard tests are used to determine the suitability of a particular concrete for service under cycles of freezing and thawing. However, in these tests, failure takes place by a different mechanism than would occur in service. It may be possible to obtain a better prediction of the actual performance of the concrete in service by including an examination of the microstructure of the air-void system as part of the test procedure. Scanning electron micrographs of two concretes exposed to the same environmental conditions illustrate this point.

108. Dhir, R. K., K. Tham, and J. Dransfield. "Durability of Concrete With a Superplasticizing Admixture." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

The experimental work proved that superplasticized concrete specimens possessed greater durability than the normal concrete specimens, with the difference between two corresponding mixes increasing as the design strength of concrete increases.

The improved freeze-thaw durability exhibited by the superplasticized, normal-workability, was a result of the following:

- Higher air content
- Favorable air bubble size and distribution
- Improved morphology of the hydration products and the micropore system of the concrete.

Permeability tests showed that superplasticized concrete, for a given w/c ratio and strength, recorded lower air and water permeability.

109. Dhir, R. K., and A. W. F. Yap. "Superplasticized high-workability concrete: some properties in the fresh and hardened states." *Magazine of Concrete Research* Vol. 35, No. 125 (December 1983): pp. 214-228.

The paper describes the first stage of a wide-ranging investigation into superplasticized high-workability concrete. The properties studied were, in the fresh state, flow characteristics, stability (bleeding and segregation) and air content and, in the hardened, compressive strength (both early and subsequent up to 90 days) and drying shrinkage. A ranking order of the superplasticizers used was obtained, together with proposals on the flow and segregation behavior in response to variations in cement content and sand grading. The bleeding of the superplasticized high-workability concrete was found to be higher, and the air content generally lower, than for the corresponding normal concrete. Compressive strength was found to be generally of the same order as that of normal concrete, whilst drying shrinkage was higher for the superplasticized high-workability concrete.

110. Dobrolubov, G., and B. Romer. "Applied Microscopy in Building Materials Testing." *Leitz Company Publications* pp. 135-144.

Microscopy can reveal the fine structure of a body. This makes it possible to recognize the intrinsic relations especially with heterogeneous and anistropic substances.

The microscopic structural investigation is evaluated quantitatively with corresponding stereological evaluation, as well as qualitatively, i.e., purely morphologically.

This report is confined to the relations in the microstructure of a substance, distinguishing between the main components such as:

Cementing agents in hardened form
Aggregates and fillers
Cavities (capillaries, pores, cracks).

The article does not claim to be comprehensive in the description of all possibilities. It outlines the simplest and most useful principle of investigation for practicing building experts. The main emphasis lies on the description of the methods of investigation used by the author within the last 5 years.

The report does not describe in detail the purely microscopically analytical procedure; it is confined to the discussion of the relations of component analysis in the microscope with regard to the image differentiation required for this, as well as the relation to the qualitatively morphological assessment.

111. Dolar-Mantuani, L. "Soundness and Deleterious Substances." ASTM STP 169B (1978).

During the past 100 or more years many tests have been developed and applied to assess the quality of concrete aggregates. This paper is a discussion of the significance of five aggregate quality tests currently in use. One of them, the sulfate soundness test (ASTM Test for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate C88), is perhaps the most widely used of all methods for determining the overall quality of aggregate. The other four tests are used to determine the presence of specific harmful particles or substances which influence the mix proportions of fresh concrete or its early stage hardening, or which damage the concrete surface under specific circumstances.

112. Dolch, W. L. *Significance of Tests and Properties of Concrete and Concrete-Making Materials*, American Society for Testing and Materials, Porosity, ASTM STP-169B (Chapter 37), 1978. pp. 646-656.

Most of the important properties of concrete aggregates are influenced strongly by the volume and dimensions of the internal pore system of the material. These properties include density, strength, absorption, and freeze-thaw resistance.

The purpose of this article is to discuss the parameters related to the pore system of an aggregate, the methods for their measurement, and the properties of the aggregate and concrete they so strongly influence. Many of these topics were covered in earlier papers of which this the successor. It is not intended to repeat details needlessly, but to emphasize subsequent developments.

113. Dolen, T. P. "The Use of Fly Ash Concrete for Upper Stillwater Dam Roller-Compacted Concrete." Seventh International Ash Utilization Symposium and Exposition, Orlando, FL, 1985, pp. 613-639.

This paper discusses the design, construction concepts, and concrete materials investigations of roller-compacted concrete (RCC) used in the Upper Stillwater Dam, which is being constructed in Utah. The unique design of the dam and severe climatic conditions at the site required the use of high-strength concrete with a low heat-generating capacity. This was accomplished with a 75 percent replacement of cement with fly ash in the concrete mix design. Properties of RCC were determined from laboratory studies of mortar and concrete and from testing cores extracted from a field test placement. Extensive mix design studies were conducted including tests to determine compressive and tensile strengths and elastic properties, creep, tensile and shear strength of joints, adiabatic temperature rise, diffusivity, thermal expansion, density, permeability, drying shrinkage, and freeze-thaw resistance. Analysis of the results of the above tests and the guidelines arrived at, for the design and construction of RCC are presented.

114. Dubberke, W., and V. J. Marks. *The Effect of Deicing Salt on Aggregate Durability*, Iowa Dept. of Transportation, Ames, Iowa, Progress Report, Project HR-266, January 1985.

The Iowa DOT has been using rapid freezing in air and thawing in water to evaluate coarse aggregate durability in concrete since 1962. Earlier research had shown that the aggregate pore system was a major factor in susceptibility to D-cracking rapid deterioration.

There are case were service records show rapid deterioration of concrete containing certain aggregates on heavily salted primary roads and relatively good performance with the same aggregate in secondary pavements with limited use of deicing salt. A five-cycle salt treatment of the coarse aggregate prior to durability testing has yielded durability factors that correlate well with aggregate service records on heavily salted primary pavements. X-ray fluorescence analyses have shown that sulfur contents correlate well with aggregate durabilities with higher sulfur contents producing poor durability. Trial additives that affect the salt treatment durabilities would indicate that one factor in the rapid deterioration mechanism is an adverse chemical reaction.

The objective of the current research is to develop a simple method of determining aggregate susceptibility to salt related deterioration. This method of evaluation includes analyses of both the pore system and chemical composition.

115. Dubberke, W., and V. J. Marks. "Evaluation of Carbonate Aggregate Using X-Ray Analysis." *Transportation Research Record* No. 1250 (1989): pp. 17-24.

Iowa has more than 13,000 miles of portland cement concrete (PCC) pavement. Some pavements have performed well for over 50 years, while others have been removed or overlaid due to the premature deterioration of joints and cracks. Some of the premature deterioration is classical D-cracking, which is attributed to a critically saturated aggregate pore system (freeze-thaw damage). However, some of the premature deterioration is related to adverse chemical reactivity involving carbonate coarse aggregate. The objective of this paper is to demonstrate the value of a chemical analysis of carbonate aggregate using X-ray equipment to identify good or poor quality. At least 1.5 percent dolomite is necessary in a

carbonate aggregate to produce a discernible dolomite peak. The shift of the maximum-intensity X-ray diffraction dolomite d-spacing can be used to predict poor performance of a carbonate aggregate in PCC. A limestone aggregate with a low percentage of strontium (less than 0.013) and phosphorus (less than 0.010) would be expected to give good performance in PCC pavement. Poor performance in PCC pavement is expected from limestone aggregates with higher percentages (above 0.050) of strontium.

116. Dubberke, W., and V. J. Marks. "The Relationship of Ferroan Dolomite Aggregate to Rapid Concrete Deterioration." *Transportation Research Record* No. 1110 (1987): pp. 1-10.

Some of Iowa's 13,200 miles of portland cement concrete (pcc) pavements have remained structurally sound for more than 50 years, while others have suffered premature deterioration. Research has shown that the type of coarse aggregate used in the pcc is the major cause of this premature deterioration. Some coarse aggregates for concrete exhibit a nonuniform performance history. They contribute to premature deterioration on heavily salted primary roadways while providing long maintenance-free life on unsalted secondary pavements. This inconsistency supports the premise that there are at least two mechanisms that contribute to the deterioration. Previous research has shown that one of these mechanisms is a bad pore system. The other is apparently a chemical reaction. The objective of this research is to develop simple rapid test methods to predict the durability of carbonate aggregate in pcc pavements. X-ray diffraction analyses of aggregate samples have been conducted on various beds from numerous quarries producing diffraction plots for more than 200 samples of dolomitic or dolomite aggregates. The crystalline structures of these dolomitic aggregates show maximum-intensity dolomite/ankerite peaks ranging from a d-spacing of 2.884 angstroms for good aggregates to a d-spacing of 2.914 angstroms for nondurable aggregates. If coarse aggregates with known bad pore systems are removed from this summary, the d-spacing values of the remaining aggregates correlate well with expected service life. This may indicate that the iron substitution for magnesium in the dolomite crystal is associated with the instability of the ferroan dolomite aggregates in pcc pavement.

117. Dubberke, W., and V. J. Marks. *The Relationship of Ferroan Dolomite Aggregate to Rapid Concrete Deterioration*, Iowa Highway Research Board, Research Project HR-266, January 1987.

The objective of this research is to develop simple rapid test methods to predict the durability of carbonate aggregate in PCC pavement.

X-ray diffraction analyses of aggregate samples have been conducted on various beds from numerous quarries producing diffraction plots that form more than 200 samples of dolomitic or dolomite aggregates. The crystalline structures of these dolomitic aggregates show maximum intensity dolomite/ankerite peaks ranging from a d-spacing of 2.884 angstroms for good aggregates to a d-spacing of 2.914 angstroms for non-durable aggregates. If coarse aggregates with known bad pore systems are removed from this summary, the d-spacing values of the remaining aggregates correlate very well with expected service life. This may indicate that the iron substitution for magnesium in the dolomite crystal is associated with the instability of the ferroan dolomite aggregates in PCC pavement.

118. Dunn, J. R., and P. P. Hudec. *The Influence of Clays on Water and Ice in Rock Pores*, New York State Department of Public Works, Report No. RR65-5, 1965.

Unique quantitative cold differential thermal analysis (electrocalorimetric) equipment has been constructed at Rensselaer Polytechnic Institute for the purpose of studying one phase of the nature of water and ice in rock pores. The temperature of freezing, the heat of freezing and the nature of freezing of water in rock can be systematically analyzed for the first time with this unit. The DTA (differential thermal analysis) equipment is capable of detecting the freezing of 0.001% water in an average 40 gram rock sample or a temperature differential of 0.001C.

The construction and calibration of the DTA equipment and corrections for variations of heat of freezing of water with number of degrees of supercooling and for variations of specific heat and conductivity are described in detail.

Typical temperature differential traces are described and interpreted.

119. Dunstan, M., and R. Joyce. "High Fly Ash Content Concrete: A Review and a Case History." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

Concretes containing large quantities of fly ash have now been used in the UK and elsewhere for ten years. This type of concrete, which has become known as high fly ash content concrete (HFCC), was originally developed as a roller-compacted concrete for dams. The mix proportions of HFCC are designed considering the fly ash to be an integral ingredient in the concrete as opposed to a portland cement replacement.

The uses of HFCC have now been extended to road construction and structural concrete, including high-workability and high-strength concretes. Throughout the development of HFCC, testing of the concrete in situ has been considered to be of paramount importance in addition to the usual laboratory trials. This paper traces the development of HFCC and considers a particular case history in which a direct comparison was made, over a period of four years, between two airfield pavements. One pavement contained conventional portland cement concrete and the other high fly ash content concrete. The results of testing for cube and core compressive strength and flexural strength are presented together with the results of a limited number of test of the 4-year old pavement for durability. The paper concludes that in this particular case, both pavements exhibited comparable strength and durability characteristics generally, although the HFCC pavement seemed to have better weathering and abrasion resistance as well as a significant economic advantage.

120. Edwards, A. L. "Numerical Model for Saturated-Unsaturated Flow in Deformable Porous Media: 2. The Algorithm." *Water Resources Research* Vol. 14, No. 2 (April 1978): pp. 255-261.

An integrated finite difference algorithm is presented for numerically solving the governing equation of saturated-unsaturated flow in deformable porous media. In recognition that stability of the explicit equation is a local phenomenon a mixed explicit-implicit procedure is used for marching in the time domain. In this scheme the explicit changes in potential are first computed for all elements in the system, after which implicit corrections are made only for those elements for

which the stable time step is less than the time step being used. Time step sizes are automatically controlled in order to optimize the number of iterations, to control maximum change in potential during a time step, and to obtain desired outputs. Time derivatives, estimated on the basis of system behavior during two previous time steps, are used to start the iteration process and to evaluate nonlinear coefficients. Boundary conditions and sources can vary with time or with the dependent variable. Input data types of truncation errors, and convergence errors. The algorithm constitutes an efficient tool for analyzing linear and nonlinear fluid flow problems in multidimensional heterogeneous porous media with complex geometry. An important limitation is that the model cannot conveniently handle arbitrary anisotropy and other general tensorial quantities.

121. Enüstün, B. V., B. W. Gunnink, W. Dubberke, and T. Demirel. *Frost Action in Rocks and Concrete*, Iowa State University, Engineering Research Institute, Iowa DOT Project HR-258, ERI Project 1648, April 30, 1986.

The objectives of the project were to develop methodologies for (i) prediction and measurement of the magnitude of pressure which develops within pores of saturated porous materials upon freezing; (ii) determination of pore structure (pore size distribution) of porous materials; (iii) prediction and measurement of the rate with which pore ice grows; and (iv) prediction of frost susceptibility of porous materials with varying pore structures.

As with all research endeavors the solution of one problem leads to another one and this project was no exception. Emergence of new problems and the measures taken as the work progressed were discussed in progress reports submitted to the board. This final report will discuss only the conclusive finds and suggest measures to be taken for future investigations. The theory discussed in the proposal is not repeated in this report for the sake of brevity. However, the paper published as part of this project containing the theory is attached as Appendix I for the reader interested in the theory. In conformity with the objectives, this report consists of four parts.

122. Enüstün, B. V., K. S. Soo, and K. L. Bergeson. "Frost Susceptibility of Concrete in Near-Saturated States." *Journal of Materials in Civil Engineering* (October 1991).

A two-stage freezing model is proposed for concrete at a near-saturated state. The first-stage involves a mechanism considered by Powers, while the second-stage is based on the plastic ice theory due to Everett. The volumetric consequences of this model checked by dilatometry do not perfectly materialize, since the pore-air is not compressible enough as assumed in Powers' theory. Experiments qualitatively confirm the expected critical dependence of frost damage on saturation level. The role of air entrainment in minimizing the frost damage in the field is explained partly by its retardation of the second-stage-freezing by increasing the compressibility of the gas phase, but mainly by lowering the rate of saturation. Experiments also confirm that the dilatometric expansion on freezing is a measure of significant damage as predicted by the proposed model. On grounds of this observation, a simple immersion expansion test is tentatively proposed to evaluate field-frost-susceptibility of concrete. It is based on dilatometric measurements during freezing. The results appear to be promising.

123. Everett, D. H. "The Thermodynamics of Frost Damage to Porous Solids." *Transactions of the Faraday Society* Vol. 57 (1961): pp. 1541-1551.

The thermodynamics of the formation of "ice lenses" in porous materials is discussed in relation to experience and experiment on the damage caused by frost to roads and building materials. Qualitatively the theory is in accordance with known facts, but a precise quantitative correlation is difficult partly because of the complexity of porous materials and partly because of lack of a reliable value for the surface tension of ice. Studies of ice lens formation using simple apparatus might, however, provide a method of determining the surface tension of ice.

124. Fagerlund, G. "Critical Moisture Contents at Freezing of Porous Materials." Second International CIB/RILEM Symposium on Moisture Problems in Buildings, Rotterdam, September 1974, Swedish Cement and Concrete Research Institute.

The frost resistance of a material is a function of the materials and the environmental properties. The materials properties are expressed in a critical degree of saturation. This cannot be exceeded during one single freezing without risk of substantial damage. The environmental properties are expressed in an actual degree of saturation. Its value depends on the way of using the material. The frost resistance is then defined as the difference between the critical degree of saturation and the actual degree of saturation. This approach has many advantages such as:

- Rapid and general freeze-test method is made possible.
- Consideration can be taken to different ways of using the material.
- Quantification of frost resistance, which facilitates rational materials choice.
- Better understanding of relations between materials properties and frost resistance.
- Clarification of the many obscurities connected to the problem of frost resistance.

125. Fagerlund, G. *The Critical Degree of Saturation Method of Assessing the Freeze-Thaw Resistance of Concrete*, RILEM Committee 4 CDC. Swedish Cement and Concrete Research Institute.

This report gives detailed descriptions of the methods of assessing the critical degree of saturation, the method of assessing the capillary degree of saturation, and calculation of the freeze-thaw resistance. Also included are detailed instructions and formulae as well as a practical example.

126. Fagerlund, G. *The International Cooperative Test of the Critical Degree of Saturation Method of Assessing the Freeze-Thaw Resistance of Concrete*, RILEM Committee 4 CDC. Swedish Cement and Concrete Research Institute, 1975.

Experimental work was conducted in 5 different laboratories to determine both the critical degree of saturation (SCR) and the capillary degree of saturation (SCAP).

SCR was determined by multi-cycle freezings and thawings of sealed specimens while SCAP was found by the capillary water uptake. It should be noted that specimens were made of concrete with or without air-entraining agents.

The test results showed that the air-entrained concrete was more durable than the non air-entrained concrete. For both concretes, however, the deviations in SCR and SCAP obtained were small. The freeze-thaw resistance, defined as the difference between SCR and SCAP, was nearly the same at all laboratories. Values of SCR obtained from the dilatometric measurements were similar to the values obtained in the main test. This showed the usefulness of one cycle freeze-thaw in determining SCR. Also, the results of the air-pore analysis were in agreement with the results obtained at all laboratories. The spacing factor was found higher than critical for non air-entrained concrete but lower than critical for air-entrained concrete.

127. Fagerlund, G. "The Significance of Critical Degrees of Saturation at Freezing of Porous and Brittle Materials." *Journal of the American Concrete Institute* SP 47-2 (April 1975).

The paper treats the problem "Frost Resistance," as a general problem for all porous materials. The basis is the undeniable fact that well defined critical degrees of saturation exist for all porous materials.

The difference between the new way of defining critical degree of saturation (as a materials constant) and the usual way (as functions of a combination of properties of material and environment) is discussed. The method of determination is shown and discussed.

Possible definitions of moisture conditions are provided.

By comparison of the critical degree of saturation and the actual reached in practice the frost resistance can by expressed by a plain figure, which makes a rational choice of material possible. The method is exemplified. A method of determination of the actual water content is shown. Hypotheses are put forward as regards frost resistance of layered structures or particle composites and frost resistance through the use of thawing salts.

On the basis of the hydraulic pressure theory, connections between materials' properties and critical degree of saturation are derived. Measurements of amount of ice formed, rate of ice formation and length changes together with estimations on temperature-permeability relations show the reasonableness of the hydraulic pressure theory. Connections between pore properties and actual degree of saturation are discussed.

128. Fagerlund, G. "Studies of the Destruction Mechanism at Freezing of Porous Materials." The 6th International Congress on Problems Raised by Frost Action, CBI Reports, Fondation Francaise d'Etudes Nordiques, Le Havre, April 23-25, 1975.

The value of the critical degree of saturation was proved to be individual for each type of materials. It was also proved that the number of freezings and thawings have no or very little effect on the degree of saturation as long as the specimens were sealed.

When freezing in the presence of deicing agents, more severe damage of specimens was observed. Experience showed the existence of a pessimum concentration of deicing agent that gave more damage than lower or higher concentrations. In the case of NaCl, the pessimum concentration ranged from 3 to

5% and 12% concentration for $CaCl_2$. However, the damage of this latter was of a chemical nature.

The author concluded that the critical degree of saturation was a function of the salt concentration of pore water. Insofar as the actual degree of saturation was concerned, it was discovered that at constant temperature, there was no significant influence of salt concentration on the degree of saturation. Whereas temperature cycling (-18° C to +5° C) gave higher values of saturation for salt solutions than for pure water. Further studies were made on other parameters in conjunction with freezing. These parameters included critical distances, defined as the thickest completely water-saturated materials' volume that may freeze without damage. Critical distances were the critical spacing between air-pores in cement paste and the critical size of concrete aggregates. It is stated that a relation existed between critical distance and critical air content as well as air bubble size.

129. Faulkner, T., and R. D. Walker. "Rapid One-Cycle Test for Evaluating Aggregate Performance When Exposed to Freezing and Thawing in Concrete." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

Previous work demonstrated that carefully monitored length change measurements during the first freeze period of a concrete specimen containing the aggregate being evaluated show a "fingerprint" that can be successfully correlated with the "Durability Factor" that is obtained after many later cycles of freezing and thawing. Six different coarse aggregates were used in this study to (1) further substantiate the conclusions of the previous work and to (2) attempt to shorten the test evaluation procedure from eight to three days. The slope of the cumulative length change vs. temperature and the length change vs. time curve of the first freeze cycle near the freezing point of water was used as the "finger print." Although attempts to shorten the procedure by using a boiling water accelerated curing procedure were considered successful, it was recommended that other methods of accelerating early strengths be attempted. The tests indicated that the procedure was satisfactory for screening aggregate durability factor.

130. Fears, F. K. "A Study of the Air-Void Characteristics of Hardened Concrete." Ph.D. diss., Purdue University, January 1957.

Thirty-eight beams from nineteen mixes were used to study the correlation between each of the five air-void characteristics and durability. These beams had shown varying degrees of durability as measured by resistance to deterioration in laboratory freezing and thawing tests. Durability factors were used to express the durability of each of these beams. The five air-void characteristics ranked in the order of their correlation with durability beginning with the one showing the best correlation are: (1) spacing factor, (2) specific surface, (3) number of voids per inch, (4) hypothetical number of voids per cubic inch, and (5) total air content.

The spacing factor and the specific surface were found to be of almost equal importance in producing durable concrete. Hence, either of these two characteristics may be used as a criterion for determining the air requirements for frost-resistant concrete.

131. Feldman, R. F. "Dependence of Durability of Mortars on and Sand/Cement Ratio and Microsilica (Silica Fume) Addition." *Durability of Building Materials* Vol. 4, No. 2 (1986): pp. 137-149.

Cement mortars containing 0% and 10% silica fume were prepared with a water/(cement + silica fume) ratio of 0.60 and 0.70. Sand/cement ratios of 0, 0.5, 1.0, 1.5, 1.8, 2.0, 2.25 and 3.0 were used. Results indicate a large increase in frost resistance for specimens with 10% silica fume plus (sand)/(cement + silica fume) ratio of > 2.25 at w/(c + sf) of 0.60, with the greatest resistance for a sand/(cement + silica fume) ratio of 3.0. The improved frost resistance was attributed to the formation of pores in the 97,000 - 875 nm range at the sand-cement interface.

132. Feldman, R. F. "Influence of Condensed Silica Fume and Sand/Cement Ratio on Pore Structure and Frost Resistance of Portland Cement Mortars." Second CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Madrid, Spain, April 1986, pp. 973-989.

Pore-structure changes in silica fume portland cement blend mortars fabricated with 0, 10, and 30% silica fume at a water/binder ratio of 0.60 and a sand/cement ratio of 2.25 have been monitored by mercury porosimetry while being cured for 1 to 180 days. The threshold value for pore intrusion increases with pore size and becomes less abrupt with silica fume addition; it is in the 0.5 to 20 x 10 cubic nm region.

Mortars were also made with and without 10% silica fume at a water/cement ratio of 0.60 and sand/cement ratios of 0, 1.0, 1.5, 1.8, 2.0, 2.25, and 3.0; the sand passed ASTM C 109. Mercury intrusion measurements were carried out after 14 days of curing. In the presence of silica fume, pore volume in the 0.5 to 20 x 10 cubic nm pore diameter range increased with sand/cement ratio. Mortar prisms were subjected to freezing-and-thawing cycles (two cycles in 24 h) according to ASTM standard test method C 666, Procedure B. Freezing-and-thawing resistance was monitored by measuring changes in residual length and weight. Results indicate that if the sand/cement ratio is 2.25 or more, expansion is less than 0.02% after 500 cycles. At lower sand/cement ratios, 10% silica fume gives little protection.

133. Feldman, R. F. "Pore Structure Formation During Hydration of Fly Ash and Slag Pastes." Editor S. Diamond, Symposium N Proceedings, pp. 124-134. Boston: Materials Research Society, 1981.

Three mixes, a reference cement, one fly-ash blend containing 35% fly-ash, and one with 70% slag, were cured in water at 21, 35 and 55C at a w/c = 0.45. After 2, 7, 14, 28, 90, 180, 365 and 550 days $Ca(OH)_2$ content, porosity, pore size distribution, compressive strength, Young's modulus and microhardness of the products were determined. The logarithms of these mechanical properties were plotted against porosity. Higher temperature increased the rate of reaction of the reference cement for up to two days, then retarded it. This acceleration period was considerably extended for the cement blends. Mechanical properties at zero porosity were generally improved in blends hydrated at room temperature; and all blends had a finer pore and lower $Ca(OH)_2$ content than the cement specimen.

134. Feldman, R. F. "Pore Structure Damage in Blended Cements Caused by Mercury Intrusion." *Journal of American Ceramic Society* Vol. 67, No. 1 (1984): pp. 30-33.

Hydrated blast furnace slag and fly ash cement blends have been shown to be very impermeable. Porosity measurements of these materials by methanol and helium pycnometry have been less than the values obtained by Hg intrusion to 410 MPa. Results of the three techniques for hydrated portland cement were the same. A technique was used in which mercury could be removed by distillation after Hg intrusion, and intrusion was then repeated. This was performed on several cements and cement blends. Pore-size distribution for the hydrated cement changed marginally but both blended materials changed markedly, displaying a coarser pore distribution. It was concluded that the latter bodies are composed of relatively large, but discontinuous pores, into which Hg enters by breaking through the pore structure.

135. Feldman, R. F., and J. J. Beaudoin. "Pretreatment of Hardened Hydrated Cement Pastes for Mercury Intrusion Measurements." *Cement and Concrete Research* Vol. 21 (1991): pp. 297-308.

Porosity is one of the major factors controlling durability and strength of hydrated cement products. A measure of pore size distribution of these materials is more definitive and can lead to a basic understanding of many phenomena occurring within the material. An accurate measurement of this is, however, difficult to obtain. Hg intrusion porosimetry to 414 MPa was used in this work to measure the pore size distribution of cement pastes prepared at water/cement ratio of 0.8, 0.6 and 0.45. Specimens were predried before intrusion measurements by several techniques including solvent replacement with methanol or isopropanol, evacuation and/or heating for various periods and conditioning at 11% RH. Second Hg intrusions were also performed to investigate the effects of first intrusion. It was concluded that it is not possible to obtain an actual pore size distribution of cement paste by Hg intrusion because of its sensitivity to stress.

136. Fredlund, D. G., J. K. Gan, and H. Rahardio. *Measuring Negative Pore-Water Pressures in a Freezing Environment*, University of Saskatchewan, Saskatoon, Saskatchewan, Canada, paper no. 910505, January 1991.

The measurement of negative pore-water pressures in essential to the study of soil behavior in a freezing environment. Various devices are now available for suction measurements in unfrozen, unsaturated soils. The possibility of using these devices, in particular the thermal conductivity sensor, in the measurement of negative pore-water pressures under freezing conditions is discussed in the paper.

The thermal conductivity sensor appears to be the most promising device for suction measurement in non frozen soils. The thermal conductivity method of suction measurement in a freezing environment is examined. The theory of freezing soil and the thermal properties of soil are presented. Suction measurements in a freezing environment using thermal conductivity sensors from recent tests conducted at the University of Saskatchewan are also presented. The results are interpreted in the light of the theory of freezing soil and the thermal properties of soil. The latent heat of fusion associated with the water phase transformation of water has significant influence on the thermal conductivity reading of the sensor during freezing and thawing. The formation of ice on

freezing makes the interpretation of sensor reading difficult due to the significantly higher thermal conductivity of ice to that of water.

137. Frohnsdorff, G., and L. W. Masters. "The Meaning of Durability and Durability Prediction." *Durability of Building Materials and Components*, ASTM STP 691 (1980): pp. 17-30.

The concept of durability is not well defined. The term durability is often used to imply the possession of qualities associated with long-life. In some standards for building components, it is nonquantitative and implies that design requirements are likely to be exceeded for the design service life or some other specified period. The new ASTM Recommended Practice for Developing Short-Term Accelerated Tests for Prediction of the Service Life of Building Components and Materials (E 632 - 78), is outlined. The application of the recommended practice to service life prediction is illustrated by an example for work being planned on a protective coating for steel.

138. Fujiwara, T. "Deterioration of Concrete Used in Road Bridges Due to Freezing and Thawing." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

Concrete structures in the northern regions of Japan have a higher risk of deterioration due to freezing and thawing coming from the cold climate and heavy snows. The laboratory evaluation of resistance of concrete to freezing and thawing is studied actively in Japan, but there is still much left to be studied hereafter about the deterioration of concrete structures exposed in the field.

A survey of the deterioration of concrete used in road bridges was made in Iwate Prefecture, a district in Northeastern Japan, where there are many place with different climatic conditions. Over three hundred bridges were examined.

The majority of bridges observed in this study were in greater or lesser degree damaged by freezing and thawing. The degree of deterioration differed according to the different parts of the bridge. Although the main cause of deterioration is presumed to be the result of poor construction, it can be pointed out that the lack of consideration for design of these structures adds significantly to their deterioration.

The degree of deterioration also depends on regional climatic conditions. In this report, the relation between the degree of observed deterioration and the climatic conditions are discussed.

139. Gaidis, J. M., and A. M. Rosenberg. "New Test for Determining Fundamental Frequencies of Concrete." *Cement, Concrete and Aggregates* Vol. 8, No. 2 (Winter 1986): pp. 117-119.

The standard methods for determining fundamental frequencies of concrete specimens (ASTM Test Method for Fundamental Transverse, Longitudinal and Torsional Frequencies of Concrete Specimens [C 215]) can be markedly improved by using modern electronic equipment. In the new method, a small accelerometer pickup senses the vibrations of a concrete specimen after it is lightly struck, and a spectrum analyzer portrays the information in the frequency domain. The main advantages of the new method are speed, ability to test small specimens, and no noise; the chief disadvantage is higher equipment cost.

140. Gebler, S. H., and P. Klieger. "Effect of Fly Ash on the Air-Void Stability of Concrete." First CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete, Montebello, Canada, 1983, pp. 103-142.

Concretes containing both portland cement and fly ash were evaluated to determine the effect of fly ash on air-void stability. Ten fly ashes with a wide range of chemical and physical properties as well as geographical origins were used.

Air contents of plastic concretes were determined, and both air content and air-void parameters were measured in hardened concretes cast at four time intervals after initial mixing. These tests indicate that air contents containing Class C fly ash appear to be more stable than those in concretes containing Class F fly ash. The higher the organic matter content of fly ash, the higher will be the air-entraining admixture requirement, the greater is the air loss on extended mixing. Even though the air volume is reduced, the spacing factor, specific surface, and number of voids are little affected.

A "Foam Index" was determined for each of the ten fly ash-portland cement combinations. Air-entraining admixture requirements of actual concretes containing both portland cement and fly ash were compared to the "Foam Index" test results. These tests indicate that the "Foam Index" could be especially useful to concrete producers as a quality control test for checking the air-entraining admixture requirements requirements for different sources of lots of fly ash.

141. Gebler, S. H., and P. Klieger. "Effect of Fly Ash on the Durability of Air-Entrained Concrete." Second CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Madrid, Spain, 1986, pp. 483-519.

In this investigation, concretes containing fly ash were evaluated to establish the effect of fly ash on freeze-thaw resistance, resistance to deicer scaling, and chloride ion penetration. The effects of low-temperature curing and moisture availability during curing were also evaluated. These tests indicated that the freeze-thaw resistance of air-entrained concrete was reduced by the use of certain fly ashes when cured at low temperature. For other conditions, there was no significant influence of fly ash. Deicer scaling resistance tests showed that air-entrained concrete without fly ash generally performed somewhat better than concrete with fly ash, regardless of the type of curing provided. Air-entrained concretes made with some fly ashes were as resistant to chloride ion penetration as air-entrained concrete without fly ash. The class of fly ash did not significantly influence the degree of chloride ion penetration.

142. Gee, M. "Understanding Microsilica Concrete." *The Construction Specifier* Vol. 39, No. 12: pp. 44-50.

New types of materials that dramatically improve concrete are currently being used by producers of concrete and concrete products. Generally, these materials are composed of a high percentage of active silica and have an extremely fine particle size. An example of this type of material is condensed silica fume. The addition of microsilica to concrete can dramatically improve concrete strengths, durability, and impermeability, allowing concrete to be used in ways never before possible.

143. Gilkey, H. J. "The Autogenous Healing of Concretes and Mortars." *American Society for Testing Materials, Proceedings* Vol. 26 (1926): pp. 470-487.

To place the phenomenon of autogenous, or self, healing of portland cement concretes and mortars in the category of fully known and usable engineering knowledge would require an investigation much more comprehensive than that here recorded. The chemical action involved has been described by Abrams as a probable deposition of soluble compounds in and across cracks caused by overloading. Some have recorded instances of cracks actually disappearing and not re-appearing under subsequent increased loading.

The present tests do not touch the chemical aspects of autogenous healing. They cover mortars and concretes tested for ultimate compressive strength at various ages and re-tested from one to five times in a period up to eight months in some cases. Consideration is given to the following general range of variables and conditions: water-cement ratio varied; diameters of sand particles varied; variable curing conditions prior to first test at 28 days (part time in air); some variation of proportions; some variation in the kinds and gradings of aggregates. Mortar specimens were largely of 2 by 4-in. in size and concretes were all 6 by 12 in. All but one series were very accurately controlled laboratory mixtures. That series was on field samples taken from rather poorly controlled job concrete.

Enough tests were made on specimens dry between test and retest to clearly indicate that except for a slight strength gain due to drying out, specimens do not heal autogenously unless kept moist. No data on these preliminary tests appear in the paper. The general conclusion from all the tests made is that autogenous healing action follows the same general law as uninterrupted strength gain from continuous moist curing. Specimens salvaged without much visible damage will often develop later strengths approximately 100 per cent of what they would have had without previous tests. Healing takes place to some extent in even badly shattered specimens, but the strength may never attain that at the former test. Strong specimens (rich in cement, low in water, old or well cured) shatter so badly at ultimate load that few and often none can be salvaged for retest. The percentage recovery for such specimens is much lower than that for weak ones but the cause probably lies in the greater damage at former test. Mixtures as lean and as wet as those commonly used will often recovery fully, under moist curing, ... following test or over-stress from other cause. In these tests there was no apparent disappearance of the cracks from former test and failure usually continued along the same general lines as it started at the former test. The fact that only a few months, at most, elapsed between test and retest might account for the non-disappearance of cracks. To adequately detect the disappearance of visible cracks, they should be carefully marked immediately after test. This was not done.

144. Gilkey, H. J. "The Tensile Autogenous Healing of Portland Cement Mixtures." *American Society for Testing Materials, Proceedings* Vol. 29 (1929): pp. 593-610.

In a former paper there were recorded considerable data upon compressive autogenous healing of portland cement mortars and concretes. It was evident that, if compressive healing occurred, there must be tensile healing, since tensile, compressive and shearing resistance are, in general, but varied manifestations of the same thing. While a preliminary test referred to in the earlier paper failed to produce evident of it, subsequent experiments have shown that tensile autogenous

healing is a reality for mixtures of portland cement and water, with or without aggregate of usual accepted kinds. Healing occurs under the same conditions as initial moist curing and is essentially but a continuation or a resumption of the normal curing processes. It is evidently not in the least due to redeposition of soluble salt in cracks, as has been sometimes supposed. Standard tensile briquets of widely varying water-cement and cement-sand ratios (from 0.20 to 1.20 and from neat cement to 1:5, respectively) have been completely severed as many as six times at initial test ages of from 3 days to 27 months. All mixtures and conditions have shown measurable healing. Individual recoveries range from zero to 221 lb. at 3.5 months for a neat cement specimen initially testing 248 lb. at 3 days. Severed fragments must be closely fitted, but the amount of pressure between the halves appears to be unimportant if the crack be kept closed. Healing will occur upon re-immersion after months of drying out. It occurs in either running or stagnant water. In general the extent of healing is less after each successive retest, although there were many individual exceptions. The majority of the specimens gave no strength at the fifth or sixth breaking, although many carried a few pounds.

Knowledge of tensile healing is of practical use in various connections and in addition it should contribute to a better understanding of concrete. The healing is not related to an interesting form of crack closure that often appears in sidewalks. This crack closure may be related to the surface disappearance of cracks in air-exposed concrete as noted by Abrams, Earley and Hollister.

145. Gillott, J. E. "Effect of Deicing Agents and Sulphate Solutions on Concrete Aggregate." *Q. Jl. Engng. Geol.* Vol. 11 (1978): pp. 177-192.

The durability of portland cement concrete is adversely affected by deicing agents and sulphate solutions. Sodium chloride and calcium chloride are the commonly used deicing agents — salts thrown on roads and other pavements to help ice melt in winter. Sulphates are common in soils and clays in Britain, Europe, the Middle East, western North America and elsewhere, while chlorides and sulphates are also present in sea-water. Scanning electron micrographs of limestones (used quite commonly as aggregate in concrete) show that the surfaces of limestones scale and disintegrate when soaked in solutions of sodium chloride, calcium chloride and magnesium sulphate. The morphology of both calcite and dolomite is changed, but calcite is attacked most rapidly, the progress of the reactions being observed to be controlled by cleavages and grain boundaries; the morphological results depend on the angle between the plane of weakness and the surface. Some limestones show dimensional change during continuous soaking in salt solutions at constant temperature. The adverse effect on concrete durability of deicers and sulphate solutions may thus result from attack on limestone aggregate as well as on cement paste.

146. Giovambattista, A., and L. Traversa. "Durability of Basaltic Aggregates Contaminated with Montmorillonite." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

Contamination of basaltic rocks with clays of the montmorillonite group causes the expansion and failure of the rocks when exposed to moisture changes. When these rocks are used as concrete aggregates contamination may produce concrete degradation. In Argentina, there are some bridge structures affected by this process. The present paper considers some results obtained by the use of different tests used for basaltic aggregates evaluation and a decision criterium is proposed.

147. Girard, R. J., E. W. Myers, G. D. Manchester, and W. L. Trimm. "D-Cracking: Pavement Design and Construction Variables." *Transportation Research Record* No. 853 (1982): pp. 1-9.

Reported map cracking and D-cracking problems observed on portland cement concrete (PCC) pavements in Missouri from the late 1930s to 1981 are briefly discussed. Investigations involving studies in the laboratory and constructed pavements have contributed significantly to a better understanding of the deterioration process and its cause. Type, characteristics, and maximum size of coarse aggregate; source of cement; design of concrete mix; and type of base have been or are being studied in the field or laboratory to determine their influence to frost susceptibility of concrete. Missouri has increased the service life of its PCC pavements. This has been accomplished by (a) not using river and glacial gravels in construction of PCC pavements and (b) subjecting limestones that have a known history of D-cracking problems to increased quality restrictions, which has resulted in some ledges and entire quarries and formations being eliminated. However, D-cracking remains and, in terms of required maintenance and service life, is still a problem.

148. Gjørv, O. E. "Durability of Concrete Containing Condensed Silica Fume." *Journal of the American Concrete Institute* , No. SP79-36 (July/August 1983).

It has been found that the addition of 20 percent silica fume by weight of cement to a concrete with only 100 kg cement per cubic meter of concrete gives the same permeability as that of concrete with 250 kg cement containing no silica fume. Frost resistant concrete can be produced using silica fume. A 15 percent replacement of cement (OPC) by silica fume show durability similar to sulfate resisting portland cement exposed to sulfate solutions. Silica fume binds up the alkalis of the cement and reduces the detrimental alkali-silica reaction. Addition of 10 to 20 percent silica fume does not reduce the pH to a level lower than that of a saturated $Ca(OH)_2$ solution. The electrical resistivity of the concrete is increased dramatically. Monitoring of existing structures with such concrete has shown that embedded steel is well protected.

149. Gjørv, O. E., K. Okkenhaug, E. Bathen, and R. Husevåg. "Frost Resistance and Air-Void Characteristics in Hardened Concrete." *Nordic Concrete Research* , Publication No. 7 (December 1988): pp. 89-104.

For many construction sites it is a problem to keep the required air-void content during transportation and handling of the concrete. Also, for many concrete structures it is a problem to meet combined requirements of high compressive strength and high air-void content based on local aggregates available. Extensive testing of the air-void system in concrete from a variety of construction sites in Norway over recent years has shown that the majority of specimens had a relatively low air-void content, and only about half of the specimens had proper air-void characteristics according to common requirements. In order to provide a better basis for evaluating the observed air-void characteristics, freeze-thaw testing for a number of the concretes was also carried out, and this testing was based on the critical degree of saturation method. The results indicate that it may be difficult to establish a direct relationship between air-void characteristics and frost resistance without also taking into account information about capillary voids and strength properties. As a basis for evaluation of the potential frost resistance of a concrete the frost resistance number is introduced. This number is based on

information about compressive strength, water-cement ratio, paste fraction and amount of air-voids smaller than 300 μm.

150. Gjørv, O. E., and S. P. Shah. "Testing Methods for Concrete Durability." *Materiaux et Constructions* Vol. 4, No. 23 (1971): pp. 295-304.

Experimental techniques for measuring progressive deterioration of concrete were investigated. Specimens of pastes, mortars, and concretes were subjected to alternate wetting and drying in sodium sulfate solutions and plain water as well as freezing and thawing. The methods used to assess the effects included: changes in weight, length, and flexural strength, changes in ultrasonic pulse time, quantitative and qualitative optical microscopy, scanning electron microscopy, and energy dispersive X-ray analysis. The results of the study show that the ultrasonic pulse method can be used to detect local cracking at an early stage of formation. Of the different testing methods employed, the progressive deterioration was best reflected by the measurements of pulse time. Measurements of flexural strength also adequately reflected the state of corrosion. Measurements of weight did not consistently indicate damage, while those of length were not always reliable.

151. Gonnerman, H. F. "Tests of Concretes Containing Air-Entraining Portland Cements or Air-Entraining Materials Added to Batch at Mixer." *Journal of the American Concrete Institute* Vol. 15, No. 6 (June 1944): pp. 377-407.

This paper presents some of the more significant results obtained in extensive laboratory studies made in connection with the construction of 18 experimental road projects, and in several separate laboratory investigations conducted during the past six years with air-entraining portland cements, and with air-entraining materials added at the mixer. Concrete specimens from nearly every experimental road project and from all laboratory series were subjected to scaling and to freezing and thawing tests. These specimens consisted of slabs made in the field from the concrete used in the pavement, of cores drilled from the pavement, and of many prisms made in the laboratory from the cements used in the roads. The laboratory studies included also many slabs and prisms made with various cements.

Resistance to scaling, and freezing and thawing while immersed, was markedly improved when the concrete was made with air-entraining portland cements, or with air-entraining materials added at the mixer. Increase in air content of the concrete caused reductions in flexural and compressive strength. Each percentage point increase in air content reduced the modulus of rupture 2 to 3 percent and the compressive strength 3 to 5 percent. Taking into account both strength and resistance to freezing and thawing, excellent performance was obtained when the total amount of entrained air in the fresh concrete was about 3 percent, or about 2 percentage points higher than that of concrete without air-entraining additions. With this percentage of air, the loss in strength was generally not more than 6 percent in flexure and 10 percent in compression. Higher air contents than 3 percent caused greater reductions in strength without any compensating increase in resistance to scaling and to freezing and thawing. The performance under service conditions of experimental paving projects constructed since 1938 with air-entraining portland cements parallels the results of the laboratory studies.

152. Greening, N. R. "Some Causes for Variation in Required Amount of Air-Entraining Agent in Portland Cement Mortars." *Journal of the PCA Research and Development Laboratories* Vol. 9, No. 2 (May 1967): pp. 22-36.

Factors influencing the amount of admixture required for air entrainment in mortars were investigated. It is shown that air-entraining agent requirement increases as the specific surface of the cement increases. High alkali cements require smaller amounts of all admixtures to obtain a particular air content than do low alkali cements. Organic impurities can either decrease or increase the air-entraining agent requirement depending upon the kind and condition of impurity. In some cases an organic impurity can be effective in entraining air as in an admixture. Some discussion of air-entraining agents themselves in included as well as data indicating that divergent types of agents act similarly.

153. Grieve, R., and W. M. Slater. *Deterioration and Repair of Above Ground Concrete Water Tanks in Ontario, Canada: Report to Ontario Ministry of the Environment*, W. M. Slater & Associates, Inc., Ontario, Canada, September 1987.

The main conclusion of this report is that, without adequate protection of permeable concrete from direct contact with water and elimination of cyclic freezing in the tank wall, above ground concrete water tanks will continue to deteriorate rapidly. The report discusses the various methods used to repair different types of concrete tanks and gives recommendations for assessment and analysis of repair systems. Although corrosion of metals is not a serious problem in concrete water tanks, some corrosion of tendons and other metallic components has occurred. The report gives examples of this type of deterioration, and the remedial methods used in the rehabilitation programme. Interim guidelines have been prepared for the design and construction of new concrete water tanks in Ontario based on the experience gained during the rehabilitation programme, and from the applied research carried out. The guidelines recommend that internal waterproofing and external insulation be used as the primary protection against the deterioration of above ground concrete water tanks in Ontario.

154. Gunter, M., T. Bier, and H. Hilsdorf. "Effect of Curing and Type of Cement on the Resistance of Concrete to Freezing in Deicing Salt Solutions." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

Experimental studies on the resistance of concretes to freezing and thawing in a saturated sodium chloride solution are described. The concretes were made of various types of cement differing in content of blast furnace slag. They were cured in water for 1 to 48 days and subsequently stored in air with and without carbon dioxide. Also the effect of curing, carbonation and type of cement on the structure of hydrated cement pastes was studied by mercury intrusion porosimetry.

155. Gutmann, P. F. "Bubble Characteristics as They Pertain to Compressive Strength and Freeze-Thaw Durability." *ACI Materials Journal* Vol. 85, No. 5 (September-October 1988): pp. 361-366.

Known air-entraining additives are not entirely satisfactory with respect to the stability of the air bubbles in concrete and have a tendency to either lose air or increase air as mixing time is extended. Another disadvantage is the reduction of compressive strengths of a 10 percent strength loss per 1 percent increase in

entrained air. It is believed that this loss is due in part to irregular bubble sizing and the coalescence of bubbles in the mix causing large voids that reduce the compressive strength.

The object of this research program was to improve the air-entrained portland cement concrete, which included and additive that would entrain an air-void system having desirable characteristics when used over a wide dosage range and, also, have a superior dosage response relative to similar known additives. Another objective of this research program was to provide improved strength results that include an additive that entrains an air-void system and increases compressive strengths over known air-entraining agents. Microscopic examination of a methyl ester-derived Cocamide diethanolamine produced bubbles that were spherical, having thick walls with no coalescence, while wood-resin bubbles were relatively thin-walled and tended to be less than spherical with some shapes oblong and coalescence observed. It was believed that this difference would produce a more stable air content and more uniform bubble structure in portland cement concrete. Test results on concrete with the use of a Cocamide diethanolamine produced by a methyl ester process produced a stable volume of air having the desirable size and distribution, and, compared to known air-entraining agents, increased the resistance to freeze-thaw durability by 400 percent and increased compressive strengths 25 percent in early ages and 10 percent in later ages.

156. Haas, S. *Recycled 'D' Cracked Portland Cement Concrete Pavements in North Dakota*, North Dakota State Highway Department, 1985.

This paper presents the North Dakota approach to recycling Portland Cement Concrete pavements on the interstate system under the 4-R program. The first Portland Cement concrete pavement placed on the system was in 1958 and the first pavement recycled in 1983-84. The recycled pavement had been in service for 25 years.

A committee was appointed to develop a rehabilitation philosophy and a program that would get a fast start on project lettings. The philosophy recognizes the need for recycling and the need for an interim repair strategy to keep the system in reasonably good driving condition until reconstructed.

The program that came out of the committee started the recycling process and also developed CPR (Concrete Pavement Restoration) projects consisting of joint repair, grinding to improve ride, asphaltic concrete shoulder recycling, and interchange overlays.
The committee started its work by inspecting the entire interstate system in February 1983 followed by the second inspection in April 1984. The 1984 inspection revealed a rate of deterioration greater than originally anticipated and caused some rethinking concerning the cost effectiveness of scheduled CPR projects. The amount of joint repair, especially on the pavements with 20-foot joint spacing, will drive the cost up substantially. Originally, the CPR treatment was expected to extend pavement life 10 to 15 years, but if joint deterioration keeps accelerating 7 to 10 years may be more realistic.

157. Hallet, B. "The Breakdown of Rock Due to Freezing: A Theoretical Model." Proceedings of the Fourth International Conference on Permafrost, Fairbanks, AK, July 17-22, 1983, pp. 433-438.

Frost wedging — the breakdown of rock due to freezing — is viewed as a manifestation of slow crack propagation in rocks due to ice growth in cracks. Frost wedging is modeled through a synthesis of Gilpin's (1980a) analysis of freezing in porous media and well-established principles of fracture mechanics. The model predicts most rapid breakdown at temperatures that range from -5° to -15° C for most rocks. At higher temperatures, ice pressures sufficient to produce lower temperatures the rate of ice growth is greatly reduced because water mobility and, hence, the flux of water necessary to sustain crack growth decrease considerably. The model clarifies the dependence of frost wedging on lithology, temperature, and moisture conditions. Four important rock properties figure in the analysis: pore size, permeability, average crack length, and fracture toughness. Crack growth rate has a complex dependence on temperature and is proportional to temperature gradient. The moisture content of rock can strongly affect frost wedging rates primarily by controlling the pore water pressure. Solutes are inferred to influence crack growth rates in several distinct ways.

158. Hannant, D. J., and J. G. Keer. "Autogenous Healing of Thin Cement Based Sheets." *Cement and Concrete Research* Vol. 13 (1983): pp. 357-365.

The effect of applying tensile stresses to pre-cracked fibre reinforced mortar specimens is examined after exposure to natural weathering and to indoor storage for periods up to 2 years. It is shown that the cracks will heal sufficiently under natural weathering conditions to restore the original stiffness of the composite and the healed crack surfaces can also carry considerable tensile stress. Indoor storage does not result in similar effects.

159. Hansen, T. C., and K. E. C. Nielsen. "Influence of Aggregate Properties on Concrete Shrinkage." *Journal of the American Concrete Institute* Vol. 62, No. 48 (July 1965): pp. 783-793.

A theory of the influence of aggregate properties on concrete shrinkage is presented. An equation is derived from which the shrinkage of concrete may be computed from the fractional volume, the modulus of elasticity, and the shrinkage of cement paste and aggregate. A comparison is made between theoretical and experimental results.

160. Haque, M. N., B. W. Langan, and M. A. Ward. "High Fly Ash Concretes." *Journal of the American Concrete Institute* Vol. 81, No. 8 (January - February 1984): p. 54.

Concretes containing fly ash up to 75 percent by weight of the cementitious material have properties that make them attractive as a subbase or base course component in pavement construction. This paper describes an extensive laboratory study of air-entrained high fly as concrete mixes (air-entrained and non-air-entrained) of medium to low workability suitable for placement by slipforming and roller compaction, respectively. The concretes were characterized as to their compressive, indirect tension, and flexural strengths; drying shrinkage; and freeze-thaw durability.

It is confirmed that cohesive nonsegregating concretes can be manufactured containing 40 to 75 percent fly ash in the cementitious fraction. When air

entrained, these mixes provide concretes having adequate freeze-thaw durability, at least in the richer mixes. Tensile and compressive strengths achieved are adequate for the proposed application with drying shrinkage within acceptable limits.

161. Harman, J. W., Jr., P. D. Cady, and N. B. Bolling. "Slow-Cooling Tests for Frost Susceptibility of Pennsylvania Aggregates." *Highway Research Record* No. 328 (1970): pp. 28-50.

The results of a 2-year study of frost susceptibility of Pennsylvania concrete aggregates by slow cooling are presented. The investigation studied 60 aggregate fractions from 20 sources. Petrographic fractionation and examination, a modification of Powers' slow cooling test, and various "quick" methods were compared. Glacial gravels and gravels of suspected glacial origin had a high incidence of deleterious fractions. Grain size was found to have a very important influence on frost susceptibility. Based on test comparisons, the use of the sodium sulfate soundness test (ASTM C88) is not recommended. A new method, based on a regime plot of bulk vacuum-saturated specific gravity and vacuum-saturated absorption, is presented.

162. Hatzinikolas, M., J. Longworth, and J. Warwaruk. "Effects of Cold Weather Construction on the Compressive Strength of Concrete Masonry Walls." *Journal of the American Concrete Institute* Vol. 81, No. 43 (November - December 1984): pp. 566-571.

The effect of cold weather on the strength of plain concrete block masonry walls was studied in a program of test on 49 specimens. Exposure to cold weather began at various times after construction. Following exposure the walls were cured in a normal laboratory environment under varying moisture conditions and then tested. Results indicate that exposure of walls to freezing conditions does not significantly impair the final strength, providing further hydration of the mortar is possible following freezing. The most significant factor affecting the strength of the walls is moisture loss from the mortar inhibiting hydration.

163. Havens, J. H. "Thermal Analysis of the Freeze-Thaw Mechanisms in Concrete." Ph.D. diss., University of Kentucky, College of Engineering, March 1961.

The purpose of this study is to examine the possibilities that time-temperature records could provide heretofore unavailable information concerning the amount of freezable water in concrete undergoing freezing and thawing, the progress of saturation, permeability, the internal pressures induced by freezing at various levels of saturation, and the progress of damage to the concrete. Furthermore, a critical and informative analysis of related theories, and the extent of their practical application is offered.

164. Hedenblad, G. "Determination of Moisture Permeability in Concrete under High Moisture Conditions." *Nordic Concrete Research*, No. 7 (December 1988): pp. 105-120.

With a method relying on measurements of the flow of water vapour from a specimen and measurements of the distribution of the relative humidity in the specimen at steady state conditions, the moisture permeability can be calculated and its dependence on the relative humidity can be determined.

The specimens are of dimensions that are used in ordinary buildings.

165. Helmuth, R. A. "Capillary Size Restrictions on Ice Formation in Hardened Portland Cement Pastes." Fourth International Symposium on the Chemistry of Cement, Washington, D. C., 1960, pp. 829-833. National Bureau of Standards, 1962.

T.C. Powers' model of the pore structure of hardened portland cement paste is used to discuss the conditions that must be met for ice formation in capillaries of various sizes. It is proposed that initial ice formation in supercooled water in the capillaries occurs dendritically, just as it does in bulk water, through only those sufficiently large capillaries which are contiguous with the initially seeded capillaries. Subsequent growth of this dendritic network of ice crystals and resulting expansions during cooling depend primarily on freezing in smaller capillaries at lower temperatures. This theory is supported by the results of experiments in which freezing propagation rates and temperature rises were measured during tests with supercooled pastes, and by experiments in which dimensional changes were measured during cooling and warming through freezing temperatures.

166. Helmuth, R. A. "Dimensional Changes of Hardened Portland Cement Pastes Caused by Temperature Changes." *Highway Transportation Research Board* Vol. 40 (1961): pp. 315-336.

A theoretical basis for expecting the moisture distribution in water-soaked hardened portland cement pastes to change with temperature is presented. The theory predicts shrinkage after warming and swelling after cooling. A method for measuring length changes of paste specimens during and after temperature changes is described. The results of dimensional change measurements are consistent with the theory presented, as are also the weight changes of specimens saturated with water at 25° C and 0° C. The initial dilation produced by freezing water-soaked pastes, likewise, show the effect of moisture distribution changes.

167. Herman, W. H. "Air-Entraining Concrete - Pennsylvania Department of Highways." *Journal of the American Concrete Institute* Vol. 42 (June 1946): pp. 689-696.

The experiences of the Pennsylvania Department of Highways with air-entrained concrete, in which 331-555 bbl of normal strength portland cement containing Vinsol resin were used since 1940 are reported. The Pennsylvania department's attitude on the subject of air entrainment is characterized by more concern with the particular admixture used than with the percentage of air entrainment and such use was inspired by difficulties with finer ground cements, which prompted seeking an additive to improve pavement durability.

168. Hester, W. T. "Contractors and Production of Durable Air-Entrained Concrete." *Journal of the Construction Division* Vol. 104, No. C02 (June 1978): pp. 167-178.

Economy and durability associated with concrete makes it an ideal material for marine, transportation, or physically remote structures exposed to severe environmental conditions. To maintain durability of concrete subjected to periodic saturation and cycles of freezing and thawing, such as with parking decks and marine structures, it is necessary to utilize special concrete construction practices. Concrete freeze-thaw deterioration, surface spalling, increased

permeability, and strength loss occur when water frozen within the concrete expands and exerts large internal disruptive forces.

The designer and contractor may choose between two means of preventing this destructive action. First, by using waterproofing sealants or special production practices the concrete surface may be made so dense as to resist any water absorption. Low water cement ratio mixes and excellent aggregates combined with strong vibration may create a surface largely insensitive to water absorption and freeze-thaw damage.

However, contrary to widespread belief, high strengths and low water cement ratios are not always an adequate deterrent to freeze-thaw deterioration. If the concrete will be saturated and subject to freeze-thaw cycling, air entrainment is necessary. In the cement-rich high-strength mixes typically used in marine and bridge constructions, air entrainment does not necessarily permit a water reduction, but will substantially improve freeze-thaw durability. Numerous instances have been reported in which 5,000 psi to 8,000 psi (35,000-kN/m^2 to 55,000-kN/m^2) compressive strength concrete, with a water-cement ratio less than 0.45, rapidly deteriorated and air-entrained concrete remained durable.

169. Higginson, E. C. "Some Effects of Vibration and Handling on Concrete Containing Entrained Air." *Journal of the American Concrete Institute* Vol. 49 (September 1952): pp. 1-12.

The effects of vibration, handling, and delay in placing concrete containing entrained air were evaluated in the laboratory with some check studies made on two large dam construction jobs. Curves of the test results show the rate at which vibration removes air from air-entrained concrete at various slumps. Loss of air caused by handling and delays in placing is determined. The effect of loss of air on the concrete is evaluated. Evidence is presented that normal vibration does not materially affect bleeding, and that increased vibration may improve the surface appearance of concrete.

170. Higginson, E. C., and D. G. Kretsinger. "Prediction of Concrete Durability from Thermal Test of Aggregate." *ASTM* Vol. 53 (1953): pp. 991-1001.

Data are presented on the effect of freezing and thawing, wetting and drying, and other simulated weathering tests on various concretes containing either natural aggregate or aggregate composed of individual rocks and minerals. The effect of thermal coefficient and diffusivity of these aggregates on the deterioration occurring during these tests is discussed, but no correlation is found between the test results and the thermal properties of the materials. Evidence is presented showing that the expansion occurring in saturated concrete during the measurement of coefficient of expansion can be correlated with freezing-and-thawing test results, thus providing a quick method of predicting durability of concretes.

171. Highway Research Board. *Report on Cooperative Freezing and Thawing Tests of Concrete*, Special Report No. 47, 1959.

A program of cooperative freezing-and-thawing tests of concrete specimens was conducted by thirteen laboratories using the four ASTM Tentative Methods of Test. Three concrete mixtures were used, involving different aggregates and two

different air contents. Large variations in durability were found for the same concrete mixture and for tests by the same method, both within and between laboratories. It is indicated that these were due both to differences in the concretes as prepared in the laboratories and in treatment of the specimens by a given test method. Differences in specimens consisted mainly in unexpectedly large variations in air content and air-void characteristics revealed by microscope measurements of the air-void systems in some of the test specimens. Differences in the treatments were greatest in the methods involving freezing in air, and were probably due in part to unequal amounts of drying during freezing. A statistical examination of the data and a comparison with previous programs are presented. It is concluded that these methods provide useful procedures for comparing the relative durability of different concretes within a given laboratory; that a wide variation of results in the middle range of durability appears to be a normal characteristic of the methods; that the data do not permit recommending one test method over the others for all purposes; and that the ability of concrete to withstand a severe laboratory freezing-and-thawing test is probable indication of a high degree of durability.

172. Hirai, K. "Effect of the Blast Furnace Slag Content on the Frost Resistance of Neo-Ferrite Cement Mortar." *Journal of the American Concrete Institute* SP 79-55 (1983): pp. 1039-1059.

Results of an investigation on the effect of blast furnace slag on the frost resistance and porosity of neo-ferrite cement mortar are presented. Neo-ferrite cement is a new type of ferrite cement produced from blast furnace slag and converter slag that is a by-product of the steel industry. In this new cement the amount of limestone as a raw material in cement production is reduced by approximately 2/3 in comparison with ordinary portland cement.

For the purpose of improving the durability of the cement, freezing and thawing tests were performed on prismatic mortars made from neo-ferrite cement incorporating three different amounts of slag by weight. The mortar specimen made from neo-ferrite cement incorporating blast furnace slag approximately twenty percent (by weight) showed considerably improved resistance to frost action.

173. Hoekstra, P. "Moisture Movement in Soils under Temperature Gradients with the Cold-Side Temperature below Freezing." *Water Resources* Vol. 2, No. 2 (1966): pp. 241-250.

Moisture movement to a freezing front in an unsaturated porous medium of Fairbanks silt was measured by gamma-ray attenuation. It was shown that the presence of an ice phase greatly enhances the amount of moisture transfer under temperature gradients. The chemical potential of soil water in the frozen soil as a function of temperature is calculated. The chemical potential of unfrozen absorbed water in frozen soils, if in equilibrium with ice, is independent of total water content (unfrozen water plus ice). Consequently, no equilibrium moisture content distribution is reached, and water content in the frozen soil changes continuously. Moisture flow in the frozen soil takes place under temperature gradients through the films of unfrozen water. Since the thickness of the unfrozen films decreases with temperature, the rate of water transport also decreases rapidly with decreasing temperature below 0° C.

174. Hoff, G. C., and A. D. Buck. "Considerations in the Prevention of Damage to Concrete Frozen at Early Ages." *Journal of the American Concrete Institute* Vol. 80, No. 35 (September - October 1983): pp. 371-376.

Various protection concepts and considerations associated with placing fresh concrete in an environment where it will undergo early age freezing are reviewed. These include volume change concepts, critical strength and critical age concepts, and freezable water considerations. An experimental program is also presented to relate the dilations of concrete from one cycle of freezing to the critical (minimum) strength that the concrete would need to resist damage from that freezing. This was done in an attempt to validate the minimum (critical) compressive strength of 500 psi (3.5 MPa) recommended in ACI 306R-78, Cold Weather Concreting. Critical dilation criteria are presented. An evaluation of concrete mixtures of varying proportions indicated that, based on a dilation criteria for determining the single freezing frost resistance of concrete, the critical (minimum) strength [500 psi (3.5 MPa)] and critical age requirements of ACI 306R-78 are conservative and acceptable. This does not preclude the possibility that some permanent loss of strength may occur, however, when frozen at an early age.

175. Hooton, R. D. "Permeability and Pore Structure of Cement Pastes Containing Fly Ash, Slag and Silica Fume." *Blended Cements*, ASTM STP 897 (1986): pp. 128-143.

As part of research to develop a highly durable concrete container for radioactive waste disposal in chloride and sulfate-bearing granite groundwaters, a variety of cement pastes were studied. A sulfate resisting portland cement was used with various replacement levels of Class F fly ash and pelletized blast furnace slag at a water solids ratio (w/s) = 0.36. Blends with fly ash, slag, and silica fume were also combined with a super water reducer at w/s = 0.25. Results are presented for strength development, permeability to water, and pore size distribution after 7, 28, 91, and 182 days moist curing. As a direct measure of durability, after 91 days moist curing, paste prisms were immersed in both de-ionized water and a synthetic chloride and sulfate-bearing groundwater at 70° C.

While all three supplementary cementing materials (mineral admixtures) reduced ultimate permeabilities, silica fume was more effective in reducing permeability at early ages. Silica fume was also the most effective in reducing calcium hydroxide contents of the pastes, while slag was the least effective; (only reducing calcium hydroxide levels by dilution of the portland cement). From preliminary analysis, there does not appear to be a way of accurately predicting permeability from porosity or pore size parameters.

176. Hooton, R. D. "Properties of a High-Alkali Lignite Fly Ash in Concrete." Second CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Madrid, Spain, 1986, pp. 333-345.

This paper examines the properties of concrete incorporating a high-alkali, high-calcium fly ash produced from Western Canadian lignite coal. Because of its high alkali content, ASTM C441 mortar bars containing Pyrex fine aggregate and 25 volume percent fly ash were tested initially. Even with its 2.9 percent available alkali content, the fly ash replacement reduced expansions at one year by approximately 50 percent relative to the high-alkali portland cement alone. Based on the C441 results and good pozzolanic properties, a program was undertaken to

evaluate the performance of this lignite ash in air-entrained concrete. In this program, strength development, air-void parameters, resistance to freezing and thawing (ASTM C 666 Procedure A), permeability, and pore size parameters were investigated. Significantly lower water-to-cementing materials ratios were achieved; equal strengths were attained in only 7 days along with much higher later-age strengths; freezing-and-thawing resistance was excellent; and permeabilities and porosities were reduced. In addition, while the sulphate resistance of many lignite ashes is poor, the performance of ASTM C1012 mortar bars with 35 weight percent replacement for a 12.8 percent C3A portland cement was similar to that for moderate sulphate-resisting portland cement (C3A < 8.0 percent).

177. Hope, B. B., and P. J. Quelch. "Early Freezing of Vacuum Processed Concrete." *Journal of the American Concrete Institute* SP 39-2 (October 1973).

The effect of freezing temperatures on the compressive strength and ultrasonic pulse velocity of vacuum processed and nonprocessed concrete was investigated for two concretes with initial water-cement ratios of 0.71 and 0.45. The average reduction in water-cement ratio of 6 x 12 in. (15.2 x 30.5 cm) cylinders obtained by vacuum processing was 0.18 and 0.09 respectively. Vacuum processed and nonprocessed cylinders were stored in air maintained at 0° F (-18° C) after initial curing periods of 0, 3, 6, 12, or 24 hours at 70° F (21° C) and 100 percent relative humidity. The resistance to damage by freezing of both concretes was enhanced by vacuum processing. For both mixes the required curing time, (so that there was no significant loss in the 28-day strength of the 6 x 12 in. cylinders) was halved by vacuum processing.

178. Hover, K. C. "Analytical Investigation of the Influence of Air Bubble Size on the Determination of the Air Content of Freshly Mixed Concrete." *Cement, Concrete and Aggregates* Vol. 10, No. 1 (Summer 1988): pp. 29-34.

It has been qualitatively suggested that the pressure method for the determination of air content in freshly mixed concrete can be in error when a portion of the entrained air bubbles becomes relatively incompressible due to the increase in internal bubble pressure which accompanies a reduction in bubble diameter. This has been used to explain the observed discrepancy between air meter readings and the air volume reported by microscopic analysis. This paper reports the results of an analytical investigation of the bubble-size effect, in which it is seen that it is unlikely that a sufficient volume of bubbles with the required diameter are present so as to cause the observed discrepancy. In order to demonstrate a significant influence of bubble size on the accuracy of the air meter, one must resort to values for the surface tension of the bubble film which are unjustified. The characteristics of various meters are discussed.

179. Hover, K. C. "Closing the Gaps: How to make concrete less permeable and more durable." *Concrete Construction* Vol. 32, No. 10 (October 1987): pp. 857-860.

Most people think of concrete as a solid material. In reality, however, it's a porous material. The pore volume, size and arrangement affect how fast concrete absorbs water and how long it holds the water in the pores. Pore characteristics also influence how fast water, other liquids, and gases can penetrate concrete. Permeability is the rate at which water or other liquids flow through concrete. The more permeable concrete is, the less durable it is. Highly permeable concrete is more likely to be damaged by freezing and thawing because water enters it

easily, expands as ice is formed, and causes destructive pressures. Sulfates, acids, and other aggressive chemicals penetrate faster. Concrete carbonates to a greater depth, and this, along with increased permeability to oxygen and dissolved salts, causes rebar corrosion. Reducing permeability is an effective way to improve durability. To change the permeability, you must know which factors influence this property most.

180. Hover, K. C. "Some Recent Problems with Air-Entrained Concrete." *Cement, Concrete, and Aggregates* Vol. 11, No. 1 (Summer 1989): pp. 67-72.

Several problems are identified in regard to air-entrained concrete, which include the accuracy of the pressure air meter (ASTM C 231), the accumulation of air voids at the coarse aggregate surface, excessive loss of air volume in transit or in pumping, and the need for greater precision and detail in specification requirements of air-entrained concrete. Data are presented from four recent construction projects from a wide geographical range in the United States.

181. Hudec, P. P. "Deterioration of Aggregate - The Underlying Causes." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

This paper presents an overview of processes causing aggregate breakdown, based on the theoretical and laboratory-derived evidence accumulated in the author's lab over the last 15 years.

The answer may be found in the nature of the water in the small pores - water affected by the capillary and surface forces of the pore material. The pore water has lower vapor pressure, which prevents it from freezing, but which results in osmotic pressure differential, causing expansion. Deicing salt cations are preferentially adsorbed and concentrated on pore surfaces, further increasing the osmotic potential, expansion, and breakdown.

Methods that determine the pore size distribution, surface sorption characteristics of the pore walls, and volume changes on wetting are suggested as more definitive measures of aggregate (and concrete) durability, compared to some of the currently accepted tests.

182. Hudec, P. P. "Durability of Rock as a Function of Grain Size, Pore Size and Rate of Capillary Absorption of Water." *Journal of Materials in Civil Engineering* Vol. 1 (February 1989): pp. 1-9.

The author stated that the grain size and pore size are very important parameters in the assessment of the long term durability of concrete material.

Experiments carried out on carbonate rock specimens showed that the grain size and the pore size control the rate of absorption of water into the carbonate rock. The finer grained rocks were found to absorb water at a rate twice that of coarser grained rocks, particularly in the first few minutes of exposure to water. These findings led to the conclusion that water content and degree of saturation play a major role in the durability of rock and that the rates of absorption and durability are correlated: high rate of absorption specimens were found less durable during freezing and thawing than those with a low rate of absorption.

Another important property of carbonate rock that appeared to influence durability, was the internal surface area, measured by water adsorption. The larger the internal surface area the less durable the rock. The author finally concluded that these findings may apply to other rock types since grain size and pore size, absorption and adsorption, as well as internal surface area are common characteristics to all rocks.

183. Hughes, D. C. "Pore Structure and Permeability of Hardened Cement Paste." *Magazine of Concrete Research* Vol. 37, No. 133 (December 1985): pp. 227-233.

A review of the literature on flow through porous media suggests that the permeability of hardened cement paste should be related to pore size distribution, pore conductance, tortuosity and isotropy. It is likely that these factors do not exhibit a unique value. Tests were made on OPC and OPC/pfa pastes cured for 1, 4 and 12 weeks in $Ca(OH)_2$ solution. The permeability of both types was similar for those pastes cured for 4 and 12 weeks at 35° C, whilst after one week's curing the OPC/pfa paste was significantly the more permeable. Pore size distribution was determined by using a two-stage mercury intrusion technique. A simple model, based upon Poiseuille's formula, was developed and shown to yield a reasonable correlation with the experimental determination of permeability for the OPC pastes and on SRPC paste cured for 4 weeks. The correlation was not so good for the OPC/pfa pastes, probably as a consequence of structural damage during mercury intrusion in such pastes.

184. Hughes, D. C. "Sulphate Resistance of OPC, OPC/FA and SRPC Pastes: Pore Structure and Permeability." *Cement and Concrete Research* Vol. 15 (1985): pp. 1003-1012.

Fly ash is a slow acting pozzolan and requires substantial curing to achieve its potential strength and durability properties. Results are presented of the sulphate resistance, permeability and pore size distribution of OPC, OPC/fly ash and SRPC pastes variously cured before immersion in 0.7M Na_2SO_4. A range of pores is identified that are particularly susceptible to sulphate attack and a qualitative relationship established between the variation, with curing, of the entry size of these pores, the permeability of the paste and sulphate resistance.

185. Idorn, G. M. "Concrete Forever." *R & H Bulletin* , No. 17 (July 1990): pp. 1-15.

The ever increasing demands on building and construction for global social development require concrete as the fundamental building material. The demands are, in many regions of the world, certain to exceed the available amount of suitable resource materials: cement, water and aggregates in the near future. The concrete forever concept is therefore discussed in relation to various categories of demands on quantity and quality of concrete. The requirements for longevity of concrete buildings and structures are considered in this context, and the durability of concrete as such is therefore also discussed. The need to develop research planning and management is emphasized and essential aspects of concrete technology innovations are mentioned for quality assurance management. A provocative concrete forever perception is revealed in the concluding remarks.

186. Illinois Department of Transportation. *A Preliminary Investigation of the D-Cracking Problem in Illinois*, Bureau of Materials and Physical Research, May 1979.

D-cracking has been observed for years in Illinois, but had not been considered a serious problem within the normal 20-year service life. However, recent surveys have revealed severe D-cracking distress on relatively young CRC pavements, necessitating Department action.

D-cracking, a distress peculiar to PCC pavements, appears at the surface as a network of fine, closely spaced cracks occurring parallel and adjacent to joints, intermediate cracks, and slab edges. The distress has been traced to freeze-thaw failures in certain types of aggregates.

The conditions necessary for D-cracking are (1) a susceptible aggregate, (2) moisture accumulation, and (3) cyclic freezing and thawing. Water infiltrates the joints, cracks, and edges, accumulates at the bottom of the slab, and saturates the aggregate. The freeze-thaw cycling generates stresses that in time exceed the tensile strength of the aggregate, leading to its fracture. Progressively, the surrounding mortar and additional aggregate particles become involved and the distress spreads throughout the pavement slab.

D-cracking starts at the bottom of the slab and moves upward. Normally, the crack pattern is horizontal in the lower and middle levels of the pavement, becoming more random as it progresses to the surface. By the time the distress is visible, the bottom of the slab often is totally disintegrated. The cracking may surface in as little as three years or as late as 20 years after construction.

Since recognizing the magnitude of the D-cracking problem, the Department has adopted an interim specification for PCC pavement, base course, and widening projects that requires (1) a reduced top-size material (CA 7), (2) 564 pounds of cement per cubic yard, and (3) the use of a water-reducing admixture. While this approach should lessen the severity of D-cracking, it is considered an interim solution until more definitive information can be developed.

The Bureau of Materials and Physical Research recently has completed the first phase of a research effort to identify aggregates susceptible to D-cracking. This effort has involved (1) a review of the state-of-the-art regarding D-cracking, (2) a laboratory investigation, and (3) a field performance survey.

187. Ionescu, I., and T. Ispas. "Properties and Durability of Some Concretes Containing Binders Based on Slag and Activated Ashes." Second CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Madrid, Spain, April 1986, pp. 1475-1493.

Properties of heavy and lightweight concretes prepared with binders based on slag and activated ashes were studied as follows:

a. fresh concrete;
b. strength of concrete hardened both at normal temperature and by heat treatment;
c. permeability and resistance to freeze-thaw cycling;
d. behavior of some concrete elements under various working conditions;
e. some technico-economic aspects related to preparation and use of binders and practical conclusions for design and manufacture.

188. Ispas, T., and I. Ionescu. "Production of Fly Ash Concretes Using Superplasticizers." Second CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Madrid, Spain, 1986, pp. 763-778.

This paper presents results or investigations on the practical utilization of fly ash in concrete with and without superplasticizers. The influence of superplasticizers on the hardening process of fly ash concretes was studied at varying ages up to 730 days. The test results indicate that fly ash can be used to advantage in non-superplasticized concrete at a replacement level of up to 50 percent by weight of portland cement, and up to 25 percent by weight of cement with 15 percent of admixture in superplasticized concrete. The addition of fly ash and superplasticizer to concrete show additional advantages such as high initial and ultimate strengths, increased resistance to repeated freeze-thaw cycles, better durability, and reduction in energy required for heat-curing.

189. Iyer, L. S. "The Effect of Freezing and Thawing on Minnekahta Limestone and Sioux Quartzite Used for Concrete Aggregates." Ph.D. diss., South Dakota School of Mines and Technology, June 1974.

This investigation includes the study of dilation, the variation of modulus of elasticity and strength of crushed Minnekahta limestone and Sioux quartzite due to freezing and thawing.

The properties of the dry specimens are not affected by the freezing and thawing. In the case of saturated specimens, limestone dilates at 23° F, and quartzite dilates at 27° F, whereas no dilation and change in length is observed in the case of dry specimens. The saturated specimens show an increase in absorption, decrease in tensile strength and decrease in modulus of elasticity after 100 cycles of freezing and thawing. Smaller size specimens show less damage to freezing and thawing. No consistent variation in Poisson's ratio and compressive strength are observed due to 100 cycles of freezing and thawing. Reasonable agreement between the increased absorption and the increased permanent volume change based on the measured change in length due to freezing and thawing in obtained. A relative durability rating for these rocks indicates that both these rocks are good for concrete aggregates. Smaller quartzite and larger limestone are better from the standpoint of resistance of concrete to freezing and thawing.

190. Iyer, L. S., P. H. Rahn, V. Ramakrishnan, and J. E. Russell. "Durability Tests on Some Aggregates for Concrete." *Journal of the Construction Division* Vol. 101, No. C03 (September 1975): pp. 593-605.

The selection of aggregates for concrete is based on the probable durability along with the economy of mixture and strength of hardened mass. Durability of concrete depends on the following: 1) Resistance of aggregate to weathering; 2) no unfavorable reaction between aggregate and cement; and 3) no impurities in aggregate that reduces the strength.

American Society for Testing and Materials tests are available to check the latter two causes, whereas no direct and reliable tests are available for checking the resistance of aggregates to weathering. Weathering due to freezing and thawing is the most hazardous of deterioration of concrete in the northern part of the United States. The practice of air entrainment in concrete reduces the hazard due to freezing and thawing. The void system intentionally introduced in concrete will

accommodate the increased volume of the freezing moisture in a cement paste matrix. But in the case of aggregate, the movement of the moisture from the aggregate to the void system during freezing depends upon the pore size, porosity, and the size of the aggregate. If the pore size is small and the size of the aggregate is large, the moisture may freeze inside the aggregate to produce stresses in the aggregate as well as in the surrounding matrix. If the strength of these materials is less than the stresses developed, either the concrete or aggregate may crack. The properties of the aggregate which influence the resistance of concrete to freezing and thawing are: (1) Pore size and porosity of the aggregate; (2) size of the aggregate; (3) modulus of elasticity of the aggregate; and (4) tensile strength of the aggregate.

In South Dakota, Minnekahta limestone and Sioux quartzite are used for concrete aggregates. Minnekahta limestone is pure limestone containing 97% calcium carbonate and less than 1.0% dolomite. To illustrate the influence of the previous properties on the durability of concrete, tests were conducted to study the dilation and variation of the aforementioned properties of these rocks due to freezing and thawing.

191. Jackson, F. H. "The Durability of Concrete in Service." *Journal of the American Concrete Institute* Vol. 43 (October 1946): pp. 165-180.

Discusses the problem of concrete durability with reference primarily to highway bridge structures located in regions subject to severe frost action. Four major types of deterioration are defined and illustrated and several specific matters that have bearing on the problem, including the effect of construction variables, modern versus old fashioned cements, air entrainment, and the so-called cement-alkali aggregate reaction, are discussed. The report concludes with a series of recommendations indicating corrective measures that should be taken.

192. Jackson, F. H. "Long-Time Study of Cement Performance in Concrete. Chapter 9 - Correlation of the Results of Laboratory Tests with Field Performance Under Natural Freezing and Thawing Conditions." *Journal of the American Concrete Institute* Vol. 52 (October 1955): pp. 159-194.

Summarizes and evaluates the results of laboratory test spanning 14 years of the Long-Time Study cements and concretes containing the same cements. Many of the field installations, although subject to severe exposure, have not weathered sufficiently to allow comparisons. Of the three permitting appraisal the only positive conclusion that can be drawn now is the superior performance of air-entraining cements.

Laboratory freezing and thawing tests of concrete correlate well with field performance in showing the markedly improved durability of air-entrained concretes. Tests at two laboratories and at two of the field installations give some indications, clouded by many inconsistencies, that the Type IV cement concretes are somewhat more frost resistant than concretes made of other types of cement. However, this trend is not indicated by other investigations that show quite conclusively that damage by freezing and thawing is a physical matter and is not influenced by the chemical composition of the cement. An over-all appraisal of the results of the Long-Time Study tests to date indicates that, of the many physical tests made of the LTS cements, only the test for air content is of any value in indicating relative resistance to freezing and thawing.

193. Jackson, F. H. "A Way to Better Pavement Concrete." *Journal of the American Concrete Institute* Vol. 46 (March 1950): pp. 489-496.

Discusses the performance requirements of concrete pavements from the standpoint, primarily, of the quality of the concrete as a material. It is pointed out that the lack of durability of much of our present day concrete may be due to our methods of construction. The writer believes pavement durability could be significantly improved by using a scientifically proportioned mix of dry consistency, well-compacted by vibration or tamping, and with close control over aggregate gradation, in place of the oversanded plastic mixtures that we now use. He does not believe that air entrainment is necessarily the final answer to the problem of surface deterioration but that we should seriously consider overhauling our entire construction practice as well as our present methods of controlling the uniformity of aggregate gradation.

Current practice in the construction of concrete pavements and airport runways in Great Britain and past practice in Germany in the construction of the autobahnen are discussed to show that the placing of harsh, dry mixtures with close control of aggregate gradations is entirely feasible from the construction standpoint.

194. Jackson, F. H., and H. Allen. "Concrete Pavements on the German Autobahnen." *Journal of the American Concrete Institute* Vol. 44 (June 1948): pp. 933-976.

The condition of the German pavements is discussed from the standpoint of both structural performance and quality of concrete per se. All of the structural defects that usually develop in concrete pavements in the United States were found. However, aside from transverse cracking, which was quite common, defects such as joint spalling, joint faulting, settlement, etc. were not serious except in the area immediately north and south of Frankfurt. It is believed that the comparative freedom of the German motor roads from structural defects is due primarily to two factors: the comparatively small amount of heavy truck traffic using these roads, now and in the past, and the comparatively mild climate.

The concrete was almost without exception, of excellent quality. Scaling was confined almost entirely to the sections between Munich and Salzburg. Disintegration was practically nonexistent. An outstanding surface characteristic was the absence of the heavy layer of surface mortar, which is frequently found on pavements in the United States. It is believed that the excellent quality of the concrete is due to (1) the excellent quality of the aggregates, (2) the low water-cement ratio, (3) thorough consolidation by tamping and vibration of a dry mixture with a maximum aggregate size of about 1 in., (4) thorough curing, and (5) the comparatively mild climate. The effect of the cement is not clear. German cements were definitely inferior as judged by modern American standards. Whether they were actually inferior remains to be seen.

195. Jackson, F. H., and I. L. Tyler. "Long-Time Study of Cement Performance in Concrete, Chapter 7 - New York Test Road." *Journal of the American Concrete Institute* Vol. 47 (June 1951): pp. 773-796.

Test procedure, materials, mix proportions, and construction procedures on the New York Test Road, a part of the Long-Time Study of Cement Performance in Concrete, are described. All 27 of the Long-Time Study cements were used in conjunction with a nontest cement for adjusting equipment and mix proportions. Performance of the test sections is assessed with respect to durability of the

concrete as a material, the only property directly studied in relation to the cement used.

Seven and one-half years after the test pavement was completed no one cement proved superior to the others tested. However, the effects of air entrainment in improving resistance of the pavement to scaling and weathering overshadowed all other variables. The use of abrasives with ice control chemicals caused scaling on non air-entraining concrete. A 2- to 3-inch increase in slump of the test concrete had no appreciable effect on the durability of the concrete.

196. Janssen, D. J. *Bridge Deck Moisture Measurement*, Washington State Transportation Center and the Univ. of Washington, Seattle, Washington, July 1987.

Moisture is a primary contributing factor in the long term durability of bridge decks. Moisture is involved in freeze-thaw problems in portland cement concrete and in corrosion of reinforcing steel. Chloride ions, another factor contributing to corrosion, are normally transported through the concrete bridge deck to the reinforcing steel by moisture. Moisture measurement techniques were examined and one of the methods, Peltier-type psychrometers, was used to measure bridge deck moisture. Measurements were made at depths of 0.5, 1.5, 3.0 and 4.5 - 5.5 in. Both negative and positive moment regions were instrumented. The degree of saturation at the level of the reinforcing steel was found to be about 90 percent, with little variation over the two month period that measurements were taken. Moisture content fluctuations were greater in the negative moment region than the positive moment region. Moisture fluctuations could lead to increased migration of chloride ions to the reinforcing steel. Measurement of moisture content distributions before and after wetting a bridge deck could be used as an indicator of corrosion protection provided by overlays.

197. Janssen, D. J. "Moisture in Portland Cement Concrete." *Transportation Research Record* No. 1121 (1987): pp. 40-44.

Moisture gradients in concrete pavements cause differential shrinkage between the top and the bottom of the pavement. This leads to curling stresses in which the top of the pavement is in tension while the bottom is in compression. The magnitude of these stresses is determined by the moisture distribution, the volumetric aggregate content of the concrete, and the elastic modulus of the concrete. Pavement moisture contents were determined by field moisture measurements, laboratory measurements, and computer simulation. These indicated that substantial drying occurred only at the top surface, to a depth of less than 2 in. The rest of the pavement remained at 80 percent saturation or higher. A typical pavement moisture distribution was determined, and using an aggregate content of 74 percent and an elastic modulus of 3.6 x 10-6 psi, a stress distribution was calculated. The tensile strength of the concrete at the surface was exceeded, and cracks could be expected to form to a depth of 3/4 in. Because the tension in the concrete was concentrated near the surface instead of decreasing linearly with depth, the actual moment in the pavement caused by the moisture gradient was only 40 percent of the moment capacity of the unreinforced concrete.

198. Janssen, D. J., and D. K. Almond. "Comparison of Four Aggregates Using the Washington Hydraulic Fracture Test." *Transportation Research Record* No. 1301 (1991): pp. 57-67.

The importance of identifying D-cracking susceptible aggregates has led to a considerable number of aggregate identification test procedures. Unfortunately, the more reliable of the procedures may require 8 weeks or longer, expensive equipment, and highly skilled operators. In response to this problem, the Strategic Highway Research Program (SHRP) has issued a research contract to develop a rapid, reliable test method for identifying aggregates susceptible to D-cracking. The new test method being developed is used to examine four aggregates: two that have produced D-cracking in the field, and two with a performance history of no D-cracking. The test method involves covering an oven-dried aggregate sample with water, and then pressurizing the water to 1,150 psi (7,930 kPa). The pressure is quickly released, and then the pressurization and release cycle is repeated. Ten cycles per day are run for a total of 50 cycles. The amount of aggregate fracturing is determined and indicates D-cracking potential. The D-cracking susceptibility of the four aggregates tested was clearly identified even though the samples were different materials from diverse origins and locations.

199. Janssen, D. J., and B. J. Dempsey. "The Effect of AC Overlays on D-Cracking in PCC Pavements." *Transportation Research Record* No. 1062 (1986).

Durability cracking (D-cracking) is the progressive deterioration of Portland cement concrete (PCC) and is normally caused by winter freeze-thaw cycling. The PCC coarse aggregate source has been identified as causing well designed mixes to develop D-cracking.

A common rehabilitation procedure for D-cracked PCC pavements is to overlay the PCC with asphalt concrete (AC). This renews the surface, but little is known about the long term effect of AC overlays on D-cracked pavements. Specifically, will an AC overlay stop the progression of D-cracking, or accelerate it.

The primary climatic factors responsible for D-cracking are moisture and temperature. Finite-difference transient flow computer moisture movement modelling as well as field instrumentation and laboratory measurements indicated that AC overlays have negligible effect on the PCC pavement moisture regime. This is due to the extremely low hydraulic conductivity of PCC. Evaporative drying of the PCC extends less than 2-in. into the PCC pavement.

The effect of AC overlays on the PCC temperature regime was evaluated by finite-difference heat transfer computer modeling. AC overlays were found to decrease the number of freeze-thaw cycles and the rate of cooling in PCC pavements. The cooling rate at the top of an 8-in. PCC pavement in the St. Louis, Missouri area was decreased from 1.19 to 0.24 degrees Fahrenheit per hour by a 4-in. overlay.
Laboratory freeze-thaw durability tests duplicating field conditions for Interstate 70 near Vandalia, Illinois were conducted. The laboratory PCC samples were made with the same coarse aggregate as the D-cracked I-70 pavement section. The samples had either no overlay, or 2-, 4-, 6-in. overlays. A freeze-thaw cycle determined from actual climatic data was used to simulate winter freeze-thaw cycling. All of the PCC samples cycles to the equivalent of 5 years of winter exposure showed strength loss as determined by split tensile tests. The samples with 4-in. overlays showed the most strength loss.

It was concluded that AC overlays do not prevent the progression of D-cracking in PCC; instead some overlay thicknesses accelerate the deterioration. When AC overlays are designed for D-cracked PCC pavements, the effect of decreasing strength of the deteriorating PCC should be considered.

200. Janssen, D. J., B. J. Dempsey, J. B. DuBose, and A. J. Patel. *Predicting the Progression of D-Cracking*, Transportation Research Laboratory, Department of Civil Engineering, Engineering Experiment Station, University of Illinois at Urbana-Champaign, Illinois, July 1985.

Durability Cracking (D-cracking) is the progressive deterioration of portland cement concrete (PCC) and is normally caused by winter freeze-thaw cycling. The PCC coarse aggregate source has been identified as causing well-designed mixes to develop D-cracking.

The primary climatic factors responsible for D-cracking are moisture and temperature. Finite-difference transient flow computer moisture movement modelling as well as field instrumentation and laboratory measurements indicated that AC overlays have negligible effects on the PCC pavement moisture regime. This is due to the extremely low hydraulic conductivity of PCC. Evaporative drying of the PCC extends less than 2 in. into the PCC pavement.

The effect of AC overlays on the PCC temperature regime was evaluated by finite-difference heat transfer computer modelling. AC overlays were found to decrease the number of freeze-thaw cycles and the rate of cooling in PCC pavements. The cooling rate at the top of an 8-in PCC pavement in the St. Louis, Missouri area was decreased from 1.19 to 0.24 F/hr by a 4-in. overlay.

201. Jensen, A. D., S. Chatterji, P. Christensen, and N. Thaulow. "Studies of Alkali-Silica Reaction - Part II: Effect of Air-Entrainment on Expansion." *Cement and Concrete Research* Vol. 14 (September 9, 1983): pp. 311-314.

From an extensive petrographic investigation of concrete samples suffering from alkali-silica reaction, it has been hypothesized that a deliberately introduced air-bubble system will reduce expansion due to alkali-silica reaction. The above hypothesis has been tested using mortar bars made from 35 sand types of differing degrees of alkali-silica reactivity. The results show that on the average the introduction of 4% air decreased the expansion by about 40%. A petrographic examination of mortar bars has shown that in the case of reactive sand the air-bubbles tend to get filled up by gel, but the air-bubbles remain empty in the case of unreactive sand. It has also been noted that this filling up of the air-bubbles will decrease their effectiveness in a freeze-thaw environment.

202. Johnston, C. "Effects of Microsilica and Class C Fly Ash on Resistance of Concrete to Rapid Freezing and Thawing and Scaling in the Presence of Deicing Agents." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

The freeze-thaw durability for concretes containing up to 42% Class C fly ash or 15% microsilica by weight of cement with ratios of water to cementitious material of 0.53 - 0.88 is examined to establish the extent to which such relatively lean mixtures can yield good durability along with the satisfactory levels of strength already known to be achievable, particularly with microsilica. The results show that, while the inclusion of fly ash or microsilica does not detract from

performance in rapid freezing and thawing (Procedure A of ASTM 666), performance with respect to scaling (ASTM C672) may not be satisfactory, even with an apparently adequate air void spacing factor.

203. Kaneuji, M. "Correlation Between the Pore-Size Distributions and Freeze-Thaw Durability of Coarse Aggregates in Concrete." Ph.D. diss., Purdue University, August 1978.

This study was designed to find the correlation between the pore-size distribution of an aggregate measured by the mercury intrusion method and the freeze-thaw durability of concrete made with the aggregate.

Fourteen different types of aggregates with a wide variety of pore-size distributions were studied. Two laboratory freezing tests, the rapid freezing and thawing test (ASTM C666A) and a modified critical dilation test, were conducted. A good correlation between the pore-size distribution of an aggregate and its durability factor obtained from the rapid freezing and thawing test was found. The modified critical dilation test results generally agreed with the rapid freezing and thawing test results. The absorption test and PCA absorption-adsorption test did not indicate as well as the freeze-thaw durability as pore-size distribution.

A correlation equation between an expected durability factor for an aggregate and its pore-size distribution measured by mercury intrusion was obtained. This equation was then examined for its applicability to the field performance prediction. The aggregates with known field performance were examined. The existing concrete pavements with various degree of D-cracking were sampled, and their aggregates were examined. These studies have shown that the correlation equation is capable of predicting the frost durability of an aggregate. Based on these examinations, border lines separating durable from non-durable aggregates were tentatively determined.

204. Kanitakis, I. "Permeability of Concrete Containing Pulverized Fuel Ash." Fifth International Symposium on Concrete Technology, Monterrey, Nuevo Leon, Mexico, March 1981, pp. 311-322.

The main aim of this work was to investigate whether English-produced PFA (pulverized fuel ash) concretes are impervious enough to be used for offshore structures. A representative OPC (ordinary portland cement) concrete of high cement content and a corresponding PFA concrete were tested. These two mixes were designed to have basically the same workability and cube strength, so that their permeability could be compared. The ISAT-test (as defined in BS 1881, Part 5, 1970-6. Test for determining the Initial Absorption of Concrete) was adopted and measurements of the permeability were taken at 7, 17, 28, and 56 days. The results showed that the OPC mix has lower permeability than the PFA mix at early ages, but the difference tends to diminish at later ages. Detailed test results are reported in suitable form and discussed.

205. Kashi, M. G. "Freeze-Thaw Durability of High Strength Silica Fume Concrete." Ph.D. diss., Virginia Polytechnic Institute and State University, 1989.

Specimens from 27 batches of concrete with a water to cementitious (cement plus silica fume) ratio of 0.25 to 0.32, with and without entrained air, were tested for freeze-thaw durability in accordance with ASTM C666, procedure A (freezing and thawing in water). In addition, another set of similar specimens was moist

cured for 28 days instead of 14 days and tested in accordance with ASTM C666, procedure A to determine the effect of curing time on the freeze-thaw durability of high strength concrete. Results show that non-air-entrained high strength concrete with water-cementitious ratio of less that 0.30, regardless of the length of curing time, is frost resistant. Non-air entrained concrete with a water-cement ratio of 0.32 is durable if silica fume is not used.

206. Kayyali, O. A. "Strength and Porosity of Portland Cement Paste Subjected to Chloride Penetration." *Journal of Materials in Civil Engineering* Vol. 1 (February 1989): p. 10.

Studies made on hardened cement paste, subjected to chloride ions modified its pore structure. The modification was manifested by a significant increase in the volume of all pores that have diameters smaller than 50 nm. The observed increase was not necessarily continuous. Occurrence of discontinuity of the pore structure, however, was believed due to the collapse of the pore walls at high mercury intrusion pressures (pressure exceeding 175 mPa, which corresponded to pore diameter of about 5 nm) with respect to the paste strength, a slight loss of strength, at early age, was recorded. This effect was associated with the increase in the total pore volume.

The prolongation of initial moist curing, prior to exposure to salt solution, showed no strength loss. Moreover, the pore size distribution characteristics of the salt treated pastes were similar to those of cured ones. This phenomenon was explained by the fact that the chloride penetration continued to cause modification in the morphology of the hardened paste resulting in a decrease in permeability, thus gain in strength.

207. Kayyali, O. A., C. L. Page, and A. G. B. Ritchie. "Frost Action on Immature Cement Paste - Effects on Mechanical Behavior." *Journal of the American Concrete Institute* Vol. 76, No. 50 (November 1979): pp. 1217-1225.

Application of a limited number of freezing and thawing cycles to cement paste at very early stage of hydration induced effects that were not apparent for slightly more hydrated samples. Irreversible deterioration in strength and in fracture toughness were recorded. The effect of air entrainment, however, was shown not to be confined to retarding degradation caused by frost action. Early freezing of air-entrained paste actually had a beneficial effect on the final strength and fracture behavior of the material.

208. Kayyali, O. A., C. L. Page, and A. G. B. Ritchie. "Frost Action on Immature Cement Paste - Microstructural Features." *Journal of the American Concrete Institute* Vol. 77, No. 29 (September - October 1980): pp. 264-268.

Microstructural features, associated with the irreversible loss in strength experienced by immature plain cement paste when exposed briefly to freezing and thawing conditions, have been examined. An important factor is believed to be the formation of large, easily-cleaved portlandite crystals surrounded by stress-intensifying pores. Air-entrained paste, however, contained air voids into which segregation of portlandite occurred during early freezing and thawing. This is thought to have led to reduction in the quantity of portlandite deposited in the body of the paste when normal curing was resumed, and may account for the enhanced strength and toughness values recorded for such specimens.

209. Kellerman, W. F. "Effect of Use of Blended Cements and Vinsol Resin-Treated Cements on Durability of Concrete." *Journal of the American Concrete Institute* Vol. 48 (June 1946): pp. 681-688.

Presents a part of the results obtained from an investigation of the durability of concrete, by the Public Roads Administration using blends of portland cements with natural cements (86 percent and 14 percent by weight, respectively) and Vinsol resin-treated cements. Results presented in this contribution have a bearing on resistance to freezing and thawing tests, especially because of unusual results of a prolonged interruption of the daily freezing and thawing cycle.

210. Kennedy, H. L. "The Function of Entrained Air in Portland Cement." *Journal of the American Concrete Institute* Vol. 14, No. 6 (June 1943): pp. 529-542.

The use of air entraining agents in portland cement concrete shows considerable promise, particularly in highway concrete where resistance to scaling is an important factor. The need for fundamental research regarding the mechanism by which entrained air function is suggested and methods of tests are outlined.

Some results of exploratory investigations of the action of air entraining agents on the individual constituents of concrete are reported. It is indicated that the action of air entraining agents in cement paste differs materially from their action in concrete. The effect of air entraining agents on neat cement paste suggests a probable maximum cement content of concrete, above which the beneficial effect of air entraining agents may become negligible, their effect on strength remaining unchanged.

211. Kennedy, T. B., and K. Mather. "Correlation Between Laboratory Accelerated Freezing and Thawing and Weathering at Treat Island, Maine." *Journal of the American Concrete Institute* Vol. 50 (October 1953): pp. 141-172.

Six coarse and eight fine aggregates were used in 48 combinations to make concrete specimens, all with the same water-cement ratio, air content, and slump for comparative testing in accelerated freezing and thawing and exposure to natural weathering at mean-tide elevation at Treat Island, ME.

The two types of exposure aggregates used, test procedures, and results of dynamic testing of concrete specimens in both exposures are described. A summary is included of the examination of some of the concrete specimens and hypotheses suggested to explain differences in results in the two exposures, and a discussion of the relation of the difference between the thermal coefficients of coarse aggregate and mortar and durability factor found in these tests. The appendix contains more detailed information on the examination of the concrete and related discussion of other factors believed to be important in explaining results.

Comparison of laboratory and field results indicates that each aggregate combination behaves in an individual manner in each exposure, as influenced by differences in materials and in exposures. Prediction of behavior in one type of exposure from behavior in another cannot be made unless all the differences between the two can fully be evaluated, which is not yet possible.

212. Keune, R., and P. Hoekstra. *Calculating the Amount of Unfrozen Water in Frozen Ground From Moisture Characteristic Curves*, U.S. Army Cold Regions

Research and Engineering Laboratory, Hanover, NH, Special Report 114, July 1967.

The unfrozen water content of a soil can be determined by calculating the partial molar free energy of water ($\overline{\Delta F}_l$) at any temperature and referring this to the plot of $\overline{\Delta F}_l$ vs. the water content of the soil under consideration. A plot of $\overline{\Delta F}_l$ vs. water content can be obtained from a moisture characteristic curve at room temperature. Methods of calculating the numerical values for the graphs are outlined. Data are given for granular, clay, loam and pear soils and for Na-montmorillonite, so that the results should be useful in estimating unfrozen water by comparing an unknown soil with a similar soil in the report.

213. Keyser, J. H. "Scaling of Concrete by Frost Action." *Performance of Concrete* (1968): pp. 230-243.

From experience, factual data, theory, and experimentation, a summary has been made of the causes and effects of scaling in concrete and of the measures that can be taken to avoid its harmful effects. Using the City of Montreal as an example, it is shown how it is possible, through a carefully elaborated research program, rigid specifications, and close control to solve the annoying problem of sidewalk scaling. As indicated by the two surveys, the scaling of sidewalks, after a 3-year period, was reduced from 22 percent in 1959 to less than 0.5 percent in 1966.

214. Keyser, J. H., and M. Kushner. "Long-Term Freeze-Thaw Durability of Concrete in Catch Basins, Sidewalks, and Pavements Slabs." *Journal of the American Concrete Institute* SP 47-9 (April 1975).

The first part of the paper deals with catch basins. An information sheet was prepared to describe all possible defects. An examination of the 325 defective units revealed that 90 percent of defects were in the upper three elements, and 57 percent of these, were deteriorated due to frost action. An inspection of the manufacturing process had shown that in the manufacture of the dry cast catch basin elements (1) the sequence for adding of admixtures must be controlled (2) a practical test method is needed to determine the air content of no slump fresh concrete (3) the yield of the manufacturer's recommended dosage of air-entraining agent must be verified.

In the second part, the authors show that the sidewalk scaling problem was solved by applying research findings, revising specifications and by implementing a rigid quality control system. During concreting, each truckload of concrete is tested for air content.

The third part of the paper gives the results of an evaluation of long-term variation of the strength of 93 concrete pavement bases. The study revealed that the strength increases at the least 15 percent the first year and is expected to increase on the average by as much as 36 percent at the end of 10 years. However, the gain in strength is independent of the initial strength and may vary within a wide range.

215. Khayat, K. H., K. W. Nasser, and W. T. Hester. "Alternative Method to Measure Air Content in Fresh Concrete." *ACI Materials Journal* Vol. 87, No. 4 (July-August 1990): pp. 355-362.

The correlations of air content measurements obtained with a new air meter, called the mini air meter, and two other ASTM standard air meters were examined to establish the reliability of the new apparatus. The mini air meter used the volumetric principle to determine the air content of fresh concrete. It weighs 8 lb. (3.63 kg) and requires a concrete sample approximately 1/11 and 1/28 the size of that needed by the conventional roller and pressure meters, respectively. The laboratory work involved testing the air content of 21 concrete mixtures using the mini, roller, and pressure air meters. Both 3/8 and 1 in. (9.5 and 25.4 mm) nominal size aggregates were used to make normal weight and lightweight concretes. The water-cementitious materials ratios of the mixes ranged between 0.22 and 0.51. The cement content varied from 450 to 910 lb/yd^3 (267 to 540 kg/m^3), with silica fume added to some mixes. All mixes incorporated superplasticizers, and air- entraining agents were also added to yield air content between 1.25 and 12.5 percent.

Results indicate that the mini air meter exhibits excellent linear correlations with the other standard tests and provides a quick means to monitor air content. For the materials employed in this investigation, the accuracy of air volume measurements recorded using the mini air meter does not seem to be influenced by the density of the aggregate, nominal size of the aggregate, cement content, water-to-cementitious materials ratio, or the presence of additives.

216. Kivekas, L., and M. Leivo. "Durability of Concrete Under Arctic Offshore Conditions." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

The authors developed a new method for accelerated testing of frost resistance under arctic conditions. Specimens were made from high strength, air-entrained concretes containing superplasticizing admixtures. The air content, spacing factor and protective pore ratio results were related to the durability obtained in the freeze-thaw test. The relationship between durability and the three parameters was found to be fairly linear. Based on this, a limit of 100 cycles, believed to ensure good durability, was set and the requirements for air content, spacing factor, and protective pore ratio were then calculated from the test results.

217. Klieger, P. *Air-Entraining Admixtures*, Portland Cement Association, Research and Development Laboratories, Skokie, Illinois 60076, Bulletin 199, 1966.

The use of intentional air entrainment in concrete is now a well-established means for greatly enhancing the ability of concrete to resist the potentially destructive effect of freezing and thawing. Its use should be mandatory when concrete is to be exposed to such an environment, particularly when chemical deicers are used, as on pavements and bridge decks.

A thorough survey of the early development of air entrainment is presented by Gonnerman. The following paragraph from Gonnerman's report is of particular significance:

"These projects (test roads constructed in 1935-1937) revealed no relationship between surface scaling and composition of the cement, but they did show clearly that portland cement that inadvertently contained "crusher oil" reduced surface scaling as did many of the blends of portland and natural cement that contained tallow added during grinding of the natural cement. Laboratory tests disclosed that the beneficial effect of the crusher oil and tallow was due entirely to the additional air entrapped in the concrete by these air-entraining agents."

Other investigators came to similar conclusions during the late thirties and early forties. In these early instances, the air entrainment was not intentional but resulted form the presence of the crusher oil or the use of the tallow as a grinding aid during the production of the cement. These were the forerunners of the materials now used to produced air-entraining cements and called additions. Materials similar to presently used additions are called air-entraining admixtures when added with the other concrete ingredients at the time of mixing. This report is concerned with this class of materials. What are these materials; how do they function, both as to the process of entraining air and enhancing durability; how can they be specified and tested to insure adequate performance? These are some of the questions which we will attempt to answer in this chapter.

218. Klieger, P. "Durability Studies at the Portland Cement Association." *Durability of Building Materials and Components*, ASTM STP 691 (1980): pp. 282-300.

Durability studies at the Portland Cement Association (PCA) over the years have included both laboratory accelerated tests and field exposure to service conditions in a variety of environments. Laboratory accelerated tests have included: freezing and thawing in water, resistance to application of deicing chemicals during exposure to freezing and thawing, resistance to aggressive chemicals such as sulfates, alkali-aggregate reactions, and corrosion of reinforcing steel. Field exposures have included: full-scale concrete pavements subjected to traffic and exposed to severe weather and deicers, simulated bridge-deck sections in outdoor exposure, concretes in sulfate soils, and concrete piles and other specimens in seawater.

219. Klieger, P. "Effect of Entrained Air on Concretes Made with So-Called 'Sand-Gravel' Aggregates." *American Concrete Institute Proceedings* Vol. 45, No. 9 (September 1948 - June 1949).

Sand-gravel aggregates (maximum particle size 3/8 in.) used with non air-entraining cement produce concretes containing from 3 to 4 percent air. The same mixes made with air-entraining cement and the sand-gravel aggregates have air contents from 8 to 13 percent. Effect of this larger amount of entrained air is given in terms of tests of flexural and compressive strength, freezing and thawing resistance and length changes in varying storage conditions. Effect of "sweetening" the sand-gravel by addition of 30 percent of coarser aggregate is noted.

220. Klieger, P. "Effect of Entrained Air on Strength and Durability of Concrete Made with Various Maximum Sizes of Aggregate." *Proceedings of the Highway Research Board* (January 1952): pp. 177-201.

The results of freezing-and-thawing test indicate that for the concretes whose prior curing included a period of air drying, adequate resistance to freezing and thawing is secured at a relatively constant amount of entrained air in the mortar fraction, regardless of cement content or maximum size of aggregate. For these tests, this amount of air in the mortar fraction was approximately 9 percent. Concretes cured continuously moist required somewhat more entrained air for the same resistance to freezing and thawing.

The report also include information on the effect of entrained air on strength, resistance to salt scaling, volume change, and absorption of these concretes.

221. Klieger, P. "Effect of Mixing and Curing Temperature on Concrete Strength." *Journal of the American Concrete Institute, Proceedings* Vol. 54 (1958).

Comprehensive study was made of compressive and flexural strength produced by different types of portland cement used in concretes mixed, placed and cured at various temperatures between 25° F and 120° F. Tests indicate that there is a temperature during the early life of concrete which is considered optimum with regard to strength at later ages.

Effect of calcium chloride on strength at varying temperatures of mixing, placing, and curing is reported. Effect of cement temperature was found unimportant, except as it affected concrete temperature after mixing. More air-entraining agent was required for given air content as concrete temperature increased and slump decreased.

222. Klieger, P. "Further Studies on the Effect of Entrained Air on Strength and Durability of Concrete with Various Sizes of Aggregates." *Highway Research Board Bulletin* Vol. 128 (1956): pp. 1-19.

Previous tests using a natural sand and a crushed siliceous gravel indicated that, for concretes of constant cement content and consistency (varying water-cement ratio), adequate resistance to freezing and thawing of air-dried concretes was secured when the air content of the mortar fraction was 9 plus or minus 1 percent, regardless of the maximum size of aggregate used.

The tests reported herein are for concretes made with cements from the same source as the initial tests and the same natural sand. However, the coarse aggregate used was a crushed limestone with particle shape and texture different from those of the gravel previously used. Three cement contents were used at a constant slump of 5 to 6 inches: 4.0, 5.5 and 7.0 sacks per cubic yard of concrete. The maximum sizes of aggregate used were 3/8-in., 3/4-in. and 1 1/2-in. For each combination of cement content and maximum size of aggregate, five concretes covering a fairly wide range of air contents were prepared.

The results of freezing and thawing tests of these concretes confirmed the results of the earlier tests. Adequate resistance to freezing and thawing was obtained when the air content of the mortar fraction was in the range of 9 ± 1 percent.

The report also includes information on the effect of entrained air on strength, resistance to salt scaling, volume change and absorption of these concretes.

223. Klieger, P. "Studies of the Effect of Entrained Air on the Strength and Durability of Concretes Made with Various Maximum Sizes of Aggregate." *Proceedings of the Highway Research Board* Vol. 31 (October 1952): pp. 177-201.

Despite considerable past experience with the use of air entrainment in concrete, there are frequent and increasing demands for quantitative information concerning the proper amount of entrained air for adequate resistance to freezing and thawing and salt scaling and as to the effect of entrained air on the strength of various concretes.

The data in this report cover tests of concretes made with three cement contents, 4, 5.5, and 7 sacks per cu. yd. and five maximum sizes of aggregate, No. 4, 3/8-in., 3/4-in., and 2 1/2-in. The consistency of all concretes was 2 to 3 in. as measured by the slump test. One fine aggregate and one coarse aggregate were used. For each combination of cement content and maximum size of aggregate, eight concretes were prepared with air contents covering a fairly wide range.

The results of freezing-and-thawing tests indicate that for the concretes whose prior curing included a period of air-drying, adequate resistance to freezing and thawing is secured at a relatively constant amount of entrained air in the mortar fraction, regardless of cement content or maximum size of aggregate. For these tests, this amount of air in the mortar fraction was approximately 9 percent. Concretes cured continuously moist required somewhat more entrained air for the same resistance to freezing and thawing.

The report also includes information on the effect of entrained air on strength, resistance to salt scaling, volume change, and absorption of these concretes.

224. Klieger, P., and S. H. Gebler. "Fly Ash and Concrete Durability." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

Concretes containing Class F and Class C fly ashes were evaluated with respect to various aspects of concrete durability. A majority of concretes with fly ash produced stable air-void systems; however, the volume of air retained over period of 90 minutes was adversely affected, more in Class F than Class C fly ash concretes. Concretes with fly ash requiring a high dosage of air-entraining admixture generally exhibited poor retention of original air content. Organic matter content of the fly ash affected air-entraining admixture dosage and air content stability. Air-entrained concrete with or without fly ash and cured at 73° F (23° C) generally showed good resistance to freezing and thawing; however, when these concretes were cured at low temperature, Class F fly ash concretes showed slightly less resistance to freezing and thawing than Class C fly ash concretes. Deicer scaling tests showed that air-entrained without fly ash performed better than fly ash concretes regardless of curing provided. Both Class C and Class F fly ash concretes exhibited similar performance when subjected to deicer chemicals during freezing and thawing. The choride-ion penetration of concrete made with fly ash was not significantly affected by the class of fly ash. Class F fly ashes were significantly more effective as inhibitors of alkali-silica reaction expansion in mortar bars than were Class C fly ashes. Class F fly ashes significantly improved the sulfate resistance of concrete made with a cement

containing 8% C3A. Concretes with Class C fly ashes exhibited poor performance to sulfate solution.

225. Klieger, P., and J. A. Hanson. "Freezing and Thawing Tests of Lightweight Aggregate Concrete." *Journal of the American Concrete Institute* Vol. 57, No. 38 (January 1961): p. 779.

Nine lightweight aggregates and one natural sand and gravel aggregate were used in concretes subjected to laboratory freezing and thawing tests and, in some cases, to tests for resistance to deicer scaling. Concretes were prepared at two levels of compressive strength: 3000 psi and 4500 psi at 28 days. Both non air-entrained and air-entrained concretes were prepared, using the aggregates in an air-dried condition and in a 24-hr. saturated conditions.

The results of these tests indicate the necessity for providing intentionally entrained air to attain a high level of durability, the importance of moisture content of aggregate, and the influence of strength level i.e., water-cement ratio, on the durability. The results point to the desirability of evaluating a lightweight aggregate by means of laboratory freezing and thawing tests of air-entrained concrete made with the aggregate, as is generally done for normal weight aggregate.

226. Klieger, P., G. Monfore, D. C. Stark, and W. Teske. "D-Cracking of Concrete Pavements in Ohio." Ohio Department of Transportation, OHIO-DOT-11-74 (Final Report), October 1974.

A three-phase program was undertaken to determine the extent and severity of D-cracking in Ohio, and to determine the role of drainage and materials properties in its development. A rating system was established to evaluate the performance of materials, in particular, coarse aggregate, in existing pavements. Data from these surveys have been processed for storage in a computerized retrieval system. Laboratory freeze-thaw testing has identified the importance of source of coarse aggregate in the development of distress and has provided strong evidence that reducing the maximum particle size of the aggregate may reduce or eliminate the development of D-cracking. A test procedure has been recommended for identifying coarse aggregate sources and gradations vulnerable to freeze-thaw failure in pavements. Source of cement was found, in laboratory tests, to be of minor importance while level of air entrainment within the existing specified range was found to be of essentially no importance in this problem. The presence of bulk water or only capillary held water in granular subbases was found to have little differential effect on the degree of saturation of certain coarse aggregate materials in simulated pavement exposures. A test road has been designed to verify the importance of certain materials factors in the development of D-cracking, and a gage has been developed to measure moisture changes in subbases and pavement slabs.

227. Klieger, P., D. C. Stark, and W. Teske. "The Influence of Environment and Materials on D-Cracking." FHWA-OH-78-06 (Final Report), October 1978.

A three-phase program was undertaken to determine the effectiveness of reduced aggregate particle sizes in minimizing D-cracking in field exposures, to determine the importance of source of fine aggregate and quantity of maximum permissible aggregate particle size on freeze-thaw durability, and to evaluate the relative importance of certain field environmental conditions on D-cracking. These

objectives were approached through laboratory freeze-thaw testing of concretes, resurveys of existing pavements in Ohio, and the construction and monitoring of a test road near Vermilion. Field surveys thus far indicate that reducing maximum aggregate particle sizes is beneficial, while the laboratory tests indicate that the proportion of coarser particle sizes has a significant effect on durability. The laboratory tests also showed that source of fine aggregate has essentially no bearing on durability, even when derived from coarse aggregate material of known low durability. Outdoor test plot studies, and moisture determinations on existing pavement concrete, reveal the overriding importance of aggregate pore structure on concrete durability. The test road was built in 1974 and 1975 and, therefore, is too young for the development of D-cracking. However, interim data indicate that aggregate particle size has a pronounced effect on the frequency of occurrence of popouts, while continuously reinforced pavement on asphalt-stabilized bases show greater vulnerability to non-uniform cracking than companion pavements on cement treated bases.

228. Kobayashi, M., E. Nakakuro, K. Kodama, and S. Negami. "Frost Resistance of Superplasticizers." *Journal of the American Concrete Institute* Vol. 68 (May 1981): pp. 269-282.

First, the paper shows the results of microscope analyses of concretes using three high-range water-reducing admixtures of different chemical compositions and having different water-cement ratios and air contents in order to determine the air-void systems of concretes containing high-range water-reducing admixtures, and also discusses the selection of the air-entraining admixture to be jointly used. Secondly, the paper deals with the relation between frost resistance and spacing factor based on the results of rapid freezing and thawing tests on concretes made with high-range water-reducing admixtures and further gives air contents or spacing factors required to give concrete adequate resistance to severe frost action. The results of tests on the effects of different kinds of high-range water-reducing admixtures on surface tension, foaming, and stability of air bubbles are given.

229. Koopmans, R. W. R., and R. D. Miller. "Soil Freezing and Soil Water Characteristic Curves." *Soil Sci. Soc. Amer. Proc.* Vol. 30 (1966): pp. 680-685.

An earlier paper suggested that the soil and water characteristic (SWC) of soil should have an analogue to be called the soil freezing characteristic (SFC) that could be obtained by freezing saturated soil in an apparatus functionally related to the pressure plate apparatus. The analogy for granular soil, free of colloids, is on a different basis (capillary effects) than for soil that is wholly colloidal (absorption effects). Different rules are needed to demonstrate the analogies for the respective types. Apparatus was devised to permit SFC and SWC data to be obtained, in turn, with each material placed in the apparatus. Two silt fractions, a sodium-montmorillonite paste, and a whole soil were used. The results confirm the expected analogies and indicate that in these experiments, the ratio of the specific surface energy of an air-water interface at 20° C to that of an ice-water interface near 0° C was as 72.7:33.1. The results demonstrate significant mobility for unfrozen water at temperatures as low as -0.15° C even in clean silt fractions. It is concluded that the inherent instability of some of the residual water in soils during drying does not significantly affect the SWC in the range 0 to 4 bars of matric suction.

230. Kosmatka, S. H. "ACI 318-39 and Deicer Exposure." *Portland Cement Association* Vol. 11, No. 3 (September 1990).

The need to improve the durability of reinforced concrete exposed to deicing chemicals was met with recent changes to the Building Code Requirements for Reinforced Concrete, ACI 318-39. Aspects of durability discussed here include the resistance of reinforced concrete to frost action, deicer scaling, and corrosion of reinforcing steel.

231. Krantov, F. M., and A. G. Shlaen. "Question of the Movement of Water in Concrete When It Freezes." *Inzhenerno-Fizicheskii Zhurnal* Vol. 45, No. 4 (October 1983): pp. 621-625.

We determine the dimensions of capillaries capable of removing the excess from a freezing pore when there are no destructive processes taking place.

232. Lamond, J. F. "Twenty-Five Years' Experience Using Fly Ash Concrete." *Journal of American Concrete Institute* SP 79-2 (July - August 1983).

The U.S. Army Corps of Engineers has used fly ash as a material that partially replaces portland cement in concrete for twenty-five years. Initially, research was performed on the use of fly ash on concrete properties for bleeding, permeability, heat rise, resistance to freezing and thawing, elasticity, and compressive and flexural strength development. Those properties affected by partial replacement of portland cement with fly ash were heat rise in mass concrete, resistance to freezing and thawing, and strength development. The concrete materials properties of three massive concrete gravity dams are reported. Since construction these dams have been periodically inspected. Although these structures have some minor cracking, spalling, and erosion, their performance has been similar to other concrete gravity dams constructed using concrete without fly ash. Cost savings per cubic yd of concrete has been the benefit derived from using fly ash as a partial cement replacement material in massive concrete structures. Fly ash is specified to conform to ASTM C 618, Class C or Class F, with modifications to this specification as needed based on location or type of structure. Fly ash may replace portland cement up to 35 percent by absolute volume in interior mass concrete and 25 percent by absolute volume in exterior mass concrete and in structural concrete. Fly ash concrete has performed satisfactorily on Corps of Engineers projects over the last twenty-five years.

233. Landgren, R., and H. S. Sweet. "Investigation of Durability of Wyoming Aggregates." *Highway Research Board, Proceedings* Vol. 31 (January 1952): pp. 202-217.

This paper represents a progress report of the investigation covering seven aggregates; tests of additional materials, and other tests of those materials covered.

The test indicated three of the aggregates were potentially reactive with cement alkalies and the use of cement with low alkali content or of pozzolanic admixtures is indicated. One aggregate also caused rapid concrete deterioration under freezing-and-thawing action, wetting and drying, or rapid temperature change. Resistance to these effects was also improved by pozzolanic admixtures. Two other aggregates, not alkali reactive, were also affected by rapid temperature-change tests. Further study of the effect of rate of temperature change on concrete

deterioration indicated that too rapid a change in laboratory tests may introduce factors not present in natural weathering conditions. Some exploratory data on possible chemical factors entering into temperature-change tests are also presented.
Highway Research Board.

234. Lane, D. S. "Testing Fly Ash in Mortars for Air-Entrainment Characteristics." *Cement, Concrete, and Aggregates* Vol. 13, No. 1 (Summer 1991): pp. 25-31.

When fly ash is used in the production of air-entrained concrete, it can affect the dosage requirements of air-entraining admixture (AEA) needed to produce the desired air content. ASTM C 618 provides a uniformity requirement for the dosage of AEA needed with a particular fly ash, and ASTM C 311 provides a test to determine compliance with the requirement. In a study of fly ash uniformity, the C 311 test was found to be ineffective in evaluating the effect of fly ash characteristics on AEA dosage requirement. The problems with the C 311 test is traced to the high levels of AEA which are required in the test and is illustrated by the use of AEA dosage versus air content curves.

Modifications to the C 311 test are proposed wherein an admixture dosage is selected from the AEA dosage versus air content curve. This dosage is then used to test successive fly ash samples, and changes in air content of the test mix illustrate the variations in AEA requirement caused by the fly ash. An additional modification permits the evaluation of the fly ash's potential to lose entrained air over time.

235. Lane, D., and R. C. Meininger. "Laboratory Evaluation of the Freezing and Thawing Durability of Marine Limestone Coarse Aggregate in Concrete." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987, p. 1311.

Air-entrained concretes were subjected to extended freezing-thawing tests to determine the durability of three porous marine limestone coarse aggregates. Control concretes were made with a non-porous limestone. Prior to mixing the concrete, the coarse aggregates were soaked for 24 hours. After initial curing, the specimens were placed in a standard moist room for 13 days until freezing tests began at 14 days of age. Weight change, length changes, and dynamic modulus of elasticity were monitored throughout the test.

Specimens exposed to the freezing-in-air procedure were subjected to 1000 freezing-thawing cycles without showing significant deterioration. Except for the control group, all specimens subjected to the freezing-in-water procedure began to deteriorate between 250 and 350 cycles as indicated by increasing length and decreasing modulus of elasticity. Increasing weight of the water-frozen specimens during the first 300 cycles was attributed to water absorption. Calculations suggest that the coarse aggregate in specimens frozen in water had reached 80 to 95 percent saturation when deterioration began.

236. Lane, R. O., and J. F. Best. "Laboratory Studies on the Effects of Superplasticizers on the Engineering Properties of Plain and Fly Ash Concrete." *Journal of the American Concrete Institute* SP 62-11 (October 1979).

An investigative program was conducted by the Tennessee Valley Authority Laboratories to determine the relative performance of several super water

reducers. Both plain and fly ash concrete mixes were included to check the compatibility of pozzolans with superplasticizers. Mortar mixes served to investigate parameters of plastic volume change, drying shrinkage, bleeding, time of set, air content, compressive strength, flow, sand-cement ratio, and fly ash content. Concrete mixes were then developed to compare such properties as slump and slump loss, shrinkage, segregation, air content, time of set, compressive strength, modulus of elasticity, and freeze-thaw durability. Conclusions based on this study indicate that the superplasticizers tested are compatible with concrete containing fly ash and produce no adverse effects, although water reductions or slump gains were not as great for mixes with fly ash as for straight cement mixes. Segregation did not occur in mixes of fluid consistency but increases in consistency were lost in less than 1 hr. Properties of the hardened concrete were relatively unaffected, and the most apparent benefit of the superplasticizers is their ability to significantly increase concrete workability for short periods.

237. Lane, R. O., and J. F. Best. "Properties and Use of Fly Ash in Cement Concrete." *Concrete International* (July 1982): pp. 81-92.

The Tennessee Valley Authority (TVA) has over 25 years of experience in using fly ash in concrete mixtures. Much of this knowledge and experience is summarized in the article by covering physical and chemical properties of fly ash and their effects on freshly mixed and hardened concrete. It also includes the evaluation of engineering parameters of concrete containing fly ash. A procedure for mixture proportioning of fly ash concrete is also presented along with sample calculations for a typical mixture. Special applications such as zero-slump concrete and pumped concrete are also discussed.

238. Langan, B. W., and M. A. Ward. "Determination of the Air Void System Parameters in Hardened Concrete - An Error Analysis." *Journal of the American Concrete Institute* Vol. 83, No. 82 (November - December 1986): pp. 943-952.

ASTM C 457, "Standard Recommended Practice for the Microscopical Determination of Air Void Content and Parameters of the Air Void System in Hardened Concrete," is extensively used in the assessment of the potential durability of concrete, particularly in the assessment of concrete that has failed in service. Unfortunately, little information is available concerning the accuracy of the air void parameters obtained using this test method. In the current standard, the expected maximum single operator standard deviation is given for air content only and is based solely on theoretical calculations. To obtain an estimate of the magnitude of the total error, normal error analysis is applied to the equations used to determine the air void parameters by the modified point count method. It is shown that the expected errors in the average chord intercept, specific surface, and spacing factor can be estimated if the errors in estimating the air and paste contents and number of voids per unit length can be established. Two methods are presented to predict the maximum theoretical errors in specific surface and spacing factor. Repetitive testing of standard surfaces is used to compare theoretical and measured errors for within laboratory and inter-laboratory data. It is shown that significant differences can exist between the air void parameters determined, particularly in the interlaboratory data.

239. Langan, B. W., and M. A. Ward. "A Laboratory Investigation for Potential Durability of Ready-Mixed Concrete Retempered for Air Content and Workability." *Can. J. Civ. Eng.* Vol. 3 (1976): pp. 570-577.

The effects of agitation and retempering on some properties of fresh and hardened concrete are considered. Data are presented on the influence of agitation and retempering with an air-entraining agent on the workability, compressive strength, and air void system in hardened concrete. The results indicate that although agitation reduces air content and increases the spacing factor, the original parameters can be regained by proper retempering. It is shown that any loss in compressive strength due to retempering is accompanied by an increase in potential durability due to the improvement of the air void system.

240. Langan, B. W., and M. A. Ward. "Significance of Interrupted Testing on the Freeze-Thaw Resistance of Fly Ash Concrete - ASTM C 666 (Method A)." *Cement, Concrete and Aggregates — CCAGDP* Vol. 9, No. 1 (Winter 1987): pp. 113-116.

This investigation studied the effect of interrupted testing combined with prolonged freezing on the freeze-thaw resistance of concretes containing fly ash as part of the cementitious fraction, using ASTM Test Method for Resistance of Concrete to Rapid Freezing and Thawing (C 66-84, Method A). Also studied was the effect of "marginal" air contents on the above test parameters. Test results indicate that for fly ash concretes with air contents in excess of 5%, interrupted and/or prolonged periods of freezing do not affect the freeze-thaw resistance of the concrete. Early age freezing (14 days) of fly ash concretes did not appear to be detrimental to the performance of the fly ash concretes tested.

241. Larson, T. D. "Air Entrainment and Durability Aspects of Fly Ash Concrete." *ASTM* Vol. 64 (1964): pp. 866-886.

The recognized depressive effect of fly ash on entrained air content in concrete suggests that (1) the causes for this phenomenon should be carefully explored; (2) the methods for predicting these effects and for determining predictive reliability should be considered; (3) there is a need for studying the void system in hardened fly ash concrete; and (4) air contents of fly ash concrete should be very carefully determined before durability comparisons are made. These points are discussed in the light of published references and experimental data taken from mortar and concrete mixtures made with representative types of fly ash.

Fly ash carbon is shown to have a capacity for the selective adsorption of the organic molecular complexes composing common air-entraining agents. Predictive equations of air-entraining agent demand as a function of fly ash ignition loss are developed from mortar and concrete mixtures. The effect of fly ash on mortar workability is such that a narrower range of flow values than that permitted Method C 185 is required for developing reliable relationships. Predictive equations for concrete mixtures must be evaluated with due regard for other factors affecting air content. Particular combinations of fly ash and air-entraining agent yield the most reliable predictive relationships in either mortars or concretes, although highly significant relationships are developed for one agent used with a wide range of fly ashes.

The air-void system of fly ash concrete, evaluated by microscopic linear traverse methods, is not significantly affected by additions of various types and amounts of fly ash when an adequate air content is maintained.

Method C 290 tests on freezing and thawing durability of nominally equal strength, equal air content, fly ash concrete indicate that surface erosion is related to carbon content, but that under proper control, fly ash has no effect on resistance to freezing and thawing as determined by evaluation of internal soundness.

242. Larson, T. D. "Studies of Freeze-Thaw Durability: The Air-Void System and Associated Characteristics of Fly Ash Concrete." Ph.D. diss., Pennsylvania State University, 1962.

This dissertation is based on a study of types and amounts of fly ash used if preparing concrete specimens. Specimens were tested for strength, rapid freezing and thawing cycles in water. Linear traverse techniques were used for voids determination.

The study introduced and investigated an evaluation of freeze-thaw durability by the concept of equal strength comparison and the experimental evidence supported the significance of this concept.

The study found that replacing 10 to 20 percent of the cement with fly ash reduced the durability factor as measured by dynamic modulus. Replacement of 30 percent fly ash increased the durability factor when concrete was made with average quality fly ash and cured to the same flexural strength as controls with no fly ash, resistance to freeze-thaw cycling was found to be equal or superior to the controls. The study concluded that variations in void parameters were not positively associated with fly ash fineness.

243. Larson, T. D., P. D. Cady, M. Franzen, and J. Reed. "Critical Review of Literature Treating Methods of Identifying Aggregates Subjected to Destructive Volume Change When Frozen in Concrete and a Proposed Program of Research." *Highway Research Board Bulletin*, Special Report 80, NCHRP Project 4-3.

This report constitutes a critical review and annotated bibliography of literature pertinent to National Cooperative Highway Research Program Project 4-3(2) on "Development on Methods to Identify Aggregate Particles Which Undergo Destructive Volume Changes When Frozen in Concrete." Because of the depth and value of this interim report as a by-product of the research and in order that it may readily serve other researchers and testing engineers in this subject area, the Advisory Panel requested its publication in the Special Report Series in advance of the final report due in December 1964.

244. Larson, T. D., and P. D. Cady. *Identification of Frost-Susceptible Particles in Concrete Aggregates*, Highway Research Board, Washington, D. C., NCHRP Report No. 66, 1969.

This research report consists largely of an extensive evaluation of test methods that are described in NCHRP Report 15. That report and HRB Special Report 80 are considered to be a necessary preface to this report since they treat the philosophy and problems of aggregate testing in detail.

Two approaches to the problem of identifying frost-susceptible aggregate particles were followed. In one, relatively homogeneous aggregate fractions were tested in concrete under simulated field conditions, with two objectives: (1) to develop a rational test method incorporating elements of field exposure conditions, and (2) to establish meaningful bases of aggregate performance against which other test

methods could be compared. The second approach explored the potentialities of single aggregate particle tests as simple, quick, and economical means of identifying frost susceptible aggregates.

245. Larson, T. D., P. D. Cady, and J. T. Price. *Review of a Three-Year Bridge Deck Study in Pennsylvania*, Highway Research Board, Highway Research Record No. 226, 1968.

The results of the initial three years of continuing research project on the durability of concrete bridge decks in Pennsylvania are presented. The study involved field surveys of 38 bridge decks comprising 2,782 ten-ft long survey units. A total of 154 cores were taken from 34 of the decks. The cores were subjected to detailed laboratory analyses including determination of air void parameters by linear traverse techniques, w/c ratio determinations, and petrographic examination. Seven bridge decks were observed during construction to examine and evaluate the effect of construction practices on durability. Bridge decks were resurveyed annually to establish rates.

The major types of deterioration found were transverse cracking, fracture planes, potholes, and surface mortar deterioration. The primary causes of deterioration were indicated to be materials (aggregates) and workmanship (overfinishing, poor quality control with respect to entrained air and w/c, and improper placement of reinforcement). Recommendations to alleviate the causes of poor performance and suggested areas of needed research are included.

246. Larson, T. D., J. L. Mangusi, and R. R. Radomski. "Preliminary Study of the Effects of Water-Reducing Retarders on the Strength, Air Void Characteristics, and Durability of Concrete." *Journal of the American Concrete Institute* Vol. 60, No. 74 (December 1963): pp. 1739-1751.

Concretes made with water-reducing retarders showed improved freeze-thaw durability, primarily as a result of increased strength. Specimens made from constant slump, constant cement factor mixtures containing several agents at various dosage levels had higher flexural and compressive strengths than the control specimens. Flexural strengths at 7 and 28 days correlated significantly with the durability factor.

Microscopic studies indicated that there were minor differences between the air void systems of control and test concretes. In particular, spacing factors increased with retardation. This appeared to result from air entrainment by the water-reducing retarders and from bubble dissolution.

247. Lau, E. C. "Effect of Maximum Size of Aggregate and Other Factors on Frost Resistance of Concrete." Ph.D. diss., University of Windsor, September 1967.

The experimental program describes the use of 3-in. x 6-in. concrete specimens to determine the frost susceptibility during freezing by studying their length-changes vs. temperature patterns. A range of water-cement ratios from 0.45 to 0.60, each with three different maximum sizes of aggregates (3/4-in., 3/8-in., and 1/4-in.) was used. In order to simulate appropriate exposure conditions the specimens were conditioned to different degrees of saturation before being introduced into a freezing chamber. The main findings were: (a) low water-cement ratios increase the frost resistance of concrete; (b) large aggregate particles are more vulnerable

to freezing damage; (c) critical degree of saturation is found to be dependent on the water-cement ratio of the paste and the size of aggregates used.

248. Lawton, E. C. "Durability of Concrete Pavement — Experiences in New York State." *Journal of the American Concrete Institute* Vol. 35 (June 1939): pp. 561-580.

A resume of field behavior of some 440 miles of concrete pavement constructed for experimental purposes by New York State with different proportions and combination of aggregates is presented. Field service records of these pavements were made and compared with laboratory tests of aggregates used. The purpose was to study the durability of cement concrete pavement as affected by coarse aggregate such as stone, gravel, and slag; as affected by sands of different characteristics, such as high and low kaolin; and as affected by blended cement composed of different proportions of natural and normal portland cements. The projects studied are listed and identified by name.

249. Legg, F. E. "Freeze-Thaw Durability of Michigan Concrete Coarse Aggregates." *Highway Research Board Bulletin* No. 143 (1956): pp. 1-13.

The Michigan Highway Department is currently called upon to approve, each year, coarse aggregate for approximately one million cubic yards of concrete. These aggregates are furnished from deposits ranging in size from roadside pits up to large well-established commercial sources and are distributed over an area exceeding 600 miles between locations. There is every indication that the rate of aggregate consumption will increase with the accelerated highway construction program. This will surely require evaluation of the freeze-thaw durability, both of deposits now considered of marginal quality and of entirely new sources as proven aggregate reserves becomes depleted.

This paper presents laboratory freeze-thaw results as well as field observations on the major Michigan aggregate sources and is considered a first step in formulation of a policy regarding acceptance of future aggregates of unknown service behavior.

250. Legg, F. E., and W. W. McLaughlin. "Gravel Beneficiation in Michigan." *Journal of the American Concrete Institute* Vol. 57, No. 40 (January 1961): pp. 813-825.

Michigan natural gravel is now competing with imported high quality coarse aggregates intended for concrete subject to severe winter exposure, as a result of installation of various types of beneficiation plants. Thus, local deposits are being utilized, after upgrading, without sacrifice of concrete quality. This development was prompted in large measure by the decision of the Michigan State Highway Department that aggregate quality standards would not be relaxed despite the greatly increased demand of the accelerated highway construction program.

Many of Michigan's lower peninsula glacial gravels have been found particularly amenable to upgrading by heavy media separation, although commercial installations of elastic fractionation, jigs, and soft particle disintegrators are being tried. At present, 14 beneficiation plants are operating in the State. Laboratory concrete freeze-thaw evaluations of the effectiveness of several of the plants are presented together with observations on routine field inspection. Caution is advised against undue optimism of one beneficiation process as opposed to another for all deposits. Tailoring of the particular process to the needs of each

aggregate source, together with consideration of economics involved, seems the wiser course of action.

251. Lin, C. H. "The Effects of Freezing Rates on the Durability of Concrete." Ph.D. diss., Virginia Polytechnic Institute, June 1974.

The purpose of this dissertation was to study the effects of freezing rates on the durability of aggregates, having various levels of saturation, embedded in concrete.

Several relationships were investigated from the results of these tests, including relative dynamic modulus vs. cycles of freeze-thaw, relative dynamic modulus vs. cumulative length change, cumulative length change vs. cycles of freeze-thaw, cumulative length change vs. time, cumulative length change vs. temperature, durability factor (DF100) vs. freezing rates, and durability factor (DF100) vs. freezing points.

For concrete made from vacuum saturated aggregate, the rate of freezing did not produce any different effect on the durability of concrete. However, for concretes made from soaked or air-dried aggregates, the faster rate of freezing resulted in higher concrete durability. Concrete durability was increased by decreasing the freezing point of water solution in the aggregates used.

Test results indicated that the concrete durability of antifreeze vacuum saturated aggregate was superior to that of air-dried aggregate.

The potential field performances of aggregate vs. various levels of aggregate saturation were also described.

252. Lin, Chung-Hsing, R. D. Walker, and W. W. Payne. "Effects of Cooling Rates on the Durability of Concrete." *Transportation Research Record* No. 539 (1975): pp. 8-19.

Past research generally assumed that rapid cooling rates cause faster deterioration of concrete that is susceptible to damage from freezing and thawing. The objective of this project was to investigate the effect of varying freezing rates on an otherwise standard ASTM test. Eighty-one concrete specimens were fabricated with an aggregate capable of causing deterioration under freezing-and-thawing conditions. The aggregates were placed in the concrete at 3 different degrees of saturation. Three rates of cooling were used: 4.4° F/hour (2.45° C/hour); 6.6° F/hour (3.67° C/hour); and 13.3° F/hour (7.39° C/hour). Modifications to freezing and thawing equipment are described, and possible explanations of the results obtained are presented. If the aggregate was not initially saturated when placed in the concrete, slower freezing rates produced demonstrably faster rates of deterioration. It is theorized that a slower rate of cooling enables more water to migrate to the surroundings of the coarse aggregate. Therefore, during the thawing phase, more water is available for the coarse aggregate to become increasingly saturated. Rate of cooling seemed not to affect the rate of deterioration of concrete containing aggregates placed in the concrete already in the saturated state.

253. Lindgren, M. K. "The Prediction of Freeze-Thaw Durability of Coarse Aggregate in Concrete by Mercury Intrusion Porosimeter." Ph.D. diss., Purdue University, 1980.

D-cracking is a serious problem of concrete pavements in freezing climates. The main cause of this distress is the coarse aggregate. Kaneuji determined a correlation between the pore size distribution (from mercury intrusion) of an aggregate and the freeze-thaw durability of concrete using the same aggregate. He developed an Expected Durability Factor EDF, used to determine whether an aggregate can be expected to be durable or nondurable. The present study was designed to refine the validity of Kaneuji's correlation and better define the pore structure criteria by which to predict the performance of an aggregate.

Aggregates from fifty-two Indiana highway cores were tested, as were five rock samples supplied by the Portland Cement Association. The EDF values were determined from the pore size distributions, and an "average" value was assigned to each pavement associated with the cores. these values were then compared with the field performance of the pavement to ascertain the borderline between EDF values for durable for nondurable aggregates. A good correlation between the field performance and the "average" EDF values was found. A pavement will be durable if its coarse aggregate has an EDF value greater than 50 for 90% or more of the aggregate. This criterion applies to stone and gravel aggregates with a maximum size of 1-1/1" to 2-1/1". The pavement will be durable for at least thirty years.

254. Litvan, G. G. *Absorption Systems at Temperatures Below the Freezing Point of the Adsorptive*, National Research Council of Canada, Ottawa, Division of Building Research, 1978.

Isothermal adsorption studies and the measurement of dimensional changes below the bulk freezing point of the adsorbate indicate that substances adsorbed in porous solids are unable to freeze in situ. The difference between the vapor pressure or free energy of the unfrozen adsorbate and that of the bulk adsorptive outside of the porous system is resolved by a desorption process; the desorbed matter freezes outside of the system while the vapor pressure of the adsorbate remaining in the pores decreases through meniscus formation. Mechanical breakdown of the system occurs only when this process cannot be completed and an equilibrium state is not attained.

This mechanism was found to be valid for porous silica glass, hydrated cement paste, bricks, and even for biological substances such as animal and plant tissue, and foodstuff. This understanding has led to the development of new methods for testing the durability of building materials, clarification of some problems of the BET surface area determination method, and it suggests an explanation for the action of cryoprotective agents.

255. Litvan, G. G. "Adsorption Systems at Temperatures Below the Freezing Point of the Adsorptive." *Advances in Colloid and Interface Science* Vol. 9 (1978): pp. 253-302.

Isothermal adsorption studies and the measurement of dimensional changes below the bulk freezing point of the adsorbate indicate that substances adsorbed in porous solids are unable to freeze in situ. The difference between the vapour pressure or free energy of the unfrozen adsorbate and that of the bulk adsorptive

outside of the porous system is resolved by a desorption process; the desorbed matter freezes outside of the system while the vapour pressure of the adsorbate remaining in the pores decreases through meniscus formation. Mechanical breakdown of the system occurs, only then, when this process cannot be completed and an equilibrium state is not attained. This mechanism was found to be valid for porous silica glass, hydrated cement paste, bricks, and even for biological substances such as animal and plant tissue, and foodstuff. This understanding has led to the development of some problems of the BET surface area determination method and it suggests an explanation for the action of cryoprotective agents.

256. Litvan, G. G. "Air Entrainment in the Presence of Superplasticizers." *Journal of the American Concrete Institute* Vol. 80, No. 33 (July - August 1983): p. 326.

Air-entrained and plain mortar specimens (cement-sand ratio = 1:3, water-cement ratio = 0.65) were prepared using a modified sulfonated polymer, a naphthalene-formaldehyde condensate, or a sulfonated melamine formaldehyde admixture at two levels of concentration. The air void system determined by the linear traverse method, the pore size distribution obtained by mercury intrusion porosimetry, and frost resistance assessed by alternate freezing and thawing were compared with those of control mixes containing no superplasticizer. A large pore volume (0.3 to 2 μm) in the presence of an air-entraining admixture is assumed to be responsible for the improved frost resistance of cement paste. Superplasticizers eliminate large air voids visible under the microscope but do not significantly interfere with the action of air-entraining admixtures in the formation of small pores.

257. Litvan, G. G. "Frost Action in Cement Paste." *Materiaux et Constructions* Vol. 6, No. 34 (1973): pp. 293-298.

An earlier theory of frost action is further developed and its implications considered, particularly with regard to testing. Factors determining durability of paste, dimensions of sample, degree of saturation and rate of cooling are discussed. It is shown that cumulative residual expansion is a good indicator for testing frost resistance: samples can be evaluated after 10 to 15 freeze-thaw cycles. The results are discussed in relation to existing tests.

258. Litvan, G. G. "Frost Action in Cement in the Presence of Deicers." *Cement and Concrete Research* Vol. 6, No. 3 (May 1976): pp. 351-356.

Cement samples impregnated with water and with 5, 9, 13, 18 and 26 percent NaCl solution have been subjected to temperature cycles between +5 and -70° C and changes in their dimensions and heat content determined. The results are consistent with the theory proposed by the author for frost action in the absence of chemicals and with the findings of a study of phase transition of NaCl solution adsorbed in porous glass. These observations can be explained by the fact that solution contained in the pores, when cooled below the bulk freezing point, remains in a liquid-like state. This condition gives rise to instability, which is eliminated by mass transfer. If the process cannot proceed at a required rate, mechanical damage occurs. The well-known aggravating effect of dissolved chemicals is due, primarily, to the increased degree of saturation they promote.

259. Litvan, G. G. "Further Study of Particulate Admixtures for Enhanced Freeze-Thaw Resistance of Concrete." *Journal of the American Concrete Institute* Vol. 82, No. 66 (November - December 1985): p. 724.

Investigation of a previously developed method of increasing the resistance of concrete to freezing and thawing by the addition of porous particulates of specified pore structure is continued. Vermiculite and two grades of pumice and perlite were tested for suitability as additives, and their performance compared with that of a previously examined brick. Of the minerals tested, vermiculite, one pumice, and one perlite provide excellent resistance to freezing and thawing of cement pastes (water-cement ratios = 0.48 and 0.42), mortar (water-cement ratio = 0.75), and concrete (water-cement ratio = 0.63).

260. Litvan, G. G. "Phase Transitions of Adsorbates: IV, Mechanism of Frost Action in Hardened Cement Paste." *Journal of the American Ceramic Society* Vol. 55, No. 1 (January 1972): pp. 38-42.

The dimensional changes and the thermograms of cement specimens were determined during temperature cycles (+5 to -60° C, 0.33° C/min). In each case, freezing processes at -8 and -40° C and melting processes at -11 and 0° C were observed. The results could be explained by a theory previously developed for the porous-glass-water system. At the higher temperature, freezing occurs on the outer surface of the specimen; at the lower temperature, it occurs in the pores after redistribution of the water. Because water does not freeze in pores filled on adsorption, it migrates out of these pores when the relative humidity (expressed in terms of the vapor pressure of undercooled water) produces unavoidable decreases on cooling. Expansion is deleterious when the water content of the paste is significantly greater than the equilibrium value at the prevailing relative humidity. The effects of the water/cement ratio, degree of saturation, air entrainment, sample dimensions, and cooling rate were consistent with the theory.

261. Litvan, G. G. "Phase Transitions of Adsorbates: VI, Effect of Deicing Agents on the Freezing of Cement Paste." *Journal of the American Ceramic Society* Vol. 58, Nos.1-2 (January - February 1975): pp. 26-30.

Changes in the dimensions and heat content of hydrated cement specimens were determined as a function of temperature and concentration of deicing agent in cooling-warming cycles between +15 and -70° C. The concentration of the polar deicer (NaCl) solution varied from 0 to 26% and that of the nonpolar (urea) solution from 0 to 40%. The w/c ratios were 0.4, 0.6, and 0.8 plain and 0.5 air-entrained. Experiments were also conducted to clarify the effect of cooling rate and sample size. The observations can be explained by the mechanisms previously proposed for phase transitions of adsorbates. In the presence of salts, freezing and melting of liquid exuded from the pores on cooling proceed according to the bulk phase diagram, producing double peaks in the thermograms except at extreme concentrations. The detrimental effect of deicers is attributed mainly to the high degree of saturation, a consequence of the low vapor pressure of the solutions. A beneficial aspect is the widening of the temperature range in which transitions occur. These opposing effects result in the worst conditions at a low deicer concentration (5% NaCl) and optimum conditions at a moderately high concentration (13% NaCl). Since the effect of deicers is physical, it should be common to all chemicals. Air entrainment, although beneficial in most circumstances, can be detrimental. The best protection against "salt scaling" appears to be reduction of porosity.

262. Litvan, G. G. *Pore Structure and Frost Susceptibility of Building Materials*, National Research Council of Canada, Ottawa, Canada, research paper no. 584.

It is shown that the inability of water contained in pores to crystallize in situ leads to gradual and continuous redistribution of the adsorbate on cooling to below 0° C. Frost damage occurs when the process cannot proceed because the amount of capillary water that is becoming unstable in a unit time is greater than the flux. The established harmful effect of the intermediate-size pores, large sample dimensions, high degree of saturation and rapid cooling rate are to be expected. Correlation between nitrogen surface area and frost resistance of bricks was found to be good; this can also be explained by the theory.

263. Litvan, G. G., and J. Bickley. "Durability of Parking Structures: Analysis of Field Survey." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

A total of 215 garages in Toronto, Ottawa, and Montreal, Canada, have been surveyed to various extents by assessing delamination, half-cell potential, depth of cover, and component condition. In addition, tests were carried out on cores, in which chloride content, compressive strength, and chloride permeability were determined and the air void system was analyzed. The evidence indicates that durable garages can be built, and that poor performance must be attributed to design and construction practices whose effectiveness falls short of that required by the environment.

It follows that almost all previously built garages will eventually require repair unless upgraded before the chloride concentration of the concrete reaches a critical level. Repair by the "patch and waterproof" method was found to decrease the rate of corrosion of deteriorated garages by approximately 70 percent. Detrimental effects following installation of a waterproofing membrane over concrete with elevated chloride concentration were not observed. No relation was detected between extent of delamination and crack density or compressive strength. Half-cell potential did not prove more sensitive than the chain-drag test in detecting delamination.

264. Liu, D., and D. N. Winslow. *The Pore Structure of Concrete*, Indiana Dept. of Highways, Indianapolis, Indiana, FHWA/IN/JHRP-86/13, August 27, 1986.

The pore size distributions of cement pastes and the pastes in concrete and mortar hydrated under different conditions were measured by mercury intrusion. The measurements were made at the same degrees of hydration for all the samples. In order to measure the pore size distribution of the paste in concrete and mortar, a non-porous quartzite aggregate was used and an EDTA titration method was used to determine the paste content of the concrete and mortar. A difference was found between the pore size distributions of the plain paste and the paste in concrete and mortar. The distributions in concrete and mortar were essentially the same. The paste that forms in concrete was found to be more porous than plain paste. Further, this difference was greater for older samples with a greater degree of hydration. The majority of the extra porosity has pore diameters that are about ten times as large as the largest ones in plain paste. This was found to be true for pastes with different water:cement ratios, pastes hydrated at different temperatures, and pastes with accelerators and retarders.

265. Lord, G. W., and T. F. Willis. "Calculation of Air Bubble Size Distribution from Results of a Rosiwal Traverse of Aerated Concrete." *ASTM Bulletin* (October 1951): pp. 56-61.

Several characteristics of the dispersed air bubbles in aerated concrete have been indicated as important to the study of the function, and intelligent use, of entrained air. This paper describes a method of calculation, together with its graphical derivation, by means of which various parameters characterizing the dispersed air phase may be obtained from measurements made in a modified Rosiwal microscopic traverse. Also included is an appendix in which the method is derived in more formal mathematical terms. While originally developed for study of concrete, the method is applicable to any system containing spherical dispersoids which can be examined by the Rosiwal linear traverse technique. A sample calculation showing results for a specimen of concrete is included.

266. Lukas, W. "Chloride Penetration in Standard Concrete, Water-Reduced Concrete, and Superplasticized Concrete." *Journal of the American Concrete Institute* Vol. 68, No. 14 (May - June 1981).

Concretes display a chloride penetration that is dependent on several factors. The water-cement ratio exerts the most influence, the penetrated chloride content decreasing with a decrease in the ratio. High quality concrete with a low water-cement ratio has a considerably smaller chloride content than other concretes of the same consistency. Superplasticized concrete has a smaller tendency to absorb chloride than untreated concretes of the same water-cement ratio. Cements with pozzolanic addition show increased resistance to chloride diffusion into the concrete. If concretes are air-entrained, there is a considerable chloride concentration in the uppermost zone. This is due both to the great segregation tendency and to the air voids themselves.

267. Lyse, I. "Durability of Concrete in Sea Water." *Journal of the American Concrete Institute* Vol. 57, No. 69 (June 1961): pp. 1575-1584.

This paper deals with the durability of concrete when exposed to freezing and thawing in sea water. Extensive experimental investigations have for the past 20 years been carried out at the concrete laboratory of Norway's Institute of Technology, Trondheim; and the most important results from these investigations are reported here.

Among the more important results is that freezing and thawing in sea water is much more detrimental to the durability of the concrete than is the freezing and thawing in fresh water. Furthermore, it is shown that the amount of entrained air necessary for giving the highest resistance of the concrete to frost action in sea water is in the range of 10 to 12 percent, which is more than twice as large as for concrete in fresh water.

268. Lyse, I. "Effect of Brand and Type of Cement on Strength and Durability of Concrete." *Journal of the American Concrete Institute* Vol. 31 (January - February 1935): pp. 247-271.

The results of an investigation of the strength and durability of concrete containing 18 different cements, 13 standard portland cements and 5 high-early-strength cements is presented. The strength as well as the durability of the concrete containing different cements varied considerably. The durability was

generally found to be independent of the strength. Both strength and durability of the concrete seemed to be independent of the chemical composition of the cements tested, indicating that the method of manufacturing the cement may have been the most important cause of the variation in the quality.

269. Lyse, I., and J. M. Holme. "Durability Studies of Concrete Aggregates." *Journal of the American Concrete Institute* Vol. 30 (November - December 1933): pp. 121-128.

Results of tests of ten different aggregates, six natural sand and gravels, three types of crushed limestone, and one crushed iron ore and steel punchings were: (1) a fair agreement was found between the results of the sodium sulfate tests and the freezing and thawing tests of the fine aggregate; (2) the relation between durability and cement-water ratio was similar to the relation between strength and cement-water ratio; (3) a fair correlation was found between the durability tests of the aggregates and of the concrete; and (4) the natural sand and gravel aggregates produced a more durable concrete than did the limestone aggregates included in this investigation.

270. MacInnis, C., and J. J. Beaudoin. "Effect of Degree of Saturation on the Frost Resistance of Mortar Mixes." *Journal of the American Concrete Institute* Vol. 65, No. 16 (March 1968): pp. 203-207.

A one-cycle freezing test, involving length measurements during freeing, is used in an attempt to establish limiting maximum water-cement ratios for concretes for different exposure conditions. Mortar prisms were cast from a series of mixes, (both air-entrained and non air-entrained) covering a range of water-cement ratios from 0.40 to 0.70. After being moist cured for 1 month the prisms were then conditioned to various degrees of saturation (to simulate different exposure conditions) and subjected to the freezing test. Frost susceptibility of the various mixes was determined from the length change patterns produced in the freezing test. Critical degree of saturation was found to be approximately 90 percent. Air entrainment was found to provide protection up to a water-cement ratio of 0.58.

271. MacInnis, C., and E. C. Lau. "Maximum Aggregate Size Effect on Frost Resistance of Concrete." *Journal of the American Concrete Institute* Vol. 68, No. 16 (February 1971): pp. 144-149.

A one-cycle freezing test was used to demonstrate the effect of maximum size of aggregate on the frost resistance of concrete at a variety of water-cement ratios and degrees of saturation. After being cured for a period of at least 1 month the 3 x 6 in. concrete specimens were conditioned to various degrees of saturation, to simulate different exposure conditions. The frost susceptibility of the various specimens was determined from the length change patterns produced in the freezing test. The maximum size of aggregate was shown to have a great effect on frost resistance. For example, the 1/4-in. maximum aggregate size specimens showed expansions during freezing only when the water-cement ratio was as high as 0.60, while 3/4-in. maximum aggregate specimens showed expansions at a water-cement ratio as low as 0.45.

272. Majumdar, A. J., and A. G. Tallentire. "Glass Fiber Reinforced Cement Base Materials." *Journal of the American Concrete Institute* Vol. 44, No. 20 (August 1974).

In the United Kingdom glass fiber reinforced cement (GRC) is emerging as a new and versatile material for the construction industry. Products based on a cement matrix reinforced with 'Cem-FIL' alkali-resistant glass fiber have already been produced for a number of major construction applications in the U.K.

The importance of a thorough understanding of the mechanical properties and performance characteristics of GRC in the design of products has been clearly recognized and considerable resources are currently devoted to this aspect of the development. Detailed performance data are available to designers; and product development is being closely controlled jointly by Pilkington Brothers Ltd. and licensees to ensure inservice reliability. Continued research is being undertaken to confirm the durability of glass reinforced cement materials in a wide range of applications. This embraces not only laboratory studies of the mechanism of weathering and of accelerated testing, but also long-term full-scale performance trials under extreme climatic conditions at selected world wide sites.

273. Makoto, K. "Correlation Between the Pore Size Distributions and Freeze-Thaw Durability of Coarse Aggregates in Concrete." Ph.D. diss., Purdue University, 1978.

This study was designed to find the correlation between pore size distribution of an aggregate measured by the mercury intrusion method and the freeze-thaw durability of concrete made with the aggregate.

Fourteen different types of aggregates with a wide variety of pore size distributions were studied. Two laboratory freezing tests, the rapid freezing and thawing tests (ASTM C 666A) and a modified critical dilation test, were conducted. Also 24-hour absorption and the PCA absorption-adsorption tests were conducted. A good correlation between the pore size distribution of and aggregate and its durability factor obtained from the rapid freezing and thawing test was found. The modified critical dilation test results generally agreed with the rapid freezing and thawing test results. The absorption test and PCA absorption-adsorption test were not as good indicators of freeze-thaw durability as pore size distribution.

A correlation equation between and expected durability factor for an aggregate and its pore size distribution measured by mercury intrusion was obtained. This equation was then examined for its applicability to the field performance prediction. The aggregates with known field performance were examined, the existing concrete pavements with various degree of d-cracking were sampled and their aggregates were examined. These studies have shown that the correlation equation is capable of predicting the frost durability of an aggregate. Based on these examinations, borderlines separating durable from non-durable aggregates were tentatively determined.

274. Malhotra, V. M. "Development of Sulfur-Infiltrated High-Strength Concrete." *Journal of the American Concrete Institute* Vol. 72, No. 32 (September 1975): pp. 466-473.

Sulfur-infiltrated, high-strength concrete has been developed at early ages from 2-day old conventional concrete containing low cement content. Two infiltration procedures have been employed. Procedure A consists of moist curing fresh concrete specimens for 24 hours, drying them at 250° F (121° C) for 24 hours, immersing them in a bath of molten sulfur for 3 hours, removing them from sulfur to cool, and then testing 1 to 2 hours later. Procedure B consists of moist curing fresh concrete specimens for 24 hours, drying them at 250° F (121° C) for 24 hours, immersing them in molten sulfur under vacuum for 2 hours, releasing the vacuum and soaking them for an additional 1/2 hr, then removing them from sulfur to cool. Testing is done 1 to 2 hours later.

Satisfactory high-strength concretes have been produced using the above procedures, with superior results being obtained using Procedure B.

The sulfur-infiltrated concretes exhibit phenomenal increases in mechanical and elastic properties and durability characteristics. A typical value of the compressive strength of the infiltrated specimens using Procedure B was 8060 psi compared with 810 psi for reference moist-cured specimens. The sulfur-infiltrated specimens were in excellent condition after more than 800 cycles of freezing and thawing, whereas the moist-cured specimens had completely disintegrated after 40 cycles.

This new type of concrete appears to be eminently suited for precast concrete units, such as pipes, poles, farm silos, and railway ties, and is a practical substitute for expensive polymer-impregnated concrete.

275. Malhotra, V. M. "Effect of Repeated Dosages of Superplasticizers on Slump, Strength and Freeze-Thaw Resistance of Concrete." *Materiaux et Constructions* Vol. 14, No. 80 pp. 79-89.

Superplasticizers, when added to fresh concrete, cause large increases in its slump. However, this increase in slump is not sustained over long periods and within 60 minutes or so the concrete reverts to its original slump. In actual field applications of superplasticizers it may be necessary to add additional dosages to maintain the increase slump. This paper gives results of a laboratory investigation to determine the effect of repeated dosages of superplasticizers on workability, strength and durability of concrete.

A series of air-entrained concrete mixes was made at a water/cement ratio of 0.42 with a slump of 50 mm. Four commonly available superplasticizers were repeatedly added to the concrete, at the manufacturer's recommended dosage rates, after completion of initial mixing. This was followed by additional mixing for 2 minutes. The properties of the fresh concrete were determined and test cylinders were cast after the addition of each dosage. Test prisms were also cast for strength and durability studies after the addition of the last dosage.

The test results indicate that large increases in slumps of superplasticized concretes can be maintained for several hours by the addition of a second dosage. Apart from one instance, the addition of the third dosage is not considered desirable.

The repeated additions of sulphonated melamine- and napthalene-based superplasticizers caused substantial loss in entrained air content of the concrete; however, for concrete incorporating the lignosulphonate based superplasticizer, the reverse was true. The loss of entrained air adversely affected the performance of the concrete in freeze-thaw tests.

276. Malhotra, V. M. "Mechanical Properties, and Freezing and Thawing Resistance of Non Air-Entrained and Air-Entrained Condensed Silica-Fume Concrete Using ASTM Test C 666, Procedures A and B." Second CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, Madrid, Spain, April 1986, pp. 1069-1094.

This report presents the results of a study dealing with the resistance to repeated cycles of freezing and thawing on non air-entrained condensed silica fume concrete when tested in accordance with ASTM C 666, Procedures A and B. A total of 22 air-entrained and non air-entrained concrete mixtures, 0.06 cubic meters in size, were made. The water/(cement + silica fume) ratio of the mixtures ranged from 0.40 to 0.60; and the percentages of cement replacement by condensed silica fume were 0, 5, 10, 15, and 30% by weight. Any loss in slump due to the use of condensed silica fume was compensated for by the use of a superplasticizer.

Based upon the analysis of the test data, it is concluded that the use of non air-entrained condensed silica fume concrete is not recommended when it is to be subjected to repeated cycles of freezing and thawing. Furthermore, the users of condensed silica fume are cautioned against using high percentages of the material as a replacement for portland cement in concretes with a water/(cement + silica fume) ratio of about 0.40 if these concretes are to be exposed to repeated cycles of freezing and thawing.

277. Malhotra, V. M. *Mechanical Properties and Freeze-Thaw Resistance of No-Fines Concrete*, Industrial Minerals Laboratory, Construction Materials Section, Ottawa, Mineral Sciences Laboratories Report No. MRP/MSL 75-12(IR), January 1975.

No-fines concrete is a special type of lightweight concrete in which the fine aggregate fraction has been omitted. Like other lightweight concretes, the strength properties of this type of concrete appear to be related more to its unit weight in the fresh state than to its water-cement ratio. The 28-days' compressive strength as determined on 6 x 12-in. (152 x 305-mm) cylinders ranged from a low of 760 psi (5.2 MN/m^2) to a high of 1280 psi (8.7 MN/m^2). There are indications of strength gain with age. The flexural strengths of 3.5 x 4 x 16-in. (89 x 102 x 406 mm) prisms at 14 days ranged from 225 to 355 psi (1.5 to 2.4 MN/m^2).

Non-air-entrained prisms of no-fines concrete performed poorly when exposed to accelerated cycles of freezing and thawing, and disintegrated in less than 73 cycles. The resistance of the prisms to freeze-thaw cycling was improved with incorporation of entrained air in the mixes and the air-entrained prisms withstood up to 266 cycles of freezing and thawing.

278. Malhotra, V. M. "Mechanical Properties and Durability of Superplasticized Semi-Lightweight Concrete." *Journal of the American Concrete Institute* Vol. 68, No. 16 (May - June 1981).

This investigation was undertaken to determine whether or not the use of superplasticizers can help in the manufacture of semi-lightweight concrete having compressive strengths in excess of 30 to 40 MPa at early ages. Further, the investigation was extended to find if the combined use of superplasticizers and fly ash can produce high strength concrete with moderate cement contents.

Three series of concrete mixtures were made using normal portland cement, lightweight coarse aggregate, and natural sand. All mixtures were air-entrained and superplasticized, except the control mixture, which was only air-entrained. In the four mixtures of Series A, cement content ranged from 406 to 443 kg/m^3, and test cylinders and prisms were used for strength and durability studies. In the three mixtures of Series B, cement content ranged from 422 to 445 kg/m^3, and test cylinders were used for strength determination only. In the two mixtures of Series C, part of the cement was replaced by fly ash, and test cylinders and prisms were cast for the determination of compressive and flexural strengths.

The investigation revealed that the use of superplasticizers allows the manufacture of semi-lightweight concrete to have compressive strengths of the order of 30 and 40 MPa at 1 and 3 days, respectively. The unit weight of the fresh concrete ranged from 1835 to 1961 kg/m^3.

In the durability test, the appearance of the test prisms was characterized by a number of aggregate popouts after 300 cycles of freezing and thawing; in one instance, these became numerous after 400 cycles. Notwithstanding the above, the changes in the length of prisms after 400 to 500 cycles of freezing and thawing were well within the accepted limit of 0.07 percent, and the relative durability factors were greater than 99 percent.

It was indicated that the combined use of superplasticizers and fly ash can produce high strength, semi-lightweight concrete at moderate cement contents. Compressive strengths of 47.6 and 50.7 MPa at 28 and 365 days were obtained for concrete with cement and fly ash contents of 393 and 60 kg/m^3, respectively.

279. Malhotra, V. M. "No-Fines Concrete - Its Properties and Applications." *Journal of the American Concrete Institute* Vol. 73, No. 54 (November 1976): pp. 628-644.

No-fines concrete consists solely of normal portland cement, water and coarse aggregate. It has been used in Europe and the United Kingdom since the 1930s for the building of single story and multistory dwellings, but had found little acceptance in North America. In recent years, however, due to increased awareness of the need for conservation of nonrenewable mineral resources, increased consideration is being given to the use of no-fines concrete in Canada and the United States.

Investigations at CANMET have indicated that no-fines concrete prisms with no air-entraining agent had poor resistance to freeze-thaw cycling; the corresponding prisms incorporating an air-entraining agent were able to withstand up to 274 freeze-thaw cycles compared with 56 for prisms without an air-entraining agent.

The principal advantages claimed for no-fines concrete are economy in materials, somewhat higher thermal insulating values, lower shrinkage, and lower unit weight. The major disadvantages are its low compressive, flexural, and bond strength, and higher permeability.

The principal applications of no-fines concrete are for load-bearing cast-in-place external walls of single story and multistory housing, small retaining walls and as a dampproofing subbase material for concrete floors cast on grade. This type of concrete is also eminently suitable for construction in northern Canada because of its somewhat higher thermal insulating property and low cement content.

280. Malhotra, V. M. "Strength and Durability Characteristics of Concrete Incorporating a Pelletized Blast Furnace Slag." First CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete, Montebello, Quebec, Canada, July - August 1983, pp. 891-921.

This report gives the results of laboratory investigations to determine the strength and freeze-thaw durability characteristics of concrete incorporating pelletized iron BFS from a Canadian source.

281. Malhotra, V. M. "Strength and Freeze-Thaw Characteristics of Concrete Incorporating Granulated Blast-Furnace Slag." Fifth International Symposium on Concrete Technology, Nuevo Leon, Mexico, March 1981, pp.159-184.

A series of 32 mixes of 0.062 m^3 was made, with water/(cement + slag) ratios ranging from 0.30 to 0.65, and with the percentage of slag used as a partial replacement for normal portland cement ranging from 25 to 65% by weight. All mixtures were air entrained and some incorporated a superplasticizer in addition to an air-entraining agent. A number of 100 x 200-mm cylinders were cast for testing in compression and splitting tension at ages up to one year. Test prisms, 90 x 100 x 400 mm, were also cast to determine flexural strength and freeze-thaw durability.

Durability studies indicated that regardless of the water/(cement + slag) ratio and whether the concrete was air entrained or air entrained and superplasticized, the test prisms performed satisfactorily in freeze-thaw test (ASTM C 666, Procedure B) except for mixtures with a high water/(cement + slag) ratio and 65% slag content.

282. Malhotra, V. M., G. G. Carette, and T. W. Bremner. "Durability of Concrete Containing Supplementary Cementing Materials in Marine Environment." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987, pp. 1227-1257.

This paper deals with the evaluation in marine environment of normal and lightweight concretes incorporating supplementary cementing materials. A series of 138 concrete prisms, 305 x 305 x 915 mm in size, were cast over a five-year period starting in 1978, for long-term exposure at Treat Island, Maine. The prisms were positioned at mid-tide level on a rack at the entrance to the Bay of Fundy, and this represents what is perhaps the most severe marine exposure conditions for concrete. The test specimens are exposed to repeated cycles of wetting and drying and to an average of about 100 cycles of freezing and thawing per year.

It appears that surface deterioration can be avoided if the cement content is kept to at least a certain minimum level. The tests confirm that over long exposure duration, non air-entrained concrete is not durable in this environment.

283. Malhotra, V. M., G. G. Carette, and T. W. Bremner. "Durability of Granulated Blast-Furnace Slag Concrete in Marine Environment." International Workshop on Granulated Blast-Furnace Slag in Concrete, Toronto, Ontario, Canada, October 1987, pp. 171-201.

This paper deals with the evaluation of normal and lightweight concretes incorporating granulated BFS in marine environment. A series of 87 concrete prisms, 305 x 305 x 915 mm in size, were cast over a five-year period starting in 1978, for long-term exposure at Treat Island, Maine. The prisms were positioned at midtide level on a rack at the entrance to the Bay of Fundy, which represents perhaps the most severe marine exposure conditions for concrete. The test specimens were exposed to repeated cycles of wetting and drying and to an average of about 100 freeze-thaw cycles per year.

The test specimens, which were monitored at yearly intervals, were photographed and rated on a visual basis. Ultrasonic pulse velocity was also determined. After up to eight years of exposure, both normal-weight and lightweight air-entrained concretes showed no degradation of the mass of the concrete; however, some of the specimens showed significant surface deterioration. The amount of deterioration generally increased with increasing water to cementitious materials ratio, and increasing replacement of the cement with the slag. It appears that surface deterioration can be avoided if the cement content is kept to a certain minimum level.

284. Malhotra, V. M., and G. G. Carette. "Performance of Concrete Incorporating Limestone Dust as Partial Replacement for Sand." *Journal of the American Concrete Institute* Vol. 82, No. 33 (May - June 1985): pp. 363-371.

Accumulation of vast amounts of limestone dust at stone quarries around the country is a cause for serious concern because of the disposal problem and environmental hazards. This investigation was thus undertaken to obtain data on the mechanical properties and durability of concrete incorporating various percentages of limestone dust as a partial replacement for fine aggregate.

Three series of concrete mixtures were made. Series I and II with water-cement ratios of 0.70 and 0.53, respectively, consisted of mixtures incorporating 5, 10, 15, and 20 percent limestone dust, whereas Series III with a water-cement ratio of 0.40 covered mixtures containing 10 and 20 percent dust. A control mix was also included in each series. Both control and limestone dust mixtures were proportioned to have a slump 80 ±15 mm and an air content of 6 ±0.5 percent.

The incorporation of up to 10 percent limestone dust as a partial replacement for fine aggregate in concrete with a 0.70 water-cement ratio and 5 percent limestone dust in concrete with a 0.53 water-cement ratio does not significantly affect the properties of fresh and hardened concrete. The loss in entrained-air content can be easily overcome by using an increased dosage of an air-entraining admixture. The increase in shrinkage of concrete appears to be of little practical consequence. The use of limestone dust imparts more cohesiveness to fresh concrete and gives it a fatty appearance. This can be a decided advantage in superplasticized concrete.

285. Malhotra, V. M., and D. Malanka. "Performance of Superplasticizers in Concrete: Laboratory Investigation — Part I." *Journal of the American Concrete Institute* SP 62-12 (October 1979).

This report gives results of a laboratory investigation to determine the performance of super plasticizers in high-strength concrete.

A series of 15 concrete mixes was made at a water-cement ratio of 0.42 with a slump of 2 in. (50 mm). Various dosages of the superplasticizers — Melment L10, Mighty 150, and Mulcoplast CF — were added to the mixer after completion of initial mixing. This was followed by additional mixing for 2 min. Apart from one control concrete mix, all others were air entrained. Initial setting times of concrete, increases in slumps, and their subsequent loss with time were recorded.

Incorporating superplasticizers delayed initial setting time of concrete depending on the type and dosage used. The large increases in slump of superplasticized concrete were confirmed; however, the increased workability and its loss with time were functions of the type of superplasticizer used.

The compressive and flexural strengths of the test specimens cast from superplasticzed concretes were comparable to or greater than those of the control specimens.

In the superplasticized concrete under investigation, the bubble spacing factor varied between 0.006 and 0.01, compared with 0.006 for the reference concrete. In spite of the increased bubble spacing, durability of the superplasticized concrete test prisms is not impaired when exposed to repeated cycles of freezing in air and thawing in water.

286. Malhotra, V. M., K. A. Painter, and A. Bilodeau. "Mechanical Properties and Freezing and Thawing Resistance of High-Strength Concrete Incorporating Silica Fume." *Cement, Concrete, and Aggregates* Vol. 9, No. 2 (Winter 1987): pp. 65-79.

This report presents results of an investigation dealing with the mechanical properties and freezing and thawing resistance of high-strength, silica fume concrete using ASTM Test Method for Resistance of Concrete to Rapid Freezing and Thawing (C 666-84, Procedure A). Eighteen nonair-entrained and six air-entrained concrete mixtures, 0.06 cubic meters in size, were made. The water-to-(cement+silica fume) ratio (W/C + S) of the mixtures ranged from 0.25 to 0.36, and the percentages of cement replacement by silica fume were 0, 10, and 20% on a weight basis. Any loss in slump due to the use of silica fume was compensated for by the use of a superplasticizer.

A number of test cylinders were made for testing in compression at various ages, and test prisms were cast for determining their resistance to repeated cycles of freezing and thawing in accordance with ASTM C 666, Procedure A. Sawn sections of some of the prisms were used for determining the air void parameters of the hardened concrete.

Nonair-entrained, high-strength concrete with a compressive strength of up to 87 MPa at 28 days, regardless of the W/C + S and irrespective of the silica fume content used, had durability factors less than 12 when tested in accordance with ASTM 666, Procedure A.

Also, air-entrained concrete prisms incorporating 10 and 20% silica fume as replacement for cement failed to complete 300 cycles of freezing and thawing.

287. Malisch, W. R. "The Effect of Air Drying Upon the Freezing and Thawing Resistance of Concrete." Ph.D. diss., University of Illinois, 1966.

This dissertation is based on a study of concretes and mortars with a single water/cement ratio of 0.45. The same type of aggregate was used in all specimens: crushed limestone for the coarse aggregate and a natural river sand for the fine aggregate. The curing period was generally limited to 14 days.

The study concludes that air drying during curing of air-entrained concretes results in resistance to surface deterioration, which is significantly better than that of concrete continuously moist-cured for 14 days. Resistance to internal damage as measured by changes in the dynamic modulus was found to improve slightly by air drying. For air drying of air-entrained concretes after 1 to 7 days of moist curing, results in increasing resistance to surface deterioration were noted for concretes with the same total amount of moist curing. The period of air drying at 72° F and 50% R.H., which resulted in increases in air-entrained concrete's resistance to surface deterioration, ranged from 12 hours to 14 days.

288. Manning, D. G. "Where Have All the Bubbles Gone?" *Concrete International* Vol. 2, No. 8 (August 1980): pp. 99-103.

Seven experts in their field discussed the resistance of concrete to freezing and thawing, and particularly the widespread deterioration of concrete in recent years. Subjects covered are air entraining admixtures, air content levels, placing and finishing air-entrained concrete, and durability of air-entrained concrete. A discussion by ACI Committee 201 follows.

289. Manz, O. E., and G. J. McCarthy. "Effectiveness of Western U.S. High-Lime Fly Ash for Use in Concrete." Second CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Madrid, Spain, 1986, pp. 347-365.

Western U.S. lignite and sub-bituminous fly ashes have higher $CaO + MgO + SO_3$ and lower $Al_2O_3 + SiO_2$ than bituminous ashes. They also have lower loss on ignition and greater proportions of crystalline material. No more than one-third of the total lime is free lime. In this investigation, several chemically, physically, and mineralogically different lignite and sub-bituminous fly ashes were used in varying substitutions for portland cement in concrete and tested for the following: compressive strength, effect of admixtures, freeze-thaw durability, and resistance to sulphate solutions. The test results indicate that, depending on the mix proportions, a high-lime fly ash may not contribute more to compressive strength than one that has 50 percent less lime, and is coarser. High-lime fly ashes produce excellent freeze-thaw durability. With certain high-lime fly ashes, similar strengths are obtained by either 25 or 75 percent substitution for cement. Extremely low expansions of several high-lime fly ash concrete specimens soaking in 10 percent Na_2SO_4 for up to 3 years have indicated that the R factor, $(CaO - 5)/Fe_2O_3$, for sulphate resistance is not totally valid. Concretes using high-lime fly ashes produce higher early strengths than low-lime bituminous ashes.

290. Marks, V. J., and W. Dubberke. "Durability of Concrete and the Iowa Pore Index Test." *Transportation Research Record* No. 853 (1982): p. 25-30.

An overview of the problem of D-cracking in portland cement concrete is provided, and the Iowa Pore Index test for determining the quality of coarse aggregate for concrete is evaluated. The Iowa pore index test was developed to evaluate the durability of coarse aggregate. The test measures the amount of water that can be injected into oven-dried aggregate during a period from 1 to 15 min after application of 35 psi of pressure. The test is very effective in identifying aggregates with substantial pore system of the 0.04- to 0.2 μm-diameter size and correlates very well with aggregate service records. Test results of nonhomogeneous samples can be misleading. Laboratory tests have shown that a small amount (15 percent) of unsound materials in the coarse aggregate can produce nondurable concrete. Studies with the scanning electron microscope show that coarse aggregates associated with D-cracking are normally fine grained whereas durable aggregate is either coarse grained or extremely fine grained. The pore-size distribution of coarse aggregates was determined by using amercury porosimeter. Aggregates associated with D-cracking exhibit a predominance of 0.04- to 0.2-μm-diameter pore sizes.

291. Marsh, B. K., R. L. Day, and D. G. Bonner. "Pore Structure Characteristics Affecting the Permeability of Cement Paste Containing Fly Ash." *Cement and Concrete Research* Vol. 15 (1985): pp. 1027-1038.

Results are presented from measurements of the permeability of saturated, hardened cement pastes, with and without fly ash. Specimens tested were cured over a temperature range from 20 to 65° C for periods from seven days to one year.

The results show that a dramatic reduction in permeability occurs due to the pozzolanic reaction of the fly ash. Porosity estimates from mercury-intrusion porosimetry and helium-comparison pycnometry reduction. Traditional explanations, based on a reduction in the volume of large pores, are found to be inadequate.

292. Marshall, S. W. "Durability of Pavement Concrete — Experience in Pennsylvania." *Journal of the American Concrete Institute* Vol. 35 (April 1939): pp. 393-404.

Reports data obtained from a comprehensive survey of concrete highway paving slab behavior in three adjacent Pennsylvania areas differing appreciably in climate. Quality of concrete aggregate also varies considerably in the different areas. Observations were made from standpoints of surface condition and structural condition of the paving slab, three classes (or stages) of failure recognized. In general, check surveys confirmed original findings. A marked increase in rate of concrete deterioration is noted as climatic conditions become more severe. Concrete in all three areas is subjected to an appreciable amount of freezing and thawing, but in one area the weather conditions are particularly severe. In the area of severest weather the quality of concrete aggregate is lower than in the others and heaving of subgrade is more prevalent. The existence of many factors influencing the concrete paving slab durability is recognized but no attempt is made to interpret results of the survey in the useful life of concrete pavement that may require modification for localities in which many of the factors involved may be unfavorable to the lasting qualities of concrete.

293. Marusin, S. L. "Influence of Superplasticizers, Polymer Admixtures, and Silica Fume in Concrete on Chloride Ion Permeability." *Permeability of Concrete*, American Concrete Institute, ACI SP 108-2, 1988.

This paper summarizes the results of permeability studies that have been undertaken at Wiss, Janney, Elstner Association, Inc. (WJE) since 1979. The research used a test procedure developed during the NCHRP Project 12-19A, "Concrete Sealers for Protection of Bridge Structures," which was reprinted in 1981 as NCHRP Report No. 244. This test method utilizes 10-cm-concrete cubes; and chloride ion penetration is determined at 4 depths after 21 days exposure to 15 percent NaCl solution. The test results show that the lowering of w/c ratio in portland cement concrete or the presence of superplasticizers, polymer admixtures, and silica fumes are able to significantly reduce concrete permeability.

294. Mather, B. "Case Histories of Unsatisfactory and Abnormal Field Performance of Concrete During Construction." *Transportation Research Record* No. 651 (1977): pp.25-29.

Case histories are given relating to concrete produced in connection with the construction of three different projects. One was a major building, the second was an airfield pavement, and the third was a highway bridge deck. The projects are located in three different states on the East Coast of the United States. These case histories have in common that a major part of the problem in each was low strengths of test cylinders. In the first case, defective concrete containing the wrong aggregate and made with the wrong mixture proportions was removed and replaced. In the second case, the problem was traced to the presence in aggregate of aluminum particles from the bodies of dump trucks in which it had been transported. In the third case, there were many causes of loss of control of the concrete properties; an instance was found of greater variation of air content in a smaller volume than ever reported previously. In this case, the safety factor in design allowed the concrete to remain in the structure.

295. Mather, B. *Effect of Duration of Moist Curing on the Relative Durability of Concrete in Freezing and Thawing*, U. S. Army Engineer Waterways Experiment Station, Corps of Engineers, Vicksburg, Miss., miscellaneous paper no. 6-531, September 1962.

At the Second Pacific Area National Meeting of ASTM held in Los Angeles in 1956, the author summarized part of the data developed in one phase of the exhaustive study of pozzolans and special cements that was begun by the Concrete Division of the Waterways Experiment Station for the Office, Chief of Engineers. This summary was published by ASTM in STP 205 in 1958. The materials used in this study included 5 portland cements, 16 pozzolans or special cements, crushed limestone aggregates graded up to 3/4 in. in size, and an air-entraining admixture. Concrete mixtures were proportioned using each of the cements and using each of the pozzolans or special cements to replace cement on a solid volume replacement basis in amounts from 8 to 70%. Two classes of concrete were studied; one, designated as 0.5 water-cement ratio, always contained the same volume of water to combined solid volume of portland cement plus replacement material as the mixture without replacement material which had a water-cement ratio of 0.5 by weight; the other was similarly proportioned as 0.8 by weight. All air-entrained concrete had an air content of 6.0 plus or minus 0.5%, which is equivalent to 5% air in concrete made with 1-1/2-in. aggregate.

Three rounds of tests were made to represent each mixture. From each round, eight 3- by 6-in. cylinders and four 3-1/2- by 4-1/2- by 16-in. beams, together with other specimens, were made. One cylinder from each round was tested for compressive strength at each of eight ages. Two of the beams were tested for resistance to freezing and thawing beginning at an age of 14 days; the other two at 180 days.

An examination was made of the relations between (a) durability factors of specimens placed in laboratory freezing and thawing 14 days after molding and the 28-day compressive strength of specimens from the same batch, and (b) durability factors of additional specimens placed in freezing and thawing after 180 days moist curing and 180-day compressive strength.

296. Mather, B. *'Soundness' Tests of Concrete Aggregates*, U.S. Army Engineer Waterways Experiment Station, Corps of Engineers, Vicksburg, Mississippi, miscellaneous paper no. 6-278, July 1958.

Testing procedures for building materials that are required to resist frost action have been studied for over 130 years. Procedures based on alternate immersion in sulfate solutions and drying have been used throughout this period. Sulfate 'soundness' testing procedures now in use in testing concrete aggregates are subject to serious errors due to variation in details of performance and are of limited applicability since the behavior of aggregates in concrete is now known to be materially affected by the fact that particles are inclosed in concrete. A wide variety of reports attempting to evaluate or improve sulfate 'soundness' testing are in general agreement that the ASTM and Federal Specification descriptions of the test procedure need improvement in a considerable number of respects; that the results of the test do not correlate well with actual performance of aggregates in concrete; that the factors that control aggregate performance in concrete are not evaluated by the sulfate 'soundness' test; that the results obtained should not be compared with arbitrary limits to accept or reject materials; and that tests for the effect of aggregates on the resistance of concrete to freezing and thawing should be based on resistance to freezing and thawing of concrete specimens made using the aggregates. It is recommended that (1) when sulfate 'soundness' tests are made, the procedures of CRD-C 115 be used; (2) materials not be accepted or rejected on the basis of numerical values of sulfate 'soundness' test results, (3) emphasis be shifted to the use of freezing and thawing tests of concrete to evaluate the effects of aggregate on resistance of concrete to freezing and thawing.

297. Mather, B. "Tests of High-Range Water-Reducing Admixtures." *Journal of the American Concrete Institute* SP 62-9 (October 1979).

At the Waterways Experiment Station, four high-range water-reducing admixtures were tested for compliance with the requirements for water-reducing admixtures given in ASTM C 494-71. None passed the test for frost resistance; all met all other requirements. Water reductions ranged from 18 to 25 percent at recommended dosages. The reference concrete mixtures had durability factors ranging from 57 to 89 (average 76); the test concretes had durability factors ranging from 5 to 77 (average 36). A reference specimen from a batch having a DFE = 84 had a bubble-spacing factor of 0.003 in. Test concretes showed values of the bubble-spacing factor rising from 0.004 to 0.012 in. as the DFE dropped from 77 to 14, in spite of a proper air content in the freshly mixed concrete. Supplementary testing of additional high-range water-reducing admixtures that

was still in progress at the time of the symposium indicated that there appeared to be among these additional products at least one that would meet the requirements of ASTM C 494 with respect to frost resistance.

298. Mattimore, H. S. "Durability Tests of Certain Portland Cements." *Highway Research Board — Proceedings* (1936): pp. 135-166.

Tests on the relative resistance to freezing and thawing and certain other influences of 1:2 mortar made with ten commercial portland cements differing in chemical composition are reported. Cross bending and compression strengths of 2 by 2 by 12-in. prisms were determined after moist curing to various ages. These were compared with the strengths of other specimens which had been frozen and thawed at different rates and for different numbers of cycles. Approximately 4,000 prisms were tested at six different laboratories. The data are an important contribution to knowledge on the method of conducting the freezing and thawing test, the relation of the results of such tests to the evaporable water in the mortar and the relative resistance to freezing and thawing and to sulfate solutions of cements differing in composition.

299. Matzkanin, G. A., A. De Los Santos, and D. A. Whiting. *Determination of Moisture Levels in Structural Concrete Using Pulse NMR*, U.S. Department of Transportation, Federal Highway Administration, Washington, D. C., FHWA/RD-82/008, April 1982.

An investigation has been conducted of nuclear magnetic resonance (NMR) as the basis for nondestructively measuring moisture content in concrete. Results of a laboratory feasibility study conducted on a variety of concrete cylinders showed the NMR signatures to correlate well with evaporable moisture independently of cement type, water/cement ratio or chloride content; however, magnetic minerals contained in certain aggregates affected the correlation. On the basis of the feasibility study, an NMR Moisture Measurement system for nondestructively measuring moisture from one surface of reinforced bridge decks was designed and fabricated. Laboratory evaluations were conducted using concrete specimens of known moisture content and tests were performed on a bridge deck which was cored for verification of moisture readings. Results of these tests demonstrated the capability of the NMR system to measure the moisture from 1.25-in. to 2.75-in. (32 mm to 70 mm). Asphalt overlays up to 2-in. (51 mm) thick have little effect on the NMR-determined moisture values.

300. Matzkanin, G. A., and A. De Los Santos. *In-Situ Determination of Moisture Levels in Structural Concrete by NMR*, Office of Engineering Highway Operations, R & D, Federal Highway Administration, U.S. Department of Transportation, San Antonio, TX, FHWA/RD-85/090, July 1985.

The prototype bridge deck Nuclear Magnetic Resonance (NMR) Moisture Measurement System was modified to improve its usefulness and tested in Wichita Falls, Texas, and at the FHWA Turner-Fairbank Research Center in McLean, Virginia. Modifications included addition of an external control unit to provide for selection of desired measurement depths and automatic adjustment of the RF pulses and magnetic field for the selected measurement depth and rebar depth. Field tests were conducted on 8 bridge decks having a variety of overlays in the Wichita Falls area and on 12 concrete test slabs having a variety of rehabilitation systems at the FHWA center. The NMR system performed well under adverse field conditions and the NMR results were generally repeatable

down to depths of 2 in (51mm). At deeper depths, repeatability was sometimes affected by interferences from rebars. The NMR moisture readings generally increased with increasing depth consistent with expectations for thick slabs exposed to surface drying, and the NMR results were unaffected by overlays up to 2 in. (51 mm) thick. Good qualitative agreement was obtained between the NMR moisture results and those obtained from dry core samples at selected locations, except that the NMR results tended to be more consistent. For the FHWA test slabs, the NMR moisture values for the concrete were found to increase with increasing water/cement ratio and decrease with increasing concrete density.

301. McHenry, D., and H. W. Brewer. "Discussion of 'A Working Hypothesis for Further Studies of Frost Resistance of Concrete' (T. C. Powers)." *Journal of the American Concrete Institute* Vol. 41 (November 1945): pp. 272-9 - 272-12.

This paper presents the hydraulic pressure hypothesis. It is "a working hypothesis which, together with other hypotheses, may eventually lead to the desired solution." The comments is this discussion, based largely on experimental work in the laboratory of the Bureau of Reclamation are not intended to amplify the problem, but rather to emphasize its complexities and the need for further study and still other hypotheses.

302. McMillan, F. R., and I. Lyse. "Some Permeability Studies of Concrete." *Journal of the American Concrete Institute* pp. 101-141.

The extensive use of concrete in structures for hydraulic power developments, harbor works, irrigation, water supply, and other construction fields has brought to the attention of engineers that among the properties of concrete, watertightness may be of even greater importance than compressive strength. The importance of impermeability is not so much a matter of confining the water to its proper channels, for almost any concrete carefully made and cured will prevent serious loss of water through percolation. The real need for watertightness is to prevent the disintegration which results from the freezing of saturated porous concrete or that slow breaking down through the solution of essential ingredients. It needs only a brief survey of structures which have been exposed to severe climatic conditions to appreciate how important is the destructive effect of frost where the concrete is readily permeable. Likewise, there are everywhere examples of structures where unsightly deposits of calcium carbonate bear evidence of water percolating through some defective area or seeping along a day's work plane.

303. Mehta, P. K. In *Concrete Structure, Properties, and Materials*, New Jersey: Prentice-Hall, Inc., 1986.

There are several difficulties in preparing a scientific treatise on concrete as a materials. First, in spite of concrete's apparent simplicity, it has a highly complex structure; therefore, the structure-property relations that are generally so helpful in the understanding and control of material properties cannot be easily applied. Second, compared to other materials, the structure of concrete is not a static property of the material. This is because two of the three distinctly different components of the structure — the bulk cement paste and the transition zone between the aggregate and bulk cement paste — continue to change with time. In this respect, concrete resembles wood and other living systems. Third, unlike other materials which are delivered in a ready-to-use form, concrete often has to be manufactured just before use at or near the job site.

This book is not intended to be an exhaustive treatise on concrete. Written primarily for the use of undergraduate students in civil engineering, it is proposed to present the art and science of concrete in a simple, clear, and scientific manner.

304. Mehta, P. K. "Pozzolanic and Cementitious By-Products as Mineral Admixtures for Concrete — A Critical Review." First CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete, Montbello, Canada, 1983, pp. 1-46.

Since it is the mineralogical composition, and not the chemical composition, which would govern the pozzolanic and cementitious behavior of a mineral admixture, this review treats the entire area of mineral admixtures as a unified discipline. Mineralogical and particle characteristics of major industrial by-products suitable for use as concrete admixtures are reviewed, especially in regard to relationships between physical and mineralogical properties of admixtures and performance characteristics of concrete. The latter include water demand, consistency, bleeding, workability, setting time, air-entrainment, temperature rise in fresh concrete, strength, modulus of elasticity, creep, drying shrinkage, sulphate resistance, alkali-silica reaction, and corrosion of steel in hardened concrete. Mechanisms by which the use of these by-products in concrete can improve engineering properties are discussed, and examples of data from field and laboratory investigations are given.

305. Mehta, P. K., and O. E. Gjørv. "Properties of Portland Cement Concrete Containing Fly Ash and Condensed Silica Fume." *Cement and Concrete Research* Vol. 12 (1982): pp. 587-595.

Normal pozzolan additives, due to their low surface area and reactivity are not able to improve early strengths and durability of concrete. The problem can be solved by using a mixture of normal and highly reactive pozzolans, such as condensed silica-fume. Results of an investigation are reported here in which 30 percent portland cement in concrete was replaced by an equal volume of fly ash, condensed silica-fume, or a 50:50 mixture of the two. Sand-to-gravel proportions were adjusted to obtain workable concretes having the same water-cement ratio. As compared to the control concrete, the 7 and 28 days compressive strengths of the fly ash concretes were significantly lower; however, in the case of mixed-pozzolan addition, the 7-days strength was similar and the 28-days strength was higher. The differences in the pozzolanic activity of the additives were confirmed by a parallel investigation involving determination of free lime and pore-size distribution of the cement pastes.

306. Meininger, R. C. *Report of NSGA-NRMCA Joint Research Laboratory*, National Sand and Gravel Association, Silver Spring, Maryland, August 15, 1985.

This report contains updates on the following current and completed research projects: (a) uniformity of admixtures (series 216), (b) effect of fly ash on strength, (c) evaluation of high slump flowing concrete (series 210), (d) studies of alkali-aggregate reactivity, (e) effect of mold release agent type and application rate on cube strength of cement (series J-165), (f) cement with limestone additions (series J-164), (g) ASTM Method C 311 for testing fly ash, round-robin testing (series J-163), (h) mineral filler for asphaltic concrete (series J-162), (i) tests of neoprene pads for capping strength cylinders (series J-159), (j) durability of coarse aggregate for concrete (series J-157), (k) strength of mortar with two cement sources (series D-256), (l) use of titrator strips to measure chloride in

mortar, concrete and aggregates (series D-255), and, (m) freeze-thaw tests of quick setting patching products.

307. Meininger, R. C. *Use of Fly Ash in Air-Entrained Concrete — Report of Recent NSGA-NRMCA Research Laboratory Studies*, National Sand and Gravel Association, Silver Spring, Maryland, February 1981.

Most of us are aware of the many opportunities and benefits which can accrue through the use of fly ash in concrete. Three major reasons for the serious consideration of its use are listed below. All three of these incentives impact not only on the construction materials industries; but also on important national goals.

(1) The beneficial use of a material that would otherwise have to be wasted in an environmentally acceptable land fill operation.
(2) An overall reduction in the average amount of energy required for the cementing medium in a cubic yard of concrete.
(3) The ability to provide an alternative to reduce the demand for portland cement during periods of exceptionally high demand, thus reducing construction delays and limiting needs for imported cement or clinker.

Fly ash is used in concrete in two ways: (1) separately batched fly ash as an admixture, and (2) through the use of blended cement (mainly Types IP or IPM) which contain fly ash. In either case, the problems, or opportunities, associated with the use of fly ash in concrete can become an important factor in the proper selection, use, and quality control of the many alternative concrete materials and proportioning choices now available. There is no doubt that improved use of technology will be required in order to capitalize on the advantages possible with the use of fly ash. It is also important to be aware of potential problems which may develop if there is a change in fly ash quality or if mixtures are not properly proportioned.

308. Meyer, A. "The Importance of the Surface Layer for the Durability of Concrete Structures." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

The surface layer and the remaining core concrete of a structural member are already, immediately after curing, two different materials in composition. The difference in characteristic properties can be considerably increased by outside influences in the lifetime of the concrete building. We have to pay more attention to this fact because the surface layers are important with regard to the long-term behavior of concrete structures and the protection of steel reinforcement against corrosion. The effects on structure and characteristic properties of the surface layer by placing, compacting and curing in the early stages and later when subjected to different environmental conditions are studied and discussed. Some methods used to test in practice the properties of the surface layer - strength, porosity, alkalinity and frost resistance - are described.

309. Mielenz, R. C., and J. H. Sprouse. "High-Range Water-Reducing Admixtures: Effect on the Air-Void System in Air-Entrained and Non-Air-Entrained Concrete." *Journal of the American Concrete Institute* SP 62-10 (October 1979).

Four commercial high-range water-reducing admixtures based on naphthalene-sulfonic acid-formaldehyde condensation products and two commercial admixtures of this type based on melamine-sulfonic acid formaldehyde

condensates were investigated to determine their effect on the air-void system in fresh and hardened concrete. These admixtures usually entrain air in non air-entrained concrete and tend to increase the average size of air-voids in air-entrained concrete. Low values of the spacing factor seem to be correlated with satisfactory freeze-thaw resistance, but high values to do not necessarily indicate poor durability.

310. Mielenz, R. C., V. E. Wolkodoff, J. E. Backstrom, and H. L. Flack. "Origin, Evolution, and Effects of the Air Void System in Concrete. Part 1 - Entrained Air in Unhardened Concrete." *Journal of the American Concrete Institute* Vol. 30, No. 1 (July 1958): pp. 95-121.

Air in concrete originates in four general ways, producing "entrapped" and "entrained" voids that are differentiated by their spatial and pressure relationships to the surrounding water and solids. The action of air-entraining agents in modifying the void system in concrete is discussed. Once formed, the air void system deteriorates in characteristic ways, mainly by the interchange of air between small bubbles and large, and by the loss of a portion of the air during compaction of the concrete. Several factors determining the rate and extent of deterioration effected before hardening of the concrete are described.

The action of the air void system in improving workability and decreasing segregation and bleeding is discussed.

311. Mielenz, R. C., V. E. Wolkodoff, J. E. Backstrom, and R. W. Burrows. "Origin, Evolution, and Effects of the Air Void System in Concrete. Part 4 — the Air Void System in Job Concrete." *Journal of the American Concrete Institute* (October 1958): pp. 507-517.

The air void system observed in concrete from engineering structures is comparable to that observed in concrete specimens prepared in the laboratory. The void system in non-air-entrained concrete varies widely, the observed specific surface ranging from 107 to 1111 in^2/in^3. In air-entrained concrete, the observed specific surface ranges from 615 to 1600 in^2/in^3 and the spacing factor ranges in job concrete is assured if the recommendations of ACI 613-54 are followed. Methods for microscopical measurement of the air void system in hardened concrete are described in an appendix to Part 4.

312. Miesenhelder, P. D. "Effect of Design and Details on Concrete Deterioration." *Journal of the American Concrete Institute* Vol. 56, No. 35 (January 1960): pp. 581-590.

Features of design or construction of a concrete structure often are important contributing causes of concrete deterioration. Primarily, deterioration is a result of freezing and thawing. Such deterioration is often thought of as a consequence of the number of times freezing and thawing occurs, but in the examples pictured the major factor is the high degree of saturation that existed at the time of freezing. This high degree of saturation is usually a consequence of inadequate or no drainage provisions at critical points. This paper consists essentially of pictures of structures from a large area, which illustrate examples and the wide extent of occurrence.

313. Mikhail, R. Sh, A. M. Youssef, and M. Shater. "Air Entrainment in Portland Blast Furnace Slag Cement Pastes: Effects on Strength and Pore Structure." *Cement and Concrete Research* Vol. 7 (1977): pp. 515-522.

The compressive strength of air entrained blast furnace slag cement pastes were compared with the neat cement pastes of the same water/cement ratios. Air entrainment leads in all cases investigated to a decrease in the degree of hydration and this effect besides the increase in the porosity could lead to a decrease in compressive strength. A third factor, namely the changes taking place in the pore size distribution of micro- and mesopores, and their bearing on the strength results at different water/cement ratios is discussed.

314. Mills, R. H. "Assay of Blast Furnace Slag." Fifth International Symposium on Concrete Technology, Nuevo Leon, Mexico, March 1981, pp. 85-116.

Pelletized BFS may be used as an aggregate or may be finely ground and used as a partial substitute for portland cement. For equivalent workability, specified strength, durability and volumetric stability, the quantities of cementitious material depend on target strength, water demand and the relationship between strength and water/binder ratio. Performance of the BFS component of a blended cement is expressed as a non-dimensional efficiency factor derived from the equivalent mass of portland cement.

315. Missouri Highway and Transportation Department. *Investigation of Roadway Design Variables to Reduce D-Cracking*, Missouri Highway and Transportation Department, NCHRP 78-1, December 1987.

Eight reinforced portland cement concrete pavement test sections were constructed to determine what effect certain designs would have on the occurrence of D-cracking. Various designs included the use of a 3/4-in. and 1-in. maximum size Bethany Falls limestone paving stone produced locally, use of a 2-in. maximum size Burlington limestone paving stone produced from a source having no known history of a D-cracking problem, and pavement constructed with and without polyethylene moisture barrier.

Base variables included impermeable, dense graded Type 3 aggregate, cement treated Type 1 aggregate, plant mix bituminous source, and permeable, open graded plant mix bituminous course.

With nearly ten years of service life, there was no D-cracking observed in any test section.

Observation of the test sections will continue to determine if any of the aggregate or base variables result in improved performance.

316. Monfore, G. E., and A. E. Lentz. *Physical Properties of Concrete at Very Low Temperatures*, Portland Cement Association Research and Development Laboratories, Bulletin No. 145, May 1962. pp. 33-39.

Problems in the design of underground prestressed concrete tanks for the storage of liquified natural gas indicated the need for additional information on the properties of concrete at extremely low temperatures. Results of an investigation of compressive strengths, splitting strengths, Young's moduli of elasticity, and thermal contractions of three sand and gravel concretes and one lightweight

aggregate concrete at various temperatures from 75 to -150° F are reported in the present paper. Young's modulus of elasticity of a particular moist concrete increased as did the compressive strength at the lower temperatures.

317. Mukherjee, P. K., and B. Chojnacki. "Laboratory Evaluation of a Concrete Superplasticizing Admixture." *Journal of the American Concrete Institute* SP 62-13 (October 1979).

A superplasticizing admixture of the sulphonated melamine formaldehyde condensate type was tested in the laboratory for its effect on concrete mixes with a nominal slump of 3 in. (75 mm) and with nominal cement contents of 525, 612, and 700 lb/yd^3 (311, 363, and 415 kg/m^3, respectively). A total of nine mixes were prepared. All mixes contained an air-entraining admixture. A control set of three mixes contained a normal setting water reducer (lignosulphonate). One set of three mixes contained both the water reducer and the superplasticizer, and the remaining set of three mixes contained only the superplasticizer. To simulate anticipated field conditions for the ready-mixed concrete, the superplasticizer was added 45 minutes after initial mixing.

Slump, air content, and unit weight measurements were taken periodically on the fresh concrete up to 160 minutes after initial mixing. Initially, the addition of the superplasticizer increased the slump to 8 in. (200 mm). The slump then progressively decreased to its original value in 45 to 120 minutes. The air content was reduced by approximately 1.0 percent.

The hardened concrete was tested for compressive strength, modulus of elasticity, flexural strength, air void system, drying shrinkage, freeze-thaw resistance, and salt scaling. No adverse effect was observed.

318. Mullen, W. G., and G. W. Bodvarsson. *Determination of Air Void Content and Mixing Water Void Content of Hardened Concrete Using Electron Microscope Techniques, Part 3*, North Carolina Dept. of Transportation and Highway Safety, Raleigh, NC, ERSD-110-75-2, June 1978.

The use of the scanning electron microscope (SEM) to identify possible causes of failure of hardened concrete was examined. The three causes of failure researched were excess air content (Part I), and improper water-cement ratio and degree of hydration (Part III). Part II is a collection of unbound photographic arrays of air contents investigated in Part I to be used as visual comparison standards for determination of air content of hardened concrete. In Part I the SEM was used at a low magnification (80X) to photograph hardened concrete of various air contents (1-20%). A comparison standard was then prepared using 12 photographs to represent each air content. It is proposed that this standard be utilized for determination of air content of hardened concrete. Statistical analysis of the proposed standard indicates an accuracy of about ±1.5%.

For the analysis described in Part III, concrete samples of water-cement ratios ranging from .40 - 1.20 were prepared. The hydration time allowed, representing degree of hydration, varied from 1 day to 90 days (almost 100% hydration). SEM microphotos were taken at high magnification at each level of hydration for each of the water-cement ratios. The microphotos were then examined with emphasis upon trends that would aid in distinguishing between water-cement ratios and degree of hydration. A set of photographs was selected to illustrate an array

scheme that is proposed to be developed for estimation of water-cement ratio and degree of hydration of an unknown based upon capillary morphology changes. Presented along with the proposed scheme is a selection of characteristic features that were identified as being indicative of water-cement ratio and/or degree of hydration. It is suggested that these features be utilized in these cases where determination strictly by the proposed standard is not sufficiently accurate.

319. Munn, R. L., and W. G. Ryan. "Concretes in Australia Containing Fly Ashes and/or Slags: Their Properties and Performance in Aggressive Environments." Fifth International Symposium on Concrete Technology, Monterrey, Nuevo Leon, Mexico, March 1981, pp. 369-392.

    This paper reviews the Australian experience on the durability of concrete incorporating fly ashes and/or slags under aggressive service conditions. Data are presented from case histories and laboratory investigations into compressive strength development and durability characteristics of a wide range of concretes utilizing slags and fly ashes. In many cases, comparison is made between the performance of concretes containing slags and fly ashes and that of traditional concretes subjected to similar conditions. The studies indicate that, provided concretes are given adequate curing and compaction, pozzolanic binders play an important role in improving durability of concretes for buildings and marine structures. It is concluded that with appropriate mix design, concretes containing slags and fly ashes can match the properties of conventional concretes in all respects.

320. Murata, J., M. Kawasaki, T. Sakai, and T. Kawai. "Resistance to Freezing and Thawing of Concrete Using Ground Blast Furnace Slag." *Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete*, ACI SP-79, Vol. 2 (1983): pp. 979-1013.

    The generally high resistance to freezing and thawing of concrete using ground blast furnace slag as sand is noted; and from the standpoint of effective utilization of waste materials, development of positive uses for blast furnace slag sand is studied.

321. Mustard, J. N. "Winter Curing of Concrete as Related to the New Canadian Standard." *Journal of the American Concrete Institute* SP 39-4 (October 1973).

    This paper discusses winter curing of concrete in the light of the New Canadian Standard. The effect of freezing fresh concrete at various ages is dealt with in some detail, and test results are given to illustrate the absolute minimum protection period, and minimum protection methods. The tables from the new standard showing the relationships between concrete temperatures and protection requirements are included, and methods of attaining these requirements are outlined. The problem areas such as specific concrete delivery temperatures, and the limiting of cooling rates to avoid thermal shock are highlighted.

322. Mysyk, W. K. "Petrological Studies on Carbonate Aggregate Responsible for Pavement D-Cracking in Southern Manitoba, Canada." *Transportation Research Record* No. 1110 (1987): pp. 10-15.

    Petrographic evaluation of aggregate in portland cement concrete from Winnipeg International Airport was conducted to determine the characteristic composition, texture, and porosity of nondurable carbonate aggregate associated with

D-cracking. Aggregate in the concrete is from the glaciofluvial Birds Hill esker complex northeast of Winnipeg. Carbonate rocks (limestone and dolomite) constitute 75 to 85 percent (by volume) of aggregate in the recovered drill cores, with granite and basalt the only other significant rock types. Polarizing microscope, scanning electron microscope, and X-ray diffraction analyses of the carbonate aggregate resulted in the following conclusions: (a) All major fracturing in the concrete is associated with coarse carbonate aggregate greater than .25 in. in diameter. (b) Composition of nondurable carbonate aggregate is one of the following types: pure end member limestone, dolomite, or a chalky white silicified limestone. (c) Texturally, the carbonate rocks are massive, micritic-to-finely crystalline mudstone to packstone. Layering does not occur and clay minerals are noted in trace amounts only. (d) The uniform grain size and shape results in a narrow pore size range in the carbonate rocks mainly as intergranular porosity. (e) The expansive alkali-carbonate rock reaction is not a factor in the concrete deterioration as neither the composition nor the texture of the carbonate rocks corresponds to the documented characteristic of susceptible rock types. Also, the map-cracking characteristic of the deterioration does not occur on the apron. The few carbonate particles with reaction rims display a good bond between the cement and aggregate.

323. Nadezhdin, A., D. A. Mason, B. Malric, D. F. Lawless, and J. P. Fedosoff. "The Effect of Deicing Chemicals on Reinforced Concrete." *Transportation Research Record* No. 1157 (1988): p. 31-37.

The role played by deicing chemicals in the deterioration of reinforced concrete is addressed in this paper. Several newer and faster bench-scale methods of study and materials evaluation are described and compared to the ASTM recommended techniques. The difference in freezing temperatures between concrete pore solution and an outside deicer solution is shown to be one of the important factors in the spalling process. The importance of an anisotropic character of freezing zone is outline. The macrocell corrosion mechanism of rebar deterioration has been studied in the laboratory environment using specially constructed mini slabs. The results were correlated with previously conducted microcell corrosion studies of small encapsulated rebar probes.

324. Nakamura, N., M. Sakai, K. Koibuchi, and Y. Iijima. "Properties of High-Strength Concrete Incorporating Very Finely Ground Granulated Blast Furnace Slag." Second CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Madrid, Spain, April 1986, pp. 1361-1380.

This paper describes how some properties of high compressive-strength concrete (60-80 MPa) can be improved by the use of very fine GGBFS as a partial replacement for portland cement. The fineness of very finely ground slag is 715 m^2/kg (Blaine) made from classifying ordinary ground slag (364 m^2/kg Blaine) by the air separator. Concrete mixtures containing very finely ground slag were tested while varying the substitution ratio of slag to total content of cementitious materials (slag plus portland cement) by 10, 40, and 70%. The total cementitious materials were 500 kg/m^3, and the water/cement ratios were 0.30 and 0.325, respectively. Concrete mixtures containing other materials, such as ordinary ground slag and silica fume, were also tested.

The properties of the concrete investigated were compressive strength (at ages of 7, 28, 56 and 91 days), resistance to freezing and thawing, permeability and resistance to chloride penetration. A comparison of these properties was made between very finely ground slag and other materials similarly used. It was found that high compressive strength could be obtained with improvement of permeability, resistance to chloride penetration, and other properties, even if very finely ground slag was substituted for cement at a replacement level of 70%.

325. Narasimhan, T. N., and P. A. Witherspoon. "Numerical Model for Saturated-Unsaturated Flow in Deformable Porous Media: 1. Theory." *Water Resources Research* Vol. 13, No. 3 (June 1977): pp. 657-664.

A theory is presented for numerically simulating the movement of water in variably saturated deformable porous media. The theoretical model considers a general three-dimensional field of flow in conjunction with a one-dimensional vertical deformation field. The governing equation expresses the conservation of fluid mass in an elemental volume that has a constant volume of solids. Deformation of the porous medium may be nonelastic. Permeability and the compressibility coefficients may be nonlinearly related to effective stress. Relationships between permeability and saturation with pore water pressure in the unsaturated zone may be characterized by hysteresis. The relation between pore pressure change and effective stress change may be a function of saturation. In the transition zone where pore water pressure is less than atmospheric but greater than air entry value, soil moisture diffusivity as used in soil physics and coefficient of consolidation as used in soil mechanics are shown to be conceptually equivalent. It is believed that this model will be of practical interest in studying saturated-unsaturated systems undergoing simultaneous desaturation and deformation.

326. Narasimhan, T. N., and P. A. Witherspoon. "Numerical Model for Saturated-Unsaturated Flow in Deformable Porous Media: 3. Applications." *Water Resources Research* Vol. 14, No. 6 (December 1978): pp. 1017-1034.

This is the third and conclusive part of a three-paper series and describes the application of a numerical model for saturated-unsaturated flow in deformable porous media. In all, 10 illustrative examples are presented not only to demonstrate the validity of the method but also to highlight the fundamental unity that exists in the basic principles of the fields of hydrogeology, soil mechanics, and soil physics. The chosen examples involve such diverse phenomena as soil consolidation, infiltration, and drainage and generation of fluid pressures due to cyclic loading such as earthquakes.

327. Nasser, K. W., and G. A. Evans. "Low Temperature Effects on Hardened Air-Entrained Concrete." *Journal of the American Concrete Institute* SP 39-5 (October 1973).

A study was conducted on the influence of low temperature on the properties of hardened air-entrained concrete that was subjected to four different curing conditions. One of the curing conditions was related to the prevalent winter curing practice in Whitehorse, Yukon Territory, Canada.

The tests consisted of compression, splitting tension, impact and elastic strains. In total, over 400 specimens were tested.

The results show that the compressive and splitting strength were increased by about 80 percent at -40F (-40C) if the specimens were nominally saturated with water. The strength of specimens with low saturation of about 5 percent was not much different from the strength at normal temperature of 72F (22C).

Specimens stored outside the laboratory in the ambient fall weather showed the same dependence of strength upon their saturation condition.

328. National Slag Association. *Processed Blast Furnace Slag: the All-Purpose Construction Aggregate*, National Slag Association, Alexandria, Virginia, NSA 169-1.

This bulletin has been prepared to provide architects, engineers, contractors and other users of aggregates with general information on the properties and uses of blast furnace slag. Blast furnace slag has been widely used for all types of construction for more than 50 years. Long-time performance records in a variety of uses and climatic conditions have demonstrated its economy and durability and earned the title: Slag - the All-Purpose Construction Aggregate.

329. Neville, A. M. "Essentials of Strength and Durability of Various Types of Concrete with Special Reference to Sulfur." *Journal of the American Concrete Institute* Vol. 76, No. 41 (September 1979): pp. 973-996.

Criteria of strength of concrete and other solids are discussed with reference to the behavior of neat C3S pastes, porosity, pore-size distribution, and Griffith flaws. This is followed by a consideration of bonds within the cement paste; the absence of their influence on its modulus of elasticity is noted.

The two-phase nature of concrete is reviewed in some detail.

In considering impregnated concrete, attention is drawn to the disparity between the coefficients of thermal expansion of sulfur and of other concrete materials. A proper basis for evaluation of polymer-impregnated concretes is discussed, with special consideration of the effects of impregnation on the compressive and tensile strengths and on the modulus of elasticity.

Consideration of the durability of sulfur-impregnated concrete with respect to freezing and thawing and to chemical attack leads to a positive evaluation of this material for many purposes.

330. Neville, A. M. In *Properties of Concrete*, 3rd ed., London: Pitman Publishing, 1972.

A well-referenced textbook on portland cement and concrete. Chapters include: Portland Cement; Cements of Different Types; Properties of Aggregate; Fresh Concrete; Strength of Concrete; Elasticity, Shrinkage, and Creep; Durability of Concrete; Testing of Hardening Concrete; Lightweight and High-density Concretes; and Mix Design. Appendices include relevant ASTM and British standards.

331. Newlon, H. H. *Modification of ASTM C666 for Testing Resistance of Concrete to Freezing and Thawing in Sodium Chloride Solution*, Virginia Highway & Transportation Research Council, Charlottesville, VA, VHTRC 79-R16, September 1978.

Since 1961 the Research Council has used equipment manufactured by Conrad, Inc. for exposing concrete specimens to rapid cycles of freezing and thawing. In addition, the Materials Division of the Virginia Dept. of Highways and Transportation sends to the Research Council specimens of concrete mixtures and related materials not previously used in the Department's construction when freezing and thawing tests are required as part of the Department's acceptance procedures.

The Council's freezing and thawing procedures are based upon ASTM Designation C666 "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing", Procedure A (freezing and thawing in water), except that surrounding the specimens is a 2% solution of NaCl rather than water. Prior to exposure, specimens are moist cured for 14 days and air dried for 7 days.

Based upon about 17 years of experience in the use of this approach at the Council, the following criteria have been established for judging acceptability.

Weight loss, maximum at 300 cycles — 7%
Surface factor, maximum at 300 cycles — 3%
Durability factor at 300 cycles — 60%.

A limited evaluation of this procedure was made using NaCl solutions with concentrations of 4%, 3%, 2% and 0% (water). Concretes of three levels of expected durability were tested. Based on these tests the following conclusions were drawn.

(1) Freezing and thawing of specimens using the procedures of ASTM C666 as modified to use 2% NaCl solution as the surrounding medium rather than water is more severe and more discriminating than using water as required by the standard method.
(2) Minor variations of salt concentration likely to be encountered during the progress of the testing do not significantly affect the results.
(3) The period of drying between moist curing and exposure to freezing and thawing in an NaCl solution significantly improves the indicated performance.
(4) Based upon ACI recommendations for durable concrete, the Council's current requirements for evaluating freezing and thawing resistance may be too lenient for concrete subjected to severe exposure conditions.

332. Newlon, H. H. "Resistance to Weathering (Chapter 23)." In *Significance of Tests and Properties of Concrete and Concrete-Making Materials*, pp. 351-368. Philadelphia, PA: ASTM, 1978.

There are currently three standard test methods and one recommended practice under the jurisdiction of ASTM Committee C-9 on Concrete and Concrete Aggregates intended to aid in evaluating the resistance of concrete to freezing and thawing. In addition, several petrographic procedures are standardized that provide invaluable information for predicting the resistance of concrete to freezing and thawing and for interpreting the results of exposure in either the

laboratory or under field conditions. Two older freezing and thawing methods have been discontinued. The presently standardized methods as well as those discontinued have evolved over a period of about 50 years and reflect the inevitable compromise between the need for rapid assessment of resistance to weathering and the difficulty of translating the results from accelerated laboratory testing to the varied conditions encountered in field exposures.

333. Newlon, H. H., and K. H. McGhee. *Evaluation of Laboratory Equipment for Freezing and Thawing of Concrete*, Virginia Council of Highway Investigation and Research, Charlottesville, VA, January 1966.

Because a considerable portion of the research effort of the Research Council's Concrete Section is directed toward durability studies, the equipment discussed in this report was purchased in 1962 to achieve capability for rapid freezing and thawing studies. Approval was secured for preliminary evaluation testing as outlined in a working plan approved August 18, 1961. The objectives of these preliminary tests were: (1) To determine the ability of the equipment to give reliable estimates of the performance of field concrete, and (2) To determine the potential application of the equipment for use in rapid freezing and thawing tests of aggregate. With regard to the second objective, a detailed survey of the literature subsequent to the proposal led to the same conclusion as that more recently stated by Larson, et al. (1964), that:

> 'Unconfined freezing-and-thawing tests, like sodium sulfate tests, fail to duplicate natural conditions. Thus, they too display a general lack of correlation with field performance of aggregates in concrete. It appears, therefore, that unconfined freezing-and-thawing tests should be discontinued as soon as other suitable tests for detecting unsound aggregates can be developed.'

Based upon the conviction that the unconfined freezing-and-thawing of aggregates (aside from refined research results, the second objective was not pursued and this report is directed only toward the first objective, namely, the suitability of the equipment for freezing and thawing of concrete and aggregate in concrete.

334. Nielsen, B. S., and F. L. Kronholm. "Physical Bonds of Water in Hardened Cement Paste." *Nordic Concrete Research* , No. Publication7 (December 1988): pp. 207-221.

By means of a new measuring method based on measurement of relative equilibrium humidity, it has become possible to determine how the states of physical bonding of evaporable water changes in hardened cement mortar with low w/c ratio, as a consequence of thermal and drying influences.

The tests primarily showed:

- The calculated values for differential wetting enthalpy, ΔH_b, correspond with values obtained by Powers and Brownyard. Thus, it is possible, by two completely different measuring methods (Powers and Brownyard's wetting enthalpy was carried out by means of heat of solution calorimeter), to describe the states of physical bonding of evaporable water in hardened cement paste.

- The previous history of the samples, i.e., the drying progress, affects the way in which the structure of the cement paste reacts to temperature influence.
- The calculated wetting enthalpies, ΔH_b, change with the temperature influence which the samples are exposed to during the measuring procedure. This indicates that a change takes place of the states of physical bonding of evaporable water. Measurements indicate an irreversible change of the cement paste structure, as a consequence of physical bonding of evaporable water.

335. Noble, C. M. "Experience with Air-Entraining Concrete in New Jersey." *American Concrete Institute Proceedings* Vol. 45, No. 29 (September 1948 - June 1949).

This paper outlines experience in New Jersey with air-entraining concrete utilized primarily to combat attack by deicing chemicals. Damage to concrete pavements in New Jersey usually is associated with heavy loads. Freedom from disintegration troubles, except in isolated cases, is attributed to excellent aggregates, rigid laboratory control, mix design, inspection of material and plant equipment and construction supervision at the job site.

Air-entraining portland cement concrete was first specified for a concrete pavement contract in 1945 and since then has been used on many contracts with notable success to prevent deterioration due to scaling. The same high standards for materials, mixture design, laboratory control, field inspection and attention to details must be maintained as with ordinary concrete. Pavements, thus far constructed in New Jersey with air entrainment have not scaled or shown signs of disintegration when ice control chemicals have been properly mixed with abrasives at a rate not exceeding 75 lb/yd^3 of abrasive. It is too early to form judgement but indications show that the results achieved fully justify the use of air-entraining concrete.

336. Northwood, R., B. Chojnacki, and R. Newell. "Strength and Durability of Concrete Made With Type 10 Cements Used in Ontario." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987, pp. 973-996.

The authors conducted a laboratory investigation on both strength and durability of concretes made with various cements. Results confirmed that various brands of type 10 (ASTM Type I) portland cement affected the compressive strength. The introduction of interground limestone has a beneficial effect on the concrete strength with regard to frost resistance. Concretes made with each of the cements gave a good resistance to freezing and thawing in water. The addition of interground limestone showed no effect.

337. Norton, P. T., and D. H. Pletta. "The Permeability of Gravel Concrete." *Journal of the American Concrete Institute* (1931): pp. 1093-1132.

The research project reported in this paper was begun three years ago in the Mechanics Department at the University of Wisconsin in the hope of determining the relationship between permeability and water-cement ratio, and also the relationship between permeability and such other properties as strength, consistency, absorption, cement-voids ratio and grading of aggregate.

338. Numata, S., V. Koide, and S. Shimobayashi. "Properties of Ultra-Highly Pulverized Granulated Blast Furnace Slag-Portland Cement Blends." Second CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Madrid, Spain, April 1986, pp. 1341-1360.

This paper describes a study of the full exploitation of the inherent hydraulic behavior of granulated BFS. An attempt was made by laboratory tests and by actual concrete practices to improve the properties of conventional slag cements and to develop a high-quality binder.

Granulated BFS, pulverized and classified by an industrial mill (Blaine fineness 850 m^2/kg), was mixed with ordinary portland cement and semi-crushed, granulated BFS sand aggregate with the addition of a high-range water-reducing admixture. Workability, strength and resistance to freeze-thaw cycles, mechanical abrasion and chemical attacks were determined. Microstructures were measured by SEM, and mercury intrusion and nitrogen adsorption porosimetries.

339. Okada, E., M. Hisaka, Y. Kazama, and K. Hattori. "Freeze-Thaw Resistance of Superplasticized Concretes." *Journal of the American Concrete Institute* Vol. 68, No. 12 (May - June 1981): pp. 215-231.

Freeze-thaw resistance in terms of the durability factor was investigated with concretes containing varying dosages of beta-sodium naphthalene sulfonate formalin high condensate superplasticizer at water-cement ratios from 0.25 to 0.55 and the addition of vinsol resin soap to obtain air contents up to 4 percent, with a view to correlating these to the spacing factor.

It was established that the failure boundary curve can be described as a function of water-cement ratio and air content in hardened concrete.

The effect of the compressive strength of the volumes of water and air voids in concretes was examined. The effect of air volume on strength was found to be half that of the same volume of water.

It was found that vinsol resin is a satisfactory air-entraining agent for use in concretes superplasticized with beta-sodium naphthalene sulfonate formalin high condensate.

340. Okkenhaug, K., and O. E. Gjørv. "Influence of Condensed Silica Fume on the Air-Void System in Concrete." *FCB/SINTEF Report of the Norwegian Institute of Technology*, Trondheim, Norway, No. STF65 A82044, August 1985.

For many years the resistance of concrete exposed to freezing and thawing has been the subject for numerous papers, seminars and practical recommendations, and still there has been a significant and alarming increase in poor frost resistance over the recent years. In the USA it has been observed that concrete which were provided with intentionally entrained air during the mixing process, yet on examination of the hardened concretes had either no or inadequate air present. This has also been observed in Norway over recent years where extensive quality control from various construction sites has revealed that only half of all the air-entrained concretes had appropriate air-void characteristics. The question has been raised as to what happens to the air-void system between the time of mixing and final placement.

Recent experiences have shown that addition of condensed silica fume significantly improves the frost resistance of concrete. As part of a more comprehensive research program some experiments were also carried out on how the silica fume influences the air-void system in the concrete. Since condensed silica fume is an extremely fine-grained material (approx. 20 m^2/g) it introduces strong surface forces and improves the cohesive properties of the fresh concrete. Hence, it would be reasonable to assume that the stability of the air voids also would be improved during transportation, handling and placement of the concrete. The results of the experiments are presented above.

341. Olafsson, H. "Hydrophobing Agents for Protection of Low Quality Concrete." *Nordic Concrete Research* , No. Publication7 (December 1988): pp. 222-232.

An investigation has been made on the influence of hydrophobing agents on concrete's moisture balance and resistance to freeze-thaw action. The investigation includes both laboratory experiments and full scale experiments on exterior walls of concrete houses.
Results show a substantial favorable effect on the freeze-thaw resistance of concrete with w/c ratio over 0.55 and inadequate air entrainment, on water intrusion at varying hydrostatic pressure and on moisture content of exterior walls.

342. Oldham, P. C., and A. N. Sheriff. "Durability of a Low Cement Content Mix." *Concrete* (July 1978): pp. 19-21.

There has been an increasing tendency lately for the small builder and D.I.Y. householder to request, when ordering premixed concrete, 21 MN/m^2 or 3,000 psi grade concrete rather than 1:2:4 nominal mix, or just "concrete". This trend is largely due to the work carried out by the C&CA, BRMCA, etc, in promoting the use of concrete for small domestic jobs, and it is to be welcomed — nowadays most concrete is produced on the best weighing equipment available, with full technical control, and the gauge box confined to the odd small site. However, this trend raises questions of durability of the concrete; a 1:2:4 nominal mix normally has cement content of 275-300 kg/m^3, or even lower. It has been shown that concrete with an aggregate/cement ratio of up to 7.5:1 (about 250 kg cement per cubic meter) can normally be considered durable; this approximates, for medium workability concretes made with normal aggregates, to the maximum water/cement ratio of 0.7 suggested by Neville. Many instances have come to light recently, though, where concrete much richer than this has been severely damaged by repeated frost attack. The answer, then, is to advise the client laying a garden path or a patio to buy grade 30 MN/m^2 concrete, preferably with entrained air. However, it has been found that the client will not pay 1.50 to 2.50 pounds per cubic meter extra for such concrete, so it was decided to investigate the possibility of producing an economical and durable mix for such work, where weather resistance is as important as compressive strength.

343. Olek, J., P. J. Tikalsky, and R. L. Carrasquillo. "Production of Concrete Containing Fly Ash for Pavement Applications." Center for Transportation Research, University of Texas at Austin, Report 364-2, May 1986.

The need for more cost efficient construction materials for highway applications and the problem of waste disposal of fly ash have prompted the study presented herein. This study addresses some of the major concerns of resident highway

engineers about concrete containing fly ash for highway applications, which include: curing conditions, setting times, strength development, and durability.

This report summarizes the experimental observations and conclusions from a research program investigating the properties of both fresh and hardened pavement concrete containing fly ash. Tests were performed to establish guidelines for the selection of materials and trial mix design procedures for producing quality concrete containing fly ash. The study investigated freeze-thaw resistance, flexural and compressive strength characteristics, mixing conditions and procedures, and curing conditions such as temperature, humidity, and curing methods. Types F and C fly ashes were used in this study as a replacement for 0, 15, 25, and 35% Type I portland cement by weight. In addition, Type IP cement containing 20% Type F fly ash was used.

The results of this study show that concrete containing fly ash can be designed and proportioned to meet present Texas SDHPT specifications for highway applications. In addition, this study reveals that an optimum mix design for concrete containing fly as is both technically and economically advantageous to the Texas SDHPT.

This report provides the resident engineer with recommendations to ensure the production of quality concrete containing fly ash for highway applications.

344. Olsen, M. P. J. "A Mathematical Model for Predicting Frost Penetration and Heave in Saturated Porous Materials." Ph.D. diss., Dept. of Civil Engineering, University of Illinois, June 1979.

For many years engineers have been dealing with the problem of predicting moisture movement and frost penetration with associated stress development in various kinds of porous materials. Phenomena like D-cracking, scaling, and heaving are all known to be partly or fully caused by a combination of moisture movement and freezing of the water in concrete or soils. These phenomena have been investigated using various approaches from laboratory studies and direct measurements to mathematical and empirical models. Because of the complexity of moisture movement many simplifications are made to fit data obtained from the field. Table 1 provides information on the different kinds of heat-transfer models together with their assumptions. However, few models have attempted to simulate the situation at which water freezes, the temperature and the moisture content changes, and heave takes place at the same time.

345. Olsen, M. P. J. "A Mathematical Model for Predicting Frost Penetration in Saturated Porous Materials." Ph.D. diss., University of Illinois at Urbana-Champaign, 1982.

This report describes the development of a two-dimensional finite element computer program for solving the mathematical equations for predicting frost penetration together with the moisture regime and temperature profile in concrete and aggregates. Although the discussions and examples given in the report are related to the freezing of saturated concrete or aggregate materials, the model can be applied to other porous materials as long as the requirements of saturated condition and confined freezing are acceptable. The approach required the combination of knowledge from various areas such as soil science, concrete technology, and thermodynamics. A thorough literature review was therefore presented to familiarize the reader with terminology and concepts regarding the model development.

346. Olsen, M. P. J. "Mathematical Modeling of the Freezing Process of Concrete and Aggregates." *Cement and Concrete Research* Vol. 14 (1984): pp. 113-122.

A two dimensional finite element computer model for predicting frost penetration in saturated porous materials is presented. Based on available second order parabolic differential equations for predicting temperature and moisture content, and equations relating freezing temperature and water potential, the finite element model predicts temperature, water and ice content, frost penetration, and generated pore water pressures as a function of freezing time and given boundary conditions. Comparison of models results with available experimental data for mature cement pastes rendered reasonable agreement between the model and data.

347. Olsen, M. P. J., D. J. Janssen, and B. J. Dempsey. *D-Cracking in Portland Cement Concrete Pavements*, Dept. of Civil Engineering, University of Illinois, Urbana, Illinois, Project IHR-413, June 1982.

A study was conducted to determine the mechanisms involved in the IPIT and investigate ways to modify and supplement the testing procedure to increase its accuracy and sensitivity. In the study a modified IPIT was developed which utilized chamber pressures up to 1379 Kpa (200 psi). Instead of using the volume of water entering the aggregate pores over a specified time period the degree of saturation which occurred in the aggregates at various chamber pressures was used. Relationships between degree of saturation and chamber pressure were developed and found to provide a general index of the aggregate freeze-thaw durability properties.

348. Ong, L. T., J. G. L. Munday, and R. K. Dhir. "Moisture Related Movements in OPC/PFA Concrete." Symposium on Effects of Fly Ash Incorporation in Cement and Concrete, pp. 204-213. Boston: Materials Research Society, 1981.

The paper deals with moisture-related movements on OPC/PFA concretes caused by continuous drying and alternate wetting and drying, comparison being sought with the corresponding OPC concretes. It is shown that drying shrinkage is related to the equivalent cement content of the concrete, but cannot be related to any other single fly ash characteristic. There is an optimum level of cement replacement by fly ash, which improves the resistance of concrete to wetting/drying expansion.

349. Opsahl, O. A. "Silica in Concrete." *Report of the Norwegian Institute of Technology*, Trondheim, Norway, No. STF65 A81031 Fob/SINTEF, June 1981.

The effect of adding condensed silica fume on frost resistance in concrete has been investigated. The investigations were mainly based on freezing/thawing tests in accordance with ASTM C666-77. In addition, investigations in accordance with ASTM C457-71 have been carried out on the air void system. Freezing/thawing tests were carried out on concrete mixes containing 100, 250 and 400 kg cement per cubic meter concrete. The effects of adding 10 and 20% silica (by weight of cement) combined with water reducing admixtures are investigated in mixes containing 100 and 250 kg cement. Only water cured specimens have been tested. The addition of condensed silica fume combined with water reducing admixtures increases frost resistance in concrete. This appears to be due to decreased permeability and increased tensile strength. Required characteristics of the air void system are not the same for concretes with and without silica.

350. Ozyildirim, C. *Air-Void Characteristics of Hardened Concrete, 1945-1980: Final Report*, Virginia Highway and Transportation Research Council, Charlottesville, Virginia, VHTRC 85-R30, April 1985.

Observations at the Research Council, coupled with the national interest in possible changes in the air void characteristics of air-entrained concretes because of the wide use of admixtures and changes in cement properties, raised a question as to whether or not there was a progressive increase over the years in the size of air voids being incorporated in concrete. Thus, the main objective of the study reported here was to evaluate the changes in air void characteristics of hardened concrete as determined by ASTM C457 and by other means for concrete produced in Virginia from 1945 to 1980. Air void parameters — including the air content, specific surface, and spacing factor — were determined on 630 concretes. The results did not indicate an overall significant increase in the size of air voids; however, it was observed that, in general, they did show that the average size and the distribution of the voids were marginal compared to generally accepted values. While this finding indicates that air voids may not be as small as optimum, the freeze-thaw performance of air-entrained concretes in Virginia supplied under the present specifications generally has been satisfactory.

351. Ozyildirim, C. *Comparison of Air Void Content Measurements in Fresh Versus Hardened Concretes: Final Report*, Virginia Transportation Research Council, Charlottesville, Virginia, VTRC 90-R23, June 1990.

This study compares the air content of freshly mixed and hardened concretes. At the fresh stage, pressure meters (Types A and B) and a volumetric meter were used to determine the air content. At the hardened stage, the air content was calculated using the linear traverse method described in ASTM C 457, which is a microscopical procedure. The unit weight and compressive strength of the concretes were also determined.

The results show that, at the ranges commonly used in the construction of pavements and bridges, the air content of fresh concrete measured by pressure meters and that determined by the microscopical method for essentially the same concrete hardening are, for practical purposes, the same. The air content obtained by a volumetric meter as normally run in the field is generally lower than that obtained for the same hardened concretes by the microscopical method. The unit weight and compressive water to concrete can significantly increase the air content, as well as the slump. Thus, a higher air content in hardened concretes than that indicated by initial measurements with a pressure meter is likely to be present if water is added during placement.

352. Ozyildirim, C. *Distribution of Voids In Field Concrete*, Virginia Transportation Research Council, Charlottesville, VA, VHTRC 78-R35, February 1978.

This study was intended to evaluate the air void characteristics of concrete in an attempt to identify, quantitatively or semiquantitatively, different types of voids and to predict their influence on strength and durability.

353. Ozyildirim, C. *Experimental Use of Fly Ash Concrete in Prefabricated Bridge-Deck Slabs*. Virginia Transportation Research Council, Charlottesville, Virginia, VTRC 88-R1, July 1987.

Hydraulic cement concretes with and without fly ash were investigated to assess the suitability of using fly ash in bridge-deck concrete. Eight prefabricated concrete slabs were prepared: four were control and the remaining contained fly ash. They were used for widening two bridge structures.

Slump, air content, and unit weight were determined on the freshly mixed concrete; compressive strength, permeability, absorption, freezing and thawing durability, and the air void system were determined for the hardened concrete. Depth of cover over the reinforcing steel was measured. After three winters of exposure, slabs were surveyed visually for cracks, scaling, and spalls. Half-cell readings were taken, and chloride samples obtained and tested. Fly ash concretes required a larger amount of air-entraining admixture than the controls to achieve the required air content. Although the 28-day strength tests showed that three of the four fly ash concretes did not achieve the required strength of 4,000 psi, the strength of all concretes exceeded 4,800 psi at 6 months when moist cured. The field evaluation after 3 years of winter exposure indicates that all concretes with fly ash are performing satisfactorily.

354. Ozyildirim, C. *Investigation of Concrete Containing Condensed Silica Fume*, Virginia Highway & Transportation Research Council, Charlottesville, VA, VHTRC 86-R25, January 1986.

The properties of hydraulic cement concretes containing silica fume were investigated to assess their suitability for use in overlays with a minimum thickness of 1 1/4 in. The properties studied were compressive and flexural strengths, bond strength, modulus of elasticity, permeability, freeze-thaw resistance, thermal expansion, and drying shrinkage. The characteristics of air voids in the hardened concrete were determined by petrographic examination. The study was conducted in two stages: the first to determine the mixture proportions that would yield satisfactorily high strengths and low permeabilities, and the second to conduct the main testing program. Silica fume from two sources was used. Concretes made with silica fume from either sources yielded the desirable properties. It is expected that concretes made with silica fume can provide a cost-effective protective system for bridge decks when placed in overlays with a minimum thickness of 1 1/4 in.

355. Ozyildirim, C. *Investigation of Concrete Containing Slag - Hampton River Bridge*, Virginia Highway and Transportation Research Council, Charlottesville, Virginia, VHTRC 86-R39, May 1986.

The study evaluated the properties of concretes containing slag in a 50% replacement of the portland cement to assess their suitability as an alternative to the portland cement concretes normally used in the construction of bridge substructures. For the major portion of the study, samples were obtained from freshly mixed concrete used in the construction of the substructure for the Rte. 143 bridge over the Hampton River and also from a failed pier footing for the bridge. In the laboratory, a limited investigation was made of the effects of temperature on concretes with and without slag. The results indicate that concretes containing quality slag will perform satisfactorily in bridge substructures. However, it has been shown that strength development in concretes

containing slag is more adversely influenced by cold weather than is that of concretes without slag. Also, it is noted that in cold weather there may be a significant delay in the time of set.

356. Ozyildirim, C. "Laboratory Investigation of Concrete Containing Silica Fume for Use in Overlays." *ACI Materials Journal* (January-February 1987): pp. 3-7.

Hydraulic cement concretes containing silica fume were batched and tested in the laboratory to assess their suitability for use in overlays having a minimum thickness of 1 1/4 in. (32 mm). Tests were made for strength, permeability, and freeze-thaw resistance, and the characteristics of air voids in the hardened concrete were determined by petrographic examination. Concretes made with silica fume from two sources at a cement ratio of 0.40 or lower yielded the properties desired for thin overlays. It is thus expected that concretes made with silica fume can provide a cost-effective protective system for bridge decks when placed in overlays having a minimum thickness of 1 1/4 in. (32 mm).

357. Ozyildirim, C., and W. J. Halstead. *Optimum Mixture Proportions for Concretes Containing Fly Ash and Silica Fume*, Virginia Dept. of Transportation, Richmond, VA, FHWA/VA-91-R21, June 1991.

Concretes with equal water-cement ratios and equal paste volumes of various combinations of cement, fly ash, and silica fume were tested to establish parameters for strength and chloride permeability. Comparative specimens with Type II and Type III cement were tested. The effects of temperature and moisture availability during curing were also evaluated. In general, the laboratory tests showed that, when adequate curing in the 73° F to 100° F temperature range is provided, concretes with satisfactory early and 28-day strengths and good resistance to chloride ion penetration can be obtained with either type of cement and various combinations of fly ash and silica fume. The cementitious material can be in range of 30 to 35 percent fly ash and 5 percent silica fume, based on the weight of the cementitious material. Similar specimens cured at 43° F generally did not develop an adequate early strength, and the chloride permeability was high. Combinations of the pozzolans with Type III cement yielded higher strengths and a lower chloride permeability than did similar combinations with Type II cement.

358. Ozyildirim, C., and W. J. Halstead. "Resistance to Chloride Ion Penetration of Concretes Containing Fly Ash, Silica Fume, or Slag." *Permeability of Concrete* ACI SP-108-3 (1988): pp. 35-61.

The effects of two pozzolanic admixtures, fly ash and silica fume, and a ground-granulated blast furnace slag on the chloride ion intrusion of concretes prepared with low water-to-cementitious material ratios (w/c) (0.35 to 0.45) were investigated.

Results of the rapid permeability test (AASHTO T 277) showed that the resistance of concrete to the penetration of chloride ions increases significantly as the w/c is decreased for the same proportions of solid ingredients. Usually, concretes with pozzolans or slag exhibited higher resistance to chloride ion penetration than the control concretes containing Portland cement as the cementitious material. Results of the 90-day ponding test (similar to AASHTO T 259), which was conducted with 0.40 w/c concretes only, indicated minimal chloride content at depths below 3/4 in (19 mm) for all the test concretes.

Strength values for all concretes made with the pozzolans and slag at 90 days were in excess of 5,000 psi (34.5 MPa), which is satisfactory.

359. Ozyildirim, C., and M. M. Sprinkel. "Durability of Concrete Containing Hollow Plastic Microspheres." *Journal of the American Concrete Institute* Vol. 79, No. 31 (July - August 1982): pp. 307-312.

The potential of hollow plastic microspheres (HPMs) to provide resistance for non air-entrained portland cement concrete to damage from cycles of freezing and thawing was investigated. A mixture with an air-entraining agent (vinsol resin) was used as the control for comparison with three experimental mixtures — one with HPMs, one with high-range water-reducers (HRWRs) and HPMs, and one with fly ash and HPMs.

Mixtures with only HPMs in the amount of 1.5 percent or more by cement weight exhibited satisfactory resistance to damage from cycles of freezing and thawing. Those with HRWRs and HPMs exhibited low durability factors and failed the acceptance criterion that requires a durability factor of 60 or more. Concretes with fly ash and HPMs displayed durability factors comparable to those mixtures with HPMs only; however, weight losses of the former were higher than those of the latter.

Examinations with an optical microscope and a scanning electron microscope revealed numerous well-distributed HPM voids in the mixtures with only HPMs, but few in the mixtures with HPMs and HRWRs.

360. Ozyildirim, C., and H. N. Walker. *Evaluation of Hydraulic Cement Concretes Containing Slag Added at the Mixer*, Virginia Highway and Transportation Research Council, Charlottesville, Virginia, VHTRC 86-R1, July 1985.

The study evaluated the effect of ground, granulated, iron blast furnace slags on the properties of hydraulic cement concretes such as normally used in highway construction. Two cements with different alkali contents and two slags with different activity indices, 100 and 120, were used. Slags were used as replacements for portions of portland cement at 40%, 50%, and 65% by weight. This final report presents data on the properties of the freshly mixed concrete and the test results on time of set, heat of hydration, compressive strength, flexural strength, permeability, resistance to freezing and thawing, length change values, and the results of petrographic examinations including data on air voids, carbonation, and hydration. The test results for the laboratory specimens indicate that mixtures with the slags exhibit delay in set and slower development of compressive strength at early ages than do conventional mixtures, but have equal or better strengths at later ages. The incorporation of slag reduces the permeability of concrete considerably. It is concluded from this study that concretes in which up to 50% by weight of the cement has been replaced with a slag meeting the requirements of ASTM C989 and having a minimum activity index of 100 are satisfactory for use in highway construction.

361. Paillere, A. M., M. Reverdy, and G. Grimaldi. "Carbonation of Concrete with Low-Calcium Fly Ash and Granulated Blast Furnace Slag: Influence of Air-Entraining Agents and Freezing and Thawing Cycles." Second CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Madrid, Spain, 1986, pp. 541-562.

This investigation deals with (1) carbonation of concrete as a function of the nature of cement (i.e., portland cement and blended cement with fly ash or slag), and (2) the combined effect of freeze-thaw cycles and carbonations as a function of the nature of cement and the air content in mortars. Air-entrained cement mortars made with various types of cements and varying air contents were subjected to carbonation and freeze-thaw cycles. The carbonation depth and compressive strength were determined on all samples. The test results indicate that the carbonation of concrete is increased (1) in the presence of a high percentage of granulated blast-furnace slag in the cement and (2) after subjecting concrete to freezing and thawing cycles. Uncarbonated concrete resists freezing and thawing better than concrete carbonated previously. Air-entraining agents do not modify the carbonation when the concrete containing portland cement or cements with low-calcium fly as and granulated blast-furnace slag (< 20 percent) is subjected to freeze-thaw cycles.

362. Papayianni, J. "Strength and Bond Data for Greek High-Lime Fly Ash Concrete." Second CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Madrid, Spain, 1986, pp. 367-386.

The main objective of this investigation is to find the optimum proportion of cement replacement by lignite fly ash (LFA) in plain and reinforced concretes in order to obtain suitable strength and durability. Concrete mixtures are made incorporating LFA at cement replacement levels of 0, 30 40 ,50, 60, 70, 80, 90, and 100 percent, and properties such as compressive and flexural strengths, modulus of elasticity, permeability, freeze-thaw durability, sulphate resistance, corrosion of embedded steel drying shrinkage, creep, and others are investigated. The test results indicate that ground LFA can replace cement in the mixes up to 30-40 percent in reinforced concrete. LFA concretes can, therefore, be used in construction for strength requirements from 15 to 30 MPa. Up to 70 percent of LFA can be used in production of plain concrete for subbase applications in pavement structures.

363. Paxton, J. T. "Ohio Aggregate and Concrete Testing to Determine D-Cracking Susceptibility." *Transportation Research Record* No. 853 (1982): pp. 20-24.

Several laboratory test methods were analyzed to determine their capability of indicating the D-cracking susceptibility of coarse aggregates. Two methods were modified versions of ASTM C666 A and B, two were unconfined freeze-thaw tests of the aggregate, and the remaining two were standard sodium and magnesium soundness tests. The major modification of the ASTM C666 test methods was to determine the elongation of the test specimens versus routine weight-loss determination and/or sonic modulus determinations. Results are evaluated by plotting the percentage of expansion versus the number of cycles completed and calculating the area under the curve generated. Although 10 specimens are used in the testing, the 2 high and 2 low test results are removed before final analysis. The correlation of this test method with service records of various aggregates was found to be good; however, when the same coarse

aggregates were tested in sodium sulfate, magnesium sulfate, or unconfined freeze and thaw, the results did not correlate well with the service records.

364. Paxton, J. T., and W. R. Feltz. *Development of Laboratory and Field Methods for Detecting D-Cracking Susceptibility of Ohio Coarse Aggregates in Concrete Pavements*, Ohio Department of Transportation, FHWA/OH/79/006, October 1979.

Several laboratory test methods were analyzed, which it was hoped would indicate the D-cracking susceptibility of coarse aggregates when used in concrete for pavement slabs. Two methods were modified versions of ASTM C-666 A and B, two were unconfined freeze-thaw tests of the aggregate, and the remaining two were standard sodium and magnesium soundness tests. The major modification of the ASTM C-666 test methods was to substitute the elongation of the test specimens measured as they undergo cycles of freezing and thawing for the weight loss determinations or sonic modulus determination. Further modifications included plotting the percent expansion against the number of cycles completed and calculating the area under the curve generated. Although 10 specimens are used in the testing the two high and two low test results are removed before final analysis. The correlation of this test with service records of various aggregates was found to be excellent; however, when the same coarse aggregates were tested in sodium sulfate, magnesium sulfate or unconfined freeze and thaw, the results did not correlate well with the service records.

365. Payne, W. W. "The Effects of Prestressing on the Freeze-Thaw Durability of Some Concretes." Ph.D. diss., University of Virginia, 1972.

The effect of linear prestressing on the freeze-thaw resistance of the deep-seated (aggregate generated) type of frost damage was investigated for uniaxially prestressed beams and biaxially prestressed slabs. The prestressing force was 1000 p[illegible] and was applied by the post-tensioning method.

It was found that prestressing was effective in mitigating this type of frost damage in the direction of the prestressing force but never in the orthogonal direction (non-prestressed direction).

Loss in prestress, on the uniaxially prestressed member, was increased by this type of frost damage.

It was discovered that prestressing directionalized the disintegration of this concrete and in the biaxially prestressed member (slab), prestressing accelerated the rate of disintegration.

This accelerated effect is conjectured to be due to the "layered effect" produced by the directional effect of this deterioration.

A theory, "THE PLANE OF LEAST RESISTANCE THEORY," is presented that explains the involved physical phenomenon.

366. Pence, H. J. "Development of a One-Cycle Slow Freeze Test for Indentifying Aggregates Susceptible to Freeze-Thaw Deterioration." Ph.D. diss., Virginia Polytechnic Institute, April 1969.

The primary objective of this thesis was to develop a simple, fast, and inexpensive method that can distinguish poor performing aggregates. Secondary objectives were: 1) to study the relationship between pore characteristics of aggregates and freezing and thawing durability of concrete and 2) to investigate the feasibility of using an accelerated hot water curing process to further reduce specimen curing time and consequently, the collecting of data.

Significant correlations were shown between 100 cycle durability factor and certain characteristics of the time length change and temperature-legnth change curves for the slow freeze specimens. A sufficiently strong correlation existed between the time slope and durability factor to indicate that the slow freeze test could be used as a screening test, when durability factor can be considered as a measure of potential field performance. A detailed test using the slow freeze technique was developed in order that other laboratories could substantiate the results obtained.

One hundred and twenty-eight rock particles from various aggregate sources were selected for mercury-intrusion porosimeter tests. A sufficient correlation existed between concrete durability and pore characteristics examined on the porosimeter to indicate the feasibility of using these parameters to separate the good or bad aggregates. However, correlations between durability factor and bulk specific gravity aggregates containing significant quantities of porous chert were quite susceptible to freeze thaw deterioration.

For the accelerated curing investigation, the following variables were investigated as to their effects on the slope characteristics and freeze-thaw durability of the slow freeze specimens: temperature of curing in water baths, 40, 60, and 99 C; duration of curing in water baths, 16, 24, and 48 hours; duration of curing in steel molds, 16 and 24 hours. Two aggregates were used in concrete to fabricate 104 concrete specimens, 64 accelerated cured and 40 seven-day standard cured.

The results indicated that it is possible to reduce specimen curing time significantly and to obtain reliable results for predicting the freeze-thaw durability of concrete.

367. Perenchio, W. F., D. A. Whiting, and D. L. Kantro. "Water Reduction, Slump Loss, and Entrained Air-Void Systems as Influenced by Superplasticizers." *Superplasticizers in Concrete* SP 62-8 (October 1979): pp. 137-155.

Concretes with nominal cement contents of 376, 517, and 658 lb/yd^3 at slumps of 2 to 3 in. were prepared. Control concretes and concretes with four superplasticizers at the manufacturers' recommended dosages were included. These concretes were tested for slump loss, time of set, drying shrinkage, and compressive strength development. Similar concretes containing, entrained air were tested for air-void characteristics and resistance to freezing and thawing in water and deicer scaling. Work was also carried out on air-entrained concretes with cement contents typical of paving and bridge deck concrete (564 and 658 lb/yd^3) with dosages of superplasticizers sufficient to reduce the net water-cement

ratios to the range of 0.30 to 0.35 by weight. Work was concentrated on the rapid slump loss and reduction of desirable air-void characteristics.

Unusually high water reductions were obtainable with these materials. Compressive strength increases are generally commensurate with reductions in water-cement ratio. Two serious problems are the rapid slump loss and reduction in desirable air-void characteristics; however, tests indicate that air-entrained concretes containing superplasticizers are equal to control concretes in resistance to freezing and thawing in water and deicer scaling.

368. Perraton, D., P. C. Aitcin, and D. Vezina. "Permeabilities of Silica Fume Concrete." *Permeability of Concrete*, ACI SP-108-4 (1988): pp. 63-84.

Water, chloride-ion and air permeability of two series of silica fume and non-silica fume concretes having water/cementitious ratios of 0.4 and 0.5 were studied as well as that of a 0.24 w/c ratio silica fume concrete. Silica fume dosage varied from 5 to 20% by weight of cement.

The water permeability of concrete samples that have w/c ratios lower than 0.5 is so low that they can be considered impervious whether they contain silica fume or not.

The chloride-ion permeability provided by silica fume rivals that of latex for w/c ratios of 0.4 to 0.5 and polymer-impregnated concrete with a 0.24 w/c ratio.

The two drying methods used in this research yielded a positive correlation between silica fume dosage and air permeability. Equal variations were observed for values of up to 10%, whereas at 20%, the increase was markedly sharper.

The characterization of concrete permeability is not as simple as it appears. Sample preparation and fluid type can significantly affect the interpretation of the effect of an admixture such a silica fume.

369. Pfeifer, D. W. "Sand Replacement in Structural Lightweight Concrete - Freezing and Thawing Tests." *Journal of the American Concrete Institute* Vol. 64, No. 65 (November 1967): pp. 735-743.

The freezing and thawing resistance of 47 structural lightweight concretes containing seven lightweight aggregates and varying amounts of natural sand fines are reported. This paper is the fourth in a series regarding the partial or complete replacement of lightweight fines with sand. The seven sand and gravel aggregate concretes were evaluated at nominal compressive strengths of 3000 and 5000 psi.

The level of durability was generally raised when increasing amounts of sand fines were used in the 3000-psi concretes. All 5000-psi concretes were highly durable and the use of sand fines provided only minor improvements in this case.

370. Philleo, R. E. "The Conference on the Matrix of Concrete." *Thermal and Freezing-Thawing Behavior*, Department of Theoretical and Applied Mechanics, University of Illinois, Urbana, IL, T. A. & M. Report No. 313, January 1968.

This paper summarizes a discussion held at the conference. It was concluded that the most important effects of temperature on the matrix of concrete are those due

to a change in the state of water in the matrix. This paper suggests that that growth of ice crystals in capillaries of air voids as water diffuses from the gel is a result of differences in concentrations of the solution in the gel and capillaries as freezing proceeds or differences in vapor pressure of ice and liquid water.

371. Philleo, R. E. "Freezing and Thawing Resistance of High Strength Concrete." *Synthesis of Highway Practice*, National Cooperative Highway Research Program, No. 129, December 1986.

The highway industry pioneered the development and practical use of air entrainment as the primary defense for concrete against the ravages of freezing and thawing. For the low- and medium-strength concretes that have traditionally been used in highway applications, the use of entrained air has served very well where the exposure has not been complicated by corrosion of reinforcement caused by the application of deicing salts, as in bridge decks, or by the inclusion in the concrete of coarse aggregates of unfavorable pore characteristics, which may produce the phenomenon generally called "D-cracking."

Recent developments have made a new generation of high-strength concrete a viable material for routine construction. The two principal developments are high-range water-reducing admixtures (HRWRAs), which permit the placement of concrete of very low water-cement ratio, and silica fume, a pozzolan of extremely high fineness. The advent of this high-strength concrete has put requirements for strength and durability in conflict. Because entrained air reduces the strength of concrete, builders seek to eliminate or limit the use of entrained air. There are those who argue that high-strength concrete is of such a quality that entrained air is unnecessary. Much of the high-strength concrete is used in buildings where the probability of freezing in a saturated condition is remote; hence, relatively little attention need be given to durability. The problem cannot be avoided in exposed highway structures. Although the biggest use of concrete in highway applications, pavements, has not benefitted from the development of high-strength concrete, there are several applications that have, including bridge structural elements, dense bridge-deck overlays, and precast concrete pipe.

372. Philleo, R. E. "Frost Susceptibility of High-Strength Concrete." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987, pp. 819-842.

The two principal developments are high-range water-reducing admixtures, which permit the placement of concrete of very low water-cement ratio, and silica fume, a pozzolan of extremely high fineness. The resistance to freezing is directly dependent on the concrete's capacity for and its probability of containing freezable water. Concretes of very low water-cement ratio may have no capacity for freezable water if ambient conditions permit continuous hydration for a long period of time so that all the available space is filled with hydration products; or, short of complete space-filling, they may become so impermeable that saturation by water is unlikely in most natural exposures. High-range water-reducing admixtures do not alter the pore structure of cement paste; they merely extend traditional cement technology into a range of low water-cement ratios that were previously impractical. The addition of silica fume does alter the pore structure and places more of the pore volume in pores that are so small that water cannot freeze in them at ordinary atmospheric temperatures. It offers some hope of achieving frost resistance without entrained air.

373. Pickens, J. F., and R. W. Gillham. "Finite Element Analysis of Solute Transport Under Hysteretic Unsaturated Flow Conditions." *Water Resources Research* Vol. 16, No. 6 (December 1980): pp. 1071-1078.

The finite element method based on a Galerkin technique was used to formulate a model for the two-dimensional simulation of the transient movement of water and solutes in saturated-unsaturated soils. The model allows either nonhysteretic or hysteretic water content-pressure head relationships in the unsaturated zone. The finite element model results, including the effect of hysteresis, compared well with experimental and finite difference results for transient flow in an unsaturated sand column and provided confidence in the method of incorporation of the hysteretic relationships. The finite element model was applied to a hypothetical one-dimensional case involving vertical infiltration and redistribution of a slug of water containing a nonreactive tracer in a column of sand. Simulations were conducted using hysteretic properties and also nonhysteretic properties given by either the main drying or the main wetting curve. For the given hydraulic properties and boundary conditions, the simulations indicated that the effect of including or neglecting hysteresis was greatest in the pressure head and water content profiles and was of minor importance in the concentration profiles. Since the measurement of the hysteretic hydraulic properties of a soil material is both costly and time consuming, the illustration of the minor effect of hysteresis is of considerable practical importance in the evaluation of solute transport in unsaturated soils.

374. Pickett, G. "Flow of Moisture in Hardened Cement During Freezing." *Highway Research Board Proceedings* Vol. 32 (1953): pp. 276-284.

A mathematical analysis, based upon idealized assumptions, is made of the flow of moisture between the components of hydrated-cement paste during freezing or thawing. The components considered are the gel substance, the capillary pores, and the air-entrained spaces.

It is shown that a change in temperature for temperatures below 0° C gives rise to differences if thermodynamic potentials between gel water, capillary water, or ice, and ice frozen in the air spaces. These potentials result in part from pressures produced by volume changes resulting from freezing and, in part, from differences in the vapor pressures of ice and water. Based on these potential differences the analyses show, for example, that during freezing, in which the temperature is being lowered continuously; flow may first be from capillary to gel, then from gel to capillary, and finally again from capillary to gel. During this same time, flow may be continuously from gel to air space.

By taking into account the change in volume resulting from freezing or thawing of ice in the capillary spaces and the changes in shrinking or swelling tendency resulting from changes in amount of gel water, various volume-time-temperature relations are deduced. In particular, it is shown that water movements and volume changes for a specimen depend not only on the present temperature changes but on the past temperature history of the specimen.

375. Pigeon, M., P. C. Aitcin, and P. Laplante. "Comparative Study of the Air Void Stability in a Normal and a Condensed Silica Fume Field Concrete." *American Concrete Institute Materials Journal* Vol. 84, No. 3 (1987): pp. 194-199.

Very little reliable data exist concerning the durability of field-condensed silica fume (CSF) concrete exposed in service to freezing and thawing in the presence of deicing salts. The data available indicate that CSF concrete without the right bubble-spacing factor performs very poorly, but with the correct spacing factor, it performs satisfactorily in similar climatic conditions.

This paper reports the findings of a research program studying freeze-thaw durability and the stability of the air-void system in a specific CSF mix from batching through placement. Additional test data show shrinkage and compressive strengths.

With proper mixing and placing techniques, the air-void system of CSF concrete was found to be as stable as that of normal concrete. The proper spacing factor was obtained without any problem, and freeze-thaw tests confirmed the durability of the CSF concrete.

376. Pigeon, M., R. Gagne, and C. Foy. "Critical Air Void Spacing Factor for Low Water-Cement Ratio Concrete With and Without Silica Fume." *Cement and Concrete Research* Vol. 17 (1987): pp. 896-906.

Normal portland cement concretes with a water-cement ratio of 0.3 and concretes containing 9% condensed silica fume (CSF) at a water cementitious material ratio of 0.3 were submitted to freeze-thaw cycles in water in accordance with ASTM Standard C 666. The CSF concretes were also submitted to freeze-thaw cycles in air at 100% relative humidity. For both types of concretes and both types of tests the values of the critical air void spacing factor were found to range between 300 µm and 500 µm. Air entrainment was thus needed to protect these concretes from frost damage.

377. Pigeon, M., and M. Lachance. "Critical Air Void Spacing Factors for Concretes Submitted to Slow Freeze-Thaw Cycles." *ACI Journal* (July-August 1981): pp. 282-291.

Non-air-entrained and air-entrained concretes with varying air void systems were submitted to 300 freeze-thaw cycles in air at 100 percent relative humidity, at a freezing rate of 2° C/hr. Length change was used as the main indicator of concrete deterioration. Although almost no scaling was observed, length changes of more than 1 percent were measured on some specimens. For a water-cement ratio of 0.5, the critical air void spacing factor (the value below which concrete will be minimally damaged at 300 freeze-thaw cycles) was determined to be 680 µm, and for a water-cement ratio of 0.6, the factor was 570 µm. These two values, which are in the range of spacing factors of entrapped air voids in non-air-entrained concretes, are in good agreement with the value obtained from Powers' hydraulic pressure theory for the rate of freezing used in the tests (the calculations are based on the critical value of 250 µm for a freezing rate of 11° C/hr).

378. Pigeon, M., D. Perraton, and R. Pleau. "Scaling Tests of Silica Fume Concrete and the Critical Factor Concept." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

ASTM C 672 scaling tests were carried out on concretes containing 0, 5, and 10% silica fume, and with air-void spacing factors in the 100 to 200-μm range. Two methods of curing were compared: seven days in water and the use of a curing compound. Water containing 2.5% sodium chloride was used for the scaling tests, as well as pure water. Results indicate that although scaling tends to increase with the silica fume content, silica fume concrete can have a fair scaling resistance. Results also show that specimens cured in water, regardless of the silica fume content, have a lower resistance to scaling than specimens cured with a membrane. Considering previously published data by two of the authors, results further show that the critical air-void spacing factors obtained from ASTM C 666 (Procedure A) freeze-thaw cycle tests are not applicable to scaling. Spacing factors required for good scaling resistance are generally lower than those required for freeze-thaw durability, and total protection against scaling does not seem possible. A short review of the literature confirms that critical spacing factors are usually higher than 200 μm.

379. Pigeon, M., R. Pleau, and P. C. Aitcin. "Freeze-Thaw Durability of Concrete with and without Silica Fume in ASTM C666 (Procedure A) Test Method: Internal Cracking vs. Scaling." *Cement, Concrete and Aggregates - CCAGDP* Vol. 8, No. 2 (Winter 1986): pp. 76-85.

The freeze-thaw durability of concrete with and without silica fume was investigated in accordance with the requirements of ASTM Test Method for Resistance of Concrete to Rapid Freezing and Thawing (C 666 Procedure A). The water-cement ratio of all mixes was 0.5, and the silica-cement ratio of the silica fume mixes 0.1. The test results show that the critical value of the air-void spacing factor in these ASTM C666 tests is significantly lower for the silica fume concretes. These concretes are therefore more susceptible to internal cracking caused by rapid freeze-thaw cycles in water, even though the use of silica fume decreased the surface scaling of the test specimens. This confirms that scaling and internal cracking are two different forms of frost damage caused by rapid freeze-thaw cycles in water. The use of silica fume also decreased the internal cracking of the non air-entrained mixes damaged during the tests.

380. Pigeon, M., J. Prevost, and J. -M Simard. "Freeze-Thaw Durability Versus Freezing Rate." *ACI Journal* Vol. 82 (September-October 1985): pp. 684-692.

Non-air-entrained and air-entrained concretes with varying air-void systems were submitted to 300 freeze-thaw cycles in air at 100 percent relative humidity at freezing rates of 4 and 6° C/h. Length change and pulse velocity variation were used as indicators of concrete deterioration. For a water-cement ratio of 0.5, the critical air-void spacing factor (the value below which concrete will be minimally damaged at 300 freeze-thaw cycles) was determined to be 630 μm for a freezing rate of 4° C/h and 450 μm for 6° C/h. Considering previously published data by the first author for a freezing rate of 2° C/h, the relationship between critical air-void spacing factor and rate of freezing was established. It shows that the freezing rate has a significant influence on freeze-thaw durability. The change in the value of the critical air-void spacing factor from 680 μm at 2° C/h to 450 μm

at 6° C/h is in agreement with the equations from Powers' hydraulic pressure theory. In the tests described, almost no scaling was observed. Deterioration was always in the form of internal cracking. For a good number of specimens, length changes of more than 1 percent were measured.

381. Pigeon, M., and M. Regourd. "Freezing and Thawing Durability of Three Cements with Various Granulated Blast-Furnace Slag Contents." First CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag, and Other Mineral By-Products in Concrete, Montebello, Quebec, Canada, July - August 1983, pp. 979-998.

The freeze-thaw resistance of three cements - containing 100% clinker and 0% slag, 70% clinker and 30% slag, 30% clinker and 70% slag - was studied. Only one clinker (ground to 3165 cm^2/g Blaine) and one granulated BFS (ground to 3920 cm^2/g Blaine) were tested. Six mortar mixes (water/cement ratio = 0.5) with varying air-void characteristics were fabricated from each cement. An air-entraining agent, a water reducer and different fine aggregate gradings were used to produce a range of air-void spacing factor (L) values.

A total of 54 prisms, three of each mix, with dimensions of 70 x 70 x 280 mm, were subjected, after 28 days of moist curing, to 500 freeze-thaw cycles (freezing in air and thawing in water). To assess the degree of deterioration, changes in length, dynamic E and mass were measured. The characteristics of the three hydrated cement pastes were determined by SEM and mercury intrusion porosimetry.

The freeze-thaw durability of all mixes was found to be very good. Only three specimens (made with the cement containing 70% slag) deteriorated significantly, which was caused by the very dense and uniform structure of the hydrated paste and its fine pore texture.

382. Pihlajavaara, S. E. "Background and Principles of Long-Term Building Materials." *Durability of Building Materials and Components*, ASTM STP 691 (1980): pp. 5-16.

A review is presented of historical background information, service life expectations and the need for research in the field of the durability of materials. The necessary procedures and intervals of the maintenance of some building materials also are examined. Information on the performance of materials should be expressed clearly in terms of service years dependent on degradation factors, of degradation effects during lifetime, and of maintenance procedures and intervals.

383. Pistilli, R. S., G. Rau, and R. Cechner. "The Variability of Condensed Silica Fume From a Canadian Source and its Influence on the Properties of Portland Cement Concrete." *Cement, Concrete and Aggregates - CCAGDP* Vol. 6, No. 1 (1984): pp. 33-37.

Condensed silica fume is formed during the manufacture of ferrosilicon in electric submerged-arc furnaces. The use of condensed silica fume has been evaluated in portland cement concrete. Thirty-two samples of condensed silica fume, each collected on consecutive days, were analyzed for chemical and physical routine quality control test of pozzolan. Eight of these samples, representing the variations of the routine tests, were tested for complete ASTM Specification for

Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete (C 618) conformance. All of the samples test were found to conform to ASTM C 618 with the exception that the water requirement was excessive.

Concrete mixtures were evaluated with a fixed quantity of 24 kg/m^3 (40 lb/yd^3) of condensed silica fume. The low portland cement content mixtures show slightly higher shrinkage after 64 weeks of drying: the rich mixtures have the same shrinkage. Compressive strengths were more that 30% higher than control mixtures having low cement contents and were more than 10% higher than control mixtures having higher cement contents. This amount of condensed silica fume was found to have no effect on the time of set relative to control mixtures containing the same portland cement content.

384. Plante, P., M. Pigeon, and F. Saucier. "Air-Void Stability, Part II: Influence of Superplasticizers and Cement." *ACI Materials Journal* Vol. 86, No. 6 (November-December 1989): pp. 581-589.

Eighteen concrete mixes were prepared to analyze the influence of superplasticizers on the stability of the air-void system during mixing and agitation. For each mix, four sets of samples were cast over a period of 90 min after initial water-cement contact. The modified point count method (ASTM C 457) was used to determine the characteristics of the air-void system on each set of samples. Results indicate that superplasticizers can cause a significant increase of the value of the spacing factor. This influence of superplasticizers was found to vary very significantly with the characteristics of the cement and also with the type of air-entraining admixture. A methodology similar to the one used in this study is recommended to assess the production and the stability of the air-void characteristics in relation to the composition of the mixes and the materials that are used.

385. Pleau, R., P. Plante, R. Gagne, and M. Pigeon. "Practical Considerations Pertaining to Microscopical Determination of Air Void Characteristics of Hardened Concrete (ASTM C 457 Standard)." *Cement, Concrete, and Aggregates* Vol. 12, No. 1 (Summer 1990): pp. 3-11.

Many parameters affecting the quality of the air void characteristics measurement are reviewed and discussed. The difficulties more frequently encountered during the measurement process are described, and some simple rules are proposed in order to increase, as much as possible, the accuracy and reproducibility of the test. The influence of the sampling size is studied, and the variability of air content, specific surface, and spacing factor is estimated from a statistical analysis of about 600 different concrete mixtures. The influence of the operator's subjectivity is also investigated, and the effect produced by large air voids on the computation of the spacing factor is discussed.

386. Plowman, C. "The Chemistry of PFA in Concrete — A Review of Current Knowledge." AshTech '84: Second International Conference on Ash Technology and Marketing, London, 1984, pp. 437-443.

This paper presents a review of current knowledge on the chemical reactions involving PFA occurring in cement-based systems. The way in which the physical and chemical effects influence one another and the properties of cement

paste is discussed. The areas of discussion include: (1) chemical and mineralogical analysis of PFAs. (2) reactions of PFA in concrete. (3) influence of PFA chemistry on concrete strength properties. (4) influence of PFA chemistry on concrete durability. The study indicates that it is now largely possible to explain not only the increase in long-term strength that results from incorporating PFA in a concrete mix, but also other properties of engineering significance.

387. Podvalnyi, A. M. "Phenomenological Aspect of Concrete Durability Theory." *Materiaux et Constructions* Vol. 9, No. 51 pp. 151-162.

It is shown that concrete destruction by freezing and thawing, in dry and hot climate, under sulphate and potassium aggression occurs because of high inner tensile stresses appearing as a result of bonding in concrete conglomerate the components with widely different deformations under the action of corrosion. The problem of concrete frost resistance is considered in detail. The model of concrete as a material of "conglomerate in conglomerate" type, divided into three structural levels is proposed. The measurement of damage to concrete, being characterized by the ratio of maximum total inner stresses to local strength of structure is introduced. It is shown that the developed approach makes it possible to explain from a single viewpoint the majority of experimental facts, known in the field of concrete durability.

388. Polivka, M., P. K. Mehta, and J. A. , Jr. Baker. "Freeze-Thaw Durability of Shrinkage-Compensating Cement Concrete." *Journal of the American Concrete Institute* SP 47-4 (April 1975).

Reported are the results of a study of the effect of freezing and thawing on the durability of air-entrained shrinkage-compensating concretes made with Type K, M, and S expansive cements. The tests were performed on uniaxially restrained prisms that were water-cured for 14 days and then subjected to 300 cycles of freezing and thawing. The durability of the concretes was evaluated by determining the loss in weight of the specimens during the freeze-thaw test. The results were compared to the durability of a similar concrete made with a Type II portland cement. Since the hydration product of expansive cements contains a considerable quantity of ettringite, the effect of freezing and thawing on the stability of the microstructure of ettringite was evaluated by x-ray diffraction analysis.

Results of this investigation indicate that the freeze-thaw resistance of air-entrained, shrinkage-compensating cement concretes was similar to that of the corresponding concrete made with portland cement. Exposure to the 300 cycles of freezing and thawing caused only scaling on the surfaces and along the edges of the test prisms with no visible cracking or spalling. The x-ray diffractions patterns taken before and after the freeze-thaw exposure of ettringite indicate no alteration of this material by the freezing action.

389. Pomeroy, D. "Concrete Durability: From Basic Research to Practical Reality." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

Concrete in reality does not necessarily conform with the laboratory idealizations: the scale of operation is much greater: controlled and the composite actions between one part of a structure and another will add a further complication. There

is thus the need to use the knowledge gained from the fundamental studies to help to explain and to predict the performance of real structures.

The way in which this problem is being tackled at the Cement and Concrete Association will be discussed. Predictive models based on a basic understanding have been developed, and site observations from structures in the UK have been one used to validate or to challenge these predictions and so lead the way to improvements both in realistic understanding and prediction.

390. Porter, C. B., R. W. Gilmore, F. H. Jackson, L. H. Tuthill, and B. W. Steele. "Durability." *Journal of the American Concrete Institute* Vol. 48 (May 1952): pp. 725-752.

This article reports on conditions affecting durability of concrete structures, and discusses design modifications and changes in construction and maintenance procedures to prolong their useful life.

Surveys of structures of various ages and an evaluation of factors affecting their durability are presented along with a brief report or research on testing and developing waterproofing materials. The factors that control durability of concrete pavements are also discussed. Structural performance and durability are defined, and their relationship to each other and to water-cement ratio brought out. The role of air entrainment in improving the durability of concrete pavements, particularly under the attack of chloride salts used for ice removal, is discussed. Current thinking on the subject is summarized.

The necessity of controlling volume change and providing impermeability in mass concrete hydraulic structures contributes to the problems of durability. Mix proportioning, placement methods, use of admixtures, and other measures to increase the serviceability of such work are considered. The need for impermeable concrete is stressed as the primary requirement for lasting durability of mass hydraulic structures. Research in all phases of concrete mix and design is recommended as the answer to the need for a method of evaluating permeability in regard to its permanent effect on the durability or concrete thus establishing a realistic approach to specifying cement content of concrete mixtures in which strength is of secondary importance.

391. Porter, L. C. "Some Surface Treatments Increase Concrete Durability." *Journal of the American Concrete Institute* SP 47-10 (April 1975).

The U.S. Bureau of Reclamation's freezing and thawing and outdoor exposure tests of coated and plain concrete show pigmented epoxies to provide greatest protection against concrete deterioration while retaining a pleasing appearance. Latexes, neoprene, synthetic rubber, and some wall-seal epoxies are beneficial, but lack lasting aesthetic value under certain exposure. Tests consisted of freezing and thawing, and outdoor exposure of laboratory fabricated cylinders and prisms. Environments consisted of freezing and thawing in water, freezing by refrigerated air and immersing in water, freezing by chilled air while partially submerged, and weathering outdoors. Accelerated tests help to evaluate protective coatings. However, protection varies under different exposure and coating selection must correlate protection provided with anticipated service exposure.

392. Powers, T. C. "The Air Requirement of Frost-Resistant Concrete." Highway Research Board Proceedings 29th Annual Meeting, 1949.

According to the hydraulic-pressure hypothesis of frost action on concrete the effectiveness of entrained air depends on void spacing. The theoretical maximum permissible spacing is found analytically to be a function of paste properties, degree of saturation of the paste, and rate of cooling. Applied to experimental data from six different pastes, cooled at 20° F per hour, the theoretical calculations gave spacing factors ranging from 0.01 to 0.026 in. or more, depending on paste characteristics and void size.

A spacing factor for the voids in hardened concrete, as well as the total volume of air, can be calculated from data obtainable by the linear-traverse method. The necessary mathematical relationships are given in this paper. The actual maximum spacing factor for certain frost-resistant concretes was estimated to be about 0.01 in., a result considered to be in excellent agreement with that obtained from the theoretical calculations. The air requirement is that amount that meets the spacing requirements. In general the air requirement for a given rate of cooling depends upon the paste content, the specific surface of the voids, and the maximum permissible spacing factor.

When voids are too widely spaced to prevent failure of saturated paste, failure will also occur at moisture contents below saturation; within limits, the denser the paste the lower the degree of saturation at failure.

393. Powers, T. C. "Basic Considerations Pertaining to Freezing and Thawing Tests." *ASTM Proceedings* Vol. 55 (1955): pp. 1132-1155.

Questions about current test methods are raised and an alternative test suggested. Preparatory to this, knowledge about the mechanisms of frost action in hardened paste and in rock is summarized. Emphasis is placed on concepts of critical thickness and critical saturation, and the roles of air bubbles in paste and macropores in absorptive rock. Rapid freezing in the laboratory may destroy concrete that is immune to frost under natural conditions. In the laboratory, too, important effects of seasonal drying are not taken into account. A new procedure is proposed that takes the category of field exposure into account and uses the period of immunity to frost attack as the primary measure of frost resistance.

394. Powers, T. C. "Causes and Control of Volume Change." *Journal of the PCA Research and Development Laboratories* (January 1959): pp. 29-39.

An elementary discussion of shrinkage and swelling of hardened cement paste produced by changes of moisture content is followed by consideration of internal restraints and other factors controlling the amount of shrinkage and swelling of concrete. It is shown that the most unfavorable combinations of factors influencing volume change might result in perhaps seven times as much shrinkage as would result from the most favorable combinations.

395. Powers, T. C. "Freezing Effects in Concrete." *Journal of the American Concrete Institute* SP 47-1 (April 1975).

Theories as to the mechanism of freezing and thawing damage in concrete have been advanced for more than 40 years. The author discusses the evolution of

these theories for cement paste, aggregate, and the overall concrete. The author was prominent in the development of many of the theories.

396. Powers, T. C. *The Mechanism of Frost Action in Concrete*, National Sand and Gravel Association/National Ready Mixed Concrete Association, Silver Spring, MD, Stanton Walker Lecture No. 3, 1965.

This experiment took place in Naperville, Illinois at the Portland Cement Association.

The question asked when the Naperville experiment was planned was substantially this: what kind of concrete is most resistant to deterioration by outdoor exposure, particularly most resistant to the action of freezing: In other words, what kind of cement, what kind of aggregate, and what mix and consistency give the best results. To that question we now have the answer given at Naperville; it comes in three parts: (1) Concrete posts, made of any of the materials and combinations described and installed as described, can remain undamaged for at least 20 years; one combination of materials seems as good as another. (2) The same is true of concrete slabs on the ground, installed as described. (3) Some concrete boxes can stand at least 20 winters without appreciable damage, and some cannot be foretold in terms of materials, mix and consistency.

397. Powers, T. C. "The Nature of Concrete." *Significance of Tests and Properties of Concrete and Concrete-Making Materials*, ASTM, Technical Special Publication No. 169A, 1966. pp. 61-72.

The term concrete can be construed to include a considerable variety of products made from portland cement or other cementing media, but in this publication the term concrete usually refers to a material that was at first a plastic mixture (or mixture that became plastic as a result of manipulation, especially vibration) of portland cement, water, air, and mineral aggregate. Therefore, this discussion of the nature of concrete will have the scope indicated by that description.

398. Powers, T. C. *Prevention of Frost Damage to Green Concrete*, Portland Cement Association, Research Department Bulletin No. 148, 1962.

If there is no exchange of water between a body of green concrete and it surroundings, autogenous desiccation will make the cement paste immune to damage by freezing after the time when the saturation coefficient of the capillary spaces drops below a certain value. Data now available indicate the permissible upper limit of saturation to be about 97%, which degree of desiccation is reached when the maturity factor is 0.53 w/c. For curing at a given temperature, the necessary prehardening time can be expressed as a function of time and water-cement ratio.

399. Powers, T. C. *Resistance of Concrete to Frost at Early Ages*, Portland Cement Association, Research and Development Division, Chicago, IL.

Freezing in fresh concrete is like freezing in frost heaving soils, and freezing in set but green concrete may be like that in mature concrete. Therefore, in winter concreting, freezing phenomena of all kinds must be considered. Freezing effects in set concrete are discussed in terms of two models and three pressure producing mechanisms which can be combined according to different theories. The models

are: (1) Closed vessel having impermeable walls, and (2) a closed vessel having permeable walls. Pressure producing mechanisms are : (1) Displacement of water from freezing site (hydraulic pressure), (2) movement of water to freezing site, producing osmotic pressure and microscopic segregation of ice, and (3) movement of water to the freezing site, producing macroscopic segregation of ice. Theories based on Model 1 do not account for behavior of concrete at any stage of hydration, or the beneficial effect of entrained air. Those based on Model 2 and Mechanism 1 and 2 for some features of the behavior of mature concrete that is not too permeable. For mature concrete of relatively high permeability and low strength, and in green or fresh concrete, Model 2 after rupture or initially without tensile strength, and Mechanism 3, are applicable. The concept of critical size or thickness together with data on physical characteristics of paste and aggregate lead to adequate theories concerning the amounts of entrained air required to protect hardened paste from pressure by Mechanisms 1 and 2. Future work on theory and practice is expected to refine theory and produce empirical data needed for practical design of air-entrained concrete for all conditions and ages of exposure.

400. Powers, T. C. "Resistance to Weathering - Freezing and Thawing." *Significance of Tests and Properties of Concrete and Concrete Aggregates* STP-169 (1956): pp. 182-187.

Rate of weathering of concrete in areas outside the tropics and subtropics is in many cases affected by freezing. Effects of freezing may be anything from negligible to catastrophic, depending on various factors. Consequently, there are freezing-and-thawing tests for concrete.

The four ASTM Tentative Methods permit a wide choice of test conditions, especially in regard to permissible cooling rates. In ASTM Method C 290, the maximum rate is limited by the restriction on temperature difference; but specimen dimensions are not specified, and thus a wide range in maximum rates is still possible. In ASTM Method C291, there is no limit on the maximum rate. All four methods suggest starting the test on moist-cured specimens, 14 days old without preliminary drying, and keeping specimens wet throughout the test. Test conditions in various laboratories seem to differ more than is permissible under or suggested by the tentative methods. Cooling rates differ, particularly in the range below 32° F, and various curing schedules are used.

This paper, an evaluation of freezing-and-thawing tests in the light of our present understanding of frost action in concrete, is abstracted from a longer discussion of this subject by the author.

401. Powers, T. C. "Structure and Physical Properties of Hardened Portland Cement Paste." *Journal of the American Ceramic Society* Vol. 41 (January 1958): pp. 1-6.

Methods of studying the submicroscopic structure of portland cement paste are described, and deductions about structure are presented. The main component, cement gel, is deposited in water-filled space within the visible boundaries of a body of paste. Space filled with gel contains gel pores; space not filled by gel or other solid material is capillary space. Hygroscopicity of cement gel, and capillary pores, accounts for various aspects of the properties and behavior of concrete. Data on gel and paste structure are used in discussing strength, permeability, volume stability, and action of frost.

402. Powers, T. C. "Topics in Concrete Technology: 3. Mixtures Containing Intentionally Entrained Air." *Journal of the PCA* (September 1964): pp. 19-42.

Air bubbles are intentionally entrained in concrete to protect hardened concrete from frost action, or sometimes to improve workability. Air-entraining agents (AE agents) are either surfactants or insoluble hydrophobic colloids formed in the mixture by reaction with $Ca(OH)_2$; such agents stabilize bubbles produced mechanically by stirring or kneading. Air can be entrained in water, in wet aggregate, or in cement paste. In water, air accumulates as supernatant foam, but only if an AE agent is present; in wet aggregate it is trapped by the "aggregate screen," with or without an AE agent; in paste it accumulates by emulsification, but it cannot ordinarily be retained without an AE agent. The quantity entrained in paste depends mainly on paste consistency and stirring procedure; the quantity in concrete depends on emulsification in paste and on the aggregate screen effect, which is relatively large in lean mixtures. Grading, as a whole, controls mesh-size of the aggregate screen. Point B of the specific-void-content diagram occurs at about the same mix, regardless of air content. At constant cement content and constant slump, AE displaces aggregate and water, the more water and less aggregate the leaner the mixture; a surfactant AE agent may reduce water more than does a non-surfactant. Air bubbles can be used to replace an equal solid volume of sand, with little or no effect on slump.

403. Powers, T. C. "Topics in Concrete Technology: 4. Characteristics of Air-Void Systems." *Journal of the PCA* (January 1965): pp. 25-41.

To serve its principal purposes, entrained air must be distributed through the paste as small bubbles; the number of bubbles per unit volume of air or mean bubble size is a pre-eminent characteristic. At present, specific surface area, 'α', is the most useful function of mean bubble size. Determinants of 'α' in concrete in neat paste are the kind and dosage of air-entraining agent (AE agent), duration of stirring, stirrer speed (shear stress), and paste viscosity. Determinants of 'α' in concrete are the same as for paste, plus the influence of void characteristics of the aggregate, and the effects of manipulation. With a given AE agent, 'α', is determined approximately by '$\alpha(o)$', a value when no AE agent is present; '$\alpha(t)$', a value characteristic of the void-increment due to the presence of the AE agent; and the fraction of the total air content that is due to the agent. Manipulation may decrease air content while it increases 'α'.

Bubble size distribution is indicated approximately by: a spacing factor computed from 'α', paste content, and air content. The actual size distribution about the mean size can, in principle, be determined by methods used, but whether or not the results are accurate and worth the time and effort is yet to be learned. Theoretically, bubble size distribution might be expected to change while the concrete is fresh and the paste fluid; small bubbles diminishing while larger bubbles grow. Actually, it seems that the bubbles become stable as soon as mixing ceases, probably because of the cohesive strength of fresh paste.

404. Powers, T. C. "Void Spacing as a Basis for Producing Air-Entrained Concrete." *Journal of the American Concrete Institute* Vol. 25, No. 9 (May 1954): pp. 741-759.

Basic studies show that the function of entrained air is to protect the paste and that the effectiveness depends on the distance from void to void in the paste. Freezing and thawing tests show different mixes have nearly equal frost resistance when the spacing factor is about 0.01 in. The amount of air required for a given spacing factor is directly proportional to the paste content, and it is greater as the specific surface of the air voids becomes smaller.

The void system is made up of relatively coarse natural voids and entrained bubbles. Characteristics of natural voids vary with aggregate grading, consistency, and other mix characteristics. With a given amount of air-entraining agent in the mixing water, the amount of entrained bubbles is smaller as the quantity of cement or other fine solids in the water becomes greater.

A procedure is suggested for designing a fixed spacing factor where such procedure is economically feasible.

405. Powers, T. C. "A Working Hypothesis for Further Studies of Frost Resistance of Concrete." *Journal of the American Concrete Institute* Vol. 41, No. 4 (February 1945): pp. 245-272.

Basic information is given on the freezing of water in concrete. From this information and other published material an explanation of the mechanism of the action of frost on concrete is developed. The explanation takes into account such factors as the degree of saturation of the concrete, the permeability and strength of the concrete, hydraulic pressures generated during freezing, and air-filled cavities. It is suggested that the hypothesis be made the basis of further laboratory studies of the action of frost in concrete.

406. Powers, T. C., and T. L. Brownyard. "Studies of the Physical Properties of Hardened Portland Cement Paste, Part 1." *Journal of the American Concrete Institute* Vol. 18, No. 2 (October 1946): pp. 101-132.

This paper deals mainly with data on water fixation in hardened portland cement paste, the properties of evaporable water, the density of the solid substance, and the porosity of the paste as a whole. The studies of the evaporable water include water-vapor-adsorption characteristics and the thermodynamics of adsorption. The discussion include the following topics:

(1) Theoretical interpretation of adsorption data;
(2) The specific surface of hardened portland cement paste;
(3) Minimum porosity of hardened paste;
(4) Relative amounts of gel-water and capillary water;
(5) The thermodynamics of adsorption;
(6) The energy of binding of water in hardened paste;
(7) Swelling pressure;
(8) Mechanism of shrinking and swelling;
(9) Capillary-flow and moisture diffusion;
(10) Estimation of absolute volume of solid phase in hardened paste;
(11) Specific volumes of evaporable and non-evaporable water;
(12) Computation of volume of solid phase in hardened paste;

(13) Limit of hydration of portland cement;
(14) Relation of physical characteristics of paste to compressive strength;
(15) Permeability and absorptivity; and
(16) Freezing of water in hardened portland cement paste.

407. Powers, T. C., and T. L. Brownyard. "Studies of the Physical Properties of Hardened Portland Cement Paste, Part 2." *Journal of the American Concrete Institute* Vol. 18, No. 3 (November 1946): pp. 249-335.

In the preceding part of this paper some of the methods of studying hydrated portland cement paste were reviewed and the principal results obtained by previous investigators were presented. In this part of the paper the studies of water fixation carried out in this laboratory will be described.

408. Powers, T. C., and T. L. Brownyard. "Studies of the Physical Properties of Hardened Portland Cement Paste, Part 3. Theoretical Interpretation of Adsorption Data." *Journal of the American Concrete Institute* Vol. 18, No. 4 (December 1946): pp. 469-504.

The adsorption isotherms obtained from hardened cement paste are identical in several respects with those obtained from other materials that are very different in chemical and physical properties. For example, when glass spheres or oxide-coated cathodes or radio tubes are exposed to nitrogen vapor (at the temperature of liquid air), or when a plane mercury surface is exposed to CCl_4 vapor (11° C), the adsorption curves obtained are of the same type as those for water vapor on cement paste. Also, the same type of curve is obtained when crystalline solids such as titanic oxide, stannic oxide, zinc oxide or pulverized quartz are exposed to water vapor at room temperature. Moreover, curves of the same type may be obtained with different vapors on the same solid.

The similarities just mentioned exist not only among materials that are not porous, that is, materials on which adsorption is confined to the visible surfaces, but also among many porous solids having negligible superficial surface areas. With suitable vapors the following materials, some porous, some not, all give the same type of isotherm: building stone; cotton; asbestos fibre; wood; wood pulp; carbon black; titania gel, ferric oxide gel, rice grains; cellophane; bonechar; cellulose; silica gel; proteins; soils; wool.

It appears therefore that the curves found for portland cement paste are not characteristic of the particular substances composing the paste but represent some factor common to many dissimilar substances. We will see in what follows that this common factor is probably nothing other than a solid surface that has an attraction for the adsorbed substance.

409. Powers, T. C., and T. L. Brownyard. "Studies of the Physical Properties of Hardened Portland Cement Paste, Part 4. The Thermodynamics of Adsorption of Water on Hardened Paste." *Journal of the American Concrete Institute* Vol. 18, No. 5 (January 1947): pp. 549-602.

This discussion pertains to the energy changes that take place when water is adsorbed by hardened cement paste. The relationship of these changes to such physical effects as shrinking and swelling, capillary flow, and moisture diffusion will be considered briefly. Comparisons are made of the energy of binding of

evaporable and non-evaporable water. Analysis of the energy changes into the two main forms of energy and consideration of the relative amounts of each are of interest in connection with the question of the extent to which water is modified when it is adsorbed on the solid.

410. Powers, T. C., and T. L. Brownyard. "Studies of the Physical Properties of Hardened Portland Cement Paste, Part 5." *Journal of the American Concrete Institute* Vol. 18, No. 6 (February 1947): pp. 669-712.

This paper discusses studies of the hardened paste by means of specific-volume measurements.

411. Powers, T. C., and T. L. Brownyard. "Studies of the Physical Properties of Hardened Portland Cement Paste, Parts 6 & 7." *Journal of the American Concrete Institute* Vol. 18, No. 7 (March 1947): pp. 845-880.

Part 6 discusses the relation of physical characteristics of the paste to compressive strength and Part 7 discusses permeability and absorptivity.

412. Powers, T. C., and T. L. Brownyard. "Studies of the Physical Properties of Hardened Portland Cement Paste, Part 8." *Journal of the American Concrete Institute* Vol. 18, No. 8 (April 1947): pp. 933-969.

This part of the paper contains data on the amount of ice that can exist in hardened portland cement paste under given conditions. Also some theoretical aspects of the data are considered.

413. Powers, T. C., and T. L. Brownyard. "Studies of the Physical Properties of Hardened Portland Cement Paste, Part 9." *Journal of the American Concrete Institute* Vol. 18, No. 8 (April 1947): pp. 971-992.

In this, the final part of the paper, the concepts concerning the characteristics of hardened paste that have emerged from this study are set down in brief. It is implied that the concepts are new and unique. On the contrary, they agree in general with previously expressed views of those who have believed the colloidal state of the hydration products to be a dominant characteristic of the hardened paste. However, it is now possible to consider these characteristics in more detail and on a quantitative or semi-quantitative basis.

This summary includes only the facts and relationships that can be set down with a minimum of discussion. The reader should not depend on this part alone for an understanding of the subject, since the finer points of interpretation and many significant details and illustrative graphs are omitted.

Some of the relationships given below do not appear in the preceding part of the paper, but they are derived from relationships already given. In the preceding parts of this paper the sequence of topics was determined according to the requirements for an orderly development of concepts and interrelationships between variables. In this summary it is assumed that the reader is familiar with the background material and the subject is presented, as far as possible, in the form of an analysis of the properties of hardened paste.

The following should be noted carefully before proceeding with the summary: All the data and relationships discussed below pertain only to specimens cured

continuously at about 70 F. Without modification, they do not apply to other curing conditions.

414. Powers, T. C., L. E. Copeland, J. C. Hayes, and H. M. Mann. "Permeability of Portland Cement Paste." *Journal of the American Concrete Institute* Vol. 51, No. 14 (November 1954): pp. 285-297.

This paper deals with experiments on the permeability to water of portland cement paste. The relationship of the permeability of the paste to that of concrete as a whole is understood in a general way. The paste is a continuous body enveloping and isolating the individual aggregate particles. The over-all permeability is a function of the paste permeability, the permeability of the aggregate particles, and the relative proportions of the two. Fissures under the aggregate particles formed during the period of bleeding, and cracks caused by volume-change restraint also play a part. The permeability of paste has also an important bearing on the vulnerability of concrete to frost action. It determines the relative ease with which the cement paste and the aggregate may become resaturated after drying, and it is a principal factor determining the destructiveness of freezing — once the paste becomes water-soaked. This latter subject has been treated extensively in other papers. Studies of paste permeability have illuminated the question of hydrostatic pressure in the interior of dams. Along with other information they have helped to identify the "ultimate particles" against which hydraulic forces inside the concrete can develop. With these particles identified and their wettable areas measured, the order of magnitude of the area factor for computing hydrostatic uplift forces within concrete dams could be established.

415. Powers, T. C., and R. A. Helmuth. "Theory of Volume Changes in Hardened Portland-Cement Paste During Freezing." *Proceedings of the Thirty-Second Annual Meeting of the Highway Research Board* (1953): pp. 285-297.

New experimental data are presented on the freezing of hardened portland-cement pastes with and without entrained air. They are explained in terms of two mechanisms: 1) the generation of hydraulic pressure as water freezes in capillary cavities and 2) the growth of the bodies of ice in the capillary cavities or air voids by diffusion of water from the gel. Air voids limit the hydraulic pressure and shorten the period during which the ice in the cavities can increase. The closer the air voids are to each other the more effective they are in controlling either mechanism.

416. Powers, T. C., and H. H. Steinour. "An Interpretation of Published Researches on the Alkali-Aggregate Reaction Part 1 - The Chemical Reactions and Mechanism of Expansion." *Journal of the American Concrete Institute* Vol. 26, No. 6 (February 1955): pp. 497-516.

Research results are interpreted as having the following indications: (1) the relative reactivity of a given form of silica is determined by the number of interrupted silicon-oxygen-silicon linkages, a matter of specific surface and "holes" due to disorderly atomic arrangements; (2) caustic attack on reactive silica in the presence of excess lime produces a non swelling lime-alkali-silica complex if chemical equilibrium is reached; (3) in affected concrete some of this complex is produced, but abnormal swelling is due to the formation of an alkali-silica complex which is not in equilibrium with lime; (4) the persistence of the nonequilibrium product appears to be due to the inability of lime to diffuse into

the reactive particle where alkali-silica complex has formed; (5) expansion of concrete is probably due primarily to the swelling of solid alkali-silica complex, but it may also be due to hydraulic pressure generated by osmosis, or by both mechanisms.

417. Price, W. H. "Factors Influencing Concrete Strength." *Journal of the American Concrete Institute* Vol. 47, No. 6 (February 1951): pp. 417-430.

The effect of mix proportions, type and brand of cement, availability of moisture for curing, accelerators and curing temperatures on the rate and potential strength development of concrete are discussed. The influence of rate and frequency of load applications, dimensions of test specimens and lateral restraint on the indicated strength are also discussed; and information is furnished on the variation in strength that might be expected on a typical job. Compressive, tensile, flexural, bond and shearing strengths are compared, and the strengths of control cylinders are compared with the strengths of cores drilled from structures at later ages. Information is also furnished on strength loss from freezing and thawing and alkali-aggregate expansion.

418. Raecke, D., and J. Lott. *First Progress Report — The Control of Cracking of Concrete*, Department of Theoretical and Applied Mechanics, University of Illinois, Urbana, Illinois, Texas A & M Report No. 667, August 1966.

This report covers the two areas in which work has been performed. A cracking hypothesis is developed for the simple model of a reinforced concrete member with the reinforcement loaded in direct tension. The proposed cracking mechanism is based on similarities between the cracking phenomenon in reinforced concrete and the stable crack growth obtained in certain fracture toughness tests.

An experimental study of the resistance of several pastes and mortars to the propagation of an artificial flaw, i.e., the fracture toughness of the material, is described. Factors that might affect the crack growth have been investigated in order to better understand crack development. The coefficient of variation of the fracture toughness is generally much higher for pastes than for mortars. This is probably due to a greater degree of internal cracking of the pastes, caused by the high initial shrinkage of the pastes as compared to the mortars.

In the paste series, there seems to be a trend for the fracture toughness to decrease with increasing w/c ratio. In the mortar series, the trend is not evident.

In both the paste and mortar series, there is a trend for decreasing fracture toughness with increasing air content.

The fracture toughness of the mortars is generally higher than that of the pastes even though the w/c ratios of the mortars are greater. This would indicate that the addition of fine aggregate increased the fracture toughness although there does not seem to be a clear trend for the fracture toughness to increase with increasing sand-cement ratio.

419. Ramakrishnan, V., and P. Balaguru. "Durability of Concrete Containing Cement Kiln Dust." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

This paper presents the results of a performance evaluation study of concrete containing fly ash. The properties of fly ash concrete have been compared with their corresponding properties of regular concrete. The plastic properties of concrete compared are slump, air content, vibe-time, temperature, unit weight, and setting time of concrete. The hardened concrete properties compared are unit weight, compressive strength, splitting tensile strength, flexural strength, static modulus of elasticity, dynamic modulus of elasticity, pulse velocity, and absorption coefficient. These properties are compared at four different ages: 3, 7, 28, and 90 days. Durability under rapid freeze-thaw conditions and shrinkage deformations are also discussed.

A comparison of the physical properties of fresh concrete, on the basis of approximately equal slump and entrained air has shown the relative ease of placing and finishing of concretes containing fly ash. The rate of stiffening is lower for fly ash concretes containing Type I cement.

In general, fly ash concretes show higher strengths and higher modulus values at 90 days than their corresponding regular concretes. However, fly ash concrete has slightly higher drying shrinkage than regular concrete. The strength and elastic modulus relationships are approximately the same for both concretes.

420. Ramakrishnan, V., W. V. Coyle, J. Brown, P. A. Tlustus, and P. Venkataramanujam. "Performance Characteristics of Concretes Containing Fly Ash." Symposium on Effects of Fly Ash Incorporation in Cement and Concrete, pp. 233-242. Boston: Materials Research Society, 1981.

This paper presents the results of a performance evaluation of study of concrete containing fly ash. The properties of fly ash concrete have been compared with their corresponding properties of regular concrete. The plastic properties of concrete compared are slump, air content, vebe-time, temperature, unit weight, and setting time of concrete. The hardened concrete properties compared are unit weight, compressive strength, splitting tensile strength, flexural strength, static modulus of elasticity, dynamic modulus of elasticity, pulse velocity, and absorption coefficient. These properties are compared at four different ages: 3, 7, 28, and 90 days. Durability under rapid freeze-thaw conditions and shrinkage deformations are also discussed.

A comparison of the physical properties of fresh concrete, on the basis of approximately equal slump and entrained air, has shown the relative ease of placing and finishing of concretes containing fly ash. The rate of stiffening is lower for fly ash concretes containing Type I cement.

In general, fly ash concretes show higher strengths and higher modulus values at 90 days than their corresponding regular concretes. However, fly ash concrete has slightly higher drying shrinkage than regular concrete. The strength and elastic modulus relationships are approximately the same for both concretes.

421. Ramakrishnan, V., and W. V. Coyle. *Superplasticized Concretes for Rehabilitation of Bridge Decks and Highway Pavements*, U. S. Department of Transportation.

Research and Special Programs Administration, Washington, D. C., DOT/RSPA/DPB-50/81/3, January 1981.

The object of this research was to develop guidelines for assuring the troublefree placement of tough, high-strength, high density, durable concrete for bridge deck construction through the use of superplasticizers and steel fibers. The study was made with superplasticizers through the use of experimental mixtures conforming to the requirements dictated by statistically valid factorial designs, so that analysis of variance could be used in the evaluation. The second phase extended the findings into an evaluation of superplasticized concretes containing steel fibers. This report describes the first phase study of the statistical evaluation of superplasticized concrete properties.

Two mixes, one with medium workability and high cement content suitable for bridge deck replacement and another with high workability suitable for structural and pavement concrete were selected for intensive study. For these mixes, properties of the fresh concrete (slump, vebe-time, flow table spread, air content, initial and final setting times) are reported. The effects of retempering are described. The influence of three types of cements on the properties of plastic and hardened concrete is explained. Complete results of the following tests are presented: compressive strength, tensile strength, flexural strength, static modulus of elasticity, dynamic modulus of elasticity, pulse velocity and dry unit weight at 1, 3, 28 and 90 days curing. The selected concretes had high durability and satisfactory resistance against deicer scaling.

422. Reading, T. J. "Durability of Shotcrete." *Concrete International* (January 1981): pp. 27-33.

The low water-cement ratio of shotcrete enhances its durability for most types of exposure. However, some concern has been expressed about its resistance to frost action even though most service record reports are good, because air entrainment is not normally used and the findings of previous research are inconclusive. Samples of shotcrete from several jobs were tested for strength, air content, air spacing factor, and other properties. Most of the specimens performed poorly in the accelerated freeze-thaw test frequently used for conventional concrete. Performance in a less accelerated test — exposure in seawater off the coast of Maine — was much better. At the present state-of-the-art it appears that dense shotcrete with a low water-cement ratio should be durable under ordinary freezing and thawing. Caution should be exercised, however, where special mixes are used or the exposure is very severe.

423. Reagel, F. V. "Freezing and Thawing Tests of Concrete." *Highway Research Board (Bulletin) Proceedings* Vol. 20 (1940): pp. 586-599.

The scope and purpose of this investigation is covered in the early part of the report by a statement of the following questions: (1) What weathering conditions are the major factors causing deterioration of concrete?; (2) To what cycles of freezing and thawing may concrete be subjected in service?; (3) How shall the deterioration of concrete subjected to freezing and thawing be measured?; (4) What are the effects of various curing treatments prior to freezing?; (5) What cycle of freezing and thawing should be used?; (6) Can the effect of aggregates on the durability of concrete be predicted by a freezing and thawing
The report offers some data obtained in connection with research directed toward

producing a yardstick by which some accelerated measure of concrete durability may be obtained.

The data presented are based on tests made on concretes fabricated from a fixed mortar of good quality and coarse aggregates of varying quality. The freezing and thawing cycle used is of a fixed length of 12 hr., using varying thawing and freezing temperatures.

The needs for co-operative standardization work in this field and accurate control of test conditions are stressed.

424. Regourd, M., H. Hornain, P. C. Aitcin, and S. Sarkar. "Durability of an Arctic Concrete." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

The use of unconventional aggregates, which includes several sulphide minerals in making concrete in the Canadian Arctic aroused the interest of the authors to investigate the durability of such a concrete subjected to a very cold environment. Compressive strength measurements on concrete samples 3 and 9 years old, cored in a dock, show that the concrete is still very strong, at least 28 MPa (4000 psi). A close examination of the aggregates and concrete microstructure suggests the concrete is durable. The presence of these aggregates does not give rise to any deleterious effect. The concrete is found to be a dense one. Only a superficial layer of a few millimeters thick has been transformed by carbonation. This zone, enriched in potassium, does not contain any $Ca(OH)_2$ crystal. Its C-S-H has a low CaO/SiO_2 ratio and is sometimes replaced by a siliceous gel. Penetration of chloride and sulfate ions is also observed but is not related to any concrete damage. The presence of a large amount of $Ca(OH)_2$ and calcium rich C-S-H below the thin carbonated layer corresponds to a high chemical stability of the concrete.

425. Regourd, M., H. Hornain, and B. Mortureux. "Microstructure of Concrete in Aggressive Environments." *Durability of Building Materials and Components - ASTM STP 691* (1980): pp. 253-268.

All the constituents of concrete can be attacked. Some degradation occur after a long period of time. So, it is important to know the chemical and physical mechanisms of the corrosion and the behavior of built structures. In our studies on the durability of concrete, chemical and technological tests have been completed by microstructure examination with scanning electron microscopy and x-ray diffraction. In the present stage of our research into the attack of concrete by seawater, several factors can be noted. The formation of expansive ettringite is related to the content, the crystalline form, and the granularity of tricalcium aluminate. The carbonation reaction transforms ettringite into thaumasite. The dissolving of lime-rich compounds like hydrated silicates C-S-H brings about their progressive transformation into Ca-Mg silicates. Some aggregates have been found to have reacted with alkalis. A dense concrete with a high cement content will offer a good resistance to chemical and physical attacks.

426. Regourd, M., B. Mortureux, P. C. Aitcin, and P. Pinsonneault. "Microstructures of Field Concretes Containing Silica Fume." Proceedings of the 4th International Conference on Cement Microscopy, pp. 193-202. April 1982.

Scanning electron microscopy and electron probe microanalysis have been used in the study of the microstructure of field concretes containing condensed silica fume and used as a pavement in Canada. The texture and the elemental composition of CSH, the cement paste-aggregate bond, and the microcracks path have been considered in relation with the compressive strengths and the resistance to freezing and thawing cycles.

427. Regourd, M., B. Mortureux, and H. Hornain. "Use of Condensed Silica Fume as a Filler in Blended Cements." *Proceedings of the Second International Conference on the Use of Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete*, ACI SP-91 (1986): pp. 847-867.

At early ages, blended cement mortars with 30% hydraulic slags or active pozzolans have lower mechanical strengths than mortars incorporating 100% portland cement. The action of 5% condensed silica fume replacement for slag or pozzolan or material considered as inert has been studied from seven days to three months by measuring the mechanical strengths of mortars made according to the ISO test method and by observing the microstructure of fractured samples. The action of the condensed silica fume is a function of the nature of the additive. With hydraulic slags, there is competition between slag and silica fume for the available lime. With slightly or slowly reactive pozzolans (volcanic rock, fly ash), mechanical strengths and microporosity of mortars show improvement at 28 days. With inert material (crystalline slag or quartz), the improvement is more marked. This is due to the formation of dense C-S-H, strong cement-paste-aggregate bond and 20% increase in mechanical strength.

428. Reidenouer, D. R., and R. H. Howe. *Air Content of Plastic and Hardened Concrete*, Pennsylvania Dept. of Transportation, Harrisburg, PA, research project no. 73-1, February 1975.

A combined field and laboratory testing program was conducted to compare air content in plastic and hardened concrete and to study the relationship of air content to vibration and compressive strength. Twelve plain concrete slabs were placed under normal field conditions. The slabs represented three levels of air content, two levels of vibration, and two types of coarse aggregate. Both the plastic and hardened concrete was subjected to a number of different tests.

Air meter (Acme type) tests performed by different operators on the same batch of plastic concrete have a 95% probability of being within 0.80% of the mean. Analysis of variance of linear traverse data revealed that that test also has good precision, as long as the air content does not exceed 7%; both within-operator and between-operator variances were non-significant below this level of air. When air meter results are compared to the entrained air content of hardened concrete, as determined by the linear traverse test, there is a 95% probability that the maximum variation between the means of the two will not exceed 1.65%. There is essentially no change in the entrained air content between plastic and hardened concrete. However, vibration does very significantly reduce entrapped air. Results of freeze/thaw tests reaffirm the value of entrained air voids in cement paste in preventing frost damage to concrete. Compressive strength is

directly related to the total air content; for each percent increase in total air, the compressive strength decreases about 400 psi.

429. "Resistance of High-Strength Concrete to Freezing and Thawing." *Concrete Construction* (March 1988): pp. 344-347.

The standard test for freezing and thawing, ASTM C 666, particularly Procedure A, is a good test for judging the frost resistance of structural concrete under very severe conditions and may be used to screen aggregates for D-cracking potential.

Inclusion of silica fume in structural concrete produces a less permeable product, but it may require a longer time for reaction. Even the 14 days of water curing in C 666 is at times inadequate for air-entrained concrete containing silica fume.

The synthesis report also recommends that silica fume not be used in large quantities when durability is important.

430. Rhoades, R., and R. C. Mielenz. "Petrography of Concrete Aggregates." *Journal of American Concrete Institute* Vol. 17, No. 6 (1946): p. 581.

Serviceability of a concrete aggregate depends upon the manner in which it joins with cement to determine the quality of concrete. Yet, standard acceptance tests do not measure properties which are directly responsible for performance of aggregates enclosed in concrete; new methods of aggregate investigation are needed. Experience shows that petrographic study can supply valuable information on a routine basis, and that, wherever possible, ordinary acceptance tests should be supplemented by examination by a petrographer familiar also with problems of concrete. The significant properties of aggregates are discussed, and methods of petrographic study of aggregates are described.

An extensive bibliography is appended and referenced in the text for the benefit of readers, especially petrographers, wishing to explore further the concepts treated only briefly in this paper.

431. Richard, T. G. "Low Temperature Behavior of Cellular Concrete." *Journal of the American Concrete Institute* Vol. 74, No. 17 (April 1977): pp. 173-178.

Cellular concrete has attractive potential as a load bearing insulation in large cryogenic applications. This investigation indicates that the thermal and mechanical properties of low density cellular concrete, coupled with its cost, ease of fabrication, and availability may make this material a feasible alternative to other more expensive load-bearing insulations. Data obtained in this investigation illustrate significant increases in the strength and stiffness of selected densities, along with appreciable decreases in the thermal conductivity of cellular concrete at liquid nitrogen temperatures (-196° C).

This conclusion is supported by a characterization of the elastic modulus, secant modulus, ultimate compressive strength, and thermal conductivity of a range of dry densities from 25 to 90 pcf at -196° C. These low temperature properties are compared to room temperature (23° C) response.

432. "RILEM Recommendation: Methods of Carrying Out and Reporting Freeze-Thaw Tests on Concrete with Deicing Chemicals." *Materials and Structures, Research and Testing*, RILEM, Paris, Vol. 10, No. 58, July - August 1977, pp. 213-215.

Although the freezing and thawing program proposed in this recommendation is standardized, the approach to observing the damage caused is not. Surface weight loss is a general and average weight loss, which does not tell one if the damage is uniform or concentrated in one place. This is one of the main reasons why "before and after" photographs are specified. The depth of scaling may be of interest in the case of a road or a footpath where danger to traffic or pedestrians could be likely. The percentage area is more of an architectural aspect and the visual description is a general assessment covering any of the risks in a general way. In effect one must select the assessment to be used depending upon what sort of concrete is going to be subject to the risk.

Air-entrainment is known to improve the performance of concretes to freeze-thaw attack. One should not assume that this results in the same improved resistance to deicing salts as this particular test is much more sensitive to the bubble size and spacing of the air than the ordinary freeze-thaw test.

In all cases a 3% solution of chemical (weight/volume in water) is used as this is one of the most critical concentrations.

The solution is placed in a dam and then frozen. Although deicing chemicals are often spread onto frozen concrete, the tests described herein give qualitatively correct results in most cases.

433. "RILEM Recommendation: Methods of Carrying Out and Reporting Freeze-Thaw Tests on Concrete without Deicing Chemicals." *Materials and Structures, Research and Testing*, RILEM, Paris, Vol. 10, No. 58, July - August 1977, pp. 209-211.

The particular test or tests one selects depends upon one's interest and what risks are involved. The dilation test is the most sensitive because frost-prone concretes expand significantly more than frost-resistant concretes irrespective of the attack being in the aggregate or the mortar system. The flexural resonant frequency has been selected as the best of the testing geometries because the whole prism is flexed during the vibration. The longitudinal and torsional methods, although useful for determining the elasticity of the concrete, leave large sections of concrete undisturbed and these sections, if they have frost damage in them, would be undetected. The ultrasonic method was considered at length; but the consensus of opinion was that it was not so sensitive as the flexural resonant frequency method, and it was subject to large errors. The weight change method was also considered but rejected because of its insensitivity.

Destructive end tests are included for comparison purpose; these are carried out at the end of the test on cycled units and identical control units stored in water that have not been cycled. Dummy or control units should always be tested at the same age as the cycled units since due to the aging effect during the test, errors will arise if one compares final with initial observations.

Air-entrainment is known to improve the performance of concretes to freeze-thaw attack as well as attack by deicing chemicals; however, for the test described one should not expect resistance to deicing chemicals even if air-entrainment is used

since the deicing chemical test is much more sensitive to the bubble size and spacing of the air than the ordinary freeze-thaw test. These tests are covered in a separate report.

434. RILEM Technical Committees. "An Introduction to RILEM Methods of Testing Resistance of Concrete to Freezing and Thawing and the International Co-operative Tests on the Critical Degree of Saturation Method." *Materials and Structures* Vol. 10, No. 58: pp. 205-252.

RILEM 4-CDC held its last meeting in Madrid 1975 and decided that the following four reports would be best published in a single issue of Materials and Structures. Although 4-CDC no longer exists, the following describes the remaining work quota of that Committee: (1) dealing with international comments on the two tentative methods published in 1974 Materials and Structures, integrating these comments into final drafts and submitting them as Recommendations; (2) publication of a new tentative method dealing with the critical degree of saturation for international comment prior to its final submission as a Recommendation; and (3) publication of the international co-operative laboratory test program where the critical saturation method was used as an assessment.

435. Roberts, L. R., and P. Scheiner. "Air Void System and Frost Resistance of Concrete Containing Superplasticizers." *Developments in the Use of Superplasticizers, ACI* SP-81 (1981): pp. 189-213.

Previous workers have shown that the air-void system in air-entrained concrete containing a superplasticizer tends toward larger bubbles. This effect leads to spacing factors larger than the 0.2 μm normally accepted as a requirement for durability. Nevertheless, concretes containing such admixtures generally have been found to be frost-resistant.

The present work is an attempt to understand the reasons for durability when the accepted 0.2 μm spacing factor requirement is not met. The distribution of air-void sizes in air-entrained concretes made with and without a naphthalene sulfonate type superplasticizer were examined, using a new microprocessor-based Rosiwal linear traverse apparatus. The individual chord intercepts available with this system were fitted to a zeroth-order logarithmic distribution function, and the parameters of the fitted function were related to frost resistance as tested for by ASTM: C 666, procedure A.

Concretes containing the superplasticizer were frost-resistant, despite spacing factors in excess of 0.2 μm. The most frequently encountered chord lengths in superplasticizer-containing concrete did not change relative to equal slump reference concrete.

436. Roberts-Seymour, M. "The Effect of High-Range Water-Reducing Admixtures on Some Durability Parameters of Silica Fume Portland Cement Concretes." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987, pp. 577-585.

The author presents three experimental programs employing high-range, water-reducing admixtures to modify durability performance in portland cement silica

fume concrete. Resistivity and chloride permeability are shown to be significantly improved where fume-replaced concrete utilizes a superplasticizer. Superplasticizing has some demonstrated drawbacks where silica fume is introduced to reduce alkali-aggregate reactions.

437. Robson, G. "Durability of High-Strength Concrete Containing a High-Range of Water-Reducer." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

Recent construction of a segmental, precast concrete, cable stayed bridge across the Ohio River at Huntington, WV involved two special designed concretes; one with 6,000 psi minimum strength and one with 8,000 psi minimum strength. Attaining these strength levels was markedly enhanced by the availability and use of high-range water-reducers, even though the fear of non-durable concretes was also heightened.

Tests of the concretes produced during this field trial indicated that air entrained high strength concretes containing HRWR easily met the minimum strength requirements but would not withstand the freeze-thaw cycling of ASTM C 666.

This paper discusses the efforts involved in developing suitable concrete proportions for this work and compares freeze-thaw durability of high strength concretes with and without entrained air and with and without high-range water-reducing admixtures.

438. Rodway, L. E. "Durability of Concrete." *Cement, Concrete and Aggregates* Vol. 7, No. 1 (Summer 1985): pp. 43-48.

The durability of concrete is obviously a complex topic. This paper deals with an overview in four parts: The first part consists of durability as affected by more than 200 individual separate items involved in its constituent materials; the effect of practical matters in preparing and handling concrete aggregates; cement storage and handling and construction techniques; the physical properties of the hardened concrete: nature of exposure of the concrete; and finally the types of loading to which concrete is exposed. Second, examples of durability of nonstructural exposed concrete are given in terms of resistance to freeze-thaw forces in relation to air-void characteristics of normal concrete. Third, an example of nondurable, load bearing structural concrete is illustrated along with the causes of distress and method of repair. Finally, a recent example of a high strength structural concrete bridge deck containing a superplasticizer is presented in terms of its durability characteristics. Detailed data on each of these four classifications has been referenced to facilitate a more in-depth study by those parties who may have an interest in one or more of those topics.

439. Rodway, L. E. "Effect of Air-Entraining Agent on Air-Void Parameters of Low- and High-Calcium Fly Ash Concretes." *Cement, Concrete, and Aggregates* Vol. 10, No. 1 (Summer 1988): pp. 35-38.

Five fly ashes with widely varying lime contents from three countries were used for 25% of the cement by mass in identical concrete mixes, including the same quantity of air-entraining agent in each case. The hardened concrete resulted in a satisfactory air-void system in terms of freezing-thawing resistance, regardless of the lime content of fly ash.

440. Rogers, C. A., and B. Chojnacki. "Destruction of Concrete Water Tanks in a Severe Climate Due to Ice Lensing." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

Rogers and Chojnacki reported deterioration of a fish tank due to ice formation in the interior of the concrete wall. The wall was exposed from one side to continual cold temperatures and supplied continually with warm water from the other side. Based on the petrographic examination, core samples taken from failed areas showed a high water cement ratio of the cement paste, resulting in a poor aggregate-paste bound, a poor air-entrained content, and air void spacing factors exceeded ASTM recommendations. The failure was then attributed to formation of an ice lens within the permeable concrete.

The authors suggested that a one surface freezing test would be an excellent model, compared to conventional F-T tests, in order to assess durability of concrete subjected to such environment.

441. Romer, B., and G. Dobrolubov. "Applied Microscopy in Building Materials Testing - Concrete, Mortar, Cement, Lime, Gypsum, Ceramics." *Mitt. Wissenschaft und Technik* Vol. Bd. VI (April 1974): pp. 135-144.

Microscopy can reveal the fine structure of a body. This makes it possible to recognize the intrinsic relations especially with heterogeneous and anistropic substances.

The microscopic structural investigation is evaluated quantitatively with corresponding stereological evaluation, as well as qualitatively, i.e. purely morphologically.

This report is confined to the relations in the microstructure of a substance, distinguishing between the main components such as:

Cementing agents in hardened form
Aggregates and fillers
Cavities (capillaries, pores, cracks)

The article does not claim to be comprehensive in the description of all possibilities. It outlines the simplest and most useful principle of investigation for practicing building experts. The main emphasis lies on the description of the methods of investigation used by the author within the last 5 years.

The report does not describe in detail the purely microscopically analytical procedure; it is confined to the discussion of the relations of component analysis in the microscope with regard to the image differentiation required for this, as well as the relation to the qualitatively morphological assessment.

442. Roshore, E. C. "Durability and Behavior of Pretensioned Beams." *Journal of the American Concrete Institute* Vol. 61, No. 47 (July 1964): pp. 811-840.

To develop data on the factors affecting the durability of pretensioned concrete beams, 28 large beams containing pretensioning strands and 412 small companion specimens without pretensioning strands were fabricated. The concrete in 22 of the beams was air-entrained, that in the other six was not. An appendix presents computation used in designing the beams.

Some of the beams were subjected to laboratory tests, which indicated that the air-entrained beams showed less average camber and less midspan deflection, but the non air-entrained beams withstood greater average flexural loads. A number of the auxiliary specimens were also tested in the laboratory to determine the strength, elastic, and plastic properties of the concrete.

Some specimens were exposed to natural weathering. A few early results are noted.

443. Rossello, S. A., and J. A. L. Albala. "Study on the Permeability of Concretes with Fly Ash Using the Cale Method." ACI/RILEM Symposium '85: Technology of Concrete When Pozzolans, Slags, and Chemical Admixtures Are Used, Monterrey, Mexico, 1985, pp. 341-375.

This paper presents a new method for measuring the permeability of concrete to liquids and gases. The analysis and derivation of equations for the coefficient of permeability according to this method and the methodology are detailed. The experimental results of using this method on fly ash concrete are presented, and the improvement on the impermeability of concrete by the use of fly ash is confirmed. The improvement is enhanced by the use of plasticizer admixtures in fly ash concrete.

444. Rostasy, F. S., U. Schneider, and G. Wiedemann. "Behaviour of Mortar and Concrete at Extremely Low Temperatures." *Cement and Concrete Research* Vol. 9, No. 3 (May 1979): pp. 365-376.

The behaviour of hydrated cement paste, mortar and concrete specimens was investigated at low temperatures and after cyclic temperature time histories. The relative changes of thermal strains, compressive and tensile splitting strength as well as the alteration of pore structure were studied. The strength in the frozen state increases with decreasing temperature and rising moisture content. If the frozen water-saturated mortar or concrete is reheated to room temperature a loss of strength is registered. The loss of strength increases with the number of temperature cycles. Storing the specimens at relative humidity below 85%, no losses were registered and no irreversible expansion occurred. Water-saturated mortar showed after only 12 cycles an irreversible positive strain of 2.7%, indicating internal damage which was also proved by mercury porosimetry. Thus, the moisture content seems to be one of the decisive factors affecting the sensitivity of mortar and concrete subjected to extremely low temperatures.

445. Roy, D. M., and G. M. Idorn. "Relation Between Strength, Pore Structure and Associated Properties of Slag-Containing Cementitious Materials." *Very High Strength Cement Based Materials* Vol. 42 (1985): pp. 133-142.

Substantial increases of the strength of cement paste and mortars may be obtained in conventional processing by optimizing the material's components, the rheology and the curing, and thereby improving the microstructures. Cementitious materials with high proportions of granulated blast-furnace slag have been investigated. Higher strengths of ASTM C 109 mortars were obtained with 40 to 65% substitution of portland cement by slag, than with ordinary mix compositions and processing.

For one set of mixtures, 28-day strengths greater than 100 MPa (some as high as 240 MPa) were consistently attained after curing at temperatures ranging from 27

to 250° C. The slag substitutions developed finer pore structures as revealed by intrusion porosimetry measurements, than those with pure portland cement. This is believed to be a major reason for their enhanced durability. At each stage from 3 to 28 days, increase of curing temperatures from 27 to 90° C decreased porosity and increased the strength, reflecting an increased maturity.

Implications for practice and suggestions for further work are discussed.

446. Roy, D. M., and K. M. Parker. "Microstructure and Properties of Granulated Slag Portland Cement Blends at Normal and Elevated Temperatures." *Fly Ash, Silica Fume, Slag and other Mineral By-Products in Concrete* Vol. 1 (1984): pp. 397-414.

Blends of separately ground (fine) granulated blast furnace slag with portland cement generally possess properties equivalent to or in ways superior to typical portland cements. Heats of hydration, apparent activation energies for reaction, and structure development are modified in high slag content mixtures. by three days the strength development of blends is equivalent to that of pure portland cement at normal temperatures but this stage is achieved more rapidly at elevated temperatures, while a very fine pore structure is developed with longer time. Phase changes, microstructural and property development including permeability development as a function of time are discussed.

447. Rutkowski, T. S. *Evaluation of Penetrating Surface Treatments of Bridge Deck Concretes*, Wisconsin Dept. of Transportation, research file no. 81-5, November 1988.

The intent of this study was to develop a laboratory procedure that would determine the degree to which a surface treatment, commonly called a sealer, will protect the substrate of a concrete bridge deck from penetration of moisture in general and chloride ions in particular. The sealer is purported to prevent future surface spalling and to protect the reinforcing steel from corrosion; due to chloride contamination of the concrete. The protection is developed by means of a membrane or barrier created in the substrate below the surface by a volume of solids, or by creating a hydrophobic surface in the capillaries.

A literature search indicated the widespread use of surface treatments, despite adverse effects in early trials, which included lack of vapor permeability, concrete color change, and loss of friction. The search revealed a lack of standards or specifications accepted in the industry. At present, the primary mode of evaluation for field applied penetrating sealers in Wisconsin is visual, subjective and based on the incidence of surface distress.

WisDOT presently specifies one of four proprietary sealers as alternatives, in the contract bid item for "protective surface treatment" on all bridge repair contracts dealing with concrete overlays, deck replacements and new bridges. Linseed oil was at one time the most common surface treatment, with an approximate effective life of five years. The linseed oil treatment resisted subsequent retreatment using other products.

This study evaluated the tests of absorption, resistance to chloride ion penetration and vapor permeability. These three tests were common to most evaluations in the available literature. Absorption and resistance to chloride permeability tests were taken from AASHTO procedures, but an in-house vapor permeability test

was attempted for this study. A rapid electrical cell test procedure, developed by PCA and FHWA, was also added to the testing program. An abrasion technique, used for soil cement evaluation, AASHTO T 136-76 was adapted from a standard Florida DOT evaluation procedure for sealers and added to the testing program.

The sealers used for the study had frequent use on WisDOT projects or were included just before the testing was begun. Linseed oil treatment was included in the test program since it was previously the WisDOT standard. A control group of untreated concrete was also included in the testing program.

The majority of test specimens were cast of WisDOT Class D-AE concrete, which is a standard for bridge decks. Some impressed voltage specimens were cast of WisDOT Class B-AE concrete. All the aggregate used came from a single pit location and all the cement was from the same production batch. The sealers were applied by brushing or spraying, in accordance with the manufacturer's instructions and application rates. Four of the proprietary sealers were one component and two were two component, as was the linseed oil treatment. The linseed oil treatment also was unique in requiring two treatment applications.

The sealing rates were monitored during application by weighing either the sealing material or both the material and sealing application apparatus. An evaporation rate was computed for each test sealer to allow corrections to the application rate during sealing operations. Abrasion of test specimens, when required, was performed immediately before commencing each test period.

The individual test procedures, with the exception of the rapid electrical cell tests effectively differentiated between the proprietary products. The test results indicated that individual products could be ranked as qualitatively more effective or "better than" another product. It was not possible to extrapolate the laboratory test results to years of sealer field performance. None of the applied sealers appeared to be able to completely stop the penetration of moisture or chloride ions into the concrete substrate. The abrasion technique used in the study had no apparent effect on the test results of the second series of the impressed voltage testing where abrasion effect is also common in the rest of the test program. The depth of penetration test results, within the second series of the impressed voltage procedure, appeared to give indication of treatment penetration, but the test results were inconclusive.

It is recommended that a laboratory evaluation procedure for penetrating surface sealers be performed on candidate sealing products as a means of screening products for potential WisDOT acceptance. The average test results from a freeze-thaw scaling test and the impressed voltage test procedures used in this study would form the basis of this screening procedure. The results would be assessed to make judgments on potential field use. The rapid electrical cell test procedure, used in a modified form, had such variable results that it was withdrawn from the testing program consideration.

448. Ryell, J., and P. Smith. "Case Histories of Poor Concrete Durability in Ontario Highway Structures." *Performance of Concrete* (1968): pp. 180-204.

The purpose of this paper is to examine facets of the role (usually detrimental) water has played in the performance of highway structures in Ontario, by documenting investigations of performance undertaken by the Materials and Testing Division of the Department of Highways over the last decade.

The examples cited illustrate the importance of carefully planning such investigations and selecting methods appropriate to the circumstances. Water is the common factor in each case history described. Each of the case histories described concludes with a brief mention of the action taken.

449 Sajadi, J. "The Development and Freeze-Thaw Durability of High Fly Ash Content Concrete." Ph.D. diss., West Virginia University, 1987.

The objectives of the study were to investigate the effects on concrete strength, drying shrinkage, freeze-thaw durability, and air-void system parameters of replacing various amounts of portland cement with different types of fly ash and to compare selected characteristics of such fly ash concretes and fly ash concretes containing a high-range water-reducing admixture to those of a control mixture.

It was concluded that concrete mixtures with 90-day compressive strengths equal to the control could be produced when large amounts of cement were replaced by fly ash. When the high-range water-reducing admixture was employed, very large amounts of cement could be replaced by fly ash to yield mixtures whose compressive strengths were equal to or greater than the strengths of the control mix at all ages. The maximum amount of cement that could be replaced for equal strength mixtures depended upon the nature of the fly ash.

Relative to conditions imposed by ASTM Standard Test Method C 666, most of the fly ash concrete mixtures performed well in freeze-thaw tests. A few mixtures, particularly those containing large amounts of fly ash, performed poorly when assessment of surface conditions and/or weight loss were the bases of performance.

Different types and various amounts of fly ash had no significant effect on air-void system characteristics of concrete mixtures. Spacing factors for all concrete mixtures were smaller than the recommended value (0.008 in) for frost resistant concrete.

The optimum fly ash content in a concrete that is comparable in strength and durability to a conventional (control) concrete was influenced by the chemical and physical characteristics of the fly ash.

450. Salcedo, M. A. "Identification of Frost Susceptible Aggregates and Their Use in Concrete or Bituminous Pavements." Ph.D. diss., Purdue University, 1984.

Recently, serious damage of bituminous pavements was observed where the coarse aggregate fraction played an important role. In some concrete and bituminous pavements, a typical pattern of surface damage was also found associated to the application of deicers.

The present study was designed to investigate the significance of the details of the pore structure on the frost resistance of concrete aggregates. Likewise, the surface failure taking place in concrete and bituminous pavements were used to accomplish the objectives of this investigation: Statistical Analysis of observational data, and the Experimental Method. In addition, a simplified theoretical analysis of the freezing process was offered.

Based on field data, a discriminating function was obtained to differentiate between aggregates of varying frost resistance. This function was derived by

taking into consideration the details of the pore structure of coarse aggregates in concrete pavements.

451. Samarin, A. "Methodology of Modeling for Concrete Durability." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

The main objective of this study is to provide an architect or a structural engineer with the methodology of modeling for concrete durability under various conditions of reinforced concrete - environment interaction, which is divided into three main types: (1) concrete continuously submerged in water, (2) concrete continuously exposed to air, (3) concrete subjected to cycles of wetting and drying.

Various modes of interaction between reinforced concrete and either existing or artificially created environment are expressed as a loss in concrete serviceability, utilizing the concept of Limit State Design.

This methodology should provide the basis for an evaluation of the most important factors of architectural, structural and technological design of reinforced concrete. It clearly defines the appropriate quality assurance practices, which are both necessary and sufficient to meet the specific durability requirements for each particular case of the material - environment interaction.

452. Sawan, J. "Cracking Due to Frost Action in Portland Cement Concrete Pavements — A Literature Survey." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

A comprehensive review of the literature about durability (D-) cracking due to frost action in portland cement concrete pavements is developed. An introduction as to the definition and description of durability cracking starts this paper. The mechanisms causing this type of cracking are then discussed. Factors such as physical characteristics of aggregates and mortar, geographic location, maximum size of coarse aggregates, source of aggregates, and use of deicing agents are found to be among the main factors that affect the development of durability.

Tests to indicate frost resistance in aggregate are also reviewed. These tests may be divided into two general types: (1) Weathering tests such as unconfined and confined freeze-thaw tests; and (2) measurements of a physical property that is correlated with performance such as porosity, pore size and absorption tests.

453. Scanlon, J. M., and J. F. Lamond. "Field Applications of Fly Ash Concrete — Advantages and Precautions." MSU Symposium, January 1988.

The U.S. Army Corps of Engineers has been using fly ash in concrete since 1956 and one of the authors was fortunate to have been serving on the Corps of Engineers Engineer Training Program on the particular project that was chosen for the first use of fly ash. This project was the Sutton Dam in West Virginia. Prior to actually using fly ash by the Corps much research was performed on the use of fly ash in concrete at the Concrete Technology Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi. The research performed included the effects of fly ash on bleeding, permeability, heat rise, resistance to freezing and thawing, elasticity and compressive and flexural strength development. More recently, research was performed on such things as

the effects of fly ash on alkali, reactivity, sulphate resistance and carbonate-rock reactivity. Even today, the primary reason that the Corps of Engineers uses fly ash in concrete is for economy. All fly ash referred to in this paper complies with the requirements of ASTM C 618.

454. Schaffer, R. J. *The Weathering of Natural Building Stones*, His Majesty's Stationery Office, Dept. of Scientific and Industrial Research, London, Great Britain, special report no. 18, 1932.

Crystallization tests, in which salts are allowed to crystalize in the pores under controlled conditions, furnish a useful method of investigating the properties of building materials. Tests of this kind originated with Brard, who used a saturated solution of sodium sulphate. Specimens of stone were soaked in the solution and were allowed to dry in the air at the ordinary temperature. Brard's object was to predict the resistance to frost, but a number of investigators have since carried out comparative tests to determine the relative intensity of this artificial frost test as compared with actual freezing tests. The general consensus of opinion is that the sodium sulphate test is very much the more drastic, and that it does not give a reliable estimate to frost resistance.

455. Scholer, C. H. "Studying the Durability of Concrete." *Journal of the American Concrete Institute* Vol. 32 (May - June 1936): pp. 593-607.

A general discussion of the problem of concrete durability is presented. The various components of concrete, the method of handling, placing, finishing, and curing, and the inter-relationship of these factors and the effects of each on the character of the concrete are considered.

Methods of studying durability in the laboratory and the field and some of the variable to be evaluated in such studies are briefly presented.

456. Schrader, E., and R. A. Kaden. "Durability of Shotcrete." editor J. M. Scanlon, Concrete Durability: Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987, pp. 1071-1101.

The normally high cement factors, low water/cement ratio, and good compaction of shotcrete typically produce strong, dense, and well bonded materials when properly applied by either the wet- or dry-mix process. However, the dry-mix process is incapable of reliably, predictably, and routinely providing an adequately air-entrained hardened material that will withstand freeze-thaw cycles under conditions of saturation. Wet-mix process also has had its problems associated with conveying/pumping. Latex modifiers can be added to shotcrete, which will produce a freeze-thaw durable material. The modifiers should not be used directly as a bonding agent. Very good bond can be achieved between shotcrete layers and to a concrete substrate by unmodified shotcrete placed against a surface that is near or somewhat below a saturated surface dry condition. Durability is directly related to permeability of shotcretes.

457. Schwartz, D. R. *D-Cracking of Concrete Pavements*, Transportation Research Board, NCHRP no. 134, October 1987.

D-cracking is associated primarily with the use of coarse aggregates in concrete that disintegrate when they become saturated and are subjected to repeated cycles of freezing and thawing. The cracking originates in the coarse aggregates

particles and then propagates through the mortar matrix surrounding the aggregate. Identification of D-cracking before signs are evident on the pavement surface can be accomplished only by examination of full-depth cores taken through the pavement near intersections of longitudinal and transverse joints and cracks. There is no simple, quick and economical test procedure for determining the D-cracking susceptibility of a coarse aggregate. The testing for material acceptance should be done on a source-by-source or project-by-project basis.

458. Schwartz, D. R. *D-Cracking of Concrete Pavements*, National Cooperative Highway Research Program. Transportation Research Board, Washington, D. C., report no. 134, October 1987.

This synthesis will be of interest to pavement designers, materials engineers, maintenance engineers, and others concerned with design, construction, and maintenance of portland cement concrete pavements. Information is presented on the causes of and potential means for minimizing D-cracking of concrete pavements.

459. Scripture, E. W. , Jr. "Methods of Entraining Air in Concrete." *Journal of the American Concrete Institute* Vol. 42 (June 1946): pp. 645-648.

Discusses methods for and mechanisms of air entrainment in concrete mixes. Methods include use of aluminum and hydrogen peroxide for entrainment of hydrogen or oxygen, respectively, use of cement dispersing agents, perhaps protective colloids. Data are reported to record the relation of air content to durability as determined by freezing and thawing.

460. Scripture, E. W. , Jr., S. W. Benedict, and F. J. Litwinowicz. "Air Entrainment and Resistance to Freezing and Thawing." *Journal of the American Concrete Institute* Vol. 48 (December 1951): pp. 297-308.

Investigations were undertaken to determine the suitability of various air-entraining agents for use in concrete, the relative effects of slow and rapid cycles of freezing and thawing, and the optimum range of air contents for concrete. With normal air-entraining agents the resistance to freezing and thawing varies mainly with the air content not with the particular agent used. A rapid freezing and thawing cycle is considerably more destructive than a slow cycle, and abnormal results appear to be produced in some cases by a very fast cycle. With increasing entrained air resistance to freezing and thawing increases to a maximum and thereafter no further benefit appears to be secured. The optimum amount seems to be about 2 1/2 to 3 percent added entrained air.

461. Scripture, E. W. , Jr., F. B. Hornibrook, and D. E. Bryant. "Influence of Size Grading of Sand on Air Entrainment." *Journal of the American Concrete Institute* Vol. 20, No. 3 (November 1948): pp. 217-228.

Field reports indicated difficulty with certain sands in securing the desired amount of entrained air; this was frequently attributed to the size grading of the sand, particularly to a deficiency in the finer fractions. An experimental investigation was undertaken in view of the paucity of published data on this subject. Mixes of sand and water alone, 1:4 and 1:2 mortars, and concrete mixes were made with and without air-entraining agents and the air contents determined. While size grading of the sand had a very large influence on air entrainment in a mixture of sand and water alone, this effect was smaller in mortars and very small in concrete

mixes. It was found that maximum air was entrained by the 28-48 mesh size sand rather than the 48-100 mesh size.

462. Scripture, E. W., Jr., and F. J. Litwinowicz. "Effects of Mixing Time, Size of Batch and Brand of Cement on Air Entrainment." *Journal of the American Concrete Institute* Vol. 20, No. 9 (May 1949): pp. 653-662.

A program, partially described in previous papers, to investigate various factors affecting the amount of air entrained in concrete has been continued. The factors covered in this paper are mixing time, size of batch, and brand of cement. The entrained air rises to a maximum in the early stages of mixing and thereafter decreases. Provided mixing is adequate, the size of the batch does not appear to affect the amount of air entrained. Wide variations are found in the amounts of air entrained by different cements, and it does not appear possible to correlate these variations with any easily and quickly determinable characteristic of the cement.

463. Scripture, E. W., Jr., and F. J. Litwinowicz. "Some Factors Affecting Air Entrainment." *Journal of the American Concrete Institute* Vol. 20, No. 6 (February 1949): pp. 433-442.

A program was undertaken to investigate the influence of various factors on the amount of air entrained in concrete mixes with and without air-entraining agent added. The variables so far studied are slump, cement factor, and sand-total aggregate ratio. The results indicate that the two latter factors are of major importance but that slump has less effect. In general, entrained air content increases with increasing slum, decreases with increasing cement factor, and increases with increasing sand-total aggregate ratio.

464. Seegebrecht, G. W., A. Litvin, and S. H. Gebler. "Durability of Dry-Mix Shotcrete." *Concrete International: Design & Construction* Vol. 11, No. 10 (October 1989): pp. 47-50.

Dry-mix shotcrete specimens sawed from field-shot panels were tested for freeze-thaw durability, resistance to chloride-ion penetration, compressive strength, characteristics of their air-void systems, and absorption. Results showed that characteristics of the air-void systems, relatively high compressive strength, and low permeability resulted in freeze-thaw resistance in a fresh water environment comparable to that of properly air-entrained concrete. However, for salt water exposure in a freeze-thaw environment, dry-mix shotcrete made with portland cement may require treatment with sealers or coatings, or greater cover of shotcrete may be necessary to protect embedded steel reinforcement.

465. Sellevold, E. J. "Condensed Silica Fume in Concrete - A World Review." *CANMET Publication*, No. M38-15/86-8E, 1987.

This review is intended to cover the properties of concrete containing CSF in the fresh state, during hardening and in the hardened state (with emphasis on durability). It is based on published reports, of which about 400 are available, the majority of which are written in Norwegian. Most of the reports contain original laboratory data, some are review articles covering limited topics, and a few are concerned with laboratory investigations of concrete from old structures.

466. Senbetta, E., and G. Malchow. "Studies on Control of Durability of Concrete Through Proper Curing." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

This work was undertaken to develop test data that show the effect of curing on the durability of concrete. It was intended to obtain more data about what is already known or suspected and was not intended to be an original research to discover new facts. It is hoped that the information derived from this study will be of benefit in the continuing effort to teach practitioners the virtues of adhering to good concreting practices and the consequences of deviating from them. It was necessary to undertake this work because most of the concrete that is placed in both residential and industrial construction is not being cured properly. The result is premature failure and deterioration that, for the most part, can be prevented or at the least postponed. Quantitatively showing the cause and effect relationship between curing of concrete and the concrete's performance under service conditions is believed to help in increasing the awareness of practitioners and encouraging good concreting practices.

467. Senbetta, E., and C. F. Scholer. "A New Approach for Testing Concrete Curing Efficiency." *American Concrete Institute Journal Proceedings* Vol. 81, No. 12 (Jan-Feb 1984): p. 82-86.

The findings of a research project undertaken to develop a new approach and a new test procedure for making a quantitative assessment of how well concrete is cured is presented. This assessment was done by subjecting mortar slabs to widely different curing conditions and examining the difference in the pore structure of the paste at different depths of each test slab by means of the absorptivity of the paste. The idea was proposed that if a sample was adequately cured, it would have approximately the same pore structure at the surface region as that farther beneath the surface, and in a case of poor curing, the opposite would be true. Abrasion testing of the surface of each test specimen was also done according to ASTM C 418.

The test procedure is quick and uncomplicated, and was found to be extremely sensitive to changes in the paste as influenced by the curing condition. Curves that show changes in absorptivity with depth of the mortar test slabs were produced. The results showed significantly large changes in absorptivity of the paste between the surface and the bottom regions of poorly cured samples and negligible changes for well-cured samples.

Based on these differences in absorptivity values at depths of 1 and 6 cm from the surface, a quantitative dividing line between adequate and inadequate curing was established. The abrasion test results were also found to be in agreement with those of the absorptivity test.

468. Senior, S. A., and C. A. Rogers. *Laboratory Tests for Predicting Coarse Aggregate Performance in Ontario*, Ministry of Transportation, Ontario, Engineering Materials Office, Downsview, Ontario, Canada, paper no. 910443, January 1991.

Coarse aggregates used in granular base and asphaltic and Portland cement concrete must be sound and capable of withstanding the prevailing environment. In Canada, aggregates must be frost resistant. Durability of coarse aggregate is normally evaluated in the sulfate soundness test and water absorption tests, and by measuring resistance to impact in the Los Angeles abrasion and impact test.

These tests suffer from some disadvantages: poor precision and inadequate correlation with field performance. The Ministry of Transportation has been developing and evaluating new test procedures for a number of years. This paper presents a summary of some of the major findings. The likely performance of aggregates in granular base in best measured by the micro-Deval test and water absorption. The physical quality of Portland cement concrete aggregates is best measured by the micro-Deval test, water absorption, and unconfined freezing and thawing. The quality of asphaltic concrete aggregates is best measured by the micro-Deval test, polished stoned value test, and unconfined freezing and thawing. Petrographic examination is also an essential tool in the evaluation of aggregate quality.

469. Shakoor, A. "Evaluation Durability Characteristics of Argillaceous Carbonate Aggregates for Highway Pavements." Ph.D. diss., Purdue University, May 1982.

Coarse aggregate from three quarries and from pavement cores were studied to determine petrography, insoluble residue and clay contents, and pore size distribution.

Results indicate the poorly performing ledges are highly argillaceous, fine-grained, dolimites and dolomitic limestones with insoluble residues ranging from 20 - 50% consisting of low plasticity silts to medium plasticity silty clays. Illite is the predominant clay mineral (by x-ray diffraction).

Aggregates with poorest performance are not necessarily those with the greatest insoluble residue percentage; the nature and mode of insolubles control extremes of deterioration. Rocks with more clay as insoluables, evenly distributed throughout the rock, are less durable than those with greater total insolubles consisting of silty concentrations of streaks and laminations.

470. Shakoor, A., and C. F. Scholer. "Comparison of Aggregate Pore Characteristics as Measured by Mercury Intrusion Porosimeter and Iowa Pore Index Tests." *Journal of the American Concrete Institute* Vol. 82 (July - August 1985): p. 453.

Freeze-thaw durability of concrete aggregates is strongly influenced by the size, shape, and distribution of their pores. Pore characteristics of 30 aggregate samples were investigated first by mercury intrusion porosimetry and then by the Iowa pore index test. Many of these aggregates, when used in Indiana pavements, resulted in extensive pitting and popouts in only one severe winter.

A comparison of the results of the two tests with field performance of the aggregates studied shows that the pore index test can be used as a reliable less expensive, and quicker replacement of mercury intrusion porosimetry for predicting aggregate durability. Also the test results are more representative of the parent rock because of the large volume of the sample involved. Repetition of the test on the same aggregate sample shows that the test is reproducible and gives consistent results. It is concluded that the Iowa pore index method can be used as a quality control test for production run aggregate of varied composition.

471. Shakoor, A., T. R. West, and C. F. Scholer. "Physical Characteristics of Some Indiana Argillaceous Carbonates Regarding Their Freeze-Thaw Resistance in Concrete." Bulletin of the Association of Engineering Geologists, 1982, pp. 371-384.

Argillaceous carbonate aggregates are particularly prone to freeze-thaw failures, yet standard acceptance tests commonly do not prevent their use. Recently several Indiana highways have experienced such extensive pitting and popouts of highly argillaceous dolomites and dolomitic limestone that resurfacing was required within one year. Coarse aggregate from three quarries and from pavement cores were studied to determine petrography, insoluble residue and clay contents, and pore size distributions.

Results indicate the poorly performing ledges are highly argillaceous, fine-grained, limestones and dolomites with insoluble residues of from 20-45 percent consisting of low plasticity silts to medium plasticity silty clays. Illite is the predominant clay mineral. Aggregates with poorest performance are not necessarily those with the greatest insoluble residue percentage; the nature and mode of insolubles control extremes of deterioration. Rocks with more clay as insolubles, evenly distributed throughout the rock, are less durable than those with greater insolubles consisting of silty concentrations of streaks and laminations.

Insoluble residue content of silt and clay size and pore characteristics, as measured by either the mercury intrusion method or the pore index test, are the most reliable indicators of freeze-thaw durability. Nondurable aggregates are characterized by a residue content in excess of 20 percent, a large pore volume with small pore diameters, most being less that 0.1 μm, and pore index value more than 50 ml.

Additional tests including sulphate soundness, unconfined freeze-thaw, and absorption-adsorption tests were conducted and their results correlated with percent insoluble residue. The purpose is to develop a simpler, reliable, and more economical test to exclude nondurable argillaceous carbonate aggregates.

472. Shideler, J. J., H. W. Brewer, and W. H. Chamberlin. "Entrained Air Simplifies Winter Curing." *Journal of the American Concrete Institute* Vol. 47 (February 1951): pp. 449-460.

The investigation described was undertaken to determine the winter protection required to protect air-entrained concrete from damage by freezing. Cylinders made with Types II and V cement and various percentages of calcium chloride were cured at temperatures ranging from 10 to 70° F and tested for strength at ages ranging from 3 to 180 days. The resistance of these concretes to accelerated freezing and thawing was compared. The results indicate that the amount of winter protection, as presently specified by the Bureau of Reclamation, can be reduced when air-entrained concrete is used.

473. Sidebottom, E. W., and G. G. Litvan. "Phase Transitions of Adsorbates, Part 2: Vapour Pressure and Extension Isotherms of the Porous-Glass + Water System Below 0° C." pp. 2726-2736.

The vapour pressure and extension isotherms of the water-porous 96% silica glass were determined at +1.5, -6.4, -14.6, -25.4 and -35.3° C. Isotherms obtained at

these temperatures coincided if the amount of adsorbed water, "a", was plotted against the relative pressure with reference to that of undercooled water. This demonstrates that the isothermally adsorbed water is in a liquid-like state and confirms that the drastic reduction of "a" with declining temperature is due to a decrease of the maximum in the extension isotherm at low concentration was found, indicating that adjacent hydrogen-bonded silanol groups of the glass may not be the site of water adsorption as has been assumed in the past. Examination of the pertinent literature suggests that a minimum of the extension isotherm is obtained on the adsorption of most substances if the experimental temperature is not higher than the bulk boiling point. The contraction effect and the secondary hysteresis at low coverages are assumed to be caused by microporosity.

474. Smith, G. M. "Physical Incompatibility of Matrix and Aggregate in Concrete." *Journal of the American Concrete Institute* Vol. 52 (March 1956): pp. 791-798.

A theoretical analysis is made of the stresses that might result in a matrix surrounding a spherical body due to the thermal incompatibility of the matrix and the spherical body. The analysis indicates that the magnitude of the stresses depends upon the thermal expansion, Poisson's ratio, the modulus of elasticity, and the size of the inclusion. Although the analysis is purely qualitative, it does show the complexity of the term "thermal incompatibility," so frequently related to the durability of concrete subjected to freezing and thawing. Graphs are constructed to illustrate the effect of the various physical properties on the thermal stresses developed in a matrix. The matrix is considered to consist of cement paste or a mixture of paste, aggregate, and voids.

475. Sorensen, E. V. "Freeze-Thaw Resistance of Microsilica Concrete Exposed o Deicing Chemicals." Editor V. M. Malhotra, First CANMET/ACI International Conference on the Use of Fly Ash, Slag and Other Mineral By-Products in Concrete, Montebello, Quebec, Canada, July - August 1983, pp. 709-718.

Scaling of concrete due to freezing-and-thawing action in conjunction with the use of deicing chemicals has become a severe concrete-durability problem. This paper reports the results of freezing-and-thawing experiments performed to evaluate the effect of microsilica (beneficiated condensed silica fume) addition to concrete. Tests performed using a standard and a modified method show that the drying-rewetting history of the concrete before freezing and thawing has a significant influence on conventional concrete, where as microsilica concrete is relatively unaffected. Air entrainment has a marked beneficial effect on both conventional and microsilica concrete, although microsilica concrete with relatively low cement contents can be manufactured to be frost resistance without air entrainment.

476. Stark, D. C. "Characteristics and Utilization of Coarse Aggregates Associated with D-Cracking." *PCA Research and Development Bulletin* No. 47 (1976).

The degree of saturation of the coarse aggregate and its response to freezing and thawing are important aspects of the problem of D-cracking. Studies have indicated that nondurable materials may reach critical saturation when the concrete is in contact only with capillary-held water. Sorption properties and freeze-thaw test differentiate between durable and nondurable materials. Reducing maximum aggregate particle sizes, as indicated by the laboratory freeze-thaw test, is the most feasible method of improving durability.

477. Stark, D. C. "Effect of Vibration on the Air-Void System and Freeze-Thaw Durability of Concrete." *Portland Cement Association* RD092T (1986).

Concretes made with water-cement ratios of 0.40, 0.50, 0.60 and 0.70 were subjected to internal vibration at frequencies of 0:8000; 11,000; and 14,000 vpm. Test prisms made from these concretes were then subjected to freezing and thawing in the presence of NaCl solution. Linear traverse measurements indicated that vibration generally had a detrimental effect on quality of the entrained air-void systems, particularly in the higher water-cement ratio concretes subjected to a vibration frequency of 14,000 vpm. This trend was reflected, for the most part, in the freeze-thaw durability of hardened concretes.

478. Stark, D. C. "The Significance of Pavement Design and Materials in D-Cracking (Interim Report)." FHWA/OH-86/008, December 1986.

A two-phase program was undertaken to verify, under field conditions, that reducing maximum aggregate particle size can minimize or eliminate D-cracking. This study was carried out also to determine the role of other materials and environmental factors in D-cracking which are not amenable to laboratory study. One phase consisted of repeat pavement surveys of existing pavements to determine whether reducing maximum particle sizes has alleviated D-cracking. The other, primary, phase consisted of monitoring the performance of a test road near Vermilion, Ohio, using visual inspections and moisture measurements and examinations of concrete cores. Visual inspections confirm that reducing the maximum particle size does minimize or eliminate D-cracking. Other observations indicate that pavement concrete on clay subgrade, stabilized and granular bases with and without artificial drains, and vapor barriers, performed similarly with respect to the initial development of D-cracking. Type of joint seal, including no seal, had no significant effect on D-cracking. Moisture measurements of cores indicated an increase in degree of saturation of concrete after one year, with a general leveling off after that period. Saturation levels were, overall, somewhat higher near the bottom than near the top of the slab. Examination of cores revealed that D-cracking is developing upward from near the bottom of the slab. Other observations revealed that where maximum aggregate particle size was reduced to avoid D-cracking, a greater incidence of intermediate transverse cracking developed with attendant faulting. It is recommended that the test road continue to be monitored through visual inspection and examination of cores.

479. Stark, D. C., and P. Klieger. "Effects of Maximum Size of Coarse Aggregate on D-Cracking in Concrete Pavements." *Highway Research Record* No. 441 (1973): p. 33.

Field and laboratory observations have indicated the D-cracking is caused by freeze-thaw failures in certain types of coarse aggregate particles. In areas where durable aggregates are not available, it has been found that the rate of development of D-cracking can be reduced by decreasing the maximum particle size. These observations were extended during a laboratory investigation what was carried out to find a test procedure that would distinguish between durable coarse aggregates and those that cause D-cracking and provide an indication of the benefits to be derived by reducing the maximum particle size. Exploratory work indicated that a rapid freeze-thaw procedure similar to ASTM Designation C666-71 would be suitable. A failure criterion of 0.032 to 0.033 percent expansion in 350 or fewer cycles was established on the basis of the service

records of 15 sources from which the test materials were obtained. Studies of the effect of maximum particle size on durability indicated that decreasing the size from 1-1/2 in. to 1 in. and 1/2 in. reduced expansions to varying degrees. These findings are in line with the critical size concept for aggregate that was developed in previous work. It is recommended that, where D-cracking is a problem, similar testing programs be set up to evaluate coarse aggregate sources on an individual basis and to determine the benefits to be derived by reducing maximum particle sizes to improve durability.

480. Stroeven, P. "Application of Stereological Methods to Non-Metallic Building Materials with Particular Reference to Cement-Based Ones." Ph.D. diss., Delft University of Technology, September 1982.

A first logical step towards the establishment of a structural basis for physico-mechanical behaviour is concrete petrography. Petrographic examination of hardened mortar of concrete - a man-made rock - aims at deposition of the mortar or concrete and to classify it as to type, condition, and serviceability. Such microscopical observations date back to the beginning of this century as far as the aggregate is concerned. A recommended practice for petrographic examination of concrete aggregate is available. The use of the microscope for the study of the cement paste is even older. One century ago Le Chatelier published what is considered a first example of such an approach.

481. Sturrup, V. R., R. D. Hooton, and T. G. Clendening. "Durability of Fly Ash Concrete." *Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete* ACI SP-79, Vol. 1 (1984): pp. 71-87.

Since before the first utilization of imported fly ash by Ontario Hydro as a pozzolan in mass concrete in 1950, research programs on many aspects of its influence on durability were undertaken. Major areas addressed have been: (1) thermal crack resistance in mass concrete, (2) reduction of alkali reactivity, (3) freezing and thawing resistance, and (4) sulphate resistance (preliminary).

Major findings of the research include:

1. Fly ash has and is being used successfully in lieu of both CSA Types 20 and 40 (ASTM Types II and IV) moderate and low-heat cements to control temperature rise and thermally induced cracking in mass concrete.
2. The replacement of 25 percent of normal portland cement with fly ash has been found to be effective in reducing alkali silicate expansions.
3. As long as adequate air contents are obtained, carbon content does not adversely affect the freezing and thawing resistance of concrete at least within the 12 percent CSA and ASTM limits. As long as carbon contents are established for each delivery of fly ash, dosages of air-entraining agents can be modified easily.

482. Sturrup, V. R., R. D. Hooton, P. K. Mukherjee, and T. Carmichael. "Evaluation and Prediction of Concrete Durability - Ontario Hydro's Experience." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

This paper reviews Ontario Hydro's experience in predicting the durability of concrete and assessing its service performance. Included are data from 28 ye..s

of outdoor exposure studies, with accelerated laboratory tests on companion specimens and constituent materials, on air- and non air-entrained concretes, concretes with fly ashes of variable quality and different proportions, and concretes containing aggregates of dubious quality. The results are compared with the performance of concrete in actual structures up to 50 years old.

483. Sugiyama, M., K. Tanaka, M. Sakuta, and T. Urana. "Durability of Concrete Containing a Shrinkage Reducing Admixture." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

The authors studied the effect of shrinkage-reducing admixture on concrete durability. Three kinds of shrinkage-reducing agents were used: water-insoluable glycol ether derivative A, and water-soluable alcohol ether derivative B and C. Because of the antifoaming effect present in the derivative and acting inside the concrete mix, the addition of this glycol ether derivative produced a significant reduction of drying shrinkage of concrete (about 50 to 60% at 4% dosage) compared to conventional air-entrained concrete.

Measurements of air-void content and spacing factor in hardened concrete indicated nearly the same air content for both concretes (about 1%). However, concretes with glycol ether derivative had an air-void system extremely fine-textured. But still a large number of air voids existed. This was due to the dispersed oil drops (glycol ether exists in concrete as oil drops) believed to greatly improve the durability of concrete.

484. Sukhotskaya, S. S., V. P. Mazhorova, and Yu N. Terekhin. "Effect of Autogenous Healing of Concrete Subjected to Periodic Freeze-Thaw Cycles." *Hydrotechnical Construction* Vol. 17, No. 6 (June 1983): pp. 294-296.

It is shown that if concrete that was subjected to a load (not to failure) is placed under favorable temperature and moisture conditions, partial or complete recovery of its original solidity will occur. Such a phenomenon is called autogenous healing of concrete. During cyclic freezing and thawing of concrete internal stresses occur in it, leading to the formation of microcracks and to a change in the structure of the material similar to that which occurs under the effect of an external load. As a result of the formation of microcracks unhydrated cement particles are exposed, which leads to the development of hydrolysis and hydration processes. In the case of a small opening of the cracks under conditions of a damp environment the latter are closed by newly formed products. During hardening of concrete in air carbonization of calcium hydroxide occurs and the microcracks are filled with calcite. Equilibrium of the saturated solution with the solid phase is dynamic. Therefore, with the appearance of new active surfaces equilibrium is disturbed and the process of precipitation of the solid phase with gradual filling of the microcracks begins anew.

485. Swayze, M. A. "Finishing and Curing: A Key to Durable Concrete Surfaces." *Journal of the American Concrete Institute* Vol. 47 (December 1950): pp. 317-332.

After a comparison of past and present pavement curing and finishing techniques the significance of timing and character of finishing and the timing and mode of curing are discussed. Laboratory tests are cited to show the effect of time of finishing and curing on surface durability to freezing and thawing. It is

recommended that all concrete exposed to frost contain entrained air, have a low water-cement ratio and be thoroughly compacted after placing. A finishing and curing procedure is suggested that is adapted to the ambient conditions and to the hydration needs of the cement.

486. Sweet, H. S. "Research on Concrete Durability as Affected by Coarse Aggregate." *ASTM Proceedings* Vol. 48 (1948): pp. 988-1016.

This paper summarizes the results of laboratory studies undertaken to establish the characteristics of aggregates causing concrete pavement deterioration and of those having satisfactory performance in pavements in Indiana. Extensive field surveys have previously established the relationship in Indiana between concrete pavement performance, in terms of blowups and concrete deterioration, and the coarse aggregate component of the concrete.

The physical properties of 16 coarse aggregate materials are described, and the results of laboratory freezing and thawing tests on concrete containing these materials are presented. It is concluded, on the basis of the comparison of field performance, aggregate characteristics, and resistance of laboratory concrete to freezing and thawing, that freezing and thawing tests on concrete beams containing the aggregate can be used to differentiate materials with good field performance from those with poor performance. The other aggregate properties that were investigated showed no consistent relationship with field performance with the exception of the factor of pore volume and size; the volume of voids smaller in diameter than 0.005 mm, expressed as a ratio to the volume of solids, was less than 0.06 for the aggregates with good field performance and greater than 0.10 for the aggregates with poor service records.

487. Sweet, H. S., and K. B. Woods. "Evaluation of Aggregate Performance in Pavement Concrete." *Journal of the American Concrete Institute* Vol. 44 (June 1948): pp. 1033-1040.

This report consists essentially of a review of published information on aggregate as a variable influencing the durability characteristics of portland cement concrete. Covers the evaluation techniques that have been used in field performance studies, particularly with respect to isolating the causes of the performance. Some emphasis has been placed on such studies made in Indiana where it has been found that many miles of concrete pavements have deteriorated when certain coarse aggregates were used regardless of other variables, such as cement fine aggregate, traffic, etc. In contrast, many more miles of Indiana pavements, constructed with other coarse aggregates, are in excellent condition after as many as 20 years of service. The reactions between high alkali cements and certain aggregates are mentioned, but not treated in detail. It is concluded that aggregate acceptance tests in common use are not adequate to differentiate between good and bad aggregate materials.

488. Taber, S. "Frost Heaving." *Journal of Geology* Vol. 37, No. 5 (July-August 1929): pp. 428-461.

This paper describes a laboratory investigation of problems connected with frost heaving. The principles developed have application in geology, plant physiology, and engineering. Pressure effects accompanying the freezing of soils are due to the growth of ice crystals and not change in volume. Pressure is developed in the direction of crystal growth, which is determined chiefly by the direction of

cooling. Heaving is often greater than can be explained by expansion. It is due to the segregation of water as it freezes, more water being drawn up by molecular cohesion. The chief factors controlling segregation and excessive heaving are: size of soil particle, amount of water available, size and percentage of voids, and rate of cooling. The pressure developed is limited by the tensile strength of the water. More water may be concentrated in the surface soil through ice segregation followed by thawing than in any other way. Segregation causes shrinkage cracks below if the supply of water is limited or the soil very impermeable. Differential heaving is due chiefly to differences in soil texture and in the amount of available water, but differences in the kind and amount of soil cover are also factors.

489. Takagi, S. "An Analysis of Ice Lens Formation." *Water Resources Research* Vol. 6, No. 3 (June 1970): pp. 736-749.

A mechanism of ice lens formation is presented on the assumption that its main cause is the simultaneous flow of heat and water. The differential equations thus formulated are solved approximately by the use of a generalization of Goodman's integral method. The result is found to be not completely satisfactory when compared with an experiment. The following progress has however been made: (1) The existence of a solution to the differential equations of ice lens formation is demonstrated. (2) The solution exists for a very narrow range of initial water content determined by the amount of surcharge on the ice lens. The narrowness of the range probably accounts for the observed intermittence of lenses. (3) The Goodman technique or any generalization of it cannot yield a satisfactory solution of the problem. (4) A simplification of Portnov's method has been found. (5) The possibility of obtaining an exact solution for a short initial time interval arises when the independent variables x and t are reduced to $x/\sqrt{(t)}$ or simply $\sqrt{(t)}$, where x is the vertical coordinate and t is the time. (6) With development of the mathematical method, improvements in the assumed mechanism, and refinements in the measurements of soil properties, we may be able to completely formulate frost heaving and thereby solve a long-standing problem.

490. Tallamy, B. D. "Control of Concrete Pavement Scaling Caused by Chloride Salts." *American Concrete Institute Proceedings* Vol. 45, No. 28 (September 1948 - June 1949): p. 513.

Under modern traffic requirements on heavily traveled roads salt-treated abrasives will not remove ice quickly enough. As maintenance forces have struggled to meet the demand for uninterrupted service, the use of straight salts has become increasingly common. Direct applications of up to 600 lb of salt per two-lane mile are required to combat extreme icing conditions. Pavements constructed to withstand the weak brines deposited by salt-treated abrasives cannot stand up under straight salt. New pavements appear more vulnerable than those two or more years old.

The observed resistance to salt action of the oil-soaked center streak of uphill traffic lanes led New York state highway engineers to investigate the feasibility of the use of dilute oil applications as a protective measure. Laboratory tests indicate successful results may be expected. In the late summer of 1948, oil spray equipment was developed in time to treat nearly 60 miles of new concrete highways, which should provide a wide base for field observation of the effectiveness of the method.

491. Tanahashi, I., S. Ohgishi, H. Ono, and K. Mizutani. "Evaluation of Durability for Concrete in Terms of Watertightness by 'Permeability Coefficient Test Results'." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

Effects of fluidity and mix proportion on the permeability was investigated on a concrete of typical specimen (disk and hollow disk types). Next, the permeability coefficient of structural concrete (wall and floor) were investigated and evaluation of concrete durability was carried out. From these experiments, the following conclusion was obtained.

The permeability coefficient of typical specimen that filled into the form sufficiently can be represented by an experimental equation.

The durability of structural concrete can be evaluated from the water-tightness that is derived from comparison of measured permeability coefficient and the theoretical permeability coefficient obtained by substituting the water-cement ratio and unit water quantity of designed mix proportion into the equation.

492. Taylor, T. G. "Effect of Carbon Black and Black Iron Oxide on Air Content and Durability of Concrete." *Journal of the American Concrete Institute* Vol. 44 (April 1948): pp. 613-624.

The practice of using air-entraining cement and air-entraining admixtures has made it necessary to re-examine many of the materials added to concrete to determine their effect on these types of concrete. This paper reports tests made to determine the effect of certain coloring agents on the air content and durability of concrete.

The tests indicate that some materials when added to concrete reduce the capacity of the cement to entrain air and thereby reduce the resistance of the concrete to freezing and thawing. A recommended procedure for evaluating coloring agents for use in air-entrained concrete is given.

493. Teodoru, G. "Aggregate — The Decisive Element in the Frost Resistance of Concrete." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

Experimentation was done to determine the influence of mineralogical structure, physical-chemical properties of aggregate and their granulometric composition (especially the fine fraction). The influence of cement type and content and of admixture on the resistance of concrete to freezing was included. Investigations were done using measurements of the logarigthmic decrement from the resonance curve as well as from the decay curve of the free vibrations. For comparison, the dynamic modulus of elasticity variation and the variations of strength in compression and tensile of concrete were used.

The value of the logarithmic decrement is given. It is noted that concrete above that value is not resistant to frost damage.

494. Thompson, S. R., M. P. J. Olsen, and B. J. Dempsey. *Synthesis Report: D-Cracking in Portland Cement Concrete Pavements*, University of Illinois at Urbana-Champaign, Urbana, IL 61801, UILI-ENG-80-2014, June 1980.

A comprehensive literature review was conducted to determine the mechanisms and testing procedures for D-cracking in portland cement concrete pavements. Beneficiation procedures were also investigated. The three general responses to freezing in the aggregate/paste system included elastic accommodation, high internal pressure, and high external pressure. It was found that the critical aggregate parameters influencing D-cracking were degree of saturation, maximum particle size, permeability, porosity, and pore size distribution. Evaluation of present laboratory testing procedures indicated that the ASTM C666, VPI slow-cool, Mercury Porosimetry, and Iowa Pore Index Tests correlated the best with field performance of concrete with respect to D-cracking.

495. Thomson, W. T. "Measuring Changes in Physical Properties of Concrete by the Dynamic Method." American Society for Testing Materials, Proceedings, Forty-Third Annual Meeting,, June 1940.

In investigating the durability of concrete by freezing-and-thawing tests, it has been found that the deterioration of the specimen is accompanied by certain changes in the physical properties of the material. The properties of the material most readily affected by deterioration are the modulus of elasticity and the decrement of vibration, both of which can be measured by the dynamic method. This paper presents tests performed on concrete composed of various aggregates with different water-cement ratios. Included, also, are certain peculiarities of results obtained by the dynamic method.

496. Tikalsky, P. J., and R. L. Carrasquillo. *Durability of Concrete Containing Fly Ash*, Center for Transportation Research, University of Texas at Austin, Report 364-3, May 1986.

The variability in the chemical composition and physical properties of fly ash from different sources affect both the fresh and hardened properties of concrete containing fly ash. Resident engineers and manufacturers that ignore these differences do not ensure proper quality or durable concrete.

This report summarizes the observations and conclusions from an experimental program investigating the durability of concrete containing fly ash. Tests were performed to determine the freeze-thaw resistance, strength, shrinkage, creep, abrasion resistance, and air entrainment characteristics of concrete containing fly ash. Types A and B fly ash were used in this study as a replacement for 0, 20, and 35% Type I portland cement by weight. In addition, Type IP cement containing 20% Type A fly as was used.

The results from this study reveal that concrete containing fly ash can be designed to meet present Texas SDHPT specifications. In many cases concrete containing no fly ash is shown to be more durable and economical than plain concrete.

This report provides the resident engineer with recommendations to ensure the durability of concrete containing fly ash and points out concerns for future investigations.

497. Tikalsky, P. J., P. M. Carrasquillo, and R. L. Carrasquillo. "Strength and Durability Considerations Affecting Mix Proportioning of Concrete Containing Fly Ash." *ACI Material Journal* (November 1988).

The results of a three-year study on the properties of concrete containing fly ash are presented. Both the fresh and hardened properties are reported of concrete made using Type I cement, river gravel, natural sand, and fly ashes from several sources. The mixtures were proportioned to have similar slump and a constant cementitious content, by weight. It is shown that concrete containing fly ash can be proportioned having equal strength properties and adequate durability when a suitable ASTM C618 Class C or F fly ash is used. Test data on over 1500 laboratory and field specimens tested for freeze-thaw resistance, flexural strength, compressive strength, creep, shrinkage, and abrasion resistance are presented. Fly ash contents ranging from 0 to 35 percent by weight of portland cement were used with both Class C and Class F fly ashes. Guidelines for the selection of materials and their proportions for producing concrete containing fly ash to meet existing highway specifications for concrete are presented.

498. Tognon, G., and S. Cangiano. "Air Contained in Superplasticized Concretes." *ACI Journal* (September-October 1982): pp. 350-354.

The air-entraining activity of superplasticizers based on sulfonated naphthalene formaldehyde condensates was studied in concretes made with different water-cement ratios. Results indicated that these admixtures cause air-entrainment which is directly related to the workability of mixes.

Nevertheless, the comparison with concretes containing an air-entraining agent showed that the air bubbles introduced by the superplasticizers are not bound to the cement particles and are characterized by sizes two to four times as high as those due to an air-entraining agent. Also, when working with superplasticized self-leveling concretes, a vibrating, even if moderate, action is necessary to eliminate the entrained air that, because of its size, is not useful against frost action.

499. Torrans, P. H., and D. L. Ivey. "Air Void Systems Affected By Chemical Admixtures and Mixing Methods." *Highway Research Record* No. 226 (1968): pp. 1-10.

Variations in the entrained-air system in hydraulic cement mortars due to different chemical types of air-entraining agents and retarders and different mixing methods were investigated. Twenty-seven mortar batches were prepared at a fundamentally constant air content using different combinations of 3 mixing sequences, 3 air-entraining agents, and 3 retarders. The Powers and Philleo spacing factors were determined on specimens from each batch, and were used as the criteria for comparison of the air void systems. Observed differences in the Powers spacing factor were found to be statistically significant for different mixing methods and different air-entraining agents. Comparatively large values of the Powers spacing factor were observed when the air-entraining agent and retarder were combined in the same water phase before being combined with the cement and sand. Relatively low values of Powers spacing factor were observed when the organic acid retarder was used, regardless of the air-entraining agent used.

500. Traetteberg, A. "Frost Action in Mortar of Blended Cement with Silica Dust." *Durability of Building Materials and Components*, ASTM STP 691 (1980): pp. 536-548.

Examinations of mortar prisms exposed to freeze-thaw cycling have been performed in order to evaluate the influence of silica dust on the frost resistance of concrete. The results, mainly based on measurements of residual length change, show that the addition of silica dust improves the durability of the mortars against frost attack. Air entrainment does not seem to have much effect in combination with silica dust. Despite the reduction in water requirement when a plasticizer is used, the admixture is not necessary to obtain a frost-resistance concrete. The improved effect caused by silica dust may be explained by an alteration of the pore size distribution leading to an increased amount of pores that seem to be efficient in combating frost action.

501. Transportation Research Board. *Admixtures and Ground Slag for Concrete*, TRB Committee on Chemical Additions and Admixtures for Concrete (A2E05). National Research Council, Washington, D. C., Transportation Research Circular No. 365, December 1990.

This report was prepared by the Transportation Research Board Committee on Chemical Additions and Admixtures for Concrete (A2E05). It is intended to provide practical information on admixtures and slag to practitioners dealing with concretes in the transportation field. The report supersedes information in Special Report 119 published in 1971 on accelerating, air-entraining, water-reducing, and pozzolanic (Type F fly ash) admixtures. In addition, it includes information concerning latex, high-range water-reducing, corrosion inhibiting, Type C fly ash, and silica fume pozzolanic admixtures and slag. The summary table in Chapter 1 provides a quick reference concerning major expected advantages and possible detrimental effects but should not be construed as being all inclusive. Significant contributions were made by past and present members of the Committee and other knowledgeable persons in the field. The Committee hopes to continue updating this document as new information is developed.

502. Traylor, M. L. "Efforts to Eliminate D-Cracking in Illinois." *Transportation Research Record* No. 853 p. 9-14.

Severe D-cracking on Interstate pavements prompted the Illinois Department of Transportation to initiate a program to identify and eliminate the use of D-cracking aggregate. More than 200 crushed-stone and gravel sources were evaluated by using both the Iowa Pore Index and ASTM C 666 freeze-thaw tests. Shortcomings in the Iowa pore index test have resulted in its use being limited to a screening test. The results of the freeze-thaw program have formed the basis for a specification that the state believes will guarantee the durability of future pavements.

503. Tremper, B., and D. L. Spellman. "Tests for Freeze-Thaw Durability of Concrete Aggregates." *Highway Research Board Bulletin* No. 305 (1961): pp. 28-50.

Tests of aggregate in air-entrained concrete have been made by methods suggested by T. C. Powers for resistance to freezing and thawing. The procedure differs from that of currently used test methods in several important respects. Among these are: (1) maintenance of the original moisture in the aggregates, (2) testing of the largest particle sizes to be used in the work, (3) subsequent

conditioning of the cured concrete by drying to a degree found appropriate to exposure conditions at the site of construction, and (4) freezing at a rate commensurate with natural conditions. Methods and apparatus used in conducting the tests are described, and results of variations in test procedure are shown.

Specifications based on the test procedure have been used for the acceptance of aggregates in construction work that is subject to severe winter conditions at high elevations in California. Many of the aggregates would not be considered to be acceptable under commonly used freeze-thaw methods. One hundred and seventy-three lane-miles of pavement have been subjected to one or two winters of severe exposure. At present, the concrete is judged to have withstood the effects of exposure without evidence of distress due to freezing and thawing.

504. Troxell, G. E., and H. E. Davis. *Composition and Properties of Concrete*. New York, NY: McGraw-Hill Book Co., Inc., 1956.

Today, more than ever before, the civil engineer is required to give thought and time to the problems of concrete making and utilization. The results accomplished in the field by the construction engineer and the concrete inspector depend upon their knowledge of concrete and of the materials from which it is made. Satisfactory designs of structures are dependent to a considerable extent upon the familiarity of the design engineer with the desirable and the undesirable characteristics of concrete.

This text and manual is designed as a guide to the student in a comprehensive course in the study of plain concrete. Part I is a descriptive text in which sufficient information is provided so that the engineer can intelligently understand the many factors having a bearing on the proportioning, production, testing, and control of plain concrete. Much of this information has appeared in publications of various technical societies and associations but has been selected and condensed here to make it more useful to the student. It may well serve as a guide to the practicing engineer in selecting and using the cement, fine aggregate, coarse aggregate, and admixtures for a given structure. It covers the proportioning and mixing of these materials, as well as the placing and curing of the concrete, to produce a finished product of suitable and predictable quality and economy.

505. Turner, L. "The Healing of Cement and Concrete." *Concrete and Constructional Engineering* Vol. 32 (February 1937): pp. 141-144.

It is not generally appreciated that cement and concrete possess to a remarkable degree the property of self-healing in the presence of moisture. In certain conditions a crack caused by failure in tension or compression is capable of healing to such an extent that the material is stronger than when first broken. About six years ago, when the writer applied vibration to bridge construction, the importance of the effect on green or partly hardened concrete of the condition that can be caused by shock being fracture and separation of surfaces, it was necessary to investigate the capability of healing in the cementitious material fractured, because the healing properties of the aggregate alone can be disregarded.

506. Tuthill, L. H., and W. A. Cordon. "Properties and Uses of Initially Retarded Concrete." *Journal of the American Concrete Institute Proceedings* Vol. 52, No. 3 (November 1955): pp. 273-286.

Loss of slump and workability and higher water requirement, particularly in warm weather, often impair quality of concrete. Investigation of corrective agents included development of a penetration resistance test to measure rate and progress of hardening, which is described. The effect of various factors such as temperature, character and amount of cement, and type and amount of retarding agent on rate of hardening, early strength, water requirement, and durability, are reported.

507. Tuutti, K., and G. Fagerlund. "Fly Ash - Its Properties and Fields of Application in the Cement Industry." ACI/RILEM Symposium '85: Technology of Concrete When Pozzolans, Slags, and Chemical Admixtures Are Used, Monterrey, Mexico, 1985, pp. 103-119.

This paper presents a number of investigations and results that supplement previous studies of fly ash. Fly ash from coal-firing is a relatively new material to be used in the cement and concrete industry in Sweden. The investigations are confined to Class F fly ash with a low CaO content. The following aspects of fly ash are studied in these investigations: fineness, glass content, and residual carbon content of fly ash, addition of fly ash (1) to the cement when grinding cement clinker, (2) as a partial replacement of cement in concrete, and durability aspects such as frost resistance and corrosion of reinforcement when using fly ash in concrete.

508. Tynes, W. O. *Investigation of High-Strength Frost-Resistant Concrete*, U. S. Army Engineer Waterways Experiment Station, Concrete Laboratory, Vicksburg, Miss., miscellaneous paper no. C-75-6, June 1975.

This study was conducted to determine if reduction in air content by vibration of a well proportioned concrete mixture of relatively high cement content reduces the frost resistance of the hardened concrete and also to determine the effect of such reduction in air content on compressive strength. One 3/4-in. (19.0-mm) maximum-size crushed limestone aggregate concrete mixture was proportioned to have a compressive strength of approximately 5500 psi (37.92 MPa) at 28 days age. The mixture had an air content of 8 plus or minus 1 percent. Various vibration times were used to reduce the air content until the samples had an air content as low as could be practically obtained. Specimens were cast for determining compressive strength, resistance to freezing and thawing, and air void parameters to evaluate the effect of reduction in air content of the concrete on strength and frost resistance. Strength test results indicate that the strength did increase as the air content decreased. The results of the tests for determining resistance to freezing and thawing indicate that frost resistance decreased as air content decreased . However, it appears that even though the durability decreased as the air content was reduced, the concrete still had adequate frost resistance with nominal air contents of 1.5 percent. Even though this is a low air content percentage, the air void spacing factor was 0.0068 in. (0.1727 mm), which is below the value that is considered adequate, i.e., 0.0080 in. (0.2032 mm).

509. Valore, R. C., Jr. "Volume Changes in Small Concrete Cylinders During Freezing and Thawing." *Journal of the American Concrete Institute* Vol. 46, No. 6 (February 1950): pp. 417-436.

The volume-temperature behavior of small concrete cylinders was observed, using a new mercury-displacement dilatometer, during freezing and thawing cycles in which the range 40 to -20° F was traversed at various rates. Specimens cast from a mix containing 6 bags of portland cement per cu yd, plain and modified by the addition of an air-entraining agent, were tested in air-dry, vacuum-saturated and partially saturated conditions.

Volume-temperature relationships for air-dry specimens yielded uniform thermal expansion data, but those for vacuum-saturated specimens showed departures in the form of transient expansions during freezing, and residual expansions following thawing of about 0.8 and 0.4 percent, respectively; as a single slow cycle produced decreases in dynamic E exceeding 60 percent.

Much smaller departures were observed for partially saturated specimens (65 to 85 percent of vacuum-saturation) and included, in addition to transient and residual expansions, secondary effects of freezing termed "shrinkage" and relaxation phenomena. The magnitude of the transient and residual expansions appeared to depend upon the rate of cooling and heating, the degree of saturation of the specimen and, during the slow cycle, upon the degree of supercooling before freezing.

510. Valore, R. C., Jr., and C. William. "Air Replaces Sand in No-Fines Concrete." *Journal of the American Concrete Institute* Vol. 47, No. 10 (June 1951): pp. 833-846.

Concretes containing high-early strength cement, 20 to 30 percent entrained air in place of fine aggregate, siliceous pea gravel and a proprietary resin of detergent air-entraining agent, were made using ordinary rotating tilt-drum mixers. The maximum air contents in mixes having a compressive strength of 500 psi (28 days) were 25 percent (3.3 bag mix) and 29 percent (5.6 bag mix). The ratio of compressive to transverse and bond strengths was about 3. The saturation coefficient and capillarity were much lower, the resistance to freezing and thawing generally higher, and the thermal conductivity (k) 30 to 40 percent lower than for a nonaerated sand-gravel concrete. The drying shrinkage was about the same as for a nonaerated concrete. The compressive strength of all mixes decreased about 100 psi for each percent increase in air content, which was difficult to control.

511. van Genuchten, M. Th. "A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils." *Soil Sci. Am. J.* Vol. 44 (1980): pp. 892-898.

A new and relatively simple equation for the soil-water content-pressure head curve, $\theta(h)$, is described in this paper. The particular form of the equation enables one to derive closed-form analytical expressions for the relative hydraulic conductivity, K_r, when substituted in the predictive conductivity models of N. T. Burdine or Y. Mualem. The resulting expressions for $K_r(h)$ contain three independent parameters which may be obtained by fitting the proposed soil-water retention model to experimental data. Results obtained with the closed-form analytical expressions based on the Mualem theory are compared with observed hydraulic conductivity data for five soils with a wide range of hydraulic

properties. The unsaturated hydraulic conductivity is predicted well in four out of five cases. It is found that a reasonable description of the soil-water retention curve at low water contents is important for an accurate prediction of the unsaturated hydraulic conductivity.

512. van Genuchten, R. *Calculating the Unsaturated Hydraulic Conductivity with a New Closed-Form Analytical Model*, Dept. of Civil Engineering, Princeton University, Princeton, NJ, research report no. 78-WR-08, September 1978.

A new and relatively simple equation for the soil moisture content-pressure head curve, $\theta(h)$, is described in this report. The particular form of the equation enables one to derive closed-form analytical expressions for the relative hydraulic conductivity, K_r, when substituted in the predictive conductivity models of Burdine (1953) or Mualem (1976a). The resulting expressions for $K_r(h)$ contain three independent parameters which may be obtained by fitting the proposed soil moisture retention model to experimental data. Two different methods of curve-fitting are discussed in the report, a simple but effective graphical method, and a least-squares method requiring computer assistance. An existing non-linear least-squares curve-fitting program was modified for this purpose and is included in an appendix, together with detailed instructions regarding its use.

Results obtained with the closed form analytical expressions based on the Mualem theory were compared with observed relative hydraulic conductivity data for five soils with a wide range in hydraulic properties. The relative hydraulic conductivity was predicted well in four out of five cases. It was found that a reasonable description of the soil moisture retention curve at low moisture contents is necessary if an accurate prediction of the hydraulic conductivity is to be made.

513. Verbeck, G. J. "Pore Structure." *Significance of Tests and Properties of Concrete and Concrete Making Materials* ASTM STP-169B (1978): pp. 262-274.

The pores, or voids, in concrete consist of pores in the hardened cement paste, entrained or untrapped air voids, and voids in the pieces of aggregate. Most of the important properties of concrete are related to the quality and the characteristics of the various types of pores in the concrete. The engineering properties, such as strength, durability, shrinkage, creep, permeability, and frost durability, are directly influenced or controlled by the relative amounts of the different types and sizes of pores.

514. Verbeck, G. J., and W. E. Haas. "Dilatometer Method for Determination of Thermal Coefficient of Expansion of Fine and Coarse Aggregate." *Highway Research Board Proceedings* Vol. 30 (1950): p. 192.

The thermal coefficients of the paste and aggregate components of concrete to a considerable extent govern the degree of physical compatibility of the components and hence may affect the durability of concrete subject to changes in temperature.

The described dilatometer method is suitable for the determination of the thermal coefficeient of expansion of sand and coarse aggregate. The method is particularly adaptable to the study of sands and also provides a means of obtaining

and testing a representative sample of a heterogeneous coarse aggregate or of the various mineralogical portions comprising the coarse aggregate.

The method determines the cubical thermal coefficient of expansion from which the mean linear thermal expansion may be calculated. With the present apparatus, the thermal coefficient is measured over a range of approximately 7° F. Both the temperature increment and the base temperature used in the determination can be easily modified.

The accuracy of the apparatus has been verified by the comparison of results obtained with materials of known thermal coefficients of expansion. The thermal coefficients of expansion of various fine and coarse aggregates are included.

515. Verbeck, G. J., and P. Klieger. *Calorimeter-Strain Apparatus for Study of Freezing and Thawing Concrete*, Highway Research Board, Washington, D. C., Bulletin No. 176, 1958. pp. 9-22.

Information and techniques available in the past have not been sufficient for a complete evaluation of the role of the various factors influencing the resistance of concrete to freezing and thawing.

It has long been recognized that the destruction of concrete exposed to freezing and thawing is due principally to the freezing of water within the concrete; concrete in a dry state will not be damaged by freezing. Water-saturated non-air-entrained concrete of normal water-cement ratio cannot resist the disruptive forces generated by the freezing of the water. Air entrainment provides a practical and fundamental solution to this freezing problem. Frost resistance is controlled by the freezable water content, air void characteristics, paste permeability, aggregate characteristics, and other factors, none of which are readily evaluated experimentally.

This paper describes the development and operation of an apparatus for determining (1) the amount of water actually freezing within a concrete specimen as a function of temperature and time, and (2) the physical response of the specimen in terms of length change as this water is frozen. Examples of the type of information that can be obtained are presented and discussed.

516. Verbeck, G. J., and P. Klieger. *Studies of 'Salt' Scaling of Concrete*, Highway Research Board, Washington, D. C., Bulletin No. 150, 1956. pp. 1-13.

The service record of air-entrained concrete pavements exposed to deicing salts is excellent. However, the mechanism by which deicers cause or accelerate surface scaling of non-air-entrained concrete is unknown. Furthermore, there is not a complete understanding of why entrained air is beneficial in this regard.

Although field experience indicates that air entrainment is a practical remedy for surface scaling, some laboratory tests indicate that under certain extremely severe conditions entrained air does not give complete protection.

The objective of this study is to provide more information on the effect of type and concentration of deicer, curing condition of concrete, air entrainment, and other variables on the surface scaling of concrete. This information should lead to a better understanding of the effect of these variations and should be of assistance in the establishment of further remedial measures.

517. Verbeck, G. J., and R. Landgren. "Influence of Physical Characteristics of Aggregates on Frost Resistance of Concrete." *ASTM Proceedings* Vol. 60 (1960): pp. 1063-1079.

The durability of concretes made with different aggregates depends upon the rate at which the aggregates become critically saturated in the concrete and upon the different physical responses of the aggregates to freezing. The time requirements for saturation of aggregates in concrete are analyzed in terms of the physical characteristics of the aggregates and the concrete. Important factors are the porosity and pore size distribution of the aggregate and the permeability and thickness of the mortar cover protecting the aggregates from water.

The different responses of aggregates and the cement paste are shown. Saturated aggregates of low porosity may accommodate pore water freezing by simple elastic expansion. Saturated aggregates of moderate or high porosity may fail internally because the particle dimension exceeds a certain critical size or may cause failure in the paste immediately adjacent to the aggregate particle because of aggregate pore water displacement. The magnitude of the hydraulic pressures developed is significantly influenced by the size of the aggregate particle and the permeability and air content of the surrounding paste.

The applicability of certain types of laboratory tests of the frost resistance of aggregates and concretes is questioned on the basis of these mechanisms.

518. Verhasselt, A. "Low-Calcium Fly Ash as a Mineral Admixture for Lean Concrete." Second CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Madrid, Spain, 1986, pp. 803-820.

The use of fly ash as a mineral admixture for lean concrete (road base concrete) has aroused a rather limited interest until now. However, this comparative study shows that there are some advantages in using low-calcium fly ash in lean concretes. The compactibility of lean concrete is improved; the maximum level of compaction (Modified Proctor test) is achieved at about 5 percent fly ash addition, whereas it is equal at 0 percent and 10 percent addition. The CBR indexes of the mixes are similar at Proctor maximum, but the higher the fly ash content, the more sensitive the index is to an increase in moisture content. At an early stage, fly ash is not very effective in strength development: it is essentially the portland cement content (2 to 5 percent) that governs the rate of strength evolution. On the other hand, at longer periods (more than 6 months), fly ash contributes very largely to strength: a factor of 1.5 between the weakest mix and the reference lean concrete without fly ash. Accordingly, a reduction of the cement content in practice can be taken into consideration. Water stability, which is obtained rapidly, is not much affected by the presence of the admixture. On the the other hand, resistance to repeated freezing and thawing cycles is delayed because of the slower strength gain for mixes containing more fly ash and less cement. The results on the whole show that the optimum low-calcium fly ash content in lean concrete for road base lies around 5 percent by mass with the possibility of reducing the cement content appreciably.

519. Virtanen, J. "Freeze-Thaw Resistance of Concrete Containing Blast-Furnace Slag, Fly Ash or Condensed Silica Fume." First CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag and Other Mineral By-

Products in Concrete, Montebello, Quebec, Canada, July - August 1983, pp. 923-962.

The use of GGFBS and fly ash has increased considerably in Finland. Silica fume has not been used in concrete in Finland so far, but research on its properties has been carried out for some years. The use of these materials has been limited because of the lack of knowledge on the durability of concrete containing slag, fly ash, or silica. The freeze-thaw resistance of concrete has been evaluated using five different methods. Both air-entrained and non air-entrained concretes were tested.

520. Vogler, R. H., and G. H. Grove. *Freeze-Thaw Testing of Coarse Aggregate in Concrete: Procedures Used by Michigan Department of Transportation and Other Agencies*, Michigan Department of Transportation, November 1987.

The procedures used to evaluate the durability of coarse aggregate in concrete by freezing and thawing were determined by a survey. Results indicate that a number of State transportation agencies use freeze-thaw procedures in place of, or in addition to, sulfate soundness and other tests. However, each agency's procedure has unique aspects. ASTM Method C 666 describes the procedures for freeze-thaw cycling and gives partial information on expressing these results, but ASTM has no standard procedure to guide the testing agency in important aspects such as: aggregate grading, aggregate moisture treatment and pretreatment, concrete mixture proportioning including cement content, air content of concrete, or curing procedure. The ASTM procedure's method of expressing results for change in length does not permit comparison between different aggregates. The information in this paper is intended to assist ASTM Committee C9 in preparing a practice for evaluation of coarse aggregate in concrete by freezing and thawing.

521. Vogler, R. H., and G. H. Grove. "Freeze-Thaw Testing of Coarse Aggregate in Concrete: Procedures Used by Michigan Department of Transportation and Other Agencies." *Cement, Concrete, and Aggregates* Vol. 11, No. 1 (1989): pp. 57-66.

The procedures used to evaluate the durability of coarse aggregate in concrete by freezing and thawing were determined by a survey. Results indicate that a number of state transportation agencies use freeze-thaw procedures in place of, or in addition to, sulfate soundness and other tests. However, each agency's procedure has unique aspects. ASTM Test Method for Resistance of Concrete to Rapid Freezing and Thawing (C 666) describes the procedures for freeze-thaw cycling and gives partial information on expressing test results, but ASTM has no standard procedure to guide the testing agency in important aspects such as: aggregate grading, aggregate moisture treatment and pretreatment, and concrete mixture proportioning (including cement content, air content of concrete, or curing procedure). The ASTM C 666 method of expressing results for change in length does not permit comparison between different aggregates. The information in this paper is intended to assist ASTM Committee C9 on Concrete and Concrete Aggregates in preparing a practice for evaluation of coarse aggregate in concrete by freezing and thawing.

522. Vondran, G. "Making More Durable Concrete with Polymeric Fibers." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA. April 27 - May 1, 1987.

The use of fibrillated polymeric fibers as secondary reinforcing to improve concrete durability is presented from a wide range of data with the purpose of demonstrating major trends. In this paper, results presented are focused on one type of polymeric fiber, collated fibrillated polypropylene (CFP), at an addition rate of 1.5 lb/yd^3. Tests on qualities that can affect durability illustrate CFP fiber reinforced concrete increases resistance to: plastic shrinkage cracking, impact, abrasion, shattering, freeze-thaw, deicing scaling, permeability, fatigue, and fire. The toughness index is increased up to 4.9 with the use of this fiber. Polypropylene will not degrade or corrode, and is not negatively affected by an alkaline environment of portland cement concrete.

523. Walder, J., and B. Hallet. "A theoretical model of the fracture of rock during freezing." *Geological Society of America Bulletin* Vol. 96 (March 1985): pp. 336-346.

We present a mathematical model for the breakdown of porous rock by the growth of ice within cracks. The model is founded upon well-established principles of fracture mechanics and recent advances in soil physics, along with the assumption that progressive crack growth results from water migrating to ice bodies in cracks, much as water migrates to ice lenses in freezing soil.

Our model predicts crack-growth rates compatible with empirical data. Calculations for a granite and a marble indicate that sustained freezing is most effective in producing crack growth when temperatures range from approximately -4° C to -15° C. At higher temperatures, thermodynamic limitations prevent ice pressure from building up sufficiently to produce significant crack growth; at lower temperatures, the migration of water necessary for sustaining crack growth is strongly inhibited. In hydraulically "open" systems, in which pore-water pressure remains near atmospheric pressure during the freezing process, crack-growth rates during continuous cooling will generally be greatest at low rates of cooling, less than approximately 0.1-0.5° C/h. At higher rates of cooling, the influx of water to growing cracks is significantly inhibited.

The model delineates clearly the role of material parameters (elastic moduli, fracture-mechanical properties, grain size and shape, and crack size), environmental conditions (temperature, temperature gradient, water pressure), and time in frost damage to rocks. Our calculations, along with recent experimental work on water migration in freezing rocks (Fukuda, 1983), lead us to question the widely accepted importance of two phenomena — freezing of water in sealed cracks and freeze-thaw cycling — in the fracture of rock exposed to natural freezing conditions.

524. Walker, H. N. "Correlation of Hardened Concrete Air-Void Parameters Obtained by Linear Traverse with Freeze-Thaw Durability as Found by ASTM C 666." *Cement, Concrete, and Aggregates* Vol. 6, No. 1 (Summer 1984): pp. 52-55.

The spacing factor for the proportional number of small air voids $\bar{L}_{ps}$ as proposed by Walker in 1980 and the air-void parameters normally obtained by ASTM Practice for Microscopical Determination of Air-Void Content and Parameters of

the Air-Void System in Hardened Concrete (C 457) were each correlated with the durability factor and weight loss found by ASTM Test for Resistance of Concrete to Rapid Freezing and Thawing (C 666) Procedure A for 151 concretes. The correlation coefficients were examined, and it was found that for the durability factor the classical spacing factor from ASTM C 457 gave a slightly but not significantly better correlation than did $\bar{L}_{ps}$. The 151 concretes were divided into three groups according to their source. In no case did the correlation obtained from $\bar{L}_{ps}$ significantly exceed the spacing factor calculated from ASTM C 457.

525. Walker, H. N. "Formula for Calculating Spacing Factor for Entrained Air Voids." *Cement, Concrete, and Aggregates* Vol. 2, No. 2 (Winter 1980): pp. 63-66.

A spacing factor only for small voids is derived from the proportion of small voids to total voids. The formula can be used with any method of air determination in hardened concrete that includes denominating some voids as large and some as small. The formula is not dependent on the size criterion used. A graphic method of estimating the spacing factors is given: L for total and and L_s for the proportion of small voids.

526. Walker, R. D., and T. C. Hsieh. "Relationship Between Aggregate Pore Characteristics and Durability of Concrete Exposed to Freezing and Thawing." *Highway Research Record* No. 226 (1968): p. 41.

Various coarse aggregates ranging from crushed limestones and traprock to gravels from glacial and nonglacial sources were obtained from different parts of the United States and Canada. Concrete specimens made from these aggregates were exposed to laboratory freezing and thawing cycles. Specimens for a mercury intrusion porosity test were broken into small particles.

For the eight aggregates tested, freeze-thaw durability was compared to aggregate pore characteristics as determined by the mercury-intrusion porosity test. Several characteristics were found to relate quite well with freeze-thaw durability, especially the amount of pores found in the 8-nm range.

527. Walker, R. D., and J. F. McLaughlin. "Effect of Heavy Media Separation on Durability of Concrete Made with Indiana Gravels." *Highway Research Board Bulletin* No. 143 (1956): p. 14.

Alternate freezing and thawing are among the most destructive of the natural weathering conditions to which concrete is subjected. Indiana pavements undergo a large number of freezing and thawing cycles each year, and in addition, several aggregates of questionable durability are found in the state. The Joint Highway Research Project at Purdue University has, therefore, done considerable research concerning the freezing and thawing of concrete.

Previous studies have produced laboratory data which can be correlated with the field performance of aggregates, but in each, either all gravel or all crushed stone coarse aggregates was used. Indiana's present field practice, however, is to blend crushed stone (for the larger sizes of the coarse aggregate) with gravel. Also, the development of commercial heavy media separation methods makes worthy of consideration the more extensive use of these methods for the improvement of

gravel aggregates. These two factors merited laboratory research and form the basis of this study.

528. Walker, R. D., H. J. Pence, W. H. Hazlett, and W. J. Ong. *One-Cycle Slow-Freeze Test for Evaluating Aggregate Performance in Frozen Concrete*, National Cooperative Highway Research Program, Report 65, Highway Research Board, Washington, D. C., 1969.

This investigation, which began in 1963, had for its purpose the development of a simple and fast test that could be used to identify aggregates that cause poor concrete performance when frozen. In the interim report definite progress toward the goal of a quick and simple test was reported. This initial work consisted of placing 3 x 3 x 16-in concrete specimens in a standard deep-freeze unit and making strain measurements with a Whittemore strain gauge every 10 minutes over a 3- to 4-hr. period It was found that the slope of the change in length versus time curve correlated well with aggregate durability as defined by standard freezing-and-thawing tests.

529. Walker, S. "Freezing and Thawing Tests of Concrete Made with Different Aggregates." *Journal of the American Concrete Institute* Vol. 40 (June 1944): pp. 573-580.

This report summarizes information of freezing and thawing tests of concrete made with different coarse aggregates and describes a "durability factor" that may be calculated as a function of the cycles of freezing and thawing and their effect on the modulus of elasticity of the concrete as measured dynamically.

530. Walker, S., and D. L. Bloem. "Studies of Concrete Containing Entrained Air." *Journal of the American Concrete Institute* Vol. 17, No. 6 (June 1946): pp. 629-639.

Problems of air entrainment in concrete have been particularly interesting to the ready-mixed concrete industry, which has to meet a wide variety of specification requirements. This prompted exploratory studies in the Research Laboratory of the National Ready Mixed Concrete Association. Data are reported on the effect of entrained air on compressive strength and mixing water requirements. Other factors considered are: mixing time, grading of aggregate, temperature, ratio of sodium hydroxide to Vinsol resin, comparisons of fresh and hardened concrete, and air content at different depths of concrete.

531. Wallace, G. B., and E. L. Ore. "Structural and Lean Mass Concrete as Affected by Water-Reducing, Set-Retarding Agents." *Effect of Water-Reducing Admixtures and Set-Retarding Admixtures on Properties of Concrete*, ASTM, Philadelphia, STP No. 266, June 1960. pp. 38-96.

Several commercial water-reducing, set-retarding agents of the lignin and hydroxylated carboxylic acid classes are explored as to their effect on mix design and on the many properties of fresh and hardened concrete. Their benefits and limitations are explained so that the agents may be intelligently and confidently utilized. Methodology consisted of comparing various concretes containing water-reducing retarding agents with similar concretes without agent. Results of several hundred laboratory and field test conducted over the past 5 years show that optimum dosages of many agents on the market today will increase the compressive, tensile, and shearing strength of mass and structural concrete and

improve its resistance to freezing and thawing and sulfate-induced expansive forces. The principal contribution of water-reducing retarding agents toward improved workability is through their ability to extend the length of time in which concrete can be consolidated by vibration and thus reduce the risk of obtaining cold joints. They do not, however, improve the ease of handling concrete as gaged by the slump test, and in a few cases will increase the rate of slump loss. Volume change due to wetting and drying, and permeability of mass concrete are not affected by water-reducing retarding agents in amounts sufficient to warrant changes in design and construction considerations. However, reduced temperature rise and savings in cooling mass concrete may be achieved as a result of lower cement requirement attendant to their use.

532. Washa, G. W., and N. H. Withey. "Strength and Durability of Concrete Containing Chicago Fly Ash." *Journal of the American Concrete Institute* Vol. 49 (April 1953): pp. 701-712.

Results of laboratory tests indicate the strength that can be obtained when various amounts of Chicago fly ash are used in concrete mixes under various conditions. Results of a group of freezing and thawing tests show that air-entrained concretes made with and without ash in concrete made with Type I portland cement increased resistance to attack by sulfuric acid. The tests were confined to fly ash from one electric utility company in Chicago and are not necessarily applicable to fly ashes from other sources.

533. Washburn, E. W. "Note on a Method of Determining the Distribution of Pore Sizes in a Porous Material." *National Academy of Science Proceedings* Vol. 7 (1921): pp. 115-116.

A method for determining the effective pore diameters in a porous material, such as charcoal, is found. Pores of various diameters are present. One may determine also the fraction of the total porosity which is due to pores having effective diameters lying between any two stated limits.

534. Waterways Experiment Station. *Investigation of Concrete in Eisenhower and Snell Locks, St. Lawrence Seaway: Examination of Cores*, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, misc. paper no. 6-493, report 2, July 1963.

During an inspection of the lower miter sill at Eisenhower Lock in April 1962, local areas of advanced concrete deterioration were observed, especially in the gate recesses. Cores were drilled from both the Eisenhower and Snell Locks for laboratory examination. Detailed laboratory study of the cores, including microscope and X-ray diffraction examinations, revealed them to consist of concrete of good quality in good physical condition. The concrete had an air content and an air-void spacing factor in the range regarded as adequate to provide frost resistance. Some voids had secondary carbonate fillings, but these did not materially affect air content or spacing factor. No evidence of deleterious chemical reactions or of undesirable physical or chemical properties in any of the constituents of the concrete was found.

535. Whiting, D. A. "Air Contents and Air-Void Characteristics in Low-Slump Dense Concretes." *Journal of the American Concrete Institute* Vol. 82 (September-October 1985): pp. 716-723.

Air-void systems of low slump, low water-cement ratio concretes (LSDC) used for "dense" concrete overlays were evaluated. Dosages of neutralized vinsol resin and alkyl-benzyl sulfonate-based air-entraining agents needed to achieve specified air contents were approximately ten times those used in conventional concrete mixtures. For two other types of agents (a tall-oil derivative and an alkali-stabilized wood resin), specified air contents had been achieved in the fresh concrete, air content and air-void characteristics in the hardened concrete were satisfactory. Entrapped air contents ranged from 1 to 2 percent and could be reduced to below 1 percent if prolonged internal vibration was employed.

536. Whiting, D. A. "Durability of High-Strength Concrete." Editor J. M. Scanlon, Katharine and Bryant Mather International Conference, Atlanta, GA, April 27 - May 1, 1987.

Concrete mixtures were designed to nominal 28-day compressive strengths of 6,000, 8,000, and 10,000 psi (41, 55, and 69 MPa) using mix designs typical of commercial production of high strength concretes. To produce the higher strength concretes, additions of fly ash (Class C), water reducers, and high-range water-reducers were utilized.

Concretes were subjected to both moist and air cures. Durability test procedures included rapid freezing and thawing in water, and application of deicing agents. All moist-cured, non air-entrained concretes performed poorly, exhibiting rapid deterioration irrespective of strength level. Entrained air contents, measured in the fresh concrete, of 3 to 4 percent were found to be necessary in order to assure adequate durability when concretes were subjected to freezing and thawing in water. However, moist-cured, air-entrained, high strength concretes, prepared at 8,000 and 10,000 psi (55 and 69 MPa), while performing satisfactorily with respect to freezing and thawing in water, were less resistant to applications of deicing agents than were air-entrained concretes prepared at the lower strength level. This was true even with air contents between 7 and 8 percent in the fresh concrete.

537. Whiting, D. A. "Permeability of Selected Concretes." *Permeability of Concrete* ACI SP-108-11 (1988): pp. 195-222.

A study of permeability was made using six concrete mixtures ranging in water-to-cementitious material (w/c) ratio from 0.26 to 0.75. Concrete specimens were tested for permeability to water and air, permeability to chloride ions (rapid and long-term), volume of permeable voids, and porosity. Results confirm that permeability is a direct function of w/c ratio. The addition of silica fume results in even greater decreases in permeability than would be anticipated based solely on w/c ratio. A period of initial moist curing of at least seven days is essential for achieving low permeability. Results also indicate that rapid test procedures offer a reasonable alternative to more lengthy and complex conventional permeability tests.

538. Whiting, D. A., and J. Schmitt. *Durability of In-Place Concrete Containing High-Range Water-Reducing Admixtures*, Transportation Research Board, NCHRP Report No. 296, September 1987.

This report documents and presents the results of a field study of the durability of portland cement concrete highway wearing surfaces containing high-range water-reducing admixtures. Durability surveys were carried out on 12 structures ranging from 4 to 12 years of age. These structures included highway bridge decks, bridge deck overlays, and pavements. The total area affected by very light to moderate scaling was minor, amounting to less than 4 percent of the area surveyed. Less than 1/2 percent was characterized by medium to heavy scaling, where coarse aggregate particles were significantly exposed. A three-parameter performance model including water-cement ratio, amount of entrained air removed from the surface, and air-void spacing factor was developed and offered reasonable correlation with the field observations. The findings of the study indicate that high quality, durable concrete can be produced using high-range water-reducing admixtures.

539. Whiting, D. A., G. W. Seegebrecht, and S. Tayabji. "Effect of Degree of Consolidation on Some Important Properties of Concrete." In *Consolidation of Concrete*, pp. 125-160. S. H. Gebler, ed., American Concrete Institute, 1987.

Concretes were prepared at degrees of consolidation varying from 100 to 85 percent. Mixtures were typical of those used for pavement applications with cement factors ranging from 520 to 610 pounds per cubic yard (308 to 360 kg/m^3) and air contents ranging from 5 to 9 percent. Additional concretes were intentionally overvibrated to the point of incipient segregation. Test specimens were cast for determination of compressive strength, bond of reinforcing steel to concrete, permeability of concrete to chloride ions, and resistance of concrete to freezing and thawing in water.

Results show that compressive strength is reduced by about 30 percent for each 5 percent decrease in degree of consolidation. Bond stress is reduced even more dramatically, suffering a loss of approximately 50 percent for 5 percent reduction in degree of consolidation. Overconsolidation has little apparent effect on compressive strength, and may increase bond strength by virtue of displacement of air in these air-entrained concretes.

Resistance to chloride ion permeability decreased at reduced degrees of consolidation, especially when aggregate with higher water demand was used and where high air contents were employed. In most cases, resistance to freezing and thawing in water was not appreciably affected within the range of variables studies.

540. Whiting, D. A., and D. C. Stark. *Control of Air Content in Concrete*, Transportation Research Board, National Research Council, Washington, D. C., NCHRP Report No. 258, May 1983.

This study was carried out under NCHRP Project 10-18 "Specifying and Obtaining Entrained Air in Concrete." Some transportation agencies have felt an increasing need for more accurate control of the air content in portland cement concrete, especially as current target values in some specifications are significantly higher than traditionally accepted limits. This is particularly true in

low-slump, low-water-cement ratio concretes, where problems in obtaining specified air contents have been encountered, or where air contents are unusually sensitive to small additions of water. Accurate control of air content is especially important for transportation facilities because air entrainment is the primary, and most cost-effective, means of providing portland cement concrete with the durability needed to withstand repeated cycles of freezing, thawing, and deicer applications.

The first phase of this investigation was the compilation of current knowledge relating to entrained air in concrete. A comprehensive literature search was conducted, from which a state-of-the-art report (App. F) was prepared. A questionnaire was distributed to all state transportation departments, plus a number of other agencies in the United States and Canada. Information was solicited on current air content specifications, test procedures, and problems in control of air content. Interviews were conducted with four agencies where problems of particular interest were reported. A limited amount of laboratory testing of job materials received from these agencies was included in the program.

The findings of the first phase of the investigation led to conclusion that there is no general problem in control of air content. Problems most commonly encountered involve failure to adequately control batching procedures, intermixing of admixtures, improper storage of admixtures, and other production variables. The need for adjustment of air entraining agent (AEA) dosage when water-reducers and retarders are used, although generally recognized, still is not fully appreciated. Mineral admixtures, though not universally used, do cause some problems in areas where they are specified. Many control problems are of a unique nature, and involve peculiarities of certain materials, contamination of aggregate and water supplies, and other concerns best handled on a case by case basis.

For sources surveyed, values for air content are quite uniform, and average close to 6 percent. However, tolerance values show wider disparity. Some agencies prefer historical limits such as plus or minus 1 percent, while others allow considerably more latitude - up to plus or minus 3 percent in one instance. Wider tolerances than currently employed by many agencies may be appropriate if specifications are to realistically reflect actual field variations in air content. In addition, there is a need for greater differentiation of specified air content with respect to type of structure and exposure. Those elements exposed to severe weathering require higher target air contents (and closer tolerances) then those sheltered from the elements.

The second phase of this project involved laboratory investigation of certain types of concrete mixtures. Air contents of mixtures having a slump close to 2 in. were found to be sensitive to small changes in water content. For example, addition 1.5 percent of the net mix water caused air content to increase by a full percentage point. This was especially true for mixtures prepared using neutralized Vinsol resin as the air-entraining agent. A synthetic air-entraining agent of the alkyl-benzyl sulfonate type showed less sensitivity at air contents between 5 and 6 percent, but it was equally sensitive when air contents near 7 percent were employed. If operations calling for slump levels close to 2 in. are anticipated, closer control of water content and additional restrictions on the use of retempering water may be required.

Low-slump, low-water-cement ratio concretes used for "dense" concrete overlays were also subject to laboratory investigations. Dosages of neutralized Vinsol resin and alkyl-benzyl sulfonate-based air-entraining agents needed to achieve specified air contents were approximately 10 times those normally used in conventional concrete mixtures. For two other types of agents, a tall-oil derivative, and an alkali-stabilized wood resin, specified air contents could not be achieved even at dosage rates approaching 1/2 percent by weight of cement. Once specified air contents had been achieved in fresh concrete, air content and air-void characteristics in the hardened concrete were found to be satisfactory, in spite of these high dosage requirements. Entrapped air contents ranged from 1 to 2 percentage points, and could be reduced to below 1 percentage point if prolonged internal vibration was employed. A set of guidelines (App. C) for control of air content was prepared. These guidelines provide guidance to persons directly responsible for production testing and placement of air-entrained concrete. The guidelines are, in essence, a condensation of the more voluminous literature synthesis, and incorporate tables that afford easy access to information concerning the influence of various parameters on air content. Materials, batching and mixing, transport, placement, consolidation, and finishing techniques are some of the variables that are addressed in these guidelines. Condense sampling and testing procedures are also described.

To afford a means of implementing these guidelines in the field, the verification program presented in Appendix D was developed. This program provides reference to information concerning control of air content that construction-site personnel can utilize quickly and efficiently. Materials prequalifications procedures, simulation of job mixtures, batch plant and job site operations, and provisions for documenting test results in a standard format are included.

541. Whitlam, E. F. "Autogenous Healing of Concrete in Compression." *The Structural Engineer* Vol. 32 (September 1954): pp. 235-243.

Concrete that has failed in compression (or tension) possesses the property of healing, providing the fractured parts are maintained damp and in intimate contact. The experimental work described in this paper was carried out to ascertain if any quantitative results could be found concerning healing in compression and how it was connected with the general hardening process in concrete. Only one mix of concrete was used and initial tests were made to ascertain the most suitable degree of failure for specimens to be healed. Concrete cylinders 5 in. in dia. x 10 in. high were used. A series of these was tested at varying ages and re-tested after further periods of curing. Load-compression (or deformation) curves were taken for each test. It was found that the healing followed the same form as the general hardening process in concrete and it is thought probable that the healing is dependent upon the damage sustained by the initial compression test. A possible law for the deformation of concrete up to the point of failure is suggested for ordinary and healed concrete. Finally, practical consideration is given to the healing process in everyday site work.

542. Wiley, G., and D. C. Coulson. "A Simple Test for Water Permeability of Concrete." *Journal of the American Concrete Institute* Vol. 34 (September-October 1937): pp. 65-75.

Engineers have long recognized permeability as one of the most important qualities of concrete. Often, however, the emphasis has been misplaced. When it is realized that leakage through construction joints and cracks may be many

thousands of times the percolation through the solid concrete itself, the effect of impermeability on water tightness does not seem so important. The real significance of impermeable concrete lies not in the fact that it may help to produce water tight structures, but that it is more durable and permanent for all structures, whether or not actual water tightness is necessary. There is every reason to believe that permeability has a large effect on resistance of concrete to freezing and thawing, for if water can enter its pores, freeze and swell, it will tend to disrupt the structure. Similarly, high permeability indicates poor resistance to sulphate and alkali waters and even if exposed only to pure water, permeable concrete will gradually be destroyed by the leaching out of lime. In their investigation of the permeability of concretes in connection with Boulder Dam, Ruettgers, Vidal and Wing developed a method whereby the useful life of concrete can actually be calculated if its permeability is accurately known and provided the concrete is subject to no other disintegrating forces.

543. Wilk, W., G. Dobrolubov, and B. Romer. "The Development of Quantitative and Qualitative Microscopic Control of Concrete Quality and Durability and of a Frost-Salt Resistance Test with Rapid Cycles." *International Cement Microscopy Association — Proceedings* pp. 309-329.

New methods of quality control of concrete during pavement construction have successfully been carried out in Switzerland on all main road, airport and bridge pavement projects since 1969. A combined quantitative and qualitative microscopic analysis has been carried out on thin sections of 2-day old concrete in more than 4,000 tests. The quantitative as well as the qualitative analysis determines the frost-salt resistance (F-S). In addition to the spacing factor, seven other factors test evaluation considerably. The evaluation of F-S resistance foresees a subdivision in three groups according to the durability factor. This is a further improvement. The qualitative morphological control analysis is done on the same thin section and at the same time the quantitative analysis is carried out. The morphological quality control determines precisely the faults in the concrete as well as their causes. It also makes it possible to rectify these faults during further construction. The morphological quality of concrete influences its durability and must be considered by the quantitative evaluation of the F-S resistance. Concrete with a high percentage of morphological faults (disturbance factor greater than or equal to -10) is controlled by the frost-thaw-salt (F-T-S) resistance test with rapid cycles. This new Dobrolubov-Romer (D-R) method makes rapid testing of concrete possible (500 cycles within a fortnight). Based on the durability factor a very good correlation has been proven between quantitative and qualitative determination of F-S resistance on one hand and the test results with rapid cycles on the other. The aforementioned method was introduced in 1977 as a guiding rule for the determination and testing of frost-salt resistance of concrete in the Swiss norm SNV-640461.

544. Wilk, W., G. Dobrolubov, and B. Romer. "Development in Quality Control of Concrete During Construction." *Transportation Research Record* Vol. 504 (1974): pp. 1-26.

New methods of quality control of concrete during pavement construction have successfully been carried out in Switzerland on all main road projects since 1969. A combined quantitative and qualitative microscopic analysis has been carried out on thin slices of 2-day-old concrete in more than 800 tests. Quantitative analysis determines the frost-salt (F-S) resistance. In addition to the spacing factor, nine other factors are being considered. The evaluation of F-S resistance foresees a

subdivision in five groups according to the durability factor. The qualitative, morphological control analysis is done on the same slice and at the same time the quantitative analysis is carried out. The morphological quality control determines precisely the faults in the concrete as well as their causes. It also makes it possible to rectify these faults during further construction. Concrete with medium or low F-S resistance (according to the quantitative analysis) or with a high percentage of morphological faults (disturbance factor greater than or equal to -10) is controlled by a frost-thaw-salt (F-T-S) resistance test with rapid cycles. This new Dobrolubov-Romer (D-R) method makes rapid testing of concrete possible (500 cycles within a fortnight). Practical application of control on site during construction is demonstrated.

545. Wilk, W., and G. Dobrolubov. "Microscopic Quality Control of Concrete Construction." *International Cement Microscopy Association — Proceedings*, pp. 330-343.

Since approximately 1965 also in Switzerland roads, Bridges and parking areas are being deiced and kept clear of snow almost exclusively by means of chemical deicing salts. The use of salts has increased the requirements of durability of concrete from a lower frost resistance to a much higher frost salt resistance. Concrete pavements suddenly developed increased frost salt damages in the form of scaling as well as of concentrated disintegration of the concrete paste structure.

The durability of concrete under the combined impact of frost and deicing salts is achieved by air-entraining the concrete and introducing an increased quantity of air voids, duly graded according to size and uniform repartition in the cement paste.

Therefore, the mere determination of the total content of air voids of the fresh concrete is not sufficient for the evaluation of the frost salt durability of concrete. Only an appropriate testing method, applied to the hardened concrete can give pertinent information on the subject.

Such an efficient and easily applicable test method, used in Swiss road construction during the last decade permits a systematic control of the concrete quality during mixing and placing as well as of its frost salt durability.

There are many influences which may cause flows in concrete and develop during mixing, placing and curing stages. The most important ones will be enumerated later.
With the aid of the mentioned testing method (control of the microstructure of concrete) not only quality imperfections during placing may be detected but also their causes may be diagnosed. Thus, errors may be rectified and potential failures prevented.

546. Wills, M. H., Jr., H. A., Jr. Lepper, R. D. Gaynor, and S. Walker. "Volume Change as a Measure of Freezing and Thawing Resistance of Concrete Made With Different Aggregates." *ASTM Proceedings* Vol. 63 (1963): pp. 946-965.

A freezing and thawing procedure, based on the method proposed by Powers in 1955, appears to offer a simplified approach to studies of concrete durability. The test involves relatively long periods of immersion of concrete test specimens in water, together with a few intervening cycles of freezing and thawing. The method has not been nationally standardized nor widely used. The investigation

described here was made with the objective of learning more about its applicability and significance. Concrete with two different coarse aggregates and curing conditions were tested by the approach just described and by ASTM Method C 291. There was good correlation between the two test methods. The results offer promise that the simplified approach, with procedures standardized and refined, may provide a good tool for investigating concrete durability.

547. Wilson, A. "Durability of Concrete and Concrete Structures by Slow Cycle Fatigue." *Journal of the American Concrete Institute* SP 47-12 (April 1975).

The purpose of this research was to develop and evaluate a slow cycle fatigue method of testing concrete that might relate in part to the durability of concrete subjected to cyclic loading conditions. Effects of freezing at an early age as well as the effects of air entrainment were evaluated and compared to standard cured specimens. Microscopic study of specimens was used as a further means co comparison and as a method of observation and evaluation. A calculation of durability factor and the total number of cycles-to-failure were used to evaluate the results. It was found that early freezing of concrete had a deteriorating effect on concrete that was later subject to slow cycle fatigue loadings. This deteriorating effect was not apparent if the compressive strength alone was taken as the controlling criteria. It was demonstrated that visible evidence could also be observed through a microscopic study of concrete specimens. A marked difference was observed between standard specimens and those damaged by early freezing. Bond cracks around and adjacent to the large aggregate were typical of damaged specimens. The slow cycle fatigue test did cause the bond cracks to expand and extend resulting ultimately in a decrease of the concrete durability.

548. Winslow, D. N. "The Rate of Absorption of Aggregates." *Cement, Concrete and Aggregates* Vol. 9, No. 2 (Winter 1987): pp. 154-158.

The rates at which aggregates approach their 24-h water absorption values have been measured for a variety of aggregates. The aggregates varied widely in both their total pore volume and median pore size. The rates of water uptake were found to vary greatly, with some aggregates taking in about 90% of their 24-h uptake within the first minute and others taking in only about 20%. Larger pore sizes and pore volumes seem to promote faster rates. It was found that aggregates with a rapid uptake would have given erroneous Iowa Pore Index test results. It was also found that there was no correlation between and aggregate's early rate of absorption and its freeze/thaw durability.

549. Winslow, D. N., and S. Diamond. "A Mercury Porosimetry Study of the Evolution of Porosity in Portland Cement." *Journal of Materials, JMLSA* Vol. 5, No. 3 (September 1970): pp. 564-585.

The pore size distributions of two series of cement pastes prepared at water:cement ratios of 0.4 and 0.6 were determined as functions of age, using mercury porosimetry. The contact angle of mercury on thoroughly dried paste was measured as 117°; for P-dried paste it was found to be 130°. It was found that much of the pore space present at all ages occurred in pores between 0.1 and 0.01 μm: that is, in between the conventional concepts of capillary and gel pore diameters. It was further observed that pore volume left unintruded by mercury at 15.000 psi was significantly less than the 28 percent by volume that should be present in mature pastes according to currently accepted ideas of the nature of cement gel. On the basis of these observations and direct examination of fracture

surfaces of cement paste, it was concluded that most of the space present is neither conventional capillary nor conventional gel space but merely space between fine individual particles of cement hydration products.

550. Winslow, D. N., M. K. Lindgren, and W. L. Dolch. *Relationship Between Pavement D-Cracking and Coarse Aggregate Pore Structure*, School of Engineering, Purdue University, West Lafayette, Indiana.

Previous research developed a relationship between the pore structure of a coarse aggregate and the freeze/thaw durability, measured in the laboratory, of concrete made with that aggregate. It permitted the calculation of an Expected Durability Factor, EDF, from a knowledge of an aggregate's median pore diameter and total pore volume. This work has been extended to a consideration of in-service pavements, some of which showed D-cracking distress and some of which appeared to be durable. Forty seven pavement sections were cored and coarse aggregate samples were removed and separated lithologically. Their pore size distributions were determined by mercury intrusion. Criteria involving the EDF and relative amounts of good and bad aggregate fractions in the pavement were correlated with the extent of observed D-cracking. These correlations were distinctly superior to absorption measurements at identifying bad aggregates. It is suggested that the established criteria might be used to predict the performance to be expected from aggregate sources and might be a valuable acceptance standard.

551. Winslow, D. N., M. K. Lindgren, and W. L. Dolch. "Relation Between Pavement D-Cracking and Coarse-Aggregate Pore Structure." *Transportation Research Record* No. 853 (1982): pp. 17-20.

Previous research has developed a relation between the pore structure of a coarse aggregate and the freeze-thaw durability, measured in the laboratory, of concrete made with that aggregate. This has permitted the calculation of an expected durability factor from a knowledge of an aggregate's median pore diameter and total pore volume. This work has been extended to a consideration of in-service pavements, some of which showed D-cracking distress and some of which appeared to be durable. Forty-seven pavement sections were cored, and coarse-aggregate samples were removed and separated lithologically. Their pore-size distributions were determined by mercury intrusion. Criteria involving the expected durability factor and relative amounts of good and bad aggregate fractions in the pavement were correlated with the extent of observed D-cracking. These correlations were distinctly superior to absorption measurements in identifying bad aggregates. It is suggested that the established criteria might be used to predict the performance to be expected from aggregate sources and might be a valuable acceptance standard.

552. Withey, M. O. "Freezing and Thawing, Permeability and Strength Tests on Vibrated Concrete Cylinders of Low Cement Content." *Journal of the American Concrete Institute* Vol. 31 (May - June 1935): pp. 528-538.

Data on the influence of external vibration in placing on the properties of over 200 concrete cylinders with cement contents between 3 and 4 sacks per cubic yard and w/c ratios, by weight, between 0.50 and 0.77 are given. The advantages in using vibration in placing dry mixes of low cement content is indicated.

553. Withey, M. O. "Progress Report, Committee on Durability of Concrete." *Highway Research Board Proceedings* Vol. 24 (1944): p. 199.

A reasonably rapid method for ascertaining the resistance of concrete to freezing and thawing has long been desired by materials testing engineers, but to date such procedures stipulated in specifications have failed to obtain a large following. Since the previous Committee on Durability of Concrete as Affected by the Cement has made some tests in which the effects of different rates of freezing on resistance of mortars to freezing and thawing had been observed, it seemed desirable to study further this important subject.

The program of tests involved: (1) a comparison of the relative severity of a carefully specified coordinating freezing and thawing test as practiced in different laboratories, (2) a comparison of the effects of the freezing and thawing procedures commonly used in these laboratories (local procedures), and (3) a comparison of the severity of the coordinating test procedure with the local laboratory procedures.

554. Wolsiefer, J. "Ultra High-Strength Field Placeable Concrete with Silica Fume Admixture." *Concrete International* (April 1984): pp. 25-31.

Ultra high-strength concrete is now available to the construction market at field placeable slumps, in the compression range of 10,000 to 18,000 psi (69 to 24 MPa). Laboratory studies and field test programs have been conducted to evaluate a new silica fume type admixture's capability to produce state-of-the-art high-quality concrete over a range of applications. The test programs included drying shrinkage, creep, freeze-thaw, and abrasion resistance, among several others.

555. Wuerpel, C. E. "Laboratory Studies of Concrete Containing Air-Entraining Admixtures." *Journal of the American Concrete Institute* Vol. 17, No. 4 (February 1946): pp. 305-359.

The effects of the incorporation of each of nine different air-entraining admixtures in concrete were investigated by the making of a large number of batches of concrete under carefully controlled laboratory conditions. The results of tests on the plastic and hardened concrete specimens from batches made in parallel with and without each admixture are presented and discussed. An interpretation of the significance of the data and their application, the successful use of air entrainment in concrete, is given.

556. Yamamoto, Y., and S. Kobayashi. "Effect of Temperature on the Properties of Superplasticized Concrete." *Journal of the American Concrete Institute* Vol. 83, No. 10 (January - February 1986): pp. 80-87.

Properties of superplasticized concrete were examined under three different temperatures: 7, 20, and 35° C (44.6, 68, and 95° F). The properties examined include bleeding, setting time, losses with time of air content and slump, compressive strength, and freeze-thaw resistance. Three normal types of superplasticizers were used throughout the experiment. When the tests were made at 35° C (95° F), the retarding types of the three superplasticizers were also employed. Additionally, the effect of the presence of a retarding type of water reducing admixture was studied at the highest temperature.

Author Index

AUTHOR INDEX

Subject Index

SUBJECT INDEX