NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT 258

CONTROL OF AIR CONTENT IN CONCRETE

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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CONTROL OF AIR CONTENT IN CONCRETE

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AREAS OF INTEREST:

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TRANSPORTATION RESEARCH BOARD
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By Staff
Transportation
Research Board

This report presents the results of a study of entrained air in portland cement concrete. It contains a review of previous research and experience on air entrainment, a tabulation of current specifications, identification of field problems in control of air content, results of laboratory investigations involving low-slump concrete, and guidelines for control of entrained air during mixing and placing of concrete. The report will be of special interest to materials engineers, specification writers, researchers, and others interested in the production and placement of air-entrained concrete that will likely be subjected to freeze-thaw cycles or deicing chemicals.

The inclusion of entrained air within the matrix of portland cement concrete has long been recognized as an effective means of improving the durability of concrete road and street pavements exposed to the freeze-thaw cycles and deicing chemicals. However, the control and measurement of entrained air in the finished pavement is not adequate at times, particularly when low slump concrete with high cement factors and low water-cement ratios are being placed. The objective of NCHRP Project 10-18 was to develop practical guidelines for specifying and obtaining the optimum amount of entrained air in portland cement concrete intended to withstand exposure to freeze-thaw cycles and deicing salts.

As the initial phase of the study, the researchers of the Construction Technology Laboratories, a Division of Portland Cement Association, prepared a comprehensive state-of-the-art report on the theory, research, and experience of the use of entrained air in concrete. This was followed by a survey of state highway and transportation agencies to identify current specifications and practices with regard to use of air entrainment and to identify field problem areas concerning measurement and control of air contents. It was determined that, when recognized procedures are followed, there is little likelihood of field problems associated with control of entrained air. Problems of a unique nature, involving peculiarities of certain materials, contamination of aggregate and water supplies, and other concerns, need to be resolved on a case-by-case basis.

A limited amount of laboratory testing was conducted using materials identified from field projects as having unique problems. Air contents of low-slump concrete with high amounts of entrained air were found to be sensitive to small changes in water content. This was also influenced by the type of air-entraining agent. When high air content is specified in very "dense" concrete, required doses of air-entraining agents may be 10 times those normally used in conventional concretes. The unique nature of interactions between concrete ingredients should be evaluated experimentally when "dense" concretes are being used.

Appendix C of this report provides guidelines for the production and control of air-entrained concrete. The comprehensive state-of-the-art review on use of entrained air in concrete is a reference document for the guidelines and is summarized in Chapter Two. It is also available as an Addendum to NCHRP Report 258.

Copies of this Addendum have been distributed to the program sponsors and are available to other interested persons on written request to the Cooperative Research Programs, Transportation Research Board, 2101 Constitution Avenue, N.W., Washington, DC 20418.

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The research reported herein was performed under NCHRP Project 10-18 by Construction Technology Laboratories, a Division of the Portland Cement Association. Mr. David C. Stark, Principal Research Petrographer, and Dr. David A. Whiting, Senior Research Engineer, Concrete Material Research Department, were the co-principal investigators for the study.

Special acknowledgment is made to the representatives of various state transportation departments who supplied information and materials during the course of this project. In particular, sincere appreciation is expressed to Mr. J. G. Gehler, Engineer of Materials and Physical Research, Mr. David H. Berry, Jr., Concrete Technology Engineer, Illinois Department of Transportation; Mr. Richard K. Smutzer, Materials Research Engineer, Indiana Department of Highways; Mr. Wayne Brule, Materials Engineer, Mr. William Chamberlin, Research Engineer, New York State Department of Transportation; and Mr. Clifford L. Heckman, Project Engineer, Mr. Robert R. Santoro, Research Engineer, New Jersey Department of Transportation.

CONTROL OF AIR CONTENT IN CONCRETE

SUMMARY

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 the 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, specified target 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 ± 1 percent, while others allow considerably more latitude - up to ± 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 of 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. Condensed 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 prequalification procedures, simulation of job mixtures, batch plant and job site operations, and provisions for documenting test results in a standard format are included.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

INTRODUCTION

For approximately the past 40 years, air entrainment has been the accepted technique for providing portland cement concrete with the durability necessary to withstand repeated cycles of freezing and thawing. It has also proven to be a reliable means of greatly increasing the resistance of concrete to premature distress brought about by repeated applications of deicing salts. As in many areas of transportation technology, the proven laboratory and demonstration project reliability of any system is subject to a multitude of variables when attempts are made to put the theory into practice.

Field-produced concrete is the end product of a long series of operations, any one of which is subject to a large number of complex and sometimes uncontrolled variables. Materials must be sampled and tested to ensure that they meet the appropriate specifications. The materials must be batched and mixed under less than ideal conditions in equipment which is subject to extreme abuse. The concrete must then be hauled, sometimes over long distances, in very hot or cold weather, to the job site. Speed of placement is often the overriding factor, and consistency of the concrete may be altered so as to increase placement speed by addition of water. Admixtures may be incorrectly dosed. The concrete may be underconsolidated, overfinished or otherwise abused during handling. These are some of the factors that can reduce durability of an otherwise well designed concrete mixture.

The control of these field variables is difficult, and the major tool needed to effect this control is education of the practitioner. In addition, changes in types of materials and construction practices and equipment over the years will necessitate frequent updating, or even revision, of long-established practices. The research described in this report had two goals. The first was to bring together a compendium of knowledge in the area of air entrainment and relevant specifications, ranging from historical experience to the latest research studies. The second goal was to present those problems which seem to be in the forefront at this particular point in time, and to suggest either possible solutions to these problems or research that needs to be done to find practical solutions.

BACKGROUND AND CURRENT KNOWLEDGE

The use of air entrainment in cementitious products dates back to antiquity. Materials such as milk and animal byproducts were added to mortars and concretes to obtain improvements in workability. Samples of concrete taken from Roman aqueducts (1) show a considerable number of air bubbles in the range of sizes now considered to represent entrained air. Through the early part of this century, various materials, which today could be classified as simple air entraining agents (2), were used as concrete additives.

It was not until the 1920's, when the automobile and truck became the primary means of transportation that increased demand for rapid conveyance required roadways over which high speeds could be maintained safely and efficiently. Thus, concrete paving increased and, at the same time, a means had to be found for ensuring the continued driveability of these highways under all weather conditions. This eventually took the form of what is now called "deicing salt," which was originally a calcium chloride/sand or abrasive mixture, now predominantly sodium chloride (rock salt). Thus, throughout the late 1920's and 1930's the volume of roads paved with concrete increased considerably, and the percentage of roadways subject to deicer applications likewise increased.

By the middle of the 1930's serious scaling problems were evident in many of the northern (or "frost-belt") states. The observed scaling would develop one to two years after the first application of salts, and it progressed steadily until the entire concrete surface was virtually disintegrated. It was proven that the severity of scaling was proportional to the amount of chemicals used and to their frequency of application. Research began to find solutions to this problem, with agencies such as the New York Department of Public Works, the Universal Atlas Cement Company, and the Portland Cement Association making early contributions.

The New York State Department of Public Works noted that blends of portland cement and natural cement provided more scale resistant pavements than did straight portland cements. This was traced to the use of beef tallow as a grinding aid for natural cement. When tallow was added to portland cement, similar favorable results were obtained as was the case with addition of fish oil stearates. During the same time period, Vinsol resin was found to be even more effective than tallow and fish oil stearates, and it came into wide use as a cement additive. Field installations during this period verified that it was the increased air content, rather than the chemical action of the additives used, that imparted freeze-thaw and scale resistance to the concrete.

Since the 1940's it was recognized that a host of variables could influence the final air content of any given concrete. During symposia sponsored by the American Concrete Institute in the mid-to-late 1940's, foundations were laid for current knowledge in this area. The effects of mix design, sand gradation, cement chemistry, water content, mixing time, manipulation of concrete, and many other parameters were all discussed in these proceedings. Much of this information is still valid and forms the core of information presented in Appendix C of this report.

Currently, air entrainment is recognized as the primary means for protecting concrete against freeze-thaw scaling. All 50 state transportation agencies now specify air entrainment in at least some categories of concrete. This is primarily because of improved durability, but also because of its beneficial effects in terms of increased workability and water reduction. Specifications generally call for air contents to fall within certain limits in order to be acceptable. In most cases these limits are from 4 to 8 percent by volume of the concrete. These specification limits have been slowly increasing over the years, as can be seen from Figure 1. During the past decade they seem to have stabilized with little change evident between 1975 and 1981 (see App. A).

Air-entraining agents themselves are surface-active agents, generally of the anionic type. For the most part, they fall into seven major categories. This classification scheme dates from a study published by the Bureau of Public Roads in 1954, but it is still valid. Newly introduced formulations are, for the most part, simply variations on these basic types.

No single type, or brand, of air-entraining agent has proven superior to others in all applications. However, instances may arise when one admixture may be more desirable than others for a particular set of materials or job conditions. Current knowledge concerning specific interactions of air-entraining agents with other materials is not sufficient to predict behavior in advance of preparation of the concrete batch. While manufacturers do supply information on recommended dosage rates for their products, these rates should be viewed as no more than starting estimates, and should not be used for determining the exact amount of agent to be used on any particular job.

Thus, the state of the art, with respect to achieving and maintaining control of air content is such that, while most of the factors which may influence air content are known, quantitative relationships between these factors and final net air contents are so complex that exact prediction of air content is not possible. While development of analytical relationships is commendable as a long range goal, it was not within the limited scope of the present project. Instead, the aim of this program is to afford the practitioner with practical guidelines (App. C) which can be used, in the context of an pre-qualification and trial batching program, to develop recommended dosage rates for his particular operation. This will permit him to maintain control over air contents through a well-documented verification program (App. D).

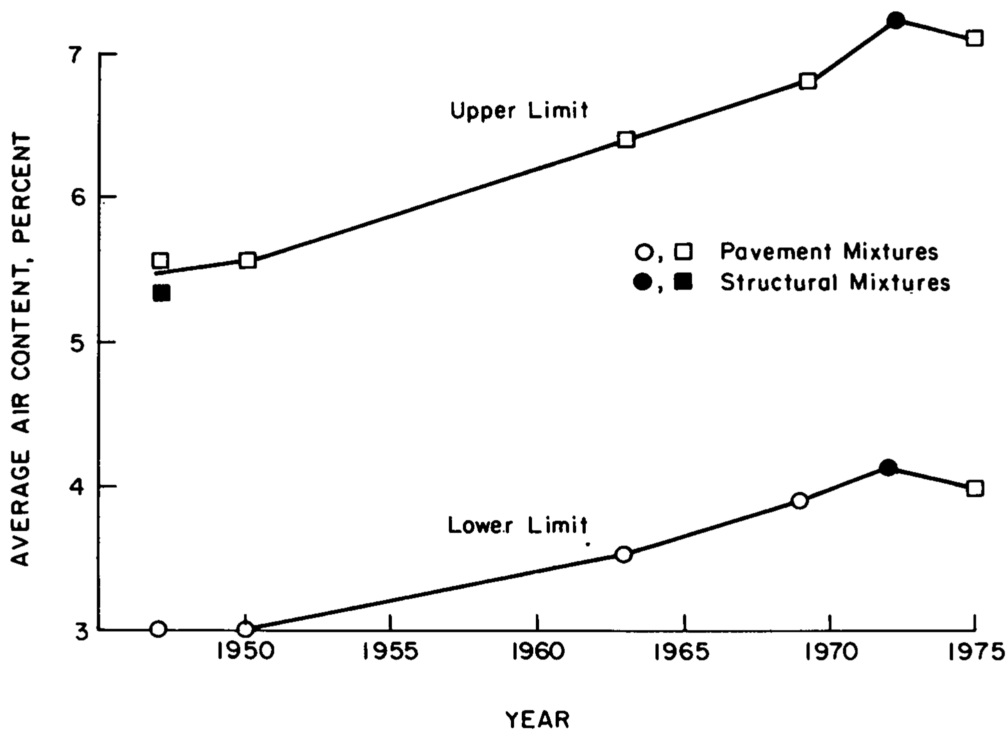

Figure 1. Trend of average specified air contents from 1947 through 1975.

RESEARCH APPROACH

The research approach taken towards such a broad-reaching topic was necessarily diverse. The first step was to compile a comprehensive literature synthesis in the subject area. It was recognized that several review articles and bibliographies on air entrainment already existed. However, many of these addressed only particular topics within this area, or they were very general and were meant as only an introduction to the subject. The purpose of compiling a comprehensive review was to provide the reader with an in-depth treatment in a single volume, with sufficient references so that any one topic could then be researched in more detail.

It was recognized that not all information relative to air entrainment would be accessible from the open literature. This is especially true in the case of field experiences, which are often prepared as case studies by separate agencies but never reported outside of that agency. To overcome this limitation, a questionnaire was prepared and mailed to all 50 state transportation departments, the District of Columbia transportation department, and a number of other agencies. The questionnaire solicited information on current air content specifications, test procedures, and problems. As a follow up to the questionnaire, interviews were arranged with representatives of four state transportation departments. This allowed for more in-depth discussions of specific problems with control of air content experienced by these agencies. Subsequent to these meetings, materials in question were obtained from the agencies and evaluated at the Construction Technology Laboratories (CTL). In addition, studies were carried out on the sensitivity of air content to small changes in water content, and on air void characteristics in low-slump, dense concretes.

All information obtained from the literature synthesis, questionnaire, interviews, and laboratory studies was used to prepare a set of guidelines for production of air entrained concrete. Also, a verification program which could be used by field personnel was assembled.

Results of this research are discussed in the remaining chapters of this report. Additional details of the research effort are included in Appendixes A through E. An abstract and table of contents for the state-of-the-art report are included as Appendix F. (The complete report is reproduced in an addendum, which is available on a loan basis or for the cost of reproduction from the Director, Cooperative Research Programs, Transportation Research Board, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.)

CHAPTER TWO

FINDINGS

The findings of this study indicate that no general, nationwide problem in control of air content exists. For the most part, problems that are encountered can be explained using knowledge developed during the past 40 years since air entrainment has been used in concrete. Specifications are slowly evolving towards more realistic formats, and an appreciation of the need for improved sampling techniques has developed. Some special cases, such as low slump slipform and dense overlay mixtures, do require more careful control and stricter attention to such items as dosage rates and additions of water. While most problems which develop apparently stem from lack of appreciation of the effects of construction practices and concrete production methods on air content, materials interactions do exist. These interactions are so complex that their complete elucidation is not possible at this time. In this chapter, findings will be discussed in the context of their impact on control of air content.

SUMMARY OF LITERATURE STATE OF THE ART

The literature review represents a compilation of much of the currently available knowledge concerning the use and effects of air entrainment in portland cement concrete. Objectives were to critically review the literature on air entrainment and, from this review, to suggest directions that may be taken to find solutions to current problems. The literature review, although extensive, was not completely comprehensive. Over 1,000 references to published literature were reviewed during compilation of the review. However, it is likely that many times more are contained in the unpublished literature. This summary is presented in a concise manner to acquaint the reader with salient findings of the review. Those wishing to review or study the synthesis in more detail may obtain a copy of the complete document from NCHRP (see App. F).

Historical Review

Air entrainment has now been an accepted fact in concrete technology for more than 40 years. Although historical references indicate that certain archaic (1) and early 20th century (2) concretes were indeed inadvertently "air-entrained," the New York State Department of Public Works (3) and the Universal Atlas Cement Company (4) were among the first to recognize that controlled additions of certain naturally occurring organic substances derived from animal and wood by-products could materially increase the resistance of concrete in roadways to attack brought on by repeated applications of deicing agents.

Laboratory and field investigations carried out by various highway agencies, the cement industry, and others led to a general consensus that the improved resistance was achieved through the presence of a system of minute air bubbles dispersed throughout the mortar matrix of the concrete. The formation of bubbles was enhanced by the surfactant properties of the organic additives which enabled the bubbles to be stabilized or "entrained" within the fresh concrete. Subsequent commercialization of these products and synthetic derivatives has led to a large market for "air-entraining agents."

Tests and specifications for both air-entraining admixtures and the air-entrained concrete itself were developed by ASTM, AASHTO, state highway departments, and other agencies. Air-entraining agents must now pass a rigorous series of quality and performance tests before being accepted under these specifications. Tests for air content in fresh concrete based on pressure-volume relationships (5, 6, 7) have come to be accepted as useful quality control tools. Check tests using simple volumetric displacement meters (8) have merit as a rapid quality control tool if used carefully and with knowledge of their limitations. More rapid means of determination of air content of in-place concrete as well as determination of the air-void system in advance of the final hardening of the concrete are needed.

Specifications

Specified air content limits have generally increased over the years. Initially, limits of 2 to 5 percent on entrained air were considered acceptable (9). Current limits range from 4 to 8 percent with the upper values of this range being recommended by most authorities. It has been found, however, that tolerances on air content are often unrealistically rigid (10) and do not reflect the true variability of the product. Specifications based on statistical sampling theory are increasing in popularity and more effort in this direction is to be expected in the years ahead.

Types of Air-Entraining Agents

Air-entraining agents themselves are composed of molecules having both hydrophilic and hydrophobic characteristics, much like soap and many other surfactant formulations. By virtue of their ability to lower the surface tension of water and to precipitate a film around air bubbles formed during the mixing process, air-entraining agents are able to stabilize air bubbles until the concrete begins to harden. This prevents them from escaping from the mixture (11). The most commonly used types of air-entraining agents are wood resins, sulfonated hydrocarbons, fatty and resinous acids, and synthetic materials (12). More information is required concerning the exact makeup of these products, and rapid techniques for analysis of these products in the laboratories of purchasing agencies are needed.

Materials Factors

While the particular air-entraining agent being used has an effect on the number and distribution of air voids generated in concrete, factors such as cement, sand, aggregates, and other admixtures also play important roles. As a general rule, air contents will increase with increase in cement alkali levels (13) and decrease with significant increase in cement fineness (14). Chemical admixtures such as water-reducers (15), retarders, and accelerators (16) may increase air content to some extent when used in normal dosage ranges. Therefore, it is necessary to adjust the dosage of air-entraining agent when using such admixtures.

Some newer types of admixtures, such as high-range water reducers, commonly referred to as "superplasticizers," apparently interact with cements and air-entraining agents such that the void size distribution of the entrained air is altered (17). This results in spacing factors higher than normally considered acceptable for good resistance to freezing and thawing. Substitute cementitious materials, such as fly ash, may also alter air-entraining agent dosage rates. Some fly ashes, especially those high in carbon, may require unusually large dosages of air-entraining agents for the concrete to meet specified air contents (18). Impurities in cement, sand, water, or other materials usually have a minor influence on air content, but in some cases substantial effects have been noted (19, 20). Many pigments, especially those utilizing carbon black, have the capacity to inhibit development of entrained air void systems in concretes (21).

Mix Design Factors

The proportions in which materials for concrete are combined (concrete mix design) also influence air contents. Increasing cement content increases the amount of air-entraining agent per unit of cement needed to achieve a given air content (22). This is especially true in very rich mixtures typical of those used for high strength concretes in overlay applications (see App. E). Increasing the water-cement ratio, primarily by addition of water to increase or maintain workability, tends to increase air content up to a certain point (23). Beyond this point the fluidity of the concrete becomes so great that a stable air system cannot be maintained and air contents decrease. Use of larger maximum aggregate sizes reduces air contents in concrete as a whole. Thus it is generally recommended that air contents in the mortar fraction be held in the range of 9 ± 1 percent (24). An increase in sand content increases air content about 1 percentage point for every 10 percent increase in sand (22). Sand gradation has only a minor effect, at least within the gradings that would be acceptable under most current specifications. Other factors, such as aggregate shape and texture, may have an influence in isolated incidences; however, no general trends have been established.

Construction Practices

One of the most important areas influencing the air content of concrete is construction practice; that is, the way any given concrete load is batched, mixed, transported, placed, consolidated, and finished. The sequence in which materials are added to the mixer can have an effect on air content (25). Any procedure in which the air-entraining agent comes into contact with cement prior to the introduction of other materials may adversely affect air content. Any significant delay in addition of air-entraining agent may increase the air content. Batch size may cause air contents to rise as the full capacity of the mixer is approached (22). Air content will increase with mixing time up to a certain point which varies with the particular mixer and materials being used (26). This maximum is reached more rapidly in central mixing than in truck mixing operations. Over the range of mixing speeds commonly encountered, only slight effects of drum speed on air content are discernible. Variations in air content sometimes occur between mixers, especially on large jobs where truck mixing is employed (10).

During transport to the job site some loss of air can generally be expected. This can range from 0.5 to 1.0 percentage point and may be somewhat greater if initial air contents are above 6 percent (27). Air loss occurs both in agitated and nonagitated delivery units. If trucks are allowed to agitate the concrete over extended periods at the job site, air losses of up to 4 percentage points may be encountered (25). Little information is available on the effects of other placement techniques on air content, although some studies indicate that air content may decrease during belt conveyor (28), pumping (29), or shotcreting (30) operations.

Concern has often been raised over the possibility of significant loss of entrained air during consolidation of concrete, especially when internal vibrators are used on mechanical paving trains. While studies of vibration of concrete contained within small vessels in the laboratory do indicate that large amounts of air can be forced out by this internal vibration technique (31), significant losses have not been observed at normal paving speed and vibrator frequencies in actual field operations (32). At very high frequencies (great than 11,000 vpm), or when the paving train is stopped and vibrators are allowed to continue running, some air loss may be expected.

Manipulation of concrete subsequent to consolidation, including screeding, floating, and finishing, has little effect on air content in most instances when good practices are employed (33). Overfinishing, especially when water is worked into the surface, can alter the air-void system as well as decrease the strength of the uppermost layer of concrete.

Finally, field personnel must maintain close surveillance of both ambient air and concrete temperatures when air-entrained concrete is being placed because the amount of air-entraining agent needed to obtain a given air content may as much as double for a concrete temperature rise of about 30°F (34).

Air Content and Durability

The usefulness of air entrainment as a means of greatly increasing the durability of concrete has been demonstrated over a long series of laboratory and field investigations. Theoretical work has indicated that the minute air voids introduced into concrete during mixing must, in the final hardened state, be of such a size and spacing that disruptive forces induced by migration of moisture during freezing can be relieved before the tensile strength of the concrete is exceeded (35).

Because average void spacing decreases with increasing air content (provided the average void size is the same or less), an "optimum" air content will exist at which void spacing will be such as to prevent excessive pressures from developing. Over a wide range of conventional concrete mixtures, this optimum air content generally has been found to be that which corresponds to an air content of 9 ± 1 percent in the mortar fraction (24). When specific concrete mixtures are tested, a better correlation is obtained between freeze-thaw durability and the actual measured spacing factor of the air voids (36). For some mixtures, such as high strength concretes having low water-cement ratios, lower air contents may be sufficient to ensure good durability (37). Presumably, this is due to the beneficial effects of low water-cement ratio on reducing both the permeability and the amount of freezable water in the concrete, and increasing the tensile strength of the concrete.

Other factors such as aggregate type, degree of saturation, water-cement ratio, degree of consolidation, and cement content also are important in ensuring good durability (38). Air entrainment will provide only marginal improvement in durability where frost-susceptible aggregates have been employed. When subjected to repeated applications of deicing agent such as sodium or calcium chloride, water contents must be held to a minimum and good curing practices should be used. Concrete should be allowed to dry for some time after curing and prior to the first application of deicing salts (39).

Effects of Air Content on Other Properties of Concrete

Air entrainment has been found to have a beneficial effect on most properties of fresh and hardened concrete provided that the mixture is well proportioned and advantage has been taken of the effects of air entrainment on slump and workability of the mix. If this is done, workability can be increased, bleeding decreased, finishing expedited, and a more uniform product obtained. Entrained air has only minor effects on such properties as shrinkage, creep, fatigue, bond strength, and abrasion resistance of hardened concrete. The ability of concrete to withstand attack by sulfates and internal degradation by reactive aggregates is enhanced by air entrainment. The only properties that are deleteriously affected by entrained air are strength and elastic modulus. These effects can be minimized by proper mix design, although some loss of strength is still to be expected, especially in high strength concrete mixtures.

Overall, the synthesis describes in detail the many factors that may influence air content and the air void system in field production of air-entrained concrete. Armed with a knowledge of these factors and an appreciation for high quality workmanship, the practitioner will be able to produce durable, uniform, air-entrained concrete under most conditions. Many effects lie relatively unexplained, however, and there exists a need for research in many areas within the technology of air entrainment in concrete.

CURRENT AIR CONTENT SPECIFICATIONS

All 50 states, the District of Columbia, and 12 other agencies received questionnaires (App. A), in which information concerning current specifications on air content was requested. Responses from individual agencies are included as Tables A-1 and A-2. Table 1 summarizes the responses, which are separated into various categories of uses of concretes.

It is readily seen that specification limits are remarkably similar for each category of structure. This indicates that, in general, little distinction is made between various types of structures when specifications on air content are developed. For the state transportation departments, average limits run from about 4 to 7 percent, which encompasses a range of close to 3 percentage points. The average midpoint, or what might be considered as the "target value," runs from 5-1/2 to 6 percent. Values of specification limits for the other agencies surveyed are only marginally higher than for the states.

Further information on the distributions of these limits for one category of concrete, that used in pavements, is given in Table 2.

Only two states have lower limits less than 3 percent, while only three states have upper limits less than 6 percent. The bulk of the lower limits lies between 3 and 5 percent, and the bulk of the upper limits lies between 6 and 8 percent. These specification limits are not materially different from those published by the Portland Cement Association (40) in a survey conducted in 1975. Thus, it appears that there has been little change in specification on air content over the past 7 years, at least for those grades of concrete used in pavement construction.

RESULTS OF QUESTIONNAIRE

In addition to obtaining information on current air content specifications, a questionnaire was circulated to state transportation departments and other agencies to obtain information on problems in control of air content currently being

Table 1. Summary of Air Content Specifications.*

	Type of Structure				
States	Bridge Decks	Pavements	Abutments, Piers, Girders	Shoulders, Curbs, Gutters	Median Barriers
No. of Responses	50	49	49	47	46
Average Limits	4.5-7.2	4.1-7.0	4.1-7.0	4.2-7.2	4.3-7.2
Average Range	2.7	2.9	2.9	3.0	3.0
Average Midpoint	5.8	5.6	5.5	5.7	5.7
Other Agencies					
No. of Responses	12	9	12	11	9
Average Limits	4.6-7.3	4.5-7.1	4.5-7.2	4.6-7.3	4.7-7.4
Average Range	2.8	2.6	2.7	2.7	2.7
Average Midpoint	5.9	5.8	5.9	6.0	6.1

*All average data are given as percent by volume of concrete.

Table 2. Distribution of Specification Limits.

No. of States Having Lower Limit Equal to*	No. of States Having Upper Limit Equal to*
2% - 2	4% - 1
3% - 9	5% - 2
4% - 18	6% - 8
5% - 18	7% - 18
6% - 1	8% - 18
	10% - 1

*In those cases where fractional value was encountered, it was rounded to the next highest integer.

experienced by those agencies. A total of 16 questions was included. It should be noted that only two agencies indicated that no problems existed in control of air contents. Detailed summaries and statistics on agency responses are included in Appendix A. Only the major categories of responses will be discussed in this chapter.

Structural Type and Environment

The majority of problems occur in structural, as opposed to paving grade, concretes. This was attributable to the greater testing frequency on structural concretes, possible increased use of truck mixing for structural jobs, and the presence of more adequate controls on full-scale paving operations.

As far as environmental factors are concerned, most problems occur under hot, or hot and dry, weather conditions. This can be explained by the need for increased dosages of air entraining agent in hot weather, and the occurrence of slump loss problems in such climates.

Materials

Problems arising due to conventional concrete materials (i.e., cement, aggregates, and water) were relatively few. Type III or blended cements caused some concern, as did "hot" cement in two instances. Aggregates problems were tied to deficiencies in some local sources such as poorly graded sands, salt contamination, and porous aggregates. Clays, fines, and silty materials also were said to be deleterious. Some contamination of mixing water sources by mineral fines or chemical effluents also was noted.

Respondents to the questionnaire voiced some concern over the effects of water-reducers and retarders on air content. Most of these indicated either that air content was increased when water-reducers or retarders were used, or that adjustments had to be made in the dosage of air-entraining agent. Lignosulfonate-based retarders were the most prevalently mentioned in terms of their effects on air content. Superplasticizers were also mentioned as causing problems with control of air content. Some agencies noted that superplasticizers either tended to decrease air content or to alter the air-void system measured in the hardened concrete.

About half of the respondents mentioned fly ash as either influencing air content or contributing to control problems. High loss on ignition or carbon content was suspected as a cause of problems in many cases. Some agencies noted that while fly ash generally tended to lower air contents, the addition of increased amounts of air entraining agent (up to double dosage in some cases) allowed the specified air content to be obtained. A limited number of agencies experienced problems with other types of admixtures, such as pumping aids, calcium chloride, latex modifiers, and black pigments.

Batching, Mixing, and Transport

With regard to batching procedures the most prevalent problem cited was intermixing of undiluted admixtures. For instance, it was noted that mixing of air-entraining agents and retarders, in some instances caused "gelling" of the resultant solution. As failure to batch air entraining agents directly into the mix water is a direct cause of control problems, the general feeling was that admixtures should be batched separately. Some respondents advocated batching of one admixture onto the sand, the other into the batch water, while others recommended consecutive batching into the water, with care being taken to ensure that undiluted admixtures did not come into contact before reaching the water line. Other sources of problems cited were malfunctions in dispensing equipment, personnel errors, variations in batching sequence, and outdated or previously frozen air entraining agents.

Various instances where mixers and mixing procedures have led to problems with control of air content were cited. Problems in equipment maintenance, more specifically worn or concrete-encrusted mixer blades, and problems caused by over- or under-mixing are included among these. The nonuniformity of truck mixers as opposed to stationary central mixers and the use of mobile mixers were seen as a cause of problems in a few cases.

Some degree of concern with air loss in concrete was mentioned. Long hauls or other factors leading to delay between mixing and discharge were cited as being causative factors in instances of air loss. Also noted were hot weather and prolonged mixing, either separately or in combination. In addition, a few agencies noted that pumping tended to cause air losses of up to 2 to 3 percentage points.

Consolidation and Finishing

In most areas, vibration-induced air loss or poor durability are not serious problems. A few agencies appeared to feel that a certain amount of air loss was inherent to vibration, but that most of the air lost was of the entrapped type. "Over-vibration" was reported to lead to air loss, with slipform machines being mentioned as a cause of air loss problems. High frequency vibrators and high slump concrete were each seen by two agencies to be conducive to air loss.

About one third of the agencies surveyed mentioned "over" or "excessive" finishing as being a cause of either air loss or scaling, predominately in the surface layer. Addition of water to the surface of the concrete, a practice adopted by many finishers in order to speed production, was also seen as a cause of problems. Other causes mentioned were early finishing and hand finishing. Some miscellaneous occurrences mentioned were the inadvertent overlap of disc screed finishers, excessive bullfloating, and edge finishing.

A special case in the area of consolidation involves low-slump concretes. Some agencies expressed concern over failure to achieve specified air contents in low-slump concretes. Others noted that even with large dosages of air entraining agents, air contents were still on the low side of the specification. Difficulties in accurate measurement of air in low-slump concrete were also noted. These difficulties were attributed to such factors as poor consolidation (which would tend to raise the measured value over the true value) or a belief that current techniques were inherently unsuited to very stiff concretes.

FIELD PROBLEMS ENCOUNTERED

Following review of the questionnaires, a number of agencies were asked for additional information concerning on-going field problems. Those agencies experiencing major problems in control of air content were selected for in-depth interviews with the principal investigators. Four state transportation departments: Illinois, Indiana, New York, and New Jersey, were selected. The objectives of the interviews were: (1) to discuss any general problems in control of air content that did not fall into any of the obvious categories, and (2) to discuss unique problems in control of air content that might be related to particular materials or operations. Following these interviews, materials were supplied by two of the states interviewed, and follow-up laboratory work was carried out in an attempt to explain some of the control problems. Summaries of these interviews and the laboratory studies follow.

Illinois Department of Transportation

Meetings were held with representatives of the Illinois Department of Transportation. Topics of discussion included limited number of dense concrete overlay jobs as well as some unusual air loss problems on bridge deck placements. For the most part, experiences with low-slump, dense concrete overlays have been good, although some mechanical difficulties have been encountered with mobile batcher-mixers used in such projects. Compaction and air contents of the low-slump concretes were found to be satisfactory if a high-capacity paving vibrator was used, or if a superplasticizer was added to the mix to increase workability. Durability to date has been excellent, although only three years have elapsed since the first placement.

More problems in control of air content were encountered on certain bridge deck placements. Air loss was noted in a bridge deck cast using a wood resin (not Vinsol) air-entraining agent. Air content was 10 percent at the plant and 4 percent at the job. Temperatures ranged from 58°F to 62°F, and slump loss did not appear to be a problem as hauling time was only 15 minutes. The problem persisted for a number of weeks and then appeared to resolve itself. The cause of the problem was never fully determined.

In another case a Vinsol resin air-entraining agent was used with a hydroxylated polymer type retarder. The first eight loads of concrete exhibited satisfactory air contents; however, large increases in air content were seen on subsequent loads. By decreasing air entraining agent dosage by 20 percent, subsequent air contents stabilized at 6 to 7 percent. Because job records were incomplete (no records of slump and temperature were available for most of the batches), it was not possible to conclusively state the cause of the problem.

Similar problems were seen on other jobs, where various types of air-entraining agents were used alone and in combination with other admixtures.

In general, Illinois DOT engineers seemed to feel that there were fewer problems when conventional Vinsol resin-type admixtures were used than when sulfonated hydrocarbons or some of the newer type admixtures were used. In Illinois, Vinsol resins are specified in central-mix paving jobs because it is claimed that other types of admixtures do not develop air as quickly in central mixers. Illinois DOT engineers also feel that in paving jobs where large quantities of materials are used, admixtures are fresher and do not have a chance to deteriorate in drums, or freeze over in the winter season.

Indiana State Highway Commission

A meeting was held with a Materials Research Engineer of the Indiana State Highway Commission. Topics for discussion included some limited work on dense low slump mixes as well as a problem in air entrainment on a pavement job. Poor durability was noted in some dense concrete overlays placed in 1979. A report published in 1982 (41) indicated the presence of high amounts of entrapped air in cores taken from these overlays, as well as a poorly developed air-void system that failed to meet ACI recommendations (42). There appears, then, to have been problems in achieving adequate consolidation on these placements.

A second problem concerned the apparent need for large amounts of air-entraining agent on a particular paving job where ASTM Type IA cement was used in combination with an alkali-stabilized wood resin air-entraining agent. When these same materials were tested at CTL, however, dosage was similar for this agent and for a standard neutralized Vinsol resin. Type IA cement apparently contributed little to the entrained air content. The need for high dosage rates encountered on the job could not be reproduced in the laboratory. This indicated that job procedures, environment, and other factors may have been the cause of these field problems.

New York State Department of Transportation

A meeting was held with the New York State Department of Transportation. In attendance were state materials engineers, field district engineers, and two concrete producers. The major problem appeared to be a need for unusually large dosages of air-entraining agent in certain transit mix operations. The problem has been seen with a number of different cements, most of which were ASTM Type II. The problem occurred mainly over the past two years, usually where a particular sulfonate hydrocarbon type air entraining agent was used. However, the problem apparently was not confined to this agent. Water reducers were used in an attempt to lower air-entraining dosage; however, no major effects were seen. When a wood resin air-entraining agent was tried, very high amounts were needed. Producers claimed that up to 33 ounces per cu yd of concrete were necessary to obtain the 4 percent air minimum.

When these materials were tested at CTL, the need for high dosage rates was verified, and was much higher when concretes were not remixed. The cause of these high dosage requirements was attributed to a false-setting tendency in the cement supplied to this particular project. Suggested solutions were to change cement source or to include a remixing period.

No other major problems with control of air content in New York were reported. However, the lack of consistent batching procedures in some precasting plants was seen as a cause for concern in obtaining uniform air contents.

New Jersey Department of Transportation

A meeting was held with representatives of the New Jersey Department of Transportation. In attendance were representatives from the Bureau of Inspection, Engineering, Evaluation and Coordination, representatives from the Quality Control Laboratories, and representatives from the Research and Development Division. The history of air content specifications and air content control problems in New Jersey was briefly reviewed. An increase in testing frequency and improved quality control programs in recent years has highlighted the need for more control over air content.

On one project in which the air content was taken on every truckload of concrete produced, a large number of loads were found to be out of specification, and dosage rates needed to obtain specified air contents were very erratic. The most widely used air-entraining agent in New Jersey is an alkylbenzene sulfonate type, which is commonly used at 3/4 to 1 ounce per hundred weight of cement. On many mixes, however, 3 to 4 ounces per hundred weight were needed to get an air content of 6 percent. The air contents of some mixes were highly sensitive to changes in slump.

The mixes which showed the most problems were mainly what New Jersey terms "white concrete." These mixes utilize relatively finely ground white cement with a highly reflective calcite sand, and are dry-batched at the plants. It is possible that the air-entraining agent is absorbed onto the sand during batching, as most of the work in New Jersey is done by truck-mixing. That is, the water is not added until the truck, which is nonagitating, reaches the site. New Jersey, however, is in the process of shifting to central mix and transit mixing to improve control.

After the meeting, representatives from the Research Division accompanied the principal investigator to field sites on which scaling had occurred on median barriers. Some of the scaling was especially severe. It was noted that the north side of the medium barriers appeared to scale to a greater degree than the south side. Cores from these barriers showed very low air contents, low specific surfaces, and high void spacing factors. A report issued in April 1981 (43) attributed the poor durability of these median barriers, and of curbs, to unsatisfactory air-void systems. Occasionally, concrete quality was degraded by the use of high water-cement ratios and poor curing practices.

SENSITIVITY OF AIR CONTENT

The majority of the control problems documented in this investigation either involved apparently unique interactions between given sets of materials, or could be grouped into categories that have been generally recognized for many years by practitioners in the field. All of these problems can best be handled at the local level by applying general principles set forth in the guidelines (App. C) to each specific job.

There did exist, however, two areas where little previous research has been done, where some degree of concern exists, and where preliminary laboratory study was considered useful. The first of these problems relates to the tendency of some relatively low slump mixtures to be particularly sensitive to increases in water content, as reflected in changes in slump and air content. For instance, Gaynor (44) notes that "...the phenomenon of increased slump producing an increased air content is particularly critical at slumps between 2 and 3 inches...in the critical range the addition of as little as 1/2 gallon of water per cubic yard may increase slump 1 to 2 inches and air content 1 to 1.5 percent." This contrasts with the often cited rule-of-thumb that a change in net mixing water of about 3 percent (corresponding to approximately 6 to 8 lb/cu yd) will effect a change of only 1 in. in slump and 1/2 percent in air content.

To investigate this problem, a series of concrete mixtures was prepared using two different air-entraining agents (a Vinsol resin and an alkyl-benzyl sulfonate), two concrete mix designs, and nominal air contents of 5±1/2 percent, 6±1/2 percent, and 7±1/2 percent. The initial slumps were held close to 2 in. Details of the study are given in Appendix E. Results, which are summarized in Table 3, show the amounts of water needed to change slump by one inch and air content by 1 percent in this so-called "critical region."

For many of these mixtures, the amount of water (expressed as a percent of net mix water) needed to increase slump by 1 in. is less than the 3 percent figure commonly accepted. The amount of water needed to change the air content by 1 percent is even more critical. In one instance it was as low as 1.2 percent of the net mixing water.

Overall, those mixtures incorporating neutralized Vinsol resin as the air-entraining agent appear to be more sensitive to changes in water content than those prepared with the alkyl-benzyl sulfonate. In addition, sensitivity of slump and air content to changes in water increases with an increase in nominal air content. This is apparently more pronounced for the alkyl-benzyl sulfonate than for the neutralized Vinsol resin. The latter appeared to be equally sensitive at all nominal air contents.

DENSE OVERLAY MIXTURES

A second topic of interest was air entrainment in low-slump dense concrete (LSDC), which forms the basis of the so-called "Iowa" method of bridge deck resurfacing. In addition to restoring a high-quality riding surface to severely deteriorated decks, these LSDC overlays, by virtue of their very low permeability, can significantly reduce the rate of chloride ion penetration into concrete and thus protect reinforcing steel from progressive corrosion.

The LSDC incorporates a high cement factor of approximately 826 lb per cu yd, low water-cement ratios of 0.30-0.32, and air contents specified at 6.5±1.0 percent (45). Vigorous vibration is needed to achieve the required degree of consolidation. Experience in placement and performance of this system has, in general, been quite good. A study by Iowa DOT on 16 overlays ranging from 5 to 13 years of age indicated that none of the installations showed any evidence of riding surface

Table 3. Behavior in The "Critical Region".

Air Entraining Agent*	Nominal Air Content (%)	Amount of Water Needed to Change: Air Content by 1%		Slump by 1 inch	
		lb/cu yd	% net	lb/cu yd	% net
		PAVEMENT MIXTURE			
A	5±1/2	3.7	1.5	5.8	2.4
A	7±1/2	3.4	1.5	3.4	1.5
B	5±1/2	20.0	8.5	9.2	3.9
B	7±1/2	3.7	1.6	3.8	1.7
		STRUCTURAL MIXTURE			
A	6±1/2	2.9	1.2	5.6	2.2
B	6±1/2	7.6	3.0	10.2	4.0

*A - neutralized Vinsol resin
B - alkyl-benzyl sulfonate

distress (46). Likewise, LSDC overlays installed by Minnesota DOT from 1975 through 1977 have shown good performance (47). Previous laboratory studies (48), though not extensive, show that LSDC has excellent resistance to freeze-thaw deterioration as well as to deicer scaling, and develop air-void systems meeting all generally accepted requirements.

In spite of this generally good laboratory and field performance, questions still arise concerning the long-term durability of LSDC overlays. This is evidenced by information supplied in the Indiana interviews and responses to question No. 14 of the questionnaire (App. A). It was apparent that, at the very least, some preliminary laboratory work was called for if some of these concerns were to be resolved. Detailed descriptions of the laboratory studies are given in Appendix E. A summary of findings is given below.

Air Contents in Fresh Concretes

Four air-entraining agents were included in the initial series. In addition to the Vinsol resin and alkyl-benzyl sulfonate used in the previous studies, two other agents were investigated. These were a tall-oil derivative and an alkali-stabilized wood resin. The dosages needed to obtain the specified air contents in the standard "Iowa" dense concrete expressed as percentage of solids in the admixture by weight of cement (% s/c) are presented in Table 4.

The dosages of neutralized Vinsol resin and alkyl-benzyl sulfonate needed to obtain the specified air content are about one order of magnitude higher than for these same agents when used in conventional concretes. Even at very high dosages, it was not possible to obtain specified air contents with the remaining two agents. Also, for the LSDC mixtures, the sensitivity of air content to changes in air-entraining agent dosage was greatly reduced. For instance, in the case of the neutralized Vinsol resin, 0.062 percent s/c was needed to change the air content by one percentage point. This corresponds to a dosage of about 6 fl oz/per hundredweight of cement simply to increase the air content by a single percentage point. Relationships between water content and air content, however, more closely followed those of conventional concretes. The net mixing water needed to effect a change of one percentage point in air content ranged from 10.5 lb per cu yd for the alkyl benzyl sulfonate to 16.5 lb per cu yd for the neutralized Vinsol resin. These correspond to approximately 4 and 6 percent of the net mixing water, respectively.

Air Contents in Hardened Concretes

Various techniques were used to obtain information on the air content and air-void distribution in hardened concretes. These included: linear traverse measurements (ASTM C457), measurement of entrapped air-void areas, and measurement of total air content using a high-pressure air meter. Measurements for entrapped air are described in detail in Appendix E. In essence, this involved filling the large voids with a white paste, then obtaining areas of each void using a computer-assisted graphics technique. High-pressure air measurements involved filling the air voids with water under 4,000 psi pressure, and relating the mass of water uptake to the volume of air voids. All of the techniques employed are described in Appendix E.

Specimens were prepared using two different air-entraining agents, a neutralized Vinsol resin and an alkyl-benzyl sulfonate. Both external and internal vibration were studied, and comparison was made to specimens consolidated by simple rodding.

Table 5 gives the results of linear traverse measurements on seven of the dense concretes. A conventional concrete is included for comparison. For all dense concretes, a large number of voids per inch, a high specific surface, and a low spacing factor are evident. The particular air-entraining agent used apparently has little effect on air-void characteristics. Those two specimens closest in air content (A-1V and B-1R), show virtually identical characteristics. The most striking difference is between the dense concretes as a whole, and the conventional mixture. This is reflected in void size distributions (see Fig. E-14), which show that approximately 50 percent of the air voids in the dense mixtures exhibit chord intercepts less than 150 X 10^{-5} in. In comparison, the 50th percentile for the conventional concrete is not reached until an intercept of 300 X 10^{-5} in. has been exceeded.

A comparison of air contents in the hardened state, as measured by the various

Table 4. Air-Entraining Agent Dosage Requirements in Dense Concrete Mixtures.

Air-Entraining Agent	Dosage(s) (% s/c)	Air Content (%)	Slump (in.)
Neutralized Vinsol resin	0.057	5.7	0.8
Alkyl-benzyl sulfonate	0.099	6.7	0.7
Tall-oil derivative	0.10-0.40	4.1-4.2	0.9-0.4
Alkali-stabilized wood resin	0.12-0.48	5.0-4.8	0.7-0.6

Table 5. Linear Traverse Analyses - Dense Concrete Mixtures.

Specimen*	Air Content - % Plastic	Hardened	Diff.**	Voids/ in.	Specific Surface ($in.^2/in.^3$)	Spacing Factor (in.)
A-1R	5.9	4.5	1.4	13.2	1173	0.0046
A-1V	5.5	4.8	0.7	17.0	1417	0.0037
B-1R	6.7	5.1	1.6	17.0	1333	0.0038
B-1V	6.6	3.8	2.8	11.3	1189	0.0049
ARII-1	6.0	4.5	1.5	13.7	1218	0.0045
AII-2a/	6.0	5.3	0.7	13.8	1041	0.0048
AII-3b/	5.6	4.4	1.2	17.4	1582	0.0035
C	6.9	5.8	1.1	8.8	607	0.0071

*A - neutralized Vinsol resin
B - alkyl-benzyl sulfonate
R - consolidated by rodding
V - consolidated by internal vibration
C - conventional concrete mixture
**Difference between plastic and hardened air contents
a/ 24 seconds of internal vibration per layer
b/ 60 seconds of internal vibration per layer

Table 6. Air Contents Measured in Hardened Dense Concrete Mixtures.

Specimen1/	Air Content - % Linear Traverse2/	Entrapped3/	Total Estimated	High-Pressure Meter4/	Plastic5/
A-1R	4.5	1.5	4.5-6.0	5.6	5.9
A-1V	4.8	1.6	4.8-6.4	5.1	5.5
B-1R	5.1	1.6	5.1-6.7	5.9	6.7
B-1V	3.8	0.9	3.8-4.7	5.5	6.6
ARII-1	4.5	1.4	4.5-5.9	6.4	6.0
AII-2a/	5.3	1.3	5.3-6.6	4.6	6.0
AII-3b	4.4	0.8	4.4-6.2	6.2	5.6

1/ A - neutralized Vinsol resin
B - alkyl-benzyl sulfonate
R - consolidated by rodding
V - consolidated by internal vibration
2/ ASTM C457
3/ See Appendix E
4/ See Appendix E
5/ ASTM C 231
a/ 24 seconds of internal vibration per layer
b/ 60 seconds of internal vibration per layer

techniques, is given in Table 6. Column 4, which is the "total estimated" air content, merits more detailed explanation. This estimate spans the range indicated by the linear traverse result and the sum of the linear traverse plus entrapped void results. The assumption made is that not all entrapped voids are fully accounted for by linear traverse measurements due to their relatively small contribution (in terms of numbers) to the total void population. When all measurements are compared, it is seen that the high-pressure meter results generally fall closest to the air contents measured in the plastic state. The range of total estimated air content generally encompasses the plastic air content figure, thus indicating that some of the entrapped air voids indeed may not be truly measured in the linear traverse technique.

CHAPTER THREE

INTERPRETATION, APPRAISAL, AND APPLICATION

CATEGORIZATION OF VARIABLES INFLUENCING CONTROL OF AIR CONTENT

One of the most useful consequences of the literature review was the information gathered concerning the importance of certain variables on the ability to achieve adequate control of air content. These variables could be grouped into five major categories: (1) concrete materials, (2) concrete mix design, (3) production procedures, (4) construction practices, and (5) environmental conditions. Within each major category there exists a number of subsets of relatively greater or lesser importance. This categorization affords the field engineer with a means of deciding which variables need to be more closely controlled in production of air-entrained concrete, and which have a lesser impact. Thus, he is able to apply knowledge gained in day-to-day operations and coalesce some of these relatively hidden factors into a useful tool.

In the following categorization, subvariables have been listed in an order which, in general, denotes their importance relative to the others in the same category. However, it should be recognized that in certain applications and under certain conditions one or more of the "less" important variables may assume a major role. In these cases professional judgment of the engineer, complemented by the information presented in guidelines (described in a later section), should allow a valid assessment of cause.

CONCRETE MATERIALS

- Cement - alkali content, fineness
- Admixtures - air-entraining, water reducers, pozzolans, accelerators
- Aggregates - sand, coarse aggregate
- Contaminants, fine materials
- Water - algae, wash water
- Pigments

CONCRETE MIX DESIGN

- Cement content
- Water content - w/c ratio, slump
- Sand proportion
- Maximum aggregate size
- Sand gradation

PRODUCTION PROCEDURES

- Batching sequence
- Mixing time
- Mixing speed
- Admixture metering
- Haul time

CONSTRUCTION PRACTICES

- Retempering
- Consolidation - vibration
- Transport - conveyors, pumping
- Finishing

ENVIRONMENTAL CONDITIONS

- Temperature

IMPACT OF VARIABLES ON AIR CONTENT

The categorization of variables, although the end-product of a lengthy literature search, is a relatively straightforward task. However, assessment of the impact of these variables on air content - that is, how a change in one or more variables will quantitatively influence air content - is much more difficult. It is apparent from review of the literature that a quantitative assessment is not possible at this time. One may know, for instance, that an increase in cement alkali content will result in an increase in air content, all other things being equal. However, the exact magnitude of the corresponding increase in air content for an increase of 0.1 percent in alkali content cannot be accurately predicted. The same holds true for the other variables listed in the preceding section.

This limitation on quantification of effects, however, does not prohibit one from assembling information on the probable impact of each variable on air content. Such information is given in Tables 7 and 8. In Table 7 the categories of concrete materials and mix design are combined to some degree. For instance both the properties of cement and the amount of cement will influence air content. Also included is an assessment of impact on the air void system, although in this case background data on which to base a decision are often lacking. In Table 8 information concerning effects of production procedures, construction practices, and environmental variables are presented in a similar format.

This information, obtained from the literature survey, was extremely useful in the assessment of significance of replies to the questionnaire. The overwhelming majority of problems encountered could be classified into one or more of the categories included in Tables 7 and 8. This implies that most of the concerns of field personnel are not at all novel, but are the

Table 7. Effect of Concrete Constituents on Air-Entrainment.

CONSTITUENT	TYPE	EFFECT ON AIR CONTENT	EFFECT ON AIR VOID SYSTEM	CORRECTIVE ACTION(S)
MIX DESIGN	CEMENT CONTENT	Decreases with increase in cement content.	Smaller and greater number of voids with increasing cement content.	Increase AEA 50% for 200 lb./yd^3 increase in cement. Increase AEA 10X or more for very rich, low slump mixtures.
	WATER CONTENT	Increases with increase in water content. Very fluid mixes show loss of air.	Becomes coarser at high water content.	1-inch slump increases air by 1/2-1 percent. Decrease AEA accordingly.
CEMENT	COMPOSITION	Type III requires more AEA. Alkali increases air content.	Effects not well-defined.	Use 50-100% more AEA for Type III. Decrease AEA dosage 20-40% for high alkali.
	CONTAMINANTS	Oxidized oils increase air. Unoxidized oils decrease air.	Little apparent effect.	Obtain certification on cement. Test for contaminants if problems develop.
AGGREGATES	SAND	Increases with increase in sand content. Organic impurities may increase or decrease air content.	Surface texture may affect specific surface of voids.	Decrease AEA as sand content increases. Check sand with ASTM C 40 prior to acceptance.
	COARSE AGGREGATE	Decreases as max. size of aggregate increases. Crusher fines on coarse aggregate decrease air content.	Little effect.	No action needed as required air decreases with increase in aggregate size. Hold percentage fines below 4 percent.
MIX WATER		R/M truck wash water decreases air content. Algae increase air.	Unknown.	Do not use recycled wash waters. Test water supplies for algae and and other contaminants prior to acceptance.
CHEMICAL ADMIXTURES	WATER REDUCERS/RETARDERS	Lignosulfonates increase air. Other types have less effect.	Spacing factors increase at higher dosages.	Decrease AEA 50-90 percent for lignosulfonates, esp at lower temperatures. Decrease AEA 20-40 percent for other types. Do not mix admixtures prior to batching.
	ACCELERATORS	$CaCl_2$ increases air content. Other types have little effect.	Unknown.	Decrease AEA when $CaCl_2$ is used.
	SUPERPLASTICIZERS	Naphthalene-based materials increase air content. Highly fluid mixtures may lose air.	Produces coarser void systems. Spacing factors increase.	Use less AEA with naphthalenes. Specify 1-2 percent higher air content if possible.
MINERAL ADMIXTURES	FLY ASH	High L.O.I. or carbon decrease air content. Fineness of ash may have effect.	Little effect.	Increase AEA. May need up to 5X more with high carbon ash. "Foam Index" test is useful check procedure.
	PIGMENTS	Carbon-black based may absorb AEA, depress air content.	Unknown.	Pre-qualification of pigment with job materials.

Table 8. Effect of Production Procedures, Construction Practices, and Environmental Variables on Air Content.

VARIABLE	TYPE	EFFECTS	CORRECTIVE ACTION(S)
PRODUCTION PROCEDURES	BATCHING SEQUENCE	Simultaneous batching lower air.	Avoid slurry-mix addition of ARA.
		Late addition of AEA raises air.	Do not batch AEA onto cement. Maintain uniformity in batching sequence.
	MIXER CAPACITY	Air increases as capacity is approached.	Run mixer close to full capacity, avoid overloading, clean mixer frequently.
	MIXING TIME	Central mixers-air increases up to 90 sec. Truck mixers-air increases up to 10 min. Air decreases after optimum time is reached.	Establish optimum mixing time for particular mixer. Avoid overmixing.
	MIXING SPEED	Air increases up to approx. 20 rpm. Decreases at higher speeds.	Avoid high drum speeds.
	ADMIXTURE METERING	Accuracy, reliability of metering system will affect uniformity of air content.	Avoid manual dispensing gravity-feed system, timers. Positive displacement devices preferred. Establish frequent maintenance and calibration program.
	HAUL TIME	Long hauls reduce air, esp. in hot weather.	Optimize delivery schedules. Maintain concrete temperatures in recommended ranges.
CONSTRUCTION PRACTICES	RETEMPERING	Air content increases after retempering. In effective beyond 4 hours.	Retemper only enough to restore workability. Avoid addition of excess water.
	CONSOLIDATION	Air content decreases under prolonged vibration or at high frequencies.	Do not overvibrate. Avoid high-frequency vibrators. Avoid multiple passes of vibrating screeds.
	TRANSPORT	Some air (1-2%) normally lost during transport. Air lost in pumping and on belt conveyors, esp. at higher air contents.	Avoid high air contents in pumped concrete. Do not use aluminum conveyors.
	FINISHING	Air content reduced in surface layer by excessive finishing.	Avoid finishing bleed water still on surface. Avoid over-finishing. Do not sprinkle surface prior to finishing.
ENVIRONMENT	TEMPERATURE	Air content decreases with increase in temperature.	Increase AEA dosage as temperature increases.

same, or similar to, problems in control of air content which have been encountered many times in the past. There are, of course, new types of materials such as superplasticizers and latex modifiers, which create new sets of problems. However, these appear relatively minor when compared to those having more traditional origins.

Assessment of the relative degree of importance of each of the variables was complicated by a number of factors. Qualified negative responses, responses which were unclear, and responses apparently based on intuition rather than actual cases, make a quantitative ranking of priorities very difficult. Such a ranking is attempted in Table 9. However, for the reasons cited above, those categories where the number of positive responses was roughly equivalent should be considered of equal rank. A "positive" response is one in which the agency indicated that a problem with air content did exist.

Not surprisingly, the most prevalent problems involved batching procedures and

Table 9. Relative Importance of Variables Affecting Control of Air Content.

Question No.*	Category	No. of Positive Responses
8	Batching procedures	37
6	Chemical admixtures	35
5	Cement, aggregates water	31
12	Finishing	25
10	Transport	24
11	Consolidation	21
7	Mineral admixtures	20
9	Mixing	15

*See Appendix A

chemical admixtures. The two were often linked, as many agencies cited intermixing of admixtures, malfunctioning of admixture dispensers, and outdated or frozen admixtures as the source of many "batching" problems. As for the admixtures themselves, the effects of water-reducers and retarders on air content seemed to be of primary importance, with superplasticizers also causing problems in some instances.

The next four categories seemed of equal importance. However, the fact that over 20 agencies do not currently specify mineral admixtures may bias the response on this topic towards the low end. Transport, consolidation, and mixing can be considered as manipulative variables, which apparently are of less concern than the actual production of concrete and the materials used.

One final point concerns the difficulty in assigning cause of field control problems due to limitations on sampling of concrete. As sampling is normally done at the point of discharge only, it is difficult to determine, in many cases, whether changes in air content are occurring at the plant or during transport. Also, problems due to consolidation and finishing are not readily assignable unless samples are taken after the concrete has hardened, which is a time-consuming and expensive undertaking. Thus, the relative importance of these categories should be considered in light of these limitations.

SPECIAL CASES

Air Content Sensitivity

The laboratory investigation described in detail in Appendix E indicated an unusual sensitivity of certain concrete mixtures to small changes in water content. These mixtures are characterized by a slump close to 2 in. and thus would frequently be used in conventional paving operations. This sensitivity is seen over a range of initial air contents from 4.5 to 7.5 percent when neutralized Vinsol resin is used as the air-entraining agent. Addition of approximately 1.5 percent of net mix water will increase the air content by a full percentage point, and will increase slump by about 1 in. Synthetic air-entraining agents of the alkyl-benzyl sulfonate type show less sensitivity than neutralized Vinsol resin in the range of 5 to 6 percent air, but are equally sensitive when air contents near 7 percent are used.

This sensitivity near the 2-in. slump level implies that within this region concrete changes from what might be termed a "stiff" plastic to a more fluid consistency. The additions of small amounts of water, then, are highly effective in allowing more air bubbles to be generated, thus increasing the dispersion of the air-entraining agent throughout the fluid phase.

This work does not imply that this air content sensitivity will be manifested on every job. It appears that only where additions of water will bring about a change in consistency of the concrete will this type of effect be seen. This sensitivity also helps to explain seemingly ambiguous changes in slump and air content which occur on some jobs. Since slump is normally controlled to ±1 in. and the accuracy of water metering is normally no better than 1 percent, it could appear that batching had remained constant, yet small undetectable fluctuations might actually contribute to changes in slump and air contents. If operations calling for slump levels near 2 in. are anticipated, closer control of water content and stringent restrictions on additions of retempering water may be required.

Low-Slump Dense Concretes

Low-slump dense concretes are coming into increasing use as overlays for concrete bridge decks (46) when the attendant low permeability to water and chloride ions is a desirable factor. Because the ability to obtain specified air contents and an acceptable air void system affects the long term durability of such concretes, laboratory studies, described in Appendix E, were designed to investigate these areas.

The need for high dosages of air entraining admixtures to achieve air contents in the specified range of 5.5 to 7.5 percent must be recognized by field personnel. Changes in normal operations, such as increasing the capacity of admixture flow lines and holding tanks, must be anticipated.

The greatly reduced sensitivity of these mixtures to incremental changes in air-entraining agent dosage must also be recognized. For instance, if air contents slightly below the minimum specification limit are initially obtained, up to 6 fluid ounces of agent per hundredweight of cement may be needed to gain the final one percentage point of air content necessary to bring the concrete to within specification.

Failure to achieve specified air contents with certain air-entraining agents means that the agents must be prescreened in these particular concrete mixtures prior to use on the job. Screening will not only eliminate those agents found to be ineffective, but will help establish trial dosage rates for initial field operations.

Good durability is to be expected, provided that the specified air content has been attained, and that the concrete is properly consolidated, finished, and cured. Air void systems in low-slump dense concretes are generally excellent, with specific surfaces exceeding 1,000 in.^{2}/in.^{3} and spacing factors being less than 0.005 in. These parameters, coupled with the low w/c ratio used in this type of concrete, should ensure long-term durability.

Consolidation, rather than total air content, appears to be the deciding factor in determining durability of dense overlays because large amounts of entrapped air may contribute to premature deterioration (41). If doubts exist as to the efficiency of consolidation, microscopic determination of entrained and entrapped air contents should be performed. A technique developed during the project (see App. E) has been found to be quite useful in determinating entrapped air contents in low-slump dense concretes.

UTILITY AND SHORTCOMINGS OF CURRENT SPECIFICATIONS

Current specifications on air content are set up either as target values with tolerances or as range type limitations. For example, a target value of 6 percent may be specified with a tolerance of ± 1-1/2 percent. Alternatively, a range of 4.5 to 7.5 percent may be specified. These two specifications are equivalent. Specifying agencies seem to agree on appropriate values because most specifications fall into the 4 to 8 percent range. Only a few agencies, mainly those in mild, southern regions, call for lower amounts of air. For example, Hawaii specifies 2 to 4 percent, Mississippi and South Carolina specify 3 to 6 percent.

Tolerances vary considerably. Some states maintain historical tolerances of ± 1 percent, while others permit variations ranging up to ± 3 percent. It is becoming increasingly apparent that wider tolerances are needed to accommodate actual field variations in air content and to enable contractors to meet more realistic specifications. Unrealistically tight tolerances may ultimately lead to a disregard for specifications and thus defeat their intended purpose.

Specifying agencies appear to make little differentiation between various types of structures in relation to specified air contents. There is a need for some modification in this regard because structures directly exposed to deicing salts and saturated freezing conditions obviously are in a more severe environment that those elements sheltered from the weather. For instance, it may be advisable to increase target values in bridge decks and decrease them in piers, columns, and other structural components.

In addition, it may be advisable to differentiate between structural types when setting up specifications on tolerances. For instance, where unit deliveries of relatively small quantities of concrete are made, such as ready mix truck deliveries to deck and girder pours, it may be possible to sample every load, thus increasing confidence in the results obtained and allowing a tightening of tolerances to be made.

Ultimately, statistically based specifications such as those currently recommended in ACI-214 (49) for evaluation of compressive strength results may supplement current formats. Advances in this regard have been made by the Federal Highway Administration (10), the Pennsylvania Department of Transportation (50) and others. However, more background data on actual field variations of air content need to be developed before such specifications can be enforced. Statistically oriented specifications will reward those contractors able to demonstrate good control over air content by allowing them greater latitude around target air values.

AIDS TO THE USER GUIDELINES FOR CONTROL OF AIR CONTENT

The guidelines presented in Appendix C are a condensation of the more voluminous literature report compiled during the course of this research program. They also include information gathered from the questionnaire, agency interviews, and laboratory studies in a form usable by various highway personnel. The aim of the guidelines presented in Appendix C is to provide the highway construction community with a concise reference work that clearly addresses these concerns and affords guidance to persons directly responsible for production and/or inspection of air-entrained concrete. It is recognized that field personnel might not want, or even need, to study a research-type document, so the most practical aspects of the synthesis were condensed into these guidelines as Appendix C. Within the guidelines, tables readily indicate the influences that various parameters have on the air content of concrete. It should be noted that the guidelines are not intended as a specification document, but only to offer advice on achieving necessary control of air content within the context of the specification for any particular job.

Administrative Personnel will find the guidelines useful as a reference text on which to base their own agency guidelines. Quality control and quality assurance managers will find them particularly useful.

Field Personnel will be able to reinforce their knowledge which is based on past experience with information obtained from a variety of sources. The material will be useful in planning and executing all types of construction projects involving use of air-entrained concrete.

Research and Laboratory Staff can use the guidelines as a basis for further investigations into the mechanisms of air entrainment, the variables which affect air content, and improvements in test methods and procedures.

The guidelines are organized into an introduction and five sections. The topics and application of each are summarized in the following discussion.

The objectives of the guidelines are outlined and a brief summary of contents is included in the INTRODUCTION.

Section 1 - Fundamentals of Air-Entrained Concrete. In this section the formation and role of air voids in relation to durability and other properties of concrete are discussed. Recommended air contents are presented for various aggregate sizes and exposure conditions. The types of materials used for air-entraining agents are discussed. A brief history concerning the development of air entrainment is also presented in this section. Finally, guidelines pertaining to mix design with air-entrainment and its effects on concrete strengths are included.

Section 2 - Materials for Air-Entrained Concrete. In Section 2 the concrete mix design and the influence other components of the mixture exert on the air content and air-void system in the concrete are discussed. Among the mix components considered are portland cement, aggregates (especially the fine aggregate), other chemical admixtures (such as retarders and accelerators), mineral admixtures (such as fly ash and other pozzolans), and impurities or contaminants that may be inadvertently introduced into the mixture. Some aspects of mix design that have a bearing on air-entrainment in concrete are the amount of cement, water-to-cement ratio, and ratio of fine-to-coarse aggregate. These various parameters are individually discussed as to their separate influences on entrainment of air in concrete. A summary table is included that will be useful to those persons desiring ready reference to a listing of such effects.

Section 3 - Production and Handling of Air-Entrained Concrete. This section discusses those variables which may be encountered during actual field production and construction phases, and which may lead to air contents and air-void systems differing from those anticipated from laboratory trial mixtures. Some variables that may affect air content during production of concrete include the method of batching, mixing procedures and duration, and agitation and transport of concrete to the field site. At the site, placement, consolidation, and finishing procedures may affect both the air content and ultimate durability of the concrete. During all phases of field operations, environmental factors, the most important of which is temperature, may cause control problems.

This section of the guidelines should aid users in high-lighting those construction procedures where effects are encountered, and thus where caution should be exercised in production of air-entrained concrete. As in the previous section, a summary table is included for ease of reference.

Section 4 - Sampling and Testing of Air-Entrained Concrete. In this section of the guidelines, condensed sampling and testing procedures are described. A discussion of rates of sampling and recommendations as to frequency of sampling on various types of projects are included. Sources of error common to standard test methods are analyzed, and deficiencies in these methods, when applied to certain situations, are noted. A discussion of the Chace air indicator is also included.

Section 5 - Specifications for Air-Entrained Concrete. This final section discusses current specifications on the air content of concrete set by highway agencies. A table gives the distribution of air content specifications across the ranges of air content normally employed.

IMPLEMENTATION OF GUIDELINES IN THE FIELD

To provide a basis for implementing the guidelines on field jobs, the verification program presented in Appendix D was developed. The objective of this program is to provide reference to information relating to control of air content in such a manner that construction-site personnel, such as state inspectors and engineers, can utilize this information quickly and efficiently. The program covers materials prequalification, simulation of job mixtures, batch plant and job site operations, and finally, provisions for documenting test results in a standard format. There may be unique problems that will not fit into any previously defined category. However, the program is sufficiently broad to encompass all but these very rare instances.

The program is designed around a "checklist" format in which the user is also called on to enter additional information in many areas. Reference is made to both ASTM and AASHTO standard tests, especially where prequalification of materials is needed. Field operations are approached on two levels. First, the user enters the basic mix and operations parameters pertinent to his particular job. For each batch (or delivery unit) he verifies that these parameters are as specified. Any modifications are also noted. If changes in air content occur which can be correlated with any obvious changes in these variables, the checklist is cross-referenced to the appropriate section in the guidelines (App. C) which addresses the variable in question. In this manner, not only can the user easily locate information pertinent to his operation, but a detailed job record can also be created. Personnel involved in later "troubleshooting" or follow-up studies will then have access to detailed job records which simplify the task of assigning causes to potential problems.

The verification program is organized into four major sections. The topics and a brief description of each are summarized in the following discussion.

Materials Qualification

Specifications and tests that are important to air entrainment in concrete are presented in this section. A chart showing the applicability of these tests to each material is shown in Figure 2.

Trial batching is recommended as a tool for determining proper admixture dosage rates to be used with the materials selected for the job. A flow chart delineating the trial batching process is shown in Figure 3. Recommendations and cautions for simulating field batching and mixing procedures in the laboratory are included in this section.

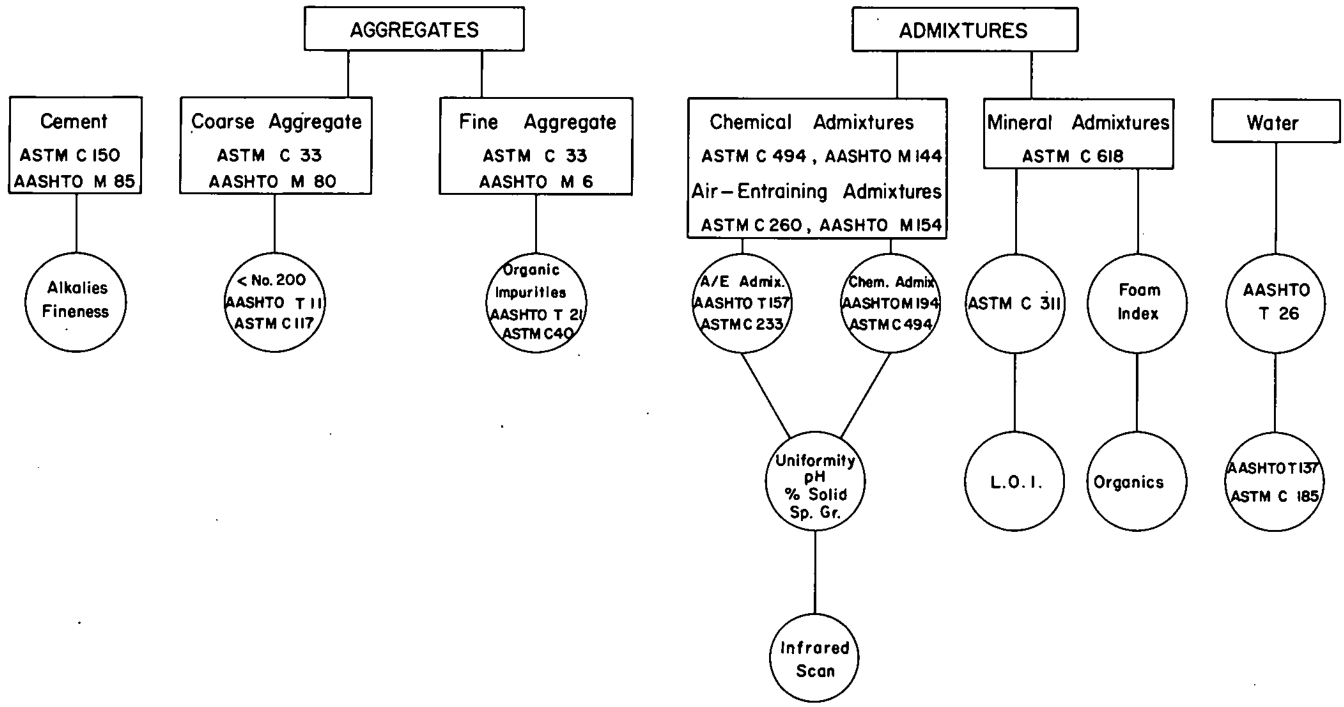

Figure 2. Materials qualification flow chart for air-entrained concrete.

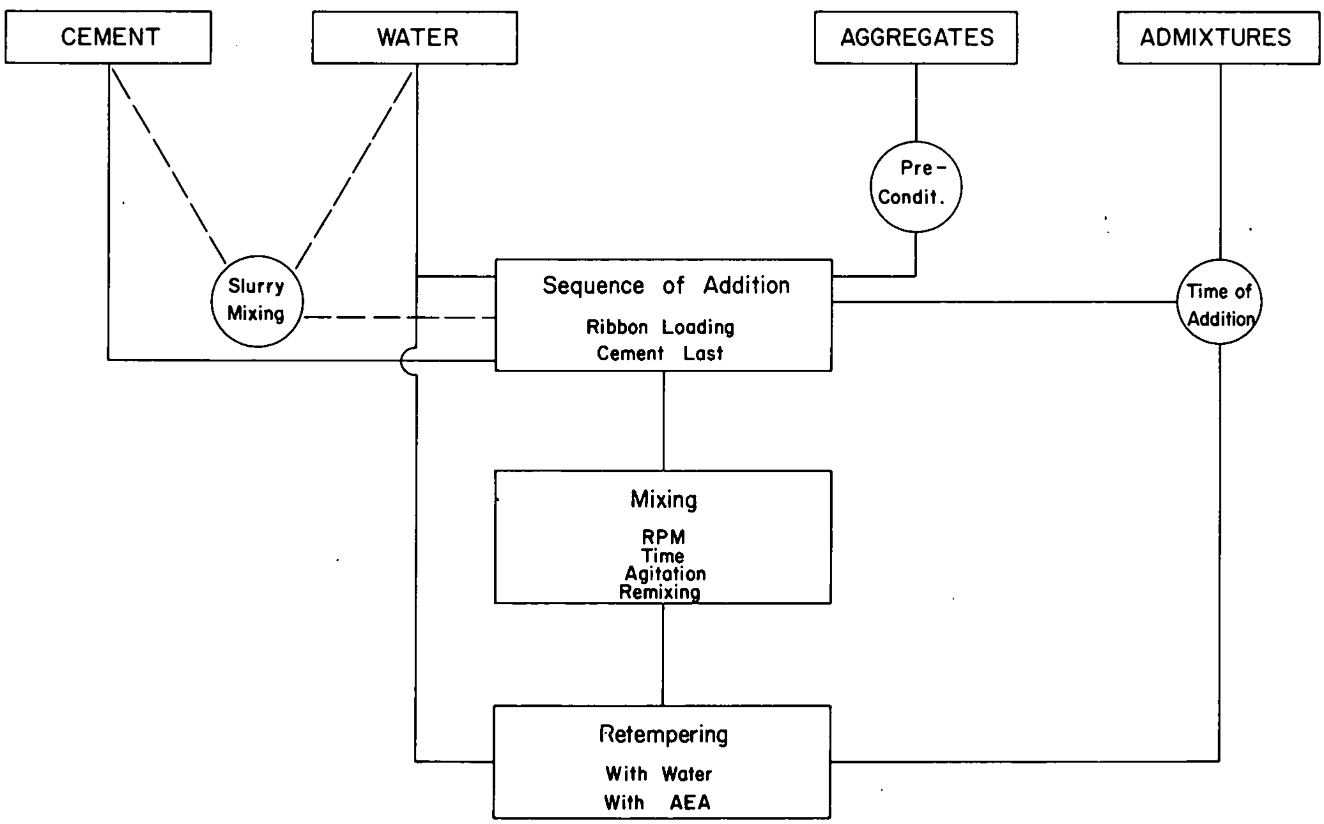

Figure 3. Trial batching process flow chart.

Batch Plant Operations

This section is devoted to mix design, materials, batching and mixing of concrete at the plant. Forms are provided for entering mix proportions and materials properties, as well as information relating to mixer operations and batching sequences. Checklists are provided in which normal operations can be verified, or notation made as to deviations from these operations.

Job Site Operations

In this section information relating to normal job procedures is entered on a project description sheet. This includes size of project, haul time, specifications on air content and slump, and placement, consolidation, and finishing techniques. A checklist is then provided in which these parameters, as well as additional items, can be verified. This includes site mixing, retempering water, site addition of admixtures, temperature and other pertinent categories.

Testing Procedures

Although detailed procedures to be followed in performance of air content tests can be found in relevant ASTM and AASHTO test methods, provisions for detailed logging of test results on actual jobs are often lacking. In this section tables are presented which can be used to record results of pressure (ASTM C 231), volumetric (ASTM C 173), and Chace Indicator methods. Information pertaining to the test apparatus is called for, such as I.D. number, date of last calibration, and operating pressure (where applicable). Information pertaining to the particular job materials and location such as aggregate correction factor, and method of consolidation of test sample, is also called for. Finally, the forms allow for a detailed record of the gross and net air contents for each load of concrete sampled.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

Based on work undertaken in this project, the following conclusions were reached:

1. Major variables affecting control of air content can be categorized into five broad classes: materials, mix design, production procedures, construction practices, and environment. Within each category, there exist a large number of factors that can have an impact on air content.

2. For the most part, current problems of control of air content do not reflect the use of new materials or adoption of new specifications, but can be assigned to causes already recognized within the categories mentioned above. Most frequently, problems occur with batching procedures and chemical admixtures.

3. Unusual sensitivity of air content to changes in water content may be evidenced with particular concrete mixtures under certain conditions. This is particularly true of relatively low-slump mixtures used in slipforming operations, and when Vinsol resin-based air-entraining admixtures are used or when relatively high air contents are specified in these mixtures.

4. Up to 10 times the normal dose of air entraining agent are sometimes needed to obtain specified air contents in low-slump, dense overlay mixtures. With particular air-entraining agents, it may not be possible to achieve specified air contents even at these high dosage rates. Once the specified air content has been achieved, however, these concretes exhibit excellent air-void systems and should offer long-term durability, provided that the concrete is adequately consolidated.

5. Administrative and field personnel will benefit from the guidelines and verification program presented in this report. The guidelines summarize existing knowledge with respect to control of air content, and the verification program presents a tool for implementation of this knowledge in field projects.

6. Current specifications for air content appear to be relatively uniform and adequate in most instances. The need for increased target values for structures subject to extreme weathering conditions, and increased tolerance values which reflect actual field variations should be recognized. Adoption of statistically based specifications should be a long-term goal.

SUGGESTED RESEARCH

In a broad research program such as this, a wide variety of future areas of research are apparent. Setting priorities for future research is often difficult because each personnel group within the highway community has its own interests. For instance, researchers may desire to know more about the basic mechanisms of air entrainment, while field personnel may want more rapid test procedures. Administrators may want more applicable specifications. Suggestions listed below are given in an order reflecting the authors' opinions of their importance with respect to highway transportation systems as a whole. Those areas deemed of highest priority are discussed first.

1. A rapid, accurate technique which could be used to measure in-place air-void system and air content would be very beneficial, as it is the in-place void system which determines the ultimate durability of concrete.

2. More work is needed on mechanisms of generation and stabilization of air bubbles in concrete. The existence of postulated "films" or "skins" on air bubbles should be verified, and the nature of these films should be studied in detail. Once the mechanism of air entrainment is firmly established, it may be possible to quantify the effects of such material variables as chemical type of air-entraining agent, cement composition, chemical admixtures, additives, pozzolans and other substances both on initial air content and stability of air with time. Currently, such information is either empirical or speculative.

3. The chemical composition and uniformity of commercial air entraining agents need to be better defined. Chemical analysis routines which could be used by specifying agencies and other users of air-entraining agents need to be developed.

4. There exists a need for better definition of the effects of actual production and construction practices on air content. More work is needed on optimizing mixing speeds and cycles, and time-of-addition of admixtures using plant-scale equipment. The effects of job site retempering with air-entraining agents need more study.

5. An expanded investigation into the sensitivity of air content to small changes in water content is needed for concretes of relatively low slump (less than 2 1/2 in.). The investigation should include various cements, air entraining agents, mixer types, and mixing procedures.

6. More work is needed to define the air-contents and air void systems needed to ensure adequate durability in low slump concretes and concretes containing super-water reducers.

7. A more complete data base is needed to relate field variations in air content to job equipment and procedures. This would ultimately allow for preparation of realistic, statistically oriented, specifications for air content.

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APPENDIX A

SUMMARY OF RESPONSES TO QUESTIONNAIRE ON CONTROL OF AIR CONTENT IN CONCRETE

At the outset of this study it was not known if problems with control of air content in portland cement concrete were widespread throughout the country or only confined to a few states. Additionally, it was not clear whether current problems in control were due to temperature variations or batching operations, which have historically been known to result in fluctuations in air content, or whether they represented entirely new problems brought about by changes in materials or specifications. It was considered necessary to collect a complete set of specifications on air contents for various types of construction, and to examine differences among various agencies with regards to these specifications.

Accordingly, a questionnaire was sent to the following agencies; 50 state transportation departments, the District of Columbia, the Federal Highway Administration, Canadian provincial highway departments which are members of AASHTO, plus agencies in the United States and Canada which are known to specify large amounts of portland cement concrete. In most cases, the questionnaire was addressed to the agency representative on the current AASHTO Highway Subcommittee on Materials.

Response to the questionnaire was excellent. Replies were received from all 50 states, the District of Columbia, the Federal Highway Administration, four Canadian provinces, three additional agencies in the United States, and two in Canada.

As each completed questionnaire was received it was examined, and an assessment of the need for follow-up information was made. If this was needed, the individual who signed the questionnaire was contacted and queried. Twenty-nine such calls were made and resulting information is included in the following summary of responses. From the responding agencies, four were selected for field visits on the basis of severity or frequency of problems and an expressed interest to cooperate further in the project. These in-depth interviews are described in Appendix B.

Following is a summary of questions and responses as they appeared on the questionnaire. Because this questionnaire was mailed in the summer of 1981, the reader should be aware that replies reflected thinking at that time. Since then, specifications and areas of concern may have changed.

Question No. 1 - Does your organization or department specify entrained air in concrete in State or Federal cost-share financed construction?

All 50 states plus the District of Columbia answered in the affirmative.

Question No. 2 - List the limits on air content for the following types of concrete structures.

	Air Content Limits (%)
A. Bridge Decks	______
B. Bridge Abutments, Piers, Girders, etc.	______
C. Pavements	______

D. Shoulders, Curbs, Gutters __________

E. Median Barriers __________

F. Other (please specify) __________

All agencies responded to this question, although not all categorized their limits as to type of structure. Summaries of these specifications are given in Table A-1 for state transportation agencies and in Table A-2 for other agencies.

Average limits, ranges, and midpoints are given at the bottom of each table. It is easily seen that all limits are remarkably similar for each category of structure. This indicates that, in general, little distinction is made between various types of structures when specifications on air content are developed. For state transportation departments, average limits run from about 4 to 7 percent. The average midpoint, or what might be considered as the "target value" runs from 5-1/2 to 6 percent. Values of limits for the other agencies surveyed are only marginally

Table A-1 Current Air Content Specifications 1981 Survey - State Transportation Departments

State	Bridge Decks	Pavements	Abutments, Piers, Girders	Shoulders, Curbs, Gutters	Median Barriers	Other(s)
Alabama	4-6	3-5	3-5	3-5[a]	3-5	Underwater concrete: 3-5
Alaska	5-9	(b)	3-7	3-7	3-7	
Arizona[1]	4-6	4-6	4-6[c]	4-6	4-6	
Arkansas	3-7	3-7	-	-	-	
California[2]	5-8	5-8	5-8	5-8	5-8	Deck overlays: 5-8
Colorado	5-7	4-7	5-7	4-7	4-7	Special projects: 5-9
Connecticut	5-7	4-6	4-6	5-7	5-7	
Delaware	5-8	4-7	4-7	4-7	5-8	
District of Columbia	5.5-7.5	5.5-7.5	5.5-7.5	5.5-7.5	5.5-7.5	
Florida	5-7	3-6	3-6	3-6	3-6	
Georgia	2.5-6	2-6.5	2.5-6	2-7.5	2.5-6	
Hawaii	2-4	2-4	-	-	-	
Idaho	5-8	4-7	5-8	5-8	5-8	Prestressed girders: 2-6
Illinois	5-8	5-8	5-8	5-8	5-8	
Indiana	5-8	5-8	5-8	5-8	5-8	
Iowa	5.5-7.5	5-8	5-8	5-8	5-8	Pavement patching: 5-8
Kansas	5.5-7.5	4-8	4-8	4-8	4-8	
Kentucky	4-7	4-7	4-7	4-7	4-7	
Louisiana	4-6	3-7[d]	3-7[d]	3-7[d]	3-7[d]	Prestressed: 3-7
Maine	5-7	5-7	5-7	5-7	5-7	
Maryland	5-8	5-8	5-8	5-8	5-8	Lightweight concrete: 6-9, Prestressed: 2.5-5.5
Massachusetts	5-7	5-7	3.5-5.5	4-6	4-6	Prestressed beams: 4.5-6.5
Michigan	5-8	5-8[e]	5-8	5-8	5-8[e]	Latex modified deck overlays: 3.5-6.5
Minnesota	4-7	4-7	4-7	4-7	4-7	Low slump overlays: 5-8
Mississippi	3-6	3-6	3-6	3-6	-	Lightweight concrete: 4-7
Missouri	4-7	4-7	4-7	4-7	4-7	Lightweight concrete: 5-9
Montana	5-7	5-7	5-7	5-7	5-7	
Nebraska	5-7	5-7.5	5-7.5	5-7.5	5-7	High density overlays: 5.5-7.5, Prestressed girders and Precast Barriers: 3-6
Nevada	5-7	4-6	4-7	4-7	5-7	
New Hampshire	5-8	(b)	4-7	-	5-8	
New Jersey	4-5-7.5	4.5-7.5	4.5-7.5	4.5-7.5	4.5-7.5	
New Mexico	4-7	4-7	4-7	4-7	4-7	
New York	4-8	4-8	4-8	4-8	4-8	
North Carolina	4.5-7.5	3.5-6.5	4.5-7.5	4.5-7.5	4.5-7.5	Prestressed concrete: 2-6
North Dakota	-	5-8	5-8	5-8	-	
Ohio	4-8	4-8	4-8	4-8	4-8	
Oklahoma	5-7	5-7	5-7	5-7	5-7	High density overlays: 5.5-7.5
Oregon	4-6	3-6	3-6	4-6	3-6	Members where any face is a wearing surface: 3-6
Pennsylvania	4.5-7.5	4.5-7.5	4.5-7.5	4.5-7.5	4.5-7.5	Prestressed beams: 3-6
Rhode Island	5-7	2.5-4.5	3.5-5.5	-	3.5-5.5	
South Carolina	3-6	3-6	3-6	3-6	3-6	
South Dakota	5-7	4.5-7.5	4.5-7.5	4.5-7.5	4.5-7.5	Concrete patches: 5-9
Tennessee	3-8	3-8	3-8	3-8	3-8	
Texas	5-7	5-7	5-7	5-7	5-7	
Utah	5-7	5.5-7.5	5-7	4-6	5-7	
Vermont	5-7	4-6	4-6	4-6	-	Prestressed units: 4.5-5.5
Virginia	5-8	4-8	4-8	4-8	4-8	Prestressed and tremie concrete: 2-6
Washington	3.5-6.5	3.5-6.5	3.5-6.5[f]	3.5-6.5	3.5-6.5	Latex modified concrete: 3-6, Dense overlays: 5.5-7.5
West Virginia	4-10	4.5-9.5	4-10	4-10	4-10	
Wisconsin	4.5-7.5	4.5-7.5	4.5-7.5	4.5-7.5	4.5-7.5	Prestressed box beams: 3.5-6, Prestressed I-beams: 6 max., Deck Overlays: 5-7
Wyoming	4-6	4-7	4-7	4-7	4-7	
Number of Responses	50	49	49	47	46	
Average Limits	4.5-7.2	4.1-7.0	4.1-7.0	4.2-7.2	4.3-7.2	
Average Range	2.7	2.9	2.9	3.0	3.0	
Average Midpoint	5.8	5.6	5.5	5.7	5.7	

(1) Air entrainment specified at elevations greater than 3,000 feet
(2) Air entrainment specified in freeze-thaw areas only

(a) No air specified for curbs or gutters
(b) No p.c.c. pavement specified
(c) Precast-prestressed girders below deck slab not air-entrained
(d) Usually not specified as air-entrained
(e) Slipform pavement and median barriers specified at 4.5-8% air
(f) Air-entrainment not specified for precast girders

higher than for the states.

When limits for individual states are inspected, it can be seen that there have been only marginal changes in limits as compared to those in force at the time of a 1975 PCA survey on pavement specifications (40). Table A-3 compares the results of these two surveys.

Table A-2 Current Air Content Specifications 1981 Survey - Other Agencies

Agency	Bridge Decks	Pavements	Abutments, Piers, Girders	Shoulders, Curbs, Gutters	Median Barriers	Other(s)
FHWA-East	4-8	-	4-8	4-8	4-8	
FHWA-CDFD	4-6	4-7	4-6	4-6	-	Culvert headwalls 4-6
FHWA-West	5-7	-	5-7	-	-	
TVA	3.5-7.5	4-7	4-7	4-7	4-7	
USBR	5-7	5-7	5-7	5-7	5-7	
Corps of Engineers	4.5-7.5	-	4.5-7.5	4.5-7.5	-	
Manitoba	5-7	5-7	5-7	5-7	5-7	
New Brunswick	5.5-7.5	5.5-7.5	5.5-7.5	5.5-7.5	6-7.5	
Nova Scotia	5-8	5-8	4-7	5-8	5-8	
Ontario	4.5-7.5	4.5-7.5	4.5-7.5	4.5-7.5	4.5-7.5	
Hydro-Quebec	4-7	4-7	4-7	4-7	4-7	
Transport Canada	5-8	4-6	5-8	5-8	5-8	
Number of Responses	12	9	12	11	9	
Average Limits	4.6-7.3	4.5-7.1	4.5-7.2	4.6-7.3	4.7-7.4	
Average Range	2.8	2.6	2.7	2.7	2.7	
Average Midpoint	5.9	5.8	5.9	6.0	6.1	

Table A-3 Comparison of 1975 and 1981 Surveys

Number of States Having Lower Limit 1/ Equal to/	1975	1981	Number of States Having Upper Limit 1/ Equal to/	1975	1981
2%	2	2	3%	1	0
3%	8	9	4%	0	1
4%	19	18	5%	0	2
5%	16	18	6%	9	8
6%	1	1	7%	17	18
			8%	18	18
			10%	1	1

1/ In those cases where fractional value was encountered, it was rounded to the next highest integer.

Question No. 3 - Have you experienced any problems with control of air content in plastic concrete, either in failure to obtain specified air content during mixing, or change in air content during transporting and placing the concrete?

States + D.C.	Yes 42	No 9
Others	Yes 11	No. 1

Answers to this question were somewhat perplexing, and it is possible that the question was ambiguous. It was intended as a "lead-in" to the remainder of the questionnaire, it being assumed that those answering No would also indicate negative responses to those questions asking for more details on problems. However, of the 10 agencies answering No, 8 agencies later in the questionnaire indicated that some control problems did exist, although in most cases these were termed "minor" or "insignificant." The remaining 2 agencies either answered No to each question or left the remainder of the questionnaire blank.

Question No. 4 - If so, in which of the types of structures listed in Question No. 2 above have you experienced these problems? Under what specific weather conditions have problems been encountered?

	NUMBER OF REPLIES
1. STRUCTURE	
A. Bridge Decks	14
B. Bridge Abutments, Piers, Girders, etc.	7
C. Pavements	9
D. Shoulders, Curbs, Gutters	2
E. Median Barriers	4
F. Other (please specify)	
Overlays	3
Precast Concrete	1
G. All (or "General")	15
2. WEATHER CONDITIONS	
A. Hot or Hot/Dry	20
B. Cold	6
C. Hot/Humid	2
D. Temperature or Seasonal Changes	3
E. High Winds	1

The response to this question indicated that the majority of control problems existed in structural, as opposed to pavement, concrete. Discussions with agency representatives during follow-up calls disclosed the feeling that more problems occurred in structural concrete because testing rates were higher. Thus, on a strictly probabilistic basis one would naturally encounter more out-of-specification concrete.

The overriding area of concern was construction during hot or hot/dry weather conditions, where greater amounts of air-entraining agent are needed and where the attendant slump loss might be expected to lead to losses in air as well.

Question No. 5 - Are there any particular types of cements, aggregates, or water with which problems in control of air content have been encountered? If so, please specify source and/or brand.

Responses to this question were quite varied. Nowhere near a majority could attribute problems with air content to any one material. With respect to cements, 6 respondents indicated problems with IP, IS, or other cements containing pozzolanic or slag additions. Four agencies noted that Type III or other high-fineness cements required large amounts of air entraining agent or, otherwise, caused control problems. Problems with particular brands of cements were noted by 5 respondents; "hot" cement by 2, and natural cement by 1.

Most problems with aggregates appeared to stem from deficiencies in local sources. For instance, one respondent indicated problems with "harsh" sands, another with granitic and limestone materials, another with salt-contaminated aggregates, and a fourth with porous aggregates. The only problems which, in some manner, could be considered general were the presence of clay or the presence of a large amount of -200 mesh material. A total of 8 replies indicated problems in these areas.

Few problems with control of air content were attributed to mixing water. Of the 6 agencies which responded affirmatively in this area, sources of problems included clay in water, soft water, effluent or chemical contamination, and recycled wash water.

Question No. 6 - Are there any particular types of chemical admixtures (such as air-entraining agents, water-reducers, set-control agents (including calcium chloride)), superplasticizers, pumping aids, or others with which problems in control of air content have been associated? If so, please specify type, source and brand of admixture.

Quite a number of agencies indicated that problems arose from the use of air-entraining admixtures in conjunction with chemical admixtures. Twenty-one respondents voiced some concern over effects of water-reducers and retarders on air content. Most of these indicated either that air content was increased when water-reducers or retarders were used, or that adjustments had to be made in the dosage of air-entraining agent. When the type of admixture was mentioned, lignosulfonate-based retarders were the most prevalent in terms of their effects on air content. Of these 21 responses, 8 responses mentioned particular brands of admixtures. Some users were of the opinion that mixing brands of admixtures (i.e., using air-entraining agents from one manufacturer and water-reducers or retarders from another) leads to problems. Others noted problems even when both admixtures were purchased from the same source. One respondent noted that a triple combination of a water-reducer, a retarder, and an air-entraining agent led to more uniform production of air entrainment than when the air-entraining agent was used in conjunction with only the retarder or water-reducer.

Superplasticizers were mentioned by 10 agencies as being the cause of some problems with control of air content. Four of these noted that superplasticizers either tended to decrease air content or to alter the air void system as measured in the hardened concrete. No particular brands of superplastizers were singled out in this regard. In fact, most of these 10 replies specifically tied problems to "all types" of superplasticizers.

Other types of chemical admixtures with which problems have been encountered included pumping aids (2 states), calcium chloride (1 state), and latex modifiers (2 states). The problem with the latex modifiers appears to be an excess of defoaming agent which limits air content of the concrete to less than the specified 3.5 percent minimum.

Question No. 7 - Are there any particular types of mineral admixtures (such as fly ash, ground granulated slag, or natural pozzolans) with which problems in control of air content have been encountered? If so, please specify type, source, and brand of admixture.

Upon review of the responses to this question, a possible deficiency in the phrasing was noted. Because many states and other agencies do not presently allow the use of mineral admixtures, the researchers were not able to discern whether simple, unqualified negative responses meant that no problems were encountered, or that no mineral admixtures were in use. Such unqualified negative (or blank) responses were included on 15 of the questionnaires. Nineteen agencies indicated no use of mineral admixtures.

Of those agencies giving a positive response, 20 agencies mentioned fly ash as either influencing air content or contributing to control problems. Of these 20, 4 agencies mentioned specific sources or brands of fly ash. High loss on ignition or carbon content was suspected as a cause of problems in many cases. Seven of these 20 agencies noted that while fly ash will generally tend to lower air content, the addition of increased amounts of air-entraining agent (up to double dosage in some cases) will allow one to obtain the specified air content. Three agencies included recent specifications on fly ash. Florida specifies use of fly ash meeting ASTM Class F with a maximum loss on ignition of 6 percent. Michigan limits loss on ignition to a maximum of 4.0 percent and particles retained on a No. 325 sieve to a maximum of 10 percent. Nebraska has modified ASTM C 618 Class F to their own specifications. They stipulate that free carbon content can not exceed 3 percent, and loss on ignition can not exceed 6 percent.

The only other types of mineral admixtures mentioned were inorganic pigments, especially those using carbon black. Three states mentioned that carbon black either increased the amount of air-entraining agent needed, or led to erratic air contents. Two states mentioned other pigments such as iron oxides and proprietary products.

Question No. 8 - Have you encountered situations where batching procedures at the concrete mixer have led to problems in control of air content in the plastic concrete? If so, please specify.

Thirty-seven agencies replied in the affirmative to this question. Of these, the large majority gave specifics. The most prevalent problem cited by 13 agencies was intermixing of undiluted admixtures. An example would be mixing air-entraining agents with retarders. In some instances "gelling" of the resultant solution was noted. The general feeling was that admixtures should be batched separately. Some respondents advocated batching of one admixture onto the sand, the other into the batch water. Others recommended consecutive batching into the water, with care being taken to ensure that undiluted admixtures did not come into contact before reaching the water line. Ten respondents specifically noted that failure to batch air-entraining agents directly into the mix water was a direct cause of control problems.

The next most frequently cited problem was malfunction of admixture dispensing equipment. This included plugging of meter lines, pressure losses in meters, inaccurate meters, faulty equipment, and more general statements. The manual introduction of air-entraining agent into the mixer was also noted by one respondent as being conducive to loss of control. Problems also occur in very cold weather, especially with agents whose viscosities are very temperature sensitive and therefore tend to clog in the dispenser lines.

Other sources of problems cited by an equal number of agencies (4 each) were personnel errors, variations in batching sequence, and outdated or previously frozen air entraining agents. Finally, 2 states noted that variations in aggregate moisture content might lead to control problems. This was most likely due to the effect on slump which would translate into attendant air content fluctuations.

Question No. 9 - Have you encountered situations where mixing procedures and/or type of mixer have led to problems in control of air content in the plastic concrete? If so, please specify.

Forty-eight responses to this question were negative, although a few were qualified by such statements as: "as long as blades are not dirty and complete mixing has been achieved," or "we attempt to ensure that mixers and mix procedures are suitable and well-maintained." These qualifiers may indicate that problems do occur when close inspection is not maintained. The general tone of the responses to this question, however, seems to imply that contemporary mixing procedures are well controlled and contribute little to problems encountered in control of air content.

The remaining 15 respondents encountered various instances where mixers and mixing procedures have led to problems with control of air content. Problems in equipment maintenance, specifically worn or concrete-encrusted mixer blades, were cited in 7 instances. Problems caused by over or under mixing were cited by 5 respondents. The nonuniformity of truck mixers as opposed to stationary central mixers was seen as a cause of problems in two cases. Problems were encountered in the use of mobile concrete batching plants in three states. Finally, miscellaneous problems cited by only one agency each included low slump concrete, small mixers, high mixing speed, and variations in w/c ratio.

Question No. 10 - Have you encountered situations where, during transport of concrete to the discharge site, problems have developed which led to air contents measured at discharge being significantly different from those measured immediately after mixing? If so, please specify.

Of the responses received, 39 respondents answered negatively to this question, although 10 respondents noted that under their specifications air content was measured at discharge only. Therefore, it is not known whether air losses did occur in these cases.

Twenty-four respondents indicated some degree of concern with air loss during transport. Long hauls or other factors leading to delay between mixing and discharge were cited in nine cases as being causative factors of air loss. Hot weather and prolonged mixing, either separately or in combination, were mentioned by 8 respondents. Four replied that pumping tends to cause air losses of up to 2 to 3 percentage points. The link between air loss and slump loss was mentioned in three of the questionnaires. The use of non-agitating transport vehicles was seen as being conducive to air loss in two instances. Miscellaneous factors mentioned by individual respondents included high early cement, water-reducers, and insufficient mixing.

Question No. 11 - Have you encountered situations where you have reasons to believe that vibration procedures have led to a loss of air and consequent durability problems in the hardened concrete? If so, specify details including type and frequency of vibration.

Forty-two agencies gave a negative response to this question, which indicates that, in most areas, vibration-induced air loss or durability problems are not serious problems. Of the remaining 21 agencies surveyed, only 3 agencies could supply cases in which durability problems could be traced to improper vibration. These involved excessive vibration by surface pan-type vibrators, overvibration by a slip-form machine, and a certain type of high-frequency vibrator which causes segregation in the concrete.

While no durability problems were mentioned, the remaining respondents did indicate some correlation between various aspects of vibration and air loss. A few agencies appeared to feel that a certain amount of air loss was inherent to vibration and that most of the air lost was of the entrapped type. Eight respondents felt that "overvibration" led to air loss. Seven replies mentioned that slip-form machines were a cause of air loss problems. Two agencies each reported that high frequency vibrators and high slump concrete were seen as being conducive to air loss.

Question No. 12 - Have you encountered situations where you have reasons to believe that finishing procedures have led to a loss of air and consequent durability problems in the hardened concrete? If so, specify further details including finishing procedures used.

Twenty-one respondents answered positively to this question. An additional three believed that finishing procedures could affect air loss or durability, but could not recall any instances where such a connection was verified. Answers were quite uniform. Thirteen mentioned "over" or "excessive" finishing as being a cause of either air loss or scaling, predominately in the surface layer. Adding water to the surface of the concrete, a practice adopted by many finishers to speed production, was seen by 11 agencies as a cause of problems. Other causes mentioned were early finishing (3), and hand finishing (3). Miscellaneous causes mentioned were the inadvertent overlap of disc screed finishers, excessive bullfloating, and edge finishing.

In all, 12 agencies noted specifically that improper finishing procedures had led to problems in durability. The most often mentioned manifestations of this were scaling and spalling of the surface layer of concrete.

Question No. 13 - Which procedures do you normally use for determining air content in plastic concrete?

(a) Gravimetric - ASTM C 138
(b) Pressure Meter - ASTM C 231
(c) Volumetric - ASTM C 173
(d) Chace Air Indicator
(e) Other - specify

Twenty-nine agencies reported that they used the pressure method, ASTM C 231 exclusively. An additional 12 agencies use either C 231 or C 173, although the latter is used primarily for lightweight, slag, or when other porous aggregates are present in the concrete. Eight agencies indicated use of either pressure, volumetric or Chace indicator methods. For the most part, the Chace indicator is used mainly as a spot check device, although one state did indicate it to be the primary means of measuring air, while another indicated its use as an acceptance but not rejection tool. Six agencies use pressure and Chace methods, two use pressure and gravimetric, and two use all four techniques. One agency uses pressure, volumetric, and gravimetric.

Only limited use is made of combinations not including the pressure method. Two agencies allow volumetric or Chace measurements, while only one uses the volumetric method as the sole technique.

Question No. 14 - Have problems in control or measurement of air content been encountered in plastic concrete having slumps of 1-inch or less, such as slipform or bridge deck overlay mixtures? Have any of the above (Questions 8-12) construction procedures contributed to these problems?

Some difficulties in interpretation of responses to this question were encountered. That is, a negative response could be taken to mean either that no problems were encountered with low slump mixtures, or that no low slump mixtures were being used by that particular agency. A total of 41 negative responses were received. Of these, seven stated that low-slump concrete was not used in their areas. The remaining negatives were unqualified.

Of the positive responses, 8 agencies expressed concern over failure to achieve the air contents specified in low-slump concretes. Others noted that even with large dosages of air entraining agents, air contents were still on the low side of the specification. Difficulties in accurate measurement of air in low-slump concrete were noted by 5 respondents. This was attributed to such factors as poor consolidation (which would tend to raise the measured value over the true value) or a belief that current techniques were inherently unsuited to very stiff concretes.

Three of the agencies found a large sensitivity of air content to slump in low-slump concrete, wherein small changes in water content give rise to large changes in air content. Two respondents tied problems with low-slump concrete to the use of particular air entraining agents. Finally, a number of agencies mentioned specific processes for production of low-slump concrete, such as slipforming, dry casting, and roller-compacting.

Question No. 15 - Do you measure air contents in the hardened concrete? If so, is this done routinely or only where durability problems have developed?

Only 5 agencies indicated any routine use of methods for determining the air content of hardened concrete. One agency noted routine use on all concrete, a second on precast, structural, and pavement cores, a third only on precast cores, a fourth only on pavement cores, and the fifth only on startup of large projects.

Fourteen additional agencies replied that hardened air content was determined only when problems arose, such as in special or research investigations or when concrete was suspect. Eight specifically mentioned durability problems as warranting the determination of air content in hardened concrete. Four utilized air measurements of hardened concrete when the air contents of plastic concrete was suspect. Two agencies mentioned the use of air determinations of hardened concrete where low strengths occurred and high air was suspected of causing the low strengths.

Question No. 16 - Are there any other factors which you have reason to believe may contribute to problems in control of air content in concrete? Please specify details.

This question elicited responses from over half of the agencies responding. For the most part, answers given in this question could have been included under previous questions because few novel or unusual problems were listed. In addition, a few of the respondents submitted lists of many factors which could influence air content. These factors appeared to be of a general nature and not related to any particular field problem. The investigators took this type of response to represent an attempt by the agency to list factors which they recognized as leading to problems in control of air content, not necessarily situations which their personnel had actually encountered.

The responses can be divided into 9 categories, with a few miscellaneous problems not fitting into any of these. The 9 categories are listed in Table A-4, along with the number of agencies responding.

The major problem areas appear to be a failure to ensure adequate storage facilities for air-entraining agents, and to dispose of outdated agents on a regular basis. A number of agencies mentioned, in follow-up calls, that this problem was prevalent mainly at small capacity ready-mix plants where storage space is limited and pro-

Table A-4 Summary of Responses to Question No. 16

Category	Factor(s)	Number of Agencies Reporting these Problems
1	Freezing, Settling out, Ageing, or Contamination of AEA.	15
2	Aggregate Characteristics (Grading, Fines, Contamination, etc.)	12
3	Poor Quality Control	10
4	Interactions or Incompatibility between AEA and other Admixtures	5
5	Mechanical Problems (Faulty Admixture Dispensers, Clogged Lines, Uncalibrated Meters, etc.)	5
6	Cement Variablity	4
7	Environmental Influences	4
8	Mixer Efficiency	3
9	Contamination of Materials	3

ducers are reluctant to dispose of costly admixtures even if they are outdated.

Problems with aggregates could justifiably have been included in the response to question no. 5. Such concerns as poor control over gradation, and excessive fines were again mentioned in these responses. Sources of contamination such as water pollution of river sands and antidusting agents applied at quarries were also mentioned.

Ten agencies mentioned poor quality control as a problem in control of air content. This included such practices as inaccuracy in metering the agents, improper batching, lack of training of personnel, and use of uncalibrated air meters. Mechanical problems, which could be considered as indicative of poor quality control, were mentioned by four additional agencies.

Other factors included "incompatibility" of air-entraining agents with other admixtures, variability in cement shipments, and environmental influences. The remaining two factors (mixer efficiency and contamination of materials) were each mentioned by only three agencies.

APPENDIX B

IN-DEPTH INTERVIEWS AND MATERIAL EVALUATIONS

During September and October of 1981 interviews were held with representatives of the Illinois, Indiana, New York, and New Jersey state transportation departments. The objectives of the interviews were: (1) to discuss any generalized problems in control of air content which did not fall into obvious categories, and (2) to discuss unique problems in control of air content which might be related to particular materials or operations.

On the whole, the only problems that were of a general nature were increased sensitivity of air content to slump in some mixtures, and problems in obtaining specified air contents and satisfactory air-void systems in dense (low w/c ratio) overlay concrete mixtures. Problems in the second category were more numerous, but could, for the most part, be correlated with faulty batching temperature fluctuations, or peculiarities in particular job materials.

Following these interviews, materials were supplied by two of the states interviewed, and follow-up laboratory work was carried out in an attempt to explain some of the control problems. Summaries of the interviews and laboratory studies follow.

ILLINOIS DEPARTMENT OF TRANSPORTATION

Two meetings were held with representatives of the Illinois Department of Transportation. The first was held in Schaumburg, Illinois, with the materials engineer for District 1, which includes Chicago and surrounding counties.

The main topic of discussion was dense concrete overlays for bridge decks. This district is currently using concrete mobiles to mix concrete for dense overlays. The first overlay was placed on an approach ramp in 1979. No deterioration has been noted to-date.

A sample taken from an overlay on a bridge deck over I-94 was obtained. Air content was stated to be 6-1/2 to 7 percent before vibration, but measurements showed 5 to 5 1/2 percent after vibration. Seven day strength was 4500 psi, cement content was approximately 780 lb per cu yd, and the water/cement ratio was 0.35. A naphthalene-based superplasticizer was used in this mix. Reason for the use of the superplasticizer was better control of air content at a slump of 2 in. versus a slump of 3/4 to 1 in. which would be obtained using the conventional Iowa mix design.

Subsequent analysis by linear traverse indicated 3.5 percent air in the hardened concrete, a specific surface of 614 $in.^2/in.^3$ and a spacing factor of 0.0098 in. This sample appeared to have a large number of very small voids. Thus, the number of voids per cu in. was calculated to be approximately 1-1/2 million. Some larger entrapped voids were evident in the bottom half of the sample. During the interview, little information with which to compare these results was available. However, subsequent studies by the Indiana State Highway Commission (described later) indicate that such air void systems may be encountered in these dense concretes.

A second meeting was held in Springfield, Illinois, with members of the Bureau of Materials, as well as with field engineers from a number of Illinois districts. Topics of discussion included a limited number of dense concrete overlay jobs as well as some unusual air loss problems on bridge deck placements.

Overlay Project

This project was a dense concrete overlay placed on I-72 near Decatur, Illinois. Some mechanical difficulty was encountered with the concrete mobiles and high air contents were measured in some of the concrete. Although zero-slump concrete was produced, adequate compaction was obtained using a high-capacity paving machine. No additional overlay jobs were planned at this time.

Bridge Decks

Three projects were discussed in detail.

(1) Air loss was noted in bridge deck concrete containing a wood resin (not Vinsol) air-entraining agent. Air content was 10 percent at the plant and 4 percent at the job site. Raising the air content to 11 percent at the plant gave 5.3 percent at the job. The weather was moderately cool, with temperatures ranging from 58°F to 62°F. Slump loss ranged from 4 in. at the plant to 3 in. at the job, and did not appear to be a problem. Concrete was mixed in a central mixer for 70 seconds, then discharged into ready-mix trucks and agitated on the way to the job. There was no remixing. Haul time was about 15 minutes. The air loss problem persisted for a number of weeks and then appeared to resolve itself. The engineers were not able to detect the cause of the problem.

(2) In this case a Vinsol resin air-entraining agent was combined with a hydroxylated polymer type retarder. The first eight loads of concrete had air contents ranging from 5.6 to 7.1 percent. However, the ninth load registered 8.5 percent air, and the tenth, after decreasing the air-entraining agent dosage by 10 percent, registered 7.7 percent. Another decrease of 10 percent in air-entraining agent dosage stabilized subsequent air contents at 6 to 7 percent. Because job records were incomplete (no records of slump and temperature for most of the batches), it was not possible to conclusively state the cause of the problem.

(3) In this case, concrete was placed in hot weather using a wood-resin type air-entraining agent and transit mixers. Using a dosage of 1.2 ounces per hundred pounds of cement produced about 4 percent air. Increasing the dosage to 3 ounces gave only 4 to 4-1/2 percent air. Finally, two additional ounces were added at the job to get the specified air content. A loss of about 1 percent was seen from plant to the job. Similar results were obtained the next day when a synthetic sulfonated hydrocarbon air-entraining agent was tried. A Vinsol resin was then used at a dosage of 1-1/2 to 2 ounces per hundredweight of cement with good results. The same materials were also used at a different batch plant but similar problems did not occur. Here, better uniformity was obtained by putting all revolutions on the truck at the plant rather than waiting to complete mixing at the job site.

In general, the engineers seemed to feel that fewer problems occurred with conventional Vinsol resin-type admixtures than with sulfonated hydrocarbons or some of the newer type admixtures. Vinsol resins are specified in central-mix paving jobs because it is claimed that other types of admixtures do not develop air as quickly in central mixers. They also feel that in paving jobs, where large quantities of materials are used, admixtures are fresher and do not have a chance to deteriorate in drums or freeze over the winter season. Finally, Illinois Department of Transportation engineers were questioned as to whether new specifications which call for air contents of 5 to 8 percent would be a problem. They did not believe so and anticipated designing for air contents of 6 to 6-1/2 percent.

INDIANA STATE HIGHWAY COMMISSION

A meeting was held at CTL with a Materials Research Engineer of the Indiana State Highway Commission. Topics for discussion included limited work on dense low slump mixes and a problem in air-entrainment on a pavement job.

Dense Concrete Overlays

Indiana's first experience with dense low slump concrete was on two bridge deck overlays placed during the summer of 1979. Mobile mixers were used for the low-slump concrete. Light scaling was noted on inspection visits during May 1981. On a subsequent job, thin forms were placed in front of the finishing machine to cast specimens for linear traverse measurements. Analyses of these specimens, given in Table B-1, indicate that those specimens having higher density (apparently subjected to more compactive effort by the finishing machine) show poorer air-void characteristics.

In a report issued by Indiana in February 1982 (41) additional linear traverse data on cores taken from two other structures on which dense concrete overlays were placed was reported. These results, given in Table B-2, show spacing factors and specific surfaces which fail to meet the recommended (42) values of a maximum of 0.008 in. and a minimum of 600 in.^{2}/in.^{3}, respectively. In this case, there is little correlation between spacing factors and unit weight of concrete. The presence of large amounts of entrapped air, however, does result in very high spacing factors. These data verify that problems do exist in obtaining adequate air void systems in dense concrete. However, this is not the case in all instances, as further discussed in Appendix E.

Pavement Project

The second topic of discussion was a pavement mix in which large amounts of air-entraining agents were apparently needed. This mix contained 564 lb/cu yd of cement and was specified to contain 5 to 8 percent air. It was produced at a central mix plant and hauled to the job in nonagitating vehicles. The concrete was placed using a slipform paver. ASTM Type 1A cement was used in combination with 3-1/2 ounces per hundredweight of cement, of a wood-resin based air-entraining agent. This is significantly higher than normal dosages of air-entraining agents. For a 1PA cement, the agent dosage had to be doubled. Materials were secured from this job and shipped to CTL for further evaluation.

Samples of a Type IA cement, concrete sand, and an alkali-stabilized wood resin air-entraining agent were received. The sand met ASTM gradation requirements and did not show evidence of organic impurities (ASTM C 40). Concrete mixtures essentially similar to those used by Indiana

Table B-1 Air Void Characteristics, Initial Indiana Overlay (41)

Overlay Specimen:	C-3			S-1		P-1	
Bulk Density[1/] (lb/cu ft)	146.4			147.2		143.7	
Linear Traverse Specimen:	LT-001	LT-002	LT-003	LT-004	LT-005	LT-006	LT-007
Length of traverse (in.)[2/]	41	41	41	51	51	52	51
Air voids (% by volume)	3.8	4.5	4.4	6.4	5.7	7.3	6.8
Number of voids/inch of traverse	5	5	5	6	5	13	13
Average chord length (in.)	0.008	0.009	0.009	0.011	0.011	0.006	0.005
Specific surface (in.^{2}/in.^{3})	515	426	465	363	374	699	778
Spacing factor (in.)	0.011	0.013	0.012	0.013	0.013	0.006	0.006

[1/]After immersion, according to ASTM C 642

[2/]Length of traverse modified from ASTM C457 recommendations.

were designed, with the exception that a locally available crushed limestone was used to avoid expenses for shipment of large quantities of crushed stone. With the Type IA cement and wood resin agent the dosage rate needed to obtain 6 percent air was 0.012 percent solids by weight of cement (% s/c) (approximately 2-1/2 fl oz/cwt). With a laboratory blend of three Type I cements the dosage rate was 0.011 percent s/c (2.3 fl oz/cwt). These are well within the manufacturer's recommended amounts (1/4 - 4 fl oz/cwt). A laboratory grade of Vinsol resin was also used in identical concrete mixtures.

Results are summarized in Table B-3. Slightly more neutralized Vinsol resin was needed, on a solids basis, than the wood resin. For a commercial neutralized Vinsol resin, formulated at about 14 percent solids, this dosage would correspond to approximately 2 fl oz/cwt, which is slightly high but still within accepted dosage rates. In this slump range changes in air content with increasing dosage were close to historical levels.

Table B-2 Air Void Characteristics, Indiana Dense Concrete Overlays (41)

Core Number	Structure Number	Location of Core	Unit Weight (lb/cu ft)	Total Air Content, (%)	Approximate Entrapped Air Content (%)	Voids Per Inch	Specific Surface (Inches^{-1})	Spacing Factor (Inches)
82-17169	I-69-153-5038 A	NBLs with light surface scaling	144.8	4.0	0.8	5.1	510	0.012
82-17170		NBLs with no surface scaling	142.4	7.2	4.3	5.7	320	0.014
82-17174	I-69-153-5038 JA	SBLs with no surface scaling	142.5	7.0	3.1	6.9	390	0.011
82-17175		SBLs with light surface scaling	141.4	5.9	0.9	8.1	550	0.009
82-17171	I-69-154 4817 A	NBLs with no surface scaling	147.5	6.3	1.5	6.8	430	0.011
82-17172	I-69-155 4818 A	NBLs with no surface scaling	145.4	7.1	4.6	4.1	230	0.018
82-17173	I-69-156-4820 A	NBLs with no surface scaling	147.4	4.4	1.2	5.3	490	0.011

Table B-3 Dosages of AEA Needed for Various Cements

Neutralized Vinsol Resin			Alkali Wood Resin		
Slump (in.)	Air (%)	Dosage (% solid by wt cement)	Slump (in.)	Air (%)	Dosage (% solid by wt cement)
Lab Blend					
1.9	4.8	0.015	2.5	5.9	0.011
2.6	6.9	0.023	2.6	7.5	0.018
Type IA					
1.4	6.0	0.019	1.7	6.2	0.012
2.0	6.3	0.019	2.4	6.4	0.012

In conclusion there seemed to be nothing peculiar about the air-entraining agent used in this project. With the same materials, and also with the laboratory blend of cement, dosage rates for neutralized Vinsol resin were somewhat on the high side. However, it should be recognized that cements differ in the amount of agent needed to obtain a given air content, and as long as dosage is within recommended limits this should not be cause for alarm.

NEW YORK STATE DEPARTMENT OF TRANSPORTATION

A meeting was held at the New York State Department of Transportation offices in Albany, New York. State materials engineers, field district engineers, and two concrete producers were in attendance. Topics of discussion included problems with particular admixtures, precast plant operations, sampling, and dense overlays.

Admixtures

Current NYSDOT specifications for class A concrete prepared with 600 lb/cu yd of cement and 1-in. maximum aggregate size call for 4 to 8 percent air. Problems were encountered in obtaining 4 percent air even at air-entraining agent dosages of 22 ounces per yard. This occurred in transit mix operations in which concrete was mixed for 70 revolutions at the plant, and then taken to the job and mixed for an additional 30 revolutions. Slumps generally ranged from 2 to 3 in., and did not show much fluctuation. Problems had been seen with a number of different cements, most of which were ASTM Type II. The problem occurred mainly during 1979-1981, and mostly where a particular sulfonated hydrocarbon type AEA was used. However, the problem apparently was not confined to this agent. Water reducers were used in an attempt to lower air-entraining dosage, but no major effects were seen. When a wood resin AEA was tried producers claimed that up to 33 ounces per cu yard of concrete were necessary to obtain the 4 percent air minimum. Some district engineers stated that switching to Vinsol resin helped alleviate the problem on a few jobs.

Laboratory Evaluations. Samples of cement, sand, A/E admixture (alkali-stabilized wood-resin) and crushed stone were received from NYSDOT. The crushed stone was similar to a local Illinois limestone in texture and particle shape. Therefore, to save on shipping costs, the Illinois stone was graded to match, as closely as possible, the gradation of the New York material, and used in all concrete mixtures. A Class A concrete mix design was used. This mix called for a cement content of 606 lb/cu yd, a maximum aggregate size of 1-1/2 in., and a slump of 2.5 to 3.5 in. Both wood resin and NVR were investigated. Results are presented in Figure B-1. The dosage rate needed to obtain 6 percent air was approximately 4 fl oz/cwt of cement. This verified the high dosages reported by NYSDOT which ranged from 17 to 18 oz/yd^3 (2.8 to 3.0 fl oz/cwt). NYSDOT reported that even at these dosages 6 percent air could not be achieved.

A 90-second mix cycle was used for these batches. It was noted that the concrete appeared much more fluid during mixing than immediately afterward, which indicated some tendency towards false set. This was confirmed by running ASTM C 359 tests, which showed some tendency, though not excessive, to a false setting behavior. When these concretes were remixed for 2 minutes, air contents were much higher, as indicated in Figure B-1. The same effect was noted with NVR, although to a lesser extent.

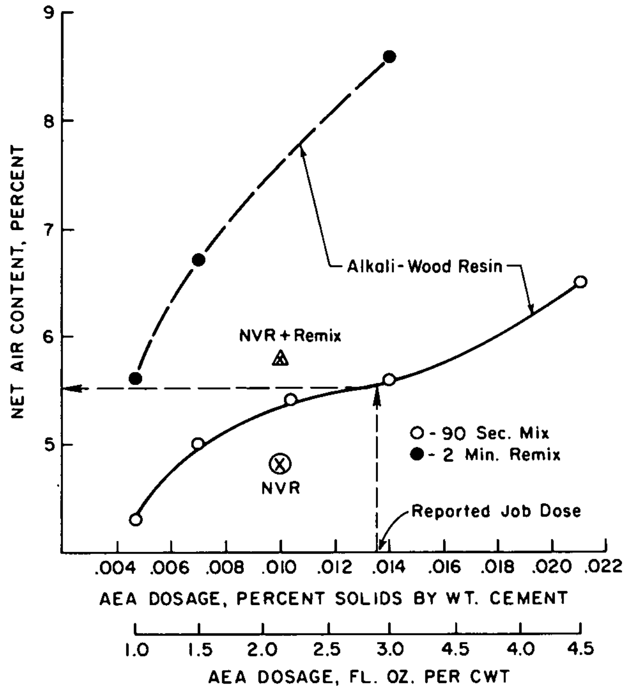

Figure B-1. Variation of air content with dosage of air-entraining agent using 90 second mix and remix cycle.

Finally, the shape of the curve of dosage rate vs air content indicates that the increase in air content with dosage is fairly steep up to about 0.01 percent s/c. The curve then "flattens-out," but rises again at dosages over 0.014 percent s/c. More than twice as much agent is needed to obtain the final percentage point of air than was needed to obtain the initial 5-1/2 percent. The investigators concluded that, at the job site, low air contents, high dosage rates, and insensitivity to increases in dosage appear to be related to a false-setting tendency of the particular cement used. Possible solutions suggested were to change cement source or to include a remixing period after the initial mixing process.

Precast Plant Operations

New York representatives apparently believed that many precast plants have inconsistent batching procedures and that air-entraining agents are added at various points in the manufacturing process which may lead to problems in control of air content. Also, they believed that human errors occur in these operations which may lead to similar problems. However, no documentation was available.

Sampling

Sampling and testing for air content are normally carried out at the rate of one per 50 cu yd of concrete. The first 1/3 of the load from the truck is usually sampled. If problems develop, sampling is done on every load, especially for bridge decks. On pavements, one air test per 500 linear feet is usually made.

Dense Overlays

For NYSDOT operations, dense overlays do not appear to present too many problems in control of air content. The major reason for this is that the materials to be used on the job are first trial-batched in the laboratory. These trial mix designs are then provided to district personnel. Specified air content is 6 ± 2 percent at slumps ranging from 1/2 to 3/4 in. Concrete mobiles are used in the field and air-entraining agent dosages in the field must be adjusted downward from those in the laboratory. This suggests that concrete mobiles are more efficient in obtaining desired air contents than laboratory pan mixers.

Overlays have been used in New York since 1976, and have generally performed well. It was noted that the concrete looks much more fluid when discharged from the concrete mobile chute than it actually is when placed. For this reason, the slump test is delayed by about 5 minutes. As a result, lower air contents are measured than would be the case if sampling had been done immediately after discharge from the truck.

NEW JERSEY DEPARTMENT OF TRANSPORTATION

A meeting was held with representatives of the New Jersey Department of Transportation in Trenton, New Jersey. In attendance were representatives from the Bureau of Inspection, Engineering, Evaluation and Coordination, representatives from the Quality Control Laboratories, and representatives from the Research & Development Division. The history of air content and air content control problems in New Jersey was briefly reviewed.

Prior to 1978, specifications called for 3 to 6 percent air and frequency of inspection was relatively low. In 1978 the Project Engineer of the Bureau of Inspection initiated a project in which air content was taken on every truckload of concrete produced. When this was done a large number of loads was found to be out of specification. Dosage rates needed to obtain specified air contents were very erratic. Because of these problems, the target air content was raised to 7 percent and tolerances were increased to ± 2 percent. Also, retempering air contents on the job was initiated.

The most widely used air-entraining agent in New Jersey is an alkyl-benzene sulfonate type, which is commonly used at 3/4 to 1 ounce per hundredweight of cement. On many mixes, however, 3 to 4 ounces per hundredweight are needed to get 6 percent air. Also, mixes are highly sensitive to slump, and an increase in slump of 1 in. may sometimes double the air content. Representatives from the Research Division felt that producers, for the most part, were deliberately maintaining low air contents so as to avoid strength penalties.

White Concrete

Mixes which show the most problems are mainly what New Jersey terms "white concrete." This mixture utilizes relatively finely ground white cement and a highly reflective calcite sand. For the most part, the calcite sand is dry-batched at the plants. It is possible that the air-entraining agent is absorbed onto the sand during batching because most of the work done in New Jersey is by truck-mixing, and water is not added until the truck, which is nonagitating, reaches the job site. New Jersey, however, is in the process of shifting to central mix and transit mixing to improve control.

Batching and Mixing

Reports were also supplied which describe instances where malfunctioning admixture meters and other batching problems led to wide fluctuations in air contents. Also included were the results of a study made on a large job where up to 36 different mixing trucks were used. Approximately 14 percent of the 1198 loads delivered were out of specifications on air content. A number of trucks appeared to be more prone to delivery of out of specification concrete than others. Data for trucks hauling over 100 loads are given in Table B-4. It is interesting to note that loads with low air content concrete predominate over those with high air. This may reinforce the views expressed by representatives of the Research Division.

Scaling of Curb and Median Barrier

After the meeting, representatives from the Research Division accompanied the principal investigator to field sites where scaling had occurred on median barriers and curbs. Some of the scaling was especially severe. It was noted that

Table B-4 Truck Mixing Out of Specification Air Content

		Number of Loads			
Truck No.[1/]	Trips	Low Air	High Air	Total	% of Trips
304	117	13	3	16	14
314	126	17	4	21	17
316	115	5	5	10	9
322	128	9	2	11	9
326	145	6	4	10	7
330	111	12	4	16	14
Total	1198	114	49	163	14

1/ Only selected trucks included.

the north side of the median barriers appeared to scale to a greater degree than the south side. Cores from these barriers showed very low air contents, low specific surfaces, and high spacing factors. A report issued in April 1981 (43) attributed the poor durability of these median barriers and curbs to unsatisfactory air void systems, and occasionally to the use of high water-cement ratios and poor curing practices. Low air contents in the fresh concrete were attributed to the practice of maintaining air towards the low end of the range, coupled with loss of air in the fresh concrete.

Because problems in control of air content in New Jersey could be related to a relatively unique set of circumstances (i.e. truck mixing, white cement, calcite sand), samples of materials were not requested. However, suggestions that control of air in the slump range of 2 to 3 inches is especially critical were taken under consideration, and some experiments in this area were carried out later in the investigation. Results are discussed in Appendix E.

APPENDIX C

GUIDELINES FOR CONTROL OF AIR-ENTRAINED CONCRETE

INTRODUCTION

Air entrainment is now accepted as the primary means for protecting portland cement concrete against deterioration caused by repeated cycles of freezing and thawing. Its major purpose is to protect against scaling of flatwork due primarily to the application of deicing agents during winter months. The air content of concrete must be held within relatively close tolerances if it is to be effective. If too low, concrete will not be protected adequately. If too high, low strength and degradation of other critical properties may result. Although a vast amount of information exists concerning precautions that must be taken to ensure adequate control, much of it is scattered throughout the literature and is difficult to obtain. The aim of these guidelines is to provide the highway community with a reference work which addresses this problem in straightforward terms.

These guidelines include a brief discussion of the formation and role of entrained air in concrete, as well as some historical perspective as to how air entrainment was developed. While these items are not a necessity for dealing with day-to-day control, they do afford the user with a better appreciation and understanding of what is being accomplished through the use of air entrainment. The types of air-entraining agents that are available will also be given, but this should not be misconstrued as an endorsement of any one product to the detriment of any other. A brief review of mix proportioning for air entrainment is also included. Those wishing to obtain more detailed procedures should consult more comprehensive reference works such as ACI 211 (51).

Other sections of the guidelines discuss the influence of various concreting materials on the ability to achieve and maintain specified air contents. The effects of various construction practices on air content, including batching and mixing procedures, transport, placement, consolidation, and finishing, are covered. The need for adjustments due to temperature changes will also be discussed.

Proper sampling and testing are essential if good control of air content is to be maintained. Sampling rates and practices in current use are included in these guidelines, as are suggestions for possible improvements. Test methods are briefly described, although details are left to standard specifications.

Finally, current specifications on air content are discussed in view of what is known about variability of field production. Their limitations, and suggested alternative specification procedures, will be mentioned. It should be noted that these guidelines are not intended as a specification document, but only point the way towards achieving good control within the context of the specifications set forth on any particular job.

SECTION 1 - FUNDAMENTALS OF AIR-ENTRAINED CONCRETE

Formation and Role of Entrained Air in Concrete

All concrete contains air voids that are formed during the mixing process. These voids are the casts of air bubbles produced by the mechanical action of the concrete mixer, especially those bubbles that are trapped between sand grains and cannot subsequently escape. The majority of bubbles in ordinary concrete, however, are not stable and either dissolve in, or escape from, the mix prior to final hardening of the concrete. Thus, in most cases, ordinary concrete will contain less than 2 percent entrapped air by volume.

However, when an air-entraning agent is added the situation is dramatically altered. The air-entraining agent is able to stabilize very small bubbles which otherwise would dissolve, and also to promote formation of additional bubbles by lowering the surface tension of the mix water. It accomplishes this by virtue of its unique molecular structure, which consists of one end of the molecule which is repelled by water (hydrophobic) and one end which exhibits an electric charge. The charged end is attracted to cement grains, and the hydrophobic ends form a coating on the air bubbles. This encases the bubbles in a film of precipitated air-entraining agent and cement, which stabilizes them and prevents their coalescence (see Fig. C-1).

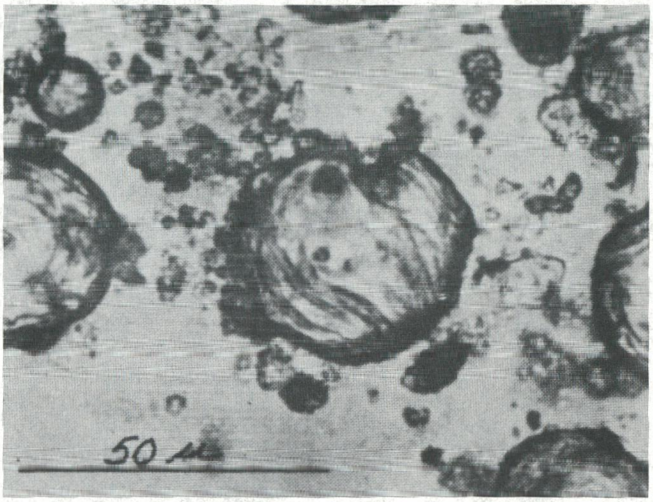

Figure C-1. Air bubbles produced in a fresh cement paste slurry (36).

The bubbles persist during the setting process and remain in the hardened concrete as a system of minute voids distributed throughout the volume of concrete. When viewed under a microscope, air voids appear as circular sections within the mortar phase of the concrete (see Fig. C-2). The majority of these voids are extremely small, with the peak in the void size distribution commonly found at diameters usually ranging from 50-100 microns (see Fig. C-3).

A single cubic inch of concrete can contain 2 million such voids. Thus the spacing between voids is also very small. The small spacing gives the voids their utility as a means of protecting concrete against freezing and thawing.

As temperatures fall below freezing, water contained in the concrete also begins to freeze. Water contained in the "large" capillary spaces of the mortar freezes first. This produces sites of ice formation to which additional water can be attracted (or "accrete" at). Expansive damage can result as ice crystals grow and begin to exert pressure on the capillary walls. Through the introduction of closely spaced air voids, ice will preferentially accrete in these voids, in which there is more room for growth of ice crystals. Thus, expansive pressures are relieved and the concrete is protected from serious damage.

A measure of the relative distance between the voids can be obtained by performing a micrometric analysis of a polished concrete surface. This technique

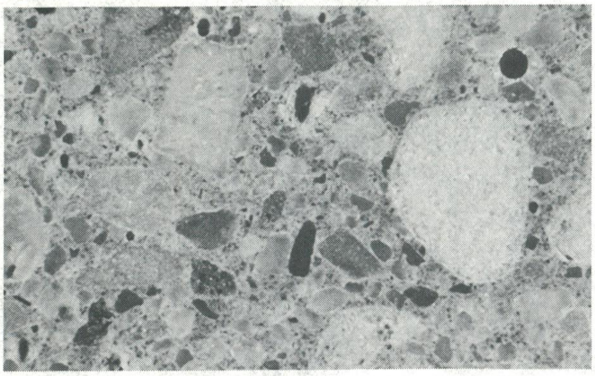

Figure C-2A. Concrete Air Content = 2.5 percent; Voids/in. = 1.64; Spacing Factor = .024 in.

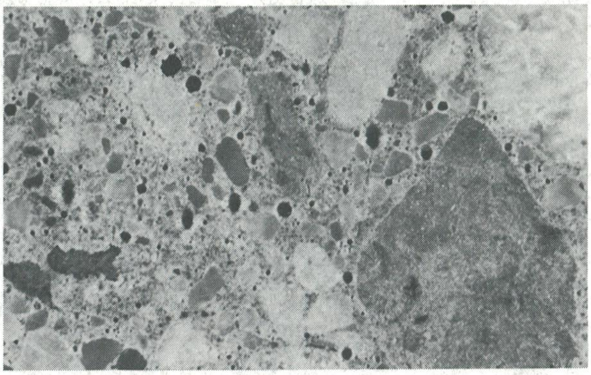

Figure C-2B. Concrete Air Content = 3.7 percent; Voids/in. = 5.08; Spacing Factor = .0097 in.

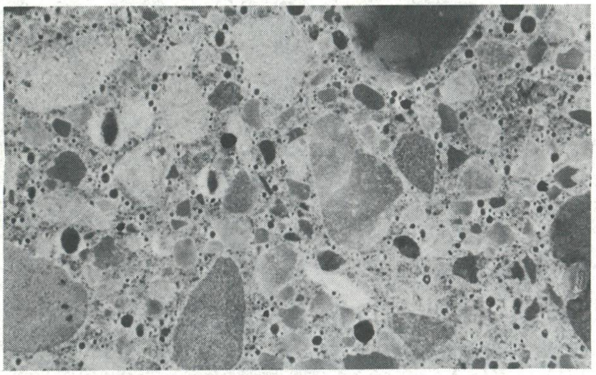

Figure C-2C. Concrete Air Content = 5.8 percent; Voids/in. = 9.96; Spacing Factor = .0063 in.

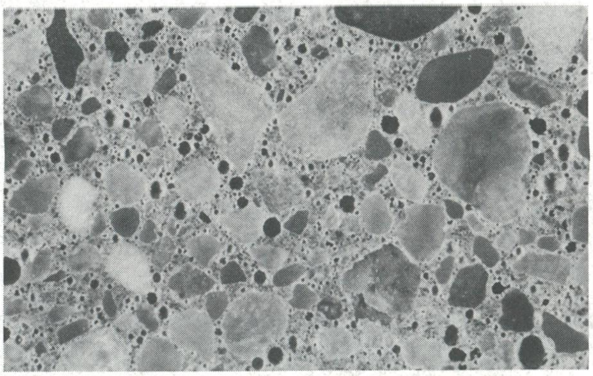

Figure C-2D. Concrete Air Content = 7.9 percent; Voids/in. = 14.98; Spacing Factor = .0042 in.

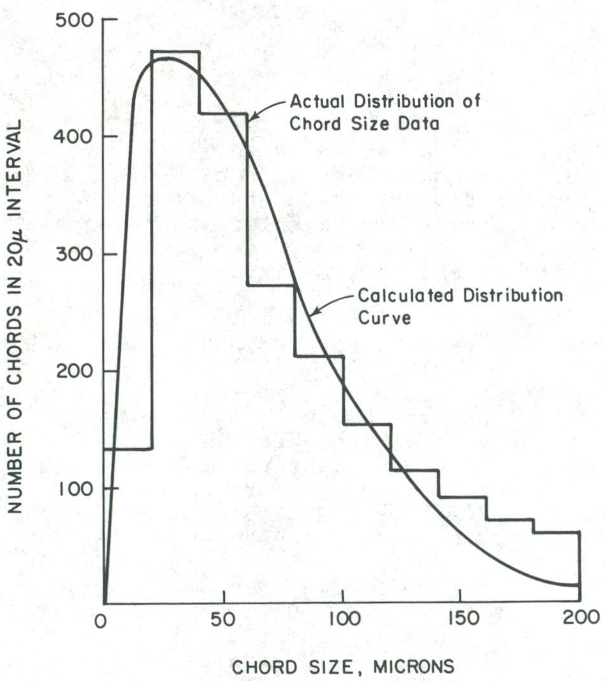

Figure C-3. Calculated versus actual chord size distributions for typical specimens.

is described in ASTM C 457. The "spacing factor" determined by this technique is only an approximation to the true distance between the voids, but it still has proven to be quite useful as an indication of the potential durability of concrete. The American Concrete Institute has recommended (42) that this factor be not greater than 0.008 in. in severe environments such as highway bridge decks.

Research and field experience has shown that, in most cases, the total volume of air measured in fresh concrete using accepted ASTM procedures will also serve as a valid indicator of concrete performance. Because the air is contained wholly within the mortar phase, the desired air content will be a function of the maximum aggregate size used. Recommended air contents, taken from ACI 201.2R-77 (38), are given in Table C-1.

It is recognized that achievement of the desired air content is a necessary, but not sufficient, condition for ensuring adequate freeze-thaw durability of concrete. Factors such as type of aggregate used, degree of saturation of the concrete, cement content, degree of consolidation,

Table C-1 Recommended Air Contents for Frost-Resistant Concrete (38)

Nominal Maximum Aggregate Size, in. (mm)	Average Air Content, percent[1/]	
	Severe[2/] Exposure	Moderate[3/] Exposure
3/8 (10)	7-1/2	6
1/2 (13)	7	5-1/2
3/4 (19)	6	5
1-1/2 (38)	5-1/2	4-1/2
3[a/] (75)	4-1/2	3-1/2
6[a/] (150)	4	3

[1/]A reasonable tolerance for air content in field construction is 1-1/2 percent.

[2/]Outdoor exposure in a cold climate where the concrete may be in almost continuous contact with moisture prior to freezing, or where deicing salts are used. Examples are pavements, bridge decks, sidewalks, and water tanks.

[3/]Outdoor exposure in a cold climate where the concrete will be only occasionally exposed to moisture prior to freezing, and where no deicing salts will be used. Examples are certain exterior walls, beams, girders, and slabs not in direct contact with soil.

[a/]These air contents apply to the whole mix, as for the preceding aggregate sizes. When testing these concretes, however, aggregate larger than 1-1/2 in. (38 mm) is removed by hand-picking or sieving and the air content is determined on the minus 1-1/2 in. (38 mm) fraction of the mix. (The field tolerance applies to this value). From this the air content of the whole mix is computed.

water-to-cement ratio, and workmanship will also play major roles. The reader of these guidelines should recognize this and strive for good control over all materials and processes used in production of concrete.

Air entrainment has been found to have a beneficial effect on many other properties of fresh and hardened concrete, provided that the mixture is well proportioned, the concrete has reached sufficient maturity, and advantage has been taken of the effects of air entrainment on slump and workability of the mix. If this is done, workability can be increased, bleeding decreased, finishing expedited, and a more uniform product obtained. In the hardened state, entrained air has only minor effects on such properties as shrinkage, creep, fatigue, bond strength, and abrasion resistance. The ability of concrete to withstand attack by sulfates and internal degradation of reactive aggregates is enhanced by air-entrainment. The only properties that are deleteriously affected by entrained air are strength and elastic modulus. By proper mix design, these effects can be minimized, although some loss of strength is still to be expected, especially in high strength concrete mixtures.

Types of Air-Entraining Agents

A large number of commercial formulations are currently available for use as air-entraining agents. Most admixtures are complex formulations which may include mixtures of more than one chemical. Perhaps the simplest, and most widely used products, are based on "Vinsol resin." This material is a by-product of a process for recovering various solvents and rosins from pine wood stumps. Vinsol resin is essentially insoluble in water and must be neutralized with caustic soda so as to form the soluble sodium soap which is the basis of commercial formulations. These formulations are generally produced with solid contents ranging from 5 to 15 percent by weight.

Another category of widely used air-entraining agents includes those derived from petroleum products. These may be derived either from sulfonation of crude oils, or by more refined synthetic techniques. Among the types that are used are aromatic sulfonic acids, organic salts of such acids, and substituted benzyl sulfonates.

Another class of air-entraining agents includes fatty and resinous acids and their salts. These are derived from the processing of animal and vegetable fats and oils which contain a variety of glycerides and waxes.

The wide variety of surface active materials, and the increasing sophistication of organic chemical synthesis, indicates that many more types of compounds may have the potential for formulation as air-entraining admixtures. However, a major advantage of naturally derived products is their ease of synthesis and their low cost. Therefore, it is expected that these compounds will continue to comprise the bulk of the air-entraining agents used in the concrete industry.

A listing of currently available types of air-entraining agents, their industrial source, generic chemical type, and some trade names is given in Table C-2. It should be noted that no single type of admixture has been proven superior in all applications. Instances may arise however, when, because of the particular set of materials or circumstances, one admixture may yield better results than others. The current state of knowledge of specific interactions of air-entraining agents and other materials is not suffiently advanced to enable the user to predict such behavior in advance of preparation of the concrete batch.

Development of Air-Entrained Concrete

Materials that could be classified as air-entraining agents have been used in concrete as early as Roman times. In the early part of this century, various oils and "waterproofing" compounds were added to concrete which no doubt resulted in entrainment of considerable amounts of air. However, it was not until the late 1930's and early 1940's that the beneficial effects of air entrainment became recognized.

Surveys made in the late 1920's and early 1930's in many of the northern states brought into sharp focus the extensive scaling which concrete surfaces exposed to deicing salts and abrasive agents were experiencing. This scaling would begin within one to two years after the first application of salts, and would progress steadily until the entire surface was virtually disintegrated. It was proven that the extent of severity of the scaling was proportional to the amount of chemicals used and their frequency of application. Research began into

Table C-2 Classification of Air-Entraining Agents

Group	Classification	Industrial Source	Chemical Type(s)	Brand Name(s)
A	Salts of wood resins	Extract of pine wood stumps	Complex mixture of lignin derivatives (phenols), carboxy resin acids, aromatics, terpenes	NVX, Sika-AER, Amex, MBVR MBAE-10, Daravair, Protex-AES
B	Synthetic detergents	Petroleum distillates	Alkyl-aryl sulfonates	Amex-210, Microair, Darex
C	Salts of sulfonated lignins	Digestion of wood chips	Complex sulfate liquors (Ca lignosulfonates, reducing sugars, carbohydrates)	Not widely used at present for AEA
D	Salts of petroleum acids	Preparation of lubricating oils	Complex, highly sulfonated aromatic and saturated ring structures	No information
E	Salts of proteinaceous materials	Alkaline treatment of animal hides	Amino acids	Airsene-L
F	Fatty and resinous acids and their salts	Hydrolyzation of animal and vegetable fats	C_{12} to C_{18} saturated acids, oleic acid, abietic acid, tall oil	Airalon, Airex-D, Septair
G	Organic salts of sulfonated hydrocarbons	Water soluble petroleum acids	Triethanolamine salts of condensed petroleum acids	Pro-Air

solutions to this problem, with agencies such as the New York Department of Public Works, the Universal Atlas Cement Co., the Lone Star Cement Corp., and the Portland Cement Association making early contributions.

The New York State Department of Public Works noted that blends of portland cement and natural cement provided more scale resistant pavements than did straight portland cements. This was traced to the use of beef tallow as a grinding aid for natural cement. When tallow was added to portland cement, similar favorable results were obtained. Benefits were also obtained by adding fish oil stearates. During the same time period Vinsol resin was found to be even more effective than the tallow and fish oil stearates, and it came into wide use as a cement additive. Laboratory work during this period verified that it was the increased air content, rather than the chemical action of the additives used, which imparted freeze-thaw and scale resistance to the concrete.

Early laboratory and field studies set the stage for more comprehensive field evaluations. During the period from 1938 to 1942, 18 experimental road projects were conducted in Illinois, Indiana, Kentucky, Maine, Massachusetts, Michigan, Minnesota, New York, Ohio, Pennsylvania, Utah, and Wisconsin. In all projects except one the admixtures were interground with cement clinker, thus producing what would be termed "treated" cements. Most of the projects incorporated Vinsol resin. Others used neutralized tallow, while only one used some of the earlier agents such as cod fish oil or other animal derivatives. The major conclusion as recorded by the Portland Cement Association was that "the tests showed the definite superiority with respect to frost resistance, of treated or untreated natural cements in such blends, which indicate that the beneficial effects obtained were not due to the natural cement per se, but to the presence of an air producing admixture introduced during grinding." Figure C-4, which shows a portion of the Illinois experimental road on Archer Avenue between Cicero Avenue and 47th Street in Chicago, serves as dramatic evidence of the ability of concrete made with treated cements to withstand deicing salt applications.

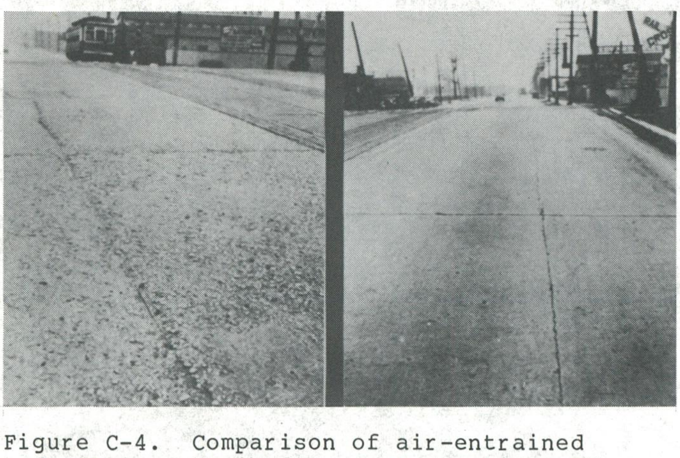

Figure C-4. Comparison of air-entrained and nonair-entrained concrete sections of test road on Archer Avenue, Chicago, Illinois.

By the early 1940's the "discovery" of air entrainment, which spanned a period of approximately 7 years, was essentially complete. Successful laboratory and field studies afforded confidence in the use of air entrainment to many other potential users not involved in the early experimental work. The stage was set for a dramatic increase in the use of air entrainment in highway construction.

Proportioning of Mixtures for Air Entrainment

The art of design of concrete mixtures has advanced to the point where the concrete technologist can use relatively straightforward procedures to obtain a satisfactory mix design for air-entrained concrete. Organizations such as the American Concrete Institute (51) and the Portland Cement Association (52) have published mix design procedures and these have been widely circulated throughout the industry. Although provisions for adjustment for air entrainment are included, little guidance is given as to how the tabulated values were derived. Some knowledge of the effects of entrained air on mix proportioning is essential for those wishing to obtain optimum performance from their concrete.

Concrete mixtures are usually designed with compressive strength as a principal criterion. In general, entrainment of air will result in a loss of strength. The magnitude of this loss increases with the cement content and strength of the mixture. As shown in Figure C-5, mixtures with relatively low cement contents will exhibit little strength loss as long as air content is held below 6 percent. In fact, strengths of lean mixtures may actually be increased by air entrainment because advantage can be taken of the increases in workability afforded by the air entrainment. This allows the designer to reduce water contents, thus offsetting strength loss caused by the entrained air voids.

For mixtures of more moderate cement contents some guidance is available as to strength loss to be anticipated when air entrainment is used. A loss of either 200 psi or 5 percent of initial (nonair-entrained) strength can be expected for every percentage point increase of air content. It should be noted, however, that the relationship between strength loss and air content is nonlinear. Proportionally greater amounts of strength are lost when increasing air contents from 7 to 8 percent, compared with initial decreases experienced from 2 to 3 percent. With compressive strengths over 8,000 psi, losses due to entrained air are much more substantial and may range upwards of 10 percent for every percentage point increase in air content.

The actual proportioning of air-entrained concrete mixtures takes advantage of the fact that air entrainment, by virtue of the buoyancy of the air voids and effects on electrostatic charge of the cement particles, will impart a significant amount of plasticity to an otherwise harsh mixture. This can allow a reduction in net mix water content from 6 to 8 pounds per cubic yard per percentage point of air entrained. Less water reduction is possible in rich mixtures than in lean mixtures. Concurrent with the reduction in water will be a reduction in fine aggregate content. In contrast to water content, this is less for lean mixtures and greater for rich mixtures. A general observation for mixtures of moderate cement content is that approximately 1 percent sand (by weight of total aggregate) may be removed for each percentage point of air that is entrained. Graphical illustration of these principles is shown in Figure C-6, which is adapted from an article by Gilkey (53).

A properly proportioned air-entrained concrete, therefore, will contain less water and sand than a nonair-entrained concrete at equal cement content. Rather than resulting in a loss of workability, the air-entrained concrete, even at the lower water content, will be more workable than its companion nonair-entrained mixture. Its response to vibration also is improved and workmen find it easier to handle. Although excessive amounts of air may tend to make some mixes "sticky," properly proportioned air-entrained concrete is easier to finish, bleeds less, and has more plasticity than nonair-entrained concrete.

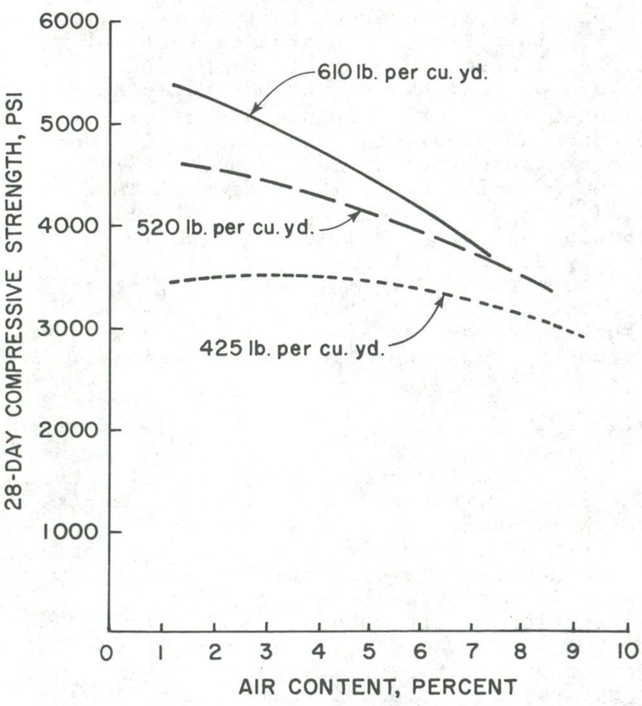

Figure C-5. Relationship between air content and 28-day compressive strength at three cement contents (22).

SECTION 2 - MATERIALS FOR AIR-ENTRAINED CONCRETE

Although the particular type and amount of air-entraining agent have significant effects on the air-entrainment process in concrete, the mix design and components of the mixture also exert significant and sometimes decisive influence on the air content and air-void system in the final product. Among the mix components that must be considered are portland cement, aggregates (especially the fine aggregate), other chemical admixtures (such as retarders and accelerators), mineral admixtures (such as fly ash and other pozzolans), and any impurities or contaminants that may be inadvertently contained in the mixture. Some aspects of mix design that have a bearing on air entrainment in concrete are the amount of cement, water-to-cement ratio, and ratio of fine-to-coarse aggregate. In this section these parameters will be individually discussed as to their separate influences on entrainment of air in concrete.

Portland Cement

As the cement content of a concrete mixture is increased, the proportional amount of air-entraining agent needed per unit weight of cement also increases. In other words, air-entraining agents become

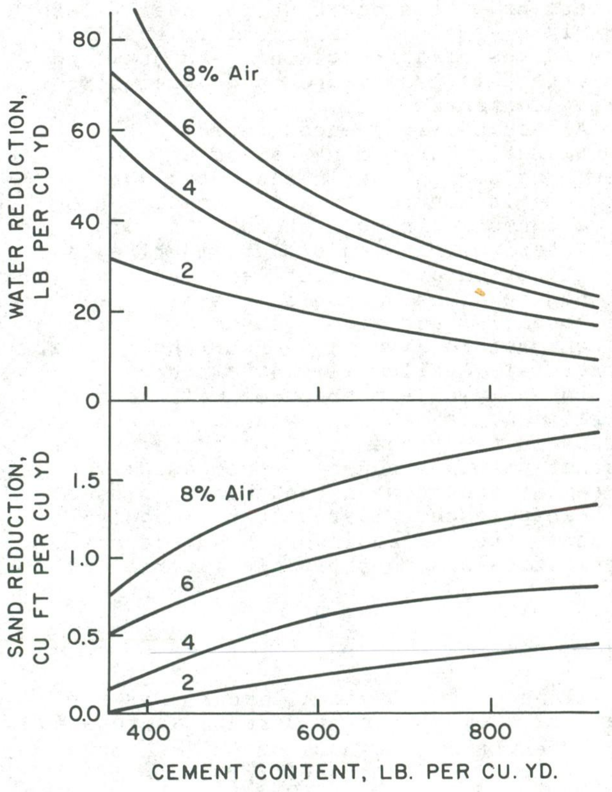

Figure C-6. Reduction in water and sand contents made possible by various percentages of entrained air (53).

less efficient as cement contents increase. At moderate cement contents of from 400 to 600 lb per cubic yard, required dosages of air-entraining agents may increase up to 50 percent as cement content is increased over the full range. At higher cement contents, however, increases in air-entraining agents needed to obtain the specified air content will be more substantial, especially for air contents of 7 to 8 percent. In these cases, a doubling of air-entraining agent dosage is not considered unusual. For dense, low-slump, high cement content mixtures such as used in bridge deck overlays, very high doses of air-entraining agents are needed. Required dosages may range up to 10 to 15 times higher than those used in ordinary concretes.

Aside from cement content, the type and chemical composition of portland cement will also affect the required dosage of air-entraining agent. ASTM Type III (high early strength) cements may require double the amount of agent used with Type I or Type II cements. Also, some high fineness cements may impose a limit on air content, beyond which increased dosages will not materially increase the air.

The major chemical constituent of cement influencing air entrainment is alkali content. In general, an increase in alkali content will decrease the amount of air-entraining agent needed to achieve a given air content. In going from a low to high alkali cement, required dosage may drop by as much as 70 percent. Most typical values are in the range of 20 to 40 percent. This decrease is usually less for Vinsol-resin based materials than for other types of air-entraining agents, and the effect is less pronounced at higher cement contents.

Although rarely encountered, contamination of cement can occur and should be considered in instances where problems in control of air content cannot be assigned to known factors. Oil from mill bearings can cause contamination, and its effect on air content is a function of the degree of oxidation of the oil. Oil-contaminated cement ground or stored at temperatures over 100°F will tend to entrain air, while oil-contaminated cement ground at lower temperatures will tend to detrain air, especially when the cement is ground in the presence of moisture. Another possible source of contamination of cement occurs when tanker trucks used to transport cement are not thoroughly cleaned after unloading such substances as fertilizers or other organic material.

Aggregates

Although the physical nature and chemical composition of certain aggregates may affect air content in some instances, by far the most important influence of aggregate is due to its effect on concrete mix design. For example, use of a larger maximum aggregate size will result in a decrease in air content. This is due to two effects on mix design:

1. An increase in maximum aggregate size reduces the mortar fraction of the mix. Because the air voids are wholly contained within the mortar phase, air content is reduced accordingly.

2. The sand-to-total aggregate ratio needed to obtain the desired mix properties will decrease as maximum aggregate size increases. Because sand itself contributes to air content by trapping air bubbles in sand grain interstices, a decrease in sand content will decrease air. For every 1 percent decrease in sand content air content will decrease about 0.1 percentage point.

Much has been said regarding the influence of sand gradation on air content. Within the ranges normally encountered in specification concrete, however, this influence is relatively minor. Over the range of fineness moduli normally encountered, air content will fluctuate approximately 0.5 percentage points about the mean value for mixtures having conventional sand contents. In addition, there is little hard evidence to support claims that certain size fractions of sand, for instance the No. 50 to No. 100 material, have a disproportionately large influence on air entrainment in concrete. The presence of large amounts of very fine materials (less than 200 mesh), however, will reduce air contents. This can be seen when crusher fines exceed 3 percent of the total coarse aggregate, or when significant amounts of clays or other silts are present in fine materials.

Various organic substances that may act as contaminants can occur naturally in sand deposits. These include humic acids, vegetable matter, tannins, and other organic decomposition products. Vigilant use of the colorimetric procedure for detection of organic impurities (ASTM C 40-79) can circumvent most potential problems arising from such sources. All finely divided materials will tend to reduce air contents. In addition, recent instances of contamination of aggregate stock piles by certain wetting agents used to control dusting have been reported.

Mix Water

The most important effect of mix water on air entrainment is the amount of water which is used. This affects both the water-to-cement ratio (w/c) and slump of the concrete. As w/c ratio increases, there is more free water available for generation of air bubbles, hence air content will increase. Air content can increase over four percentage points when w/c ratio is increased from 0.40 to 1.0. While air contents increase the void system becomes coarser, and the specific surface of air voids in the hardened concrete will generally be lower in concretes with higher water-cement ratios (Fig. C-7). It is important that close control over water additions be maintained, not only as a means of controlling air content, but also to ensure good durability of the concrete.

It is well established that the slump of concrete has a significant effect on air content. In most cases this is simply a reflection of the relationship between water-cement ratio and air content, where increases in slump for a given mixture reflect an increase in water content to improve or maintain workability. Laboratory studies, however, show that air content will increase with slump even as water-cement ratio is held constant. By increasing the net amounts of water and cement in the batch for a given amount of air-entraining agent, the air content increases as slump is increased from 1-1/2 to 4-1/2 in. Above a slump of 6 to 7 in. many mixtures become too fluid to retain entrained air and air content decreases. Typically, in the range of about 1/2 to 5 in., an increase of 1 in. in slump is accompanied by an increase of about 1/2 to 3/4 percentage points in air content.

At slumps in the range of 1 to 3 in., control of air content may be difficult. At the low end of this range some mixtures may have too stiff a consistency to entrain large amounts of air unless unusually large dosages of air-entraining agents are used. In air-entrained concrete with a 2-to 3-in. slump, the initial mixture prior to introduction of air-entraining agent actually is designed for a lower slump due to the presumed water-reducing effect of the air-entraining agent. Additions of small amounts of water (less than 1 percent of the net water content) to mixtures in this range have caused large changes in air content and slump for particular air contents and air-entraining agents. Vinsol-resin type agents appear to be more susceptible to this problem.

Aside from the amount of water added to the mixture, other characteristics of mixing water can also affect air content. Water hardness (within usually encountered ranges of municipal water supplies) is normally insignificant in its effect on air content of concrete. However, because of its extremely high alkalinity, wash water from truck mixers may cause problems in production of air-entrained concrete. Water contaminated by algae growth leads to excessive air contents in nonair-entrained concrete and would be expected to contribute to air contents in air-entrained concretes as well.

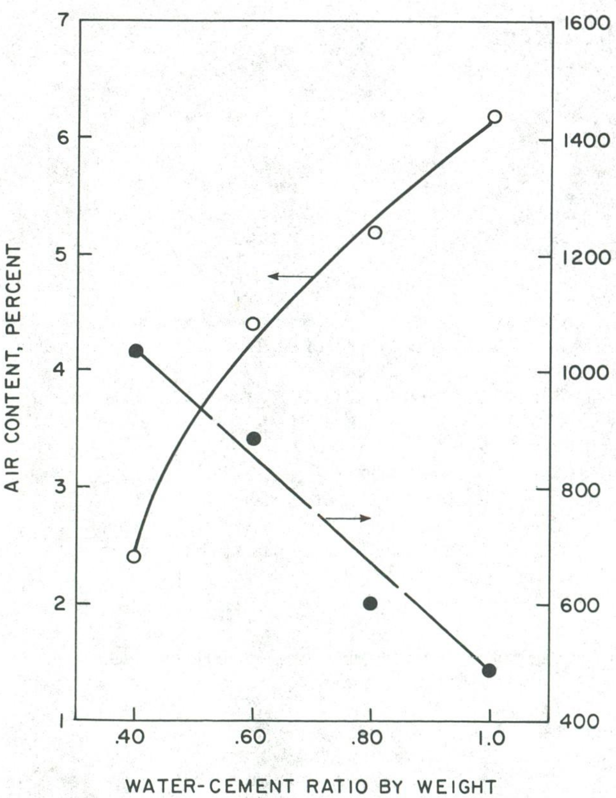

Figure C-7. Effect of water-to-cement ratio on air content and specific surface of air-entrained concrete (23).

Chemical Admixtures

The major types of chemical admixtures currently used for highway applications include water-reducing agents, retarders, and accelerators. "Superplasticizers," which are newly developed forms of water-reducers, are also coming into increasing use. All of these admixtures can affect the air content and air-void system of concrete. It should be noted that interactions between air-entraining agents, chemical admixtures, and portland cement are complex, and because of this, many exceptions to the guidelines presented herein may be found.

Conventional Water Reducers and Retarders. The most widely used conventional water-reducers and retarders can be classified (54) as follows:

1. Lignosulfonic acids and their salts.
2. Modifications and derivatives of Class 1.
3. Hydroxylated carboxylic acids and their salts.
4. Modifications and derivatives of Class 3.
5. Carbohydrates and their modifications and derivatives.

These are commonly batched into fresh concrete in liquid form at dosages ranging from 2 to 8 fl oz per hundred weight of cement, depending on the degree of water reduction or retardation desired. Numerous studies have shown that less air-entraining agent is needed to achieve a specified air content when water-reducing and retarding admixtures are used in concrete. This is true even for those materials that do not entrain air when an air-entraining agent is not used.

Lignosulfonate-based materials appear to be the most influential in this regard. In this case, the required dosage of air-entraining agent may need to be reduced from 50 to 90 percent of the amount used when no water-reducer or retarder is added. In extreme cases, and especially at low temperatures, the admixture alone may be sufficient to obtain the specified air content, and use of an air-entraining agent may place the air content out of specification on the high side. Organic-acid based admixtures pose less of a problem. For these agents, the dosage of air-entraining agent may need to be reduced only 20 to 40 percent.

Not only is gross air content influenced by the introduction of water-reducing and retarding agents into air-entrained concrete, but the parameters of the air-void system are affected as well. Spacing factors may increase with increasing dosages of these admixtures, thus possibly reducing the inherent durability of the concrete. When water-reducers are used, the reduction in w/c ratio may partially offset the increase in spacing factor as it affects durability. These changes in air-void parameters are especially noticeable when air-entraining admixtures and chemical admixtures are intermixed prior to batching. In some cases a coagulation or precipitation may be evidenced, but this is not true for all combinations. It is wise, therefore, to batch air-entraining admixtures and other admixtures separately, and to make sure that they do not come into contact prior to mixing of the concrete.

Chemical Accelerators. Chemical set accelerators have been used for many years in cold weather concreting as a means of expediting finishing operations and compensating for the reduced rate of strength gain encountered in normal concrete mixtures placed during cold weather. Calcium chloride dihydrate ($CaCl_2 \cdot 2H_2O$) has traditionally been used both in pure form and as a component of commercial formulations. However, newer admixtures based on nitrites, formates, and other compounds are becoming increasingly available in the marketplace.

For a fixed amount of air-entraining agent, the effect of added calcium chloride is to slightly increase air content. The effect is more pronounced as amounts over 1 percent by weight of cement are used. When air is being held to a specified level, the amount of air-entraining agent needed to achieve this level is decreased as calcium chloride is added. This is true over a wide temperature range. These effects are similar for Type I and Type III cements. Because of this increase in efficiency of air-entraining agent, dosages of air-entraining agent may be reduced by 40 percent for low alkali cements and 5 to 10 percent for high alkali cements when calcium chloride is used. Finally, some studies have indicated that no deleterious effects result when calcium chloride and admixtures are combined prior to introduction into the concrete batch. However, it is good practice to keep these admixtures separate until batching and then to add them at different times in the batching process.

High Range Water Reducers ("Superplasticizers"). Most high range water reducers (HRWR) are chemical admixtures based mainly on sulfonated melamine or naphthalene-formaldehyde condensation products. Other types such as modified lignosulfonates are also available. These admixtures have the potential for either reducing water content by as much as 30 percent or dramatically increasing workability and thereby producing what is termed "flowing concrete."

Most studies of high range water reducers indicate that they affect the amount of air-entraining agent needed to obtain a specified air content. The amount of air-entraining agent needed to obtain a given air content appears to be less when these admixtures are used. This is especially true for naphthalene-based products. The dosage of air-entraining agent needed to obtain an air content similar to that of concrete without superplasticizers can be reduced by about 50 percent when naphthalene products are used, but may be about equal to that of ordinary concrete or even increased when melamine-based products are employed. The quantitative nature of this relationship will vary with the particular cements and admixtures being used, and this trend seems to be quite general from most of the information available.

There are some tendencies for high range water reducers to cause a loss of air from plastic mixtures when used to produce "flowing concrete." Typically, losses average about 1-1/2 percentage points over the period of mixing and transport. In some instances losses of up to 2-1/2 percentage points have occurred in highly fluid concretes immediately after introduction of superplasticizer into the mixture.

High range water reducers affect air contents and air-void system characteristics of hardened concrete as well. While control concretes at 2 to 3 in. slump show a peak in the air-void distribution around a chord interval of about 100 to 200 x 10^{-5} in. (25 to 50 μm), concretes containing both types of high range water-reducers show a shift in this peak towards higher void sizes. A larger percentage of voids greater than about 2000 x 10^{-5} in. (500 μm) is present in the hardened concrete, and this results in higher than normal spacing factors ($\bar{L}$). In spite of these higher spacing factors, most studies dealing with durability of concretes prepared with high range water-reducers have indicated good durability. Part of this may be attributed to the beneficial effect of the lower w/c ratio which reduces both the amount of freezable water and the permeability of these concretes.

Finely Divided Mineral Admixtures

A wide variety of materials have been used, to one degree or another, as finely divided (majority of particles passing the No. 200 (75 µm sieve), mineral admixtures. These include cementitious materials such as natural cements, hydraulic lime, slag cements, or granulated blast furnace slags, and pozzolanic materials such as fly ash, volcanic glass, diatomaceous earth, and calcined shales and clays. Of these materials, fly ash is the most widely used product in the United States. It is estimated that in 1980 fly ashes were used in about 37 percent of all ready mixed concrete produced in the United States. Although still not accepted by many state transportation agencies, the use of fly ash is expected to grow in the coming years.

Fly Ash. Fly ash is a by-product derived from burning bituminous or lignitic coals, predominantly in municipal electric generating stations. It is composed chiefly of spherical glassy particles having silicon and aluminum as their major elemental constituents. Chemical and physical properties of fly ashes vary according to source of fuel and the generating station at which they are produced.

According to ASTM specification C 618 (55), fly ashes are categorized as class N, F, or C. The primary determinants are the amounts of silica, alumina, iron oxides, sulfur trioxide, and loss on ignition. Class C fly ashes generally have higher calcium oxide ("lime") contents than Class F and N ashes, and are permitted to have higher losses on ignition.

Most fly ashes increase the amount of air-entraining agent needed to obtain a specified percentage of air in concrete when compared to a similar concrete mixture containing no fly ash. This is related primarily to the loss on ignition (L.O.I.) value of the fly ash which, in turn, reflects the carbon content of the ash. Ashes having L.O.I. values close to the limit of 12 percent for Class F may increase the amount of air-entraining agent needed by as much as five times the normal amount. Fineness of fly ash may also affect the air-entraining agent demand. This may be especially important for ashes having relatively low L.O.I. values. Investigators at the Bureau of Public Roads (56) using two fly ashes with loss on ignition values of 1.2 percent each, found an air-entraining agent requirement of about 90 percent of control for fly ash A, and 150 percent of control for fly ash B. PCA studies (57) indicate that perhaps a combination of fineness and loss on ignition may better explain these differences in air-entraining agent requirements among various ashes, especially for loss on ignition values less than 6 percent.

A recently developed technique (58) termed the "Foam Index Test," may be helpful in predicting the relative amounts of air-entraining agent needed with any cement-fly ash combination. In this test cement and fly ash are shaken with water in a glass bottle. Air-entraining agent is then added and the bottle is shaken again. The minimum amount of air-entraining agent needed to create a stable foam is termed the "Foam Index." The ratio of foam index for a cement/fly ash combination to foam index for the cement alone can be used as an indication of the relative amount of air-entraining agent needed in concrete containing fly ash compared with concrete prepared with portland cement alone.

In most cases, ashes having high air-entraining agent demand pose no serious problems as long as the needed amounts of air-entraining agents are added. Users must be aware, however, that even ashes from a single generating station can vary quite markedly. Thus, a simple quality control check, such as the foam index, or frequent air meter tests on each load of concrete prepared from new lots of ash are necessary to ensure good uniformity of air content.

Pigments. A variety of pigments are available for producing colors in concrete. This includes black, blue, bright to deep reds, brown, buff and ivory tones, greens, and others. In the highway field, the most commonly used color is black. This color is used to reduce glare from pavement surfaces, to promote heat absorption on bridge decks, and to more easily delineate acceleration and deceleration lanes from major traffic flow. Certain black pigments, in particular those using carbon black, have the capability of adsorbing large amounts of air-entraining agent, thus hindering the development of entrained air in the concrete. Although many pigment products are advertised as not having adverse effects on entrained air, the user is advised to test pigments in control concrete batches prior to use on the job.

Summary

The effects of major concrete constituents on air content and air-void system are summarized in Table C-3. Corrective actions which can be taken are also given. However, the user must realize that the absolute value of reductions or increases in air-entraining agent dosages will depend heavily on the particular materials, procedures, and conditions for the job under consideration.

SECTION 3 - PRODUCTION AND HANDLING OF AIR-ENTRAINED CONCRETE

Any one set of materials may exhibit satisfactory air entrainment when initially tested under controlled laboratory conditions. However, variables encountered

Table C-3. Effect of Concrete Constituents on Air-Entrainment

CONSTITUENT	TYPE	EFFECT ON AIR CONTENT	EFFECT ON AIR VOID SYSTEM	CORRECTIVE ACTION(S)
MIX DESIGN	CEMENT CONTENT	Decreases with increase in cement content.	Smaller and greater number of voids with increasing cement content.	Increase AEA 50% for 200 lb./yd^3 increase in cement. Increase AEA 10X or more for very rich, low slump mixtures.
	WATER CONTENT	Increases with increase in water content. Very fluid mixes show loss of air.	Becomes coarser at high water content.	1-inch slump increases air by 1/2-1 percent. Decrease AEA accordingly.
CEMENT	COMPOSITION	Higher fineness Type III requires more AEA. Alkali increases air content.	Effects not well-defined.	Use 50-100% more AEA for Type III. Decrease AEA dosage 20-40% for high alkali.
	CONTAMINANTS	Oxidized oils increase air. Unoxidized oils decrease air.	Little apparent effect.	Obtain certification on cement. Test for contaminants if problems develop.
AGGREGATES	SAND	Increases with increase in sand content. Organic impurities may increase or decrease air content.	Surface texture may affect specific surface of voids.	Decrease AEA as sand content increases. Check sand with ASTM C 40 prior to acceptance.
	COARSE AGGREGATE	Decreases as max. size of aggregate increases. Crusher fines on coarse aggregate decrease air content.	Little effect.	No action needed as required air decreases with increase in aggregate size. Hold percentage fines below 4 percent.
MIX WATER		R/M truck wash water decreases air content. Algae increase air.	Unknown.	Do not use recycled wash waters. Test water supplies for algae and other contaminants prior to acceptance.
CHEMICAL ADMIXTURES	WATER REDUCERS/RETARDERS	Lignosulfonates increase air. Other types have less effect.	Spacing factors increase at higher dosages.	Decrease AEA 50-90 percent for lignosulfonates, esp at lower temperatures. Decrease AEA 20-40 percent for other types. Do not mix admixtures prior to batching.
	ACCELERATORS	$CaCl_2$ increases air content. Other types have little effect.	Unknown.	Decrease AEA when $CaCl_2$ is used.
	SUPERPLASTICIZERS	Naphthalene-based materials increase air content. Highly fluid mixtures may lose air.	Produces coarser void systems. Spacing factors increase.	Use less AEA with naphthalenes. Specify 1-2 percent higher air content if possible.
MINERAL ADMIXTURES	FLY ASH	High L.O.I. or carbon decrease air content. Fineness of ash may have effect.	Little effect.	Increase AEA. May need up to 5X more with high carbon ash. "Foam Index" test is useful check procedure.
	PIGMENTS	Carbon-black based may absorb AEA, depress air content.	Unknown.	Pre-qualification of pigment with job materials.

during field production and construction can lead to air contents and air-void systems differing from those obtained in laboratory trial mixtures. Variables that may affect air content during the production of field concrete include method of batching, mixing procedures and duration, and agitation and transport of concrete to the field site. At the site, placement, consolidation, and finishing procedures can affect both air content and ultimate durability of the concrete. In all phases of field operations, environmental factors, particularly changing temperatures, may cause control problems.

Knowledge in this area is not sufficiently advanced to enable the user to quantitatively predict the effects these variables may have on air content of a particular concrete. However, the following guidelines will highlight construction procedures that affect air content. This will indicate those areas where caution should be exercised in production of air-entrained concrete.

Batching Procedures

The manner in which materials are batched into a mixer can affect air content of the concrete. If cement and water are mixed together ("slurry-mixing"), the demand for air-entraining agent will be quite high. When all materials are batched simultaneously, air-entraining agent demand is still high, but not as high as for slurry mixing. Lowest air-entraining agent demands are obtained when introduction of air-entraining agent is delayed until all other ingredients have been mixed. Although agents may be added into a cement-water slurry, they should never be batched with dry cement or into recycled wash water.

Erratic air contents can result when air-entraining agents are mixed with other admixtures prior to introduction into the concrete batch. Although many manufacturers claim that their products are "compatible," it is wise to test these claims in trial batches prior to the job, or to stipulate that admixtures are not to be mixed together prior to introduction into the mixer.

Air-entraining agents are sometimes added onto sand that is to be weigh-batched into the mixer. While satisfactory results can be achieved with this technique, it is preferable to batch admixtures into the water lines using a positive-displacement type pump. These pumps should be interlocked with other batching equipment to prevent discharge of admixtures at unwanted times.

An example of an automatic admixture dispenser system is shown in Figure C-8. This system consists of pressurized positive displacement type admixture dispensing tanks interlocked into an automatic computer-controlled batch plant. Admixtures are stored in large holding tanks elsewhere in the building, and are pumped into the dispensing tanks to a preselected level just prior to batching. When batching commences, the admixture is drawn into hose lines and into a junction with the main water line just in front of the mixer. The various admixture dispenser lines are spaced a few inches apart along the water line.

Other devices that are acceptable include: (1) flow meters coupled with sight glasses, (2) pulse meters, (3) sight glasses with flows geared to counters or potentiometers, and (4) sight glasses with electrical contacts. Whatever the system used, dispensers should be calibrated on delivery and at regular intervals. Operators should check that all lines are clear of sludge or other deposits, and that no

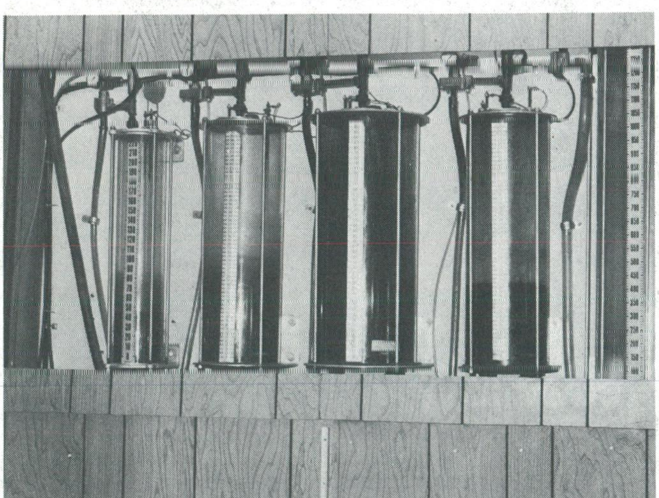

Fig. C-8. Automatic admixture dispenser tanks.

leaks are present. Most importantly, the main holding tanks should be kept in a heated area and admixtures should never be allowed to freeze.

The size of the batch in relation to the capacity of the mixer being used can also affect the final air content obtained. Air content usually increases as the full capacity of the mixer is approached. The greatest increase in air content usually occurs as the amount of material is increased from 20 to 40 percent of mixer capacity.

Mixing and Transport

Time of mixing has an important influence on air content. In most central mix operations, a minimum of 60 to 90 seconds of mixing time is recommended, and certain mixers may need more than this length of time to develop a uniform air content. The specified air content may be obtained in as little as 60 seconds and may be maintained at this level for up to 150 seconds. The minimum mix time recommended is 75 to 130 seconds. Variability in air content will be much higher with shorter mixing times. Overcharging the mixer by as much as 10 percent has little significant effect on net air contents. However, this practice can lead to less uniform mixing and should be avoided.

In ready mix trucks there is little difference in air content between concretes mixed for 50 or 150 revolutions at either 12 or 18 rpm. At these drum speeds, this corresponds to mixing times ranging from about 3 to 12 minutes. Since most specifications do not allow mixing beyond 100 revolutions at these drum speeds, reduction in air content due simply to mixing alone would generally not be seen in practice. There is a gradual increase in air content when mixing speed is increased from 12 to 24 rpm. A slight decrease in air content occurs above 25 rpm (25). Over the entire range of mixing speeds, however, this amounts to less than a ± 0.6 percentage point variation from the mean, which is within the normal precision to be expected in air content measurements. Therefore, currently used mixing speeds (within practical limits) appear to have only a minimal effect on the net air content of the concrete batch.

In discussions of the effects of transport on air content, a number of variables must be considered. One is haul time and its effect on air content. A second is the amount of agitation in ready mix trucks, or vibrations occurring during transport in nonagitating equipment. Finally, the amount of retempering of the concrete, either with water to increase slump or with air-entraining agent to increase air content, must also be considered.

Under field conditions, it is difficult to separate the effects of time on air content because transport even over short distances will usually be accompanied by either deliberate agitation or random vibrations of haulage vehicles. Laboratory data, however, do indicate that air content slowly decreases with time even in the absence of agitation. This decrease can range from about 0.5 to 1 percentage point per hour, and is somewhat greater if the initial air content of the concrete is above 6 percent.

More pertinent to actual field operations, especially for ready mix concrete, is the effect on the air content of agitation during transport of fresh concrete. Results of nearly 2000 tests run by the Cement and Concrete Institute of Sweden (59) showed a mean loss of about 0.6 percentage points in air content during transport. This loss was about 10 percent of the initial air content. Studies by NRMCA, using a single truck mixer, show rates of air loss of nearly 20 percent of initial air content after about 400 revolutions (including about 150 initial mix revolutions). A loss of 40 percent of the air content was seen after 600 revolutions. At 4 rpm these would correspond to 100 and 150 minutes of mix time, respectively. It should be noted that this concrete was retempered and remixed at 18 rpm prior to each sampling time. Therefore, air loss may be much higher for concrete which is not retempered. The reader should keep in mind that air loss is a complex function of materials, mixing equipment, and temperatures at each job site, and the values cited in these guidelines are necessarily approximate.

Water that is added to a concrete batch at the job site to restore consistency (i.e., retempering water) can also aid in regaining some of the air content lost during transport. A considerable amount of air can be regenerated during the retempering process if the concrete is retempered to its initial slump within two hours of initial mixing. In many cases, almost all of the air may be regained. After two hours, air content will gradually decrease even though the concrete is retempered to a constant slump. Air content may also be restored by addition of air-entraining agent. However, this is not commonly done in practice, and little information exists as to the amounts of admixture needed to restore the air content to its initial value.

Placement and Consolidation

Most techniques commonly used in placing concrete do not materially affect air content. This is to be expected because the concrete undergoes only minor manipulation during discharge from a chute, transport in a skip or bucket, and pushing or shoveling into place.

Some more highly automated techniques, however, do have an effect on air content, and care should be exercised in their use with air-entrained concrete. When concrete mixtures are transported on belt conveyors over relatively long distances (1,000 to 3,000 ft), there can be some loss of air, especially if the concrete was prepared at a high initial air content. Similarly, problems may be encountered in pumping of air-entrained concrete. Losses of up to 2-1/2 percentage points of air have been experienced with certain concrete pumps. At higher air contents, compressibility of air during pumping may cause a rise in pump pressure. Thus air contents should be kept closer to the lower end of specifications when concrete is being pumped. Air can also be lost from concrete during shotcreting operations. In some cases large amounts of air may be lost as the shotcrete impinges at high velocities on a surface.

One final caution concerns placement of concrete with aluminum equipment such as aluminum alloy pump lines or buckets. When exposed to high alkali solutions present in fresh concrete, aluminum surfaces react to generate hydrogen gas bubbles which lead to abnormally high air contents and, therefore, reduced strengths in hardened concrete. Such problems can occur due to abrasion of aluminum in concrete pump lines and dump trucks.

In normal practice, vibration necessary to consolidate concrete will not result in significant loss of entrained air. In fact vibration may improve the air-void system by allowing the larger entrapped voids to escape. Laboratory studies have indicated that large amounts of air can be lost during internal vibration, but these findings have been based on tests where spud-type vibrators have been held in relatively small vessels (such as unit weight buckets) for long periods of time.

In practice, where sections being vibrated are large in comparison to the radius of action of the vibrators, or where the paver is moving at speeds from 5 to 20 ft per minute, the action of the vibrators on any one section of concrete is less severe. In cases where the paving machine is stopped and vibration is allowed to continue, the potential for abnormally large losses in entrained air content does exist. This potential also exists where high slump concretes are vibrated at high frequencies, or multiple passes are made over the same section. These losses can be significant if high frequency vibrators are used, especially at frequencies exceeding 9,000 rpm. For these cases, air loss may exceed 3 percentage points. Other vibration characteristics, such as vibrator eccentric size and paver speed, appear to have little effect on final air contents.

Successful consolidation with vibratory equipment requires a knowledge of the capabilities and limitations of such equipment, and an appreciation of how the variables in each type of construction process may affect the adequacy of vibration. The reader is urged to review ACI 309-72 (60) especially Chapters 4 and 11 for recommended practices. If these recommendations are followed, successful consolidation of air-entrained concrete with minimal loss of air content will be ensured.

If proper precautions are followed, finishing techniques have a negligible effect on air content. Results of a comprehensive NCHRP study (33) showed that surface vibration such as would be imparted by oscillatory screeds only slightly affected air content, specific surface, and spacing factor. Losses in air can occur, however, if prolonged manual finishing operations are carried out after some delay after placement of the concrete. The critical period apparently occurs after the concrete has stiffened slightly but before the water sheen has left the surface. Reworking of additional water into a concrete surface will likewise cause loss of air in the surface mortar and poor long-term durability. Final finishing operations, therefore, should be delayed until water has left the surface. Finishers should not be permitted to use additional water during their operations.

Temperature Effects

Increasing temperature will require an increase in the amount of air-entraining agent needed to maintain a constant air content. The exact amount of change in air content will be a function of the particular materials and practices employed. Compared with control mixtures at 70 to 75°F, it is reasonable to assume that approximately a 30 percent decrease in the amount of air-entraining agent will be needed to obtain the desired amount of air at 40 to 50°F. A 30 percent increase in the amount of air-entraining agent will be needed to maintain this air content at 100 to 110°F. Above 75°F, concretes prepared with Type III cement require more air-entraining agent per unit increase in temperature to maintain a specified air content than Type I cements. Concretes containing Type II cements may require 75 to 100 percent more air-entraining agent at 110°F than corresponding concretes at 75°F.

Summary

The effects of the aforementioned production procedures, construction practices, and environmental variables on air content are summarized in Table C-4. General corrective actions that may be taken are also given. Specifics will depend on the particular job conditions and equipment in use.

Table C-4. Effect of Production Procedures, Construction Practices, and Environmental Variables on Air Content

VARIABLE	TYPE	EFFECTS	CORRECTIVE ACTION(S)
PRODUCTION PROCEDURES	BATCHING SEQUENCE	Simultaneous batching lowers air.	Avoid slurry-mix addition of AEA.
		Late addition of AEA raises air.	Do not batch AEA onto cement. Maintain uniformity in batching sequence.
	MIXER CAPACITY	Air increases as capacity is approached.	Run mixer close to full capacity, avoid overloading, clean mixer frequently.
	MIXING TIME	Central mixers-air increases up to 90 sec. Truck mixers-air increases up to 10 min. Air decreases after optimum time is reached.	Establish optimum mixing time for particular mixer. Avoid overmixing.
	MIXING SPEED	Air increases up to approx. 20 rpm. Decreases at higher speeds.	Avoid high drum speeds.
	ADMIXTURE METERING	Accuracy, reliability of metering system will affect uniformity of air content.	Avoid manual dispensing gravity-feed system, timers. Positive displacement devices preferred. Establish frequent maintenance and calibration program.
	HAUL TIME	Long hauls reduce air, especially in hot weather.	Optimize delivery schedules. Maintain concrete temperatures in recommended ranges.
CONSTRUCTION PRACTICES	RETEMPERING	Air content increases after retempering. Ineffective beyond 4 hours.	Retemper only enough to restore workability. Avoid addition of excess water.
	CONSOLIDATION	Air content decreases under prolonged vibration or at high frequencies.	Do not overvibrate. Avoid high-frequency vibrators. Avoid multiple passes of vibrating screeds.
	TRANSPORT	Some air (1-2%) normally lost during transport. Air lost in pumping and on belt conveyors, especially at higher air contents.	Avoid high air contents in pumped concrete. Do not use aluminum conveyors.
	FINISHING	Air content reduced in surface layer by excessive finishing.	Avoid finishing bleed water still on surface. Avoid over-finishing. Do not sprinkle surface prior to finishing.
ENVIRONMENT	TEMPERATURE	Air content decreases with increase in temperature.	Increase AEA dosage as temperature increases.

SECTION 4 - SAMPLING AND TESTING OF AIR-ENTRAINED CONCRETE

Sampling Procedures

Sampling procedures used in testing for air content should follow techniques described in standard methods such as ASTM C 172 (AASHTO T 141). Although detailed procedures are set forth in these standards, a few points in particular are worth reviewing:

1. A minimum of 1 cu ft of composite concrete sample should be used to obtain material for testing.

2. Samples should be taken from the middle portion of the batch or discharge.

3. Samples should be taken at two or more regularly spaced intervals, with elapsed time between samples not to exceed 15 minutes.

4. When the concrete contains aggregates larger than appropriate for the test procedures to be employed, the sample should be wet-sieved prior to testing to remove the large particles.

5. Concrete used for slump or unit weight tests should not be used in air content tests. Concrete used in any of these tests should not be used for casting strength test specimens.

It is good practice for the inspector to take concrete samples himself, rather than to rely on contractor personnel for these tests. Where concrete is not sampled from every batch (or load), those batches sampled should be selected randomly. Batching or mixing operators should not be given advance notice of the selection.

Sampling Rates

Currently specified rates of sampling for air content tend to vary widely. In general, sampling rates are greater for structural pours than for production of full-depth pavement. On structural pours, such as bridge deck slabs, it would be ideal to sample every load. However, because of the large amount of manpower that this would require, sampling of every load ("screening") only at the outset of the project is more realistic. Once good quality control has been established, rates could be decreased to 1 load out of every 3 or 4. The user should apply this approach with caution because it is known that truck mixers can vary widely in efficiency. This means that if new trucks are introduced into the production stream, they should be sampled independently of their position in the sampling schedule.

For full-scale paving projects an alternate approach must be adopted. As paving rates may range from 2400 to 4000 cu yd per day, it is totally impractical to sample every load delivered to the site, even as an initial screening technique. Current practices utilize rates such that 1 or 2 samples are taken every day. Because a large proportion of the concrete production thus remains unsampled, there is need for a greater rate of testing. DiCocco (10) recommended that a sampling plan consisting of 35 units taken randomly through the day would be sufficiently sensitive to reject approximately 90 percent of the defective (out of specification) loads, assuming that 4 percent of the loads were defective. This reasoning is based on a maximum standard deviation of 0.80 in air content, which is typical of that encountered in practice. Higher standard deviations would increase the probability of rejection of concrete loads.

Testing for Air Content

The two most widely used techniques for determining air content in fresh concrete are the pressure (ASTM C 231) and volumetric (ASTM C 173) methods. Only limited use is made of a third method, the Chace air indicator, which is a rapid technique for estimation of the air content of concrete. The user should be familiar with the appropriate test procedures, as well as with the mechanical operation of his particular meter.

Pressure Method. This method depends on the principle that the volume of a gas (the air entrained in the concrete) will vary inversely with the applied pressure. By precalibration of a container of known volume at a fixed pressure, the air content may be measured. The method has two variants, termed Type A and Type B. In the Type A meter, air content is related to the distance a column of water is displaced under the applied pressure. In the Type B meter, the pressure drop that occurs when air is allowed to flow from a container of known volume at fixed pressure into the container holding the concrete sample is used to indicate air content.

Various sources of error are common to both meters. These include:

1. Incomplete consolidation of sample.

2. Errors in calibration, or failure to recalibrate at frequent intervals.

3. Malfunctions in pressure gage.

4. Leaks in meter.

5. Presence of highly porous or lightweight aggregates.

6. Failure to obtain and include aggregate correction factor in determination of air content.

The final point (No. 6) is very important because aggregates can have correction factors of over 1 percent. It should be noted that this factor is not directly related to absorption, porosity, or other physical properties, and must be determined on each aggregate source for the proportions in which the aggregate will be batched into the concrete.

Some sources of error are unique to the type of meter being employed. Type A meters are sensitive to barometric pressure. A change of altitude greater than 600 ft will require recalibration. The Type B meter has certain advantages, including insensitivity to barometric pressure and somewhat quicker operations. However, it lacks resolution at higher air contents, and air contents cannot be determined beyond the range of the calibrated dial. Type A meters can be used beyond their range by recalibrating at a lower operating pressure.

Precision of the pressure methods is good. Single operator standard deviation is close to 0.2 percentage points near 3 percent air, and 0.5 percentage points near 9 percent air when different batches of concrete are tested. Testing by a number of operators on the same batch yields an average between-operator standard deviation of about 0.3 percentage points. Therefore, properly conducted pressure meter tests should be sufficiently precise for field control of air-entrained concrete.

Volumetric Method. The volumetric method relies on the removal of air from the concrete sample by displacement with water inside a vessel of precalibrated volume. A glass sight-tube contained within a standpipe on the meter is calibrated in percent air content. The percent air is obtained from the difference in volume of the sample containing air plus a measured amount of water, minus the volume after the sample is agitated and the air is allowed to escape.

The volumetric method is most useful for measuring the air content of concrete prepared with lightweight aggregates. In these instances the pressure techniques are usually inapplicable because large amounts of air contained within the aggregates will be compressed during the test and thus add greatly to the measured air content. The volumetric method can be used because air within the aggregates is normally not displaced during manipulation of the air meter.

Sources of error in the volumetric determination of air content include:

1. Inaccuracies in calibration of air meter volume.

2. Inaccurate addition of water to meter.

3. Failure to dispel all foam from meter sight glass.

4. Incomplete consolidation of sample.

5. Use of incorrect concentration, or type of defoaming agent (70 percent isopropanol is normally used).

6. Incomplete agitation of sample, hence failure to dispel all entrained air.

Problems may be encountered with the volumetric technique when applied to stiff or unusually harsh mixtures. Compacted material present in the bottom of the meter bowl after completion of the test indicates that the sample was not completely dispersed, and the test should be repeated.

When tests are properly performed on representative samples of concrete, agreement between the volumetric and pressure methods is quite good. In an extensive series of tests carried out at PCA (61), most results on the same mixtures were found to be within 1/2 percentage point in air content.

Chace Air Indicator. This device was developed as a rapid means of assessing air content of fresh concrete in the field. It is shown in Figure C-9 and consists of a small glass cylinder which tapers to a stem at one end and which can be capped with a brass cup sealed with a rubber stopper. The cup is about 4 cc in volume, and the stem graduations each represent 1 percentage point of air content in the concrete.

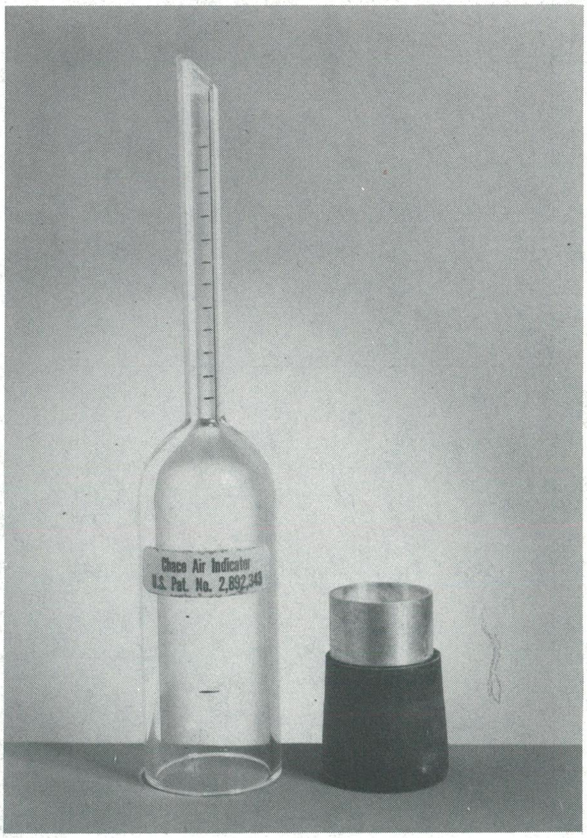

Figure C-9. Chace air indicator.

The test is performed on a small sample of mortar removed from the concrete with a sharp pointed trowel. By filling the cup with mortar and adding a known amount of alcohol to the glass cylinder, the entrained air can be displaced by inversion of the device. The reading on the stem is then multiplied by a factor related to the mortar content of the concrete.

Recent studies (62) have shown that the stem graduations may be out of calibration on some indicators. Therefore, the user should determine the volume of the graduation as a percentage of the volume of the cup (the "Chace factor") for each of his indicators. A nomograph developed by the Virginia Highway and Transportation Research Council (Fig. C-10) can then be used to obtain the correct air contents.

When properly calibrated and carefully used, results are within 1/2 percentage point of those obtained with standard techniques. However, standard deviations for the Chace indicator are around 1.0 percentage points and reproducibility is not as good as with standard methods. Tests should be run in duplicate, and if these differ by more than 2 percentage points, a third test should be performed. It is wise to check the results with a standard technique if the Chace indicator suggests that the air content is out of specification.

One area where the Chace indicator is particularly useful is for checking the air content of concrete near the surface of a finished slab. Often there may be questions as to effects of finishing or surface consolidation techniques on the air content at the surface. For these cases rapid checks for gross losses of air may be made with the Chace indicator.

SECTION 5 - SPECIFICATIONS FOR AIR-ENTRAINED CONCRETE

Current Specifications

All state transportation departments currently require the use of air-entrained

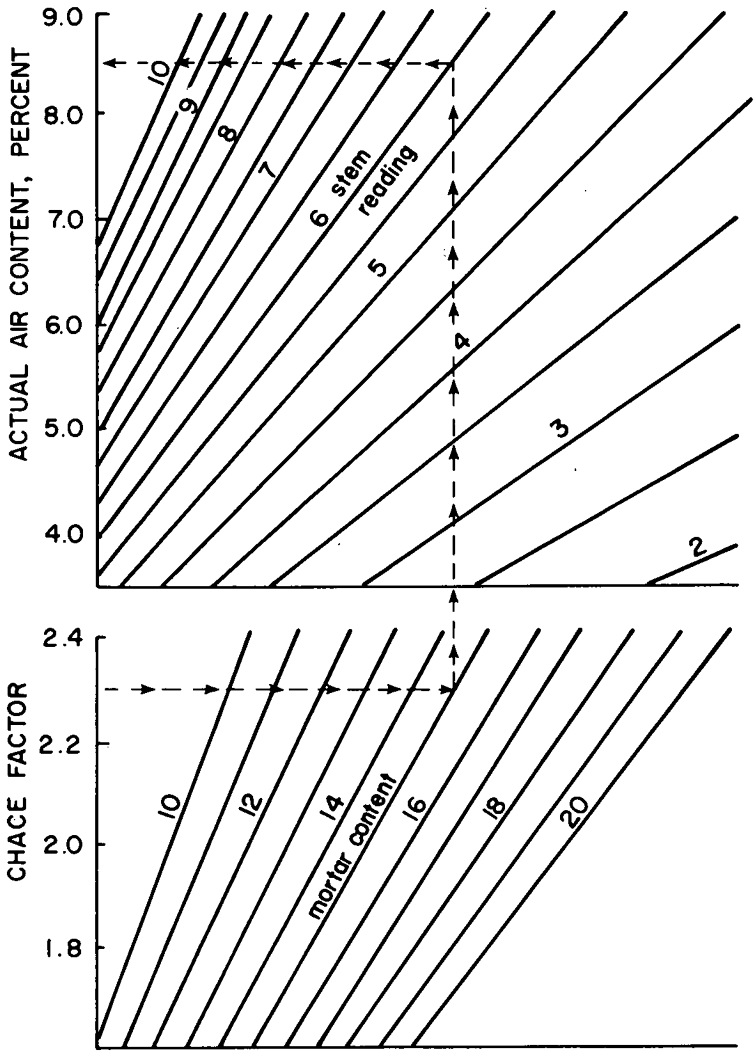

Figure C-10. Chace indicator conversion nomograph (62).

concrete, although in some cases its use is restricted to freeze-thaw localities. Through the years there has been a gradual increase in both lower and upper specification limits on air content. Most specifications up to about 1960 required from 3 to 6 percent air content in concrete. Specifications then began to change, which reflected a need for greater amounts of air to ensure good durability under adverse conditions. The form of some specifications changed to a target value/tolerance format such as 6 ± 1 percent or 6-1/2 ± 1-1/2 percent. Current limits, on the average, range from about 4 to 7 percent. The average midpoint or "target value" is between 5-1/2 and 6 percent. There are considerable deviations about these average values as shown in Table C-5. Several states have relatively low limits. These represent areas where little or no freeze-thaw activity is encountered. Upper limits for the most part range from 6 to 8 percent, with the majority of states having upper limits of 7 or 8 percent. These data are only slightly different from data compiled by the Portland Cement Association in 1975 (40). This indicates that there has been little revision of air content specifications in recent years.

Table C-5. Summary of Current Upper and Lower Limits on Air Content For Pavement Concrete - 1981 Survey

Lower Limit1/	Number of States	Upper Limit1/	Number of States
2%	2	4%	1
3%	9	5%	2
4%	18	6%	8
5%	18	7%	18
6%	1	8%	18
		10%	1

1/ In those cases where a fractional value was encountered, it was rounded to the next highest integer.

Limitations of Specifications

Realistic and practical specifications must reflect the actual variability to be encountered in any process. They must put limitations on the deviation from a target value which can be met by suppliers who exercise good control over their production. Specifications that set unduly strict or "tight" limitations cannot be met even by the most conscientious suppliers. Such specifications lead to disregard for imposed limits, failure to report test results, and even falsification of test results. Specifications then must be set, not to satisfy what the agency would term an ideal process, but rather to reflect actual sampling, testing, and materials variances encountered in the production under their jurisdiction.

When properly performed by well-trained personnel, testing variance for air content is a relatively minor component of the total variability of the process. Likewise, because obtaining a representative sample from a heterogeneous material like concrete is difficult, techniques set forth in ASTM C 172 (AASHTO 171), and reviewed in these guidelines, should be followed to allow test personnel to minimize variability due to this factor. The major factor influencing the variability of air content, then, is the "materials" component. This includes not only the materials themselves, but variances associated with batching, mixing, and transport of the concrete.

Overall variability in air content (expressed as a standard deviation) of central and paver-mixed concrete has been determined in a number of field studies (63,64) to be about 0.8 units. Truck-mixed concrete exhibits a variability of about 1.4 units (10). This is probably due to truck-to-truck variations in mixing efficiency. For central-mixed concrete, therefore, a reasonable tolerance on overall variability would be approximately ± 2 percentage points about the mean value, which would include 99 percent of the expected test results. Therefore, it would seem that limits such as 6 ± 2 percent or 5 to 9 percent should be reasonable.

These limits imply that the producer is indeed controlling on the midpoint of the specification range, while in reality, he may be targeting for a lower point on the range to avoid strength penalties for higher air contents. Thus, a significant portion of the air tests would be expected to fall below the lower limit. The inspector should keep this in mind when air content tests are being taken over the course of a day's production. Attempts should be made to convince the producer that targeting for the midpoint of the specification range will result in less chance of rejection of concrete, and in below-quality concrete being placed.

APPENDIX D
CONTROL OF AIR CONTENT-VERIFICATION PROGRAM

INTRODUCTION

The air content of concrete must be closely controlled if its use is to be beneficial. If properly controlled, concrete will be easier to place and, most importantly, have the high durability needed in severe environments such as pavements and highway bridge decks. Problems that occur in field operation can often be tied to lack of control and failure to appreciate basic knowledge that has developed over the years with regards to production and use of air-entrained concrete. Additionally, closer screening of materials and trial batches designed to simulate actual operations may be warranted in many instances, especially on jobs where new sources of materials or new construction procedures are being introduced.

In Appendix C, guidelines for the production of air-entrained concrete were presented. These guidelines represent a distillation of much of the technology of air-entrainment, and in-depth study would be advisable for three major groups of personnel; practicing engineers who wish to refresh or update their expertise in this area, persons newly exposed to the technology, and researchers wishing to complement their own studies in this field. Of necessity, the guidelines are quite general, and include reference to more variables than would be expected on any given job. Those wishing to gain information on the effect of a single variable, say ambient temperature, could locate that particular section in the guidelines. However, a means is needed to integrate these guidelines into a format suitable for ready reference on a construction project.

The objective of this verification program is to provide reference to information relating to control of air content in such a format that construction-site personnel such as state inspectors and engineers can use the information quickly and efficiently. The program covers materials prequalification, simulation of job mixtures, batch plant and job site operations, and provisions for documenting test results in a standard format. There will be some unique problems that will not fit into any previously defined category. However, the scope of the program is sufficiently broad to encompass all but these very rare instances.

The program is designed around a "checklist" format. It is not a checklist in the true sense of the word in that the user is called on to enter additional information in many areas. Reference is made to standard tests, both ASTM and AASHTO, especially where prequalification of materials is needed. Field operations are approached on two levels. First, the user enters the basic mix and operations parameters pertinent to the particular job. For each batch (or delivery unit) he then verifies that these parameters are as specified or, if made, modifications are noted. If changes in air content occur which can be correlated with any obvious changes in these parameters, the checklist is cross-referenced to the appropriate section in the guidelines (App. C) which addresses the variable in question. In this manner, not only can the user easily locate information pertinent to his operation, but a detailed job record will also be created. Personnel involved in later "troubleshooting" or follow-up studies will then have access to this detailed job record. This will make the task of assigning cause of any potential problem much easier.

MATERIALS QUALIFICATION

Standard Specifications and Tests

As a first step in a program designed to ensure production of uniform air-entrained concrete, all materials to be used must be shown to meet specifications formulated by ASTM and AASHTO. Although it is true that problems may develop even with materials meeting specifications, the probability of problems developing is much greater if inferior quality materials are accepted. Relevant specifications and tests that are particularly important with respect to air-entrained concrete are shown in the accompanying chart (Fig. D-1).

Although the chart is largely self-explanatory, some clarification of test procedures listed may be helpful. Cement should meet all requirements of ASTM C 150 (AASHTO M 85); however, particular attention should be paid to alkali content and fineness because these two parameters have been shown to have the greatest effect on air content. Similarly, aggregates should meet all requirements of ASTM C 33 (AASHTO M 6), and tests for material passing the No. 200 sieve (ASTM C 117, AASHTO T 11) and organic impurities (ASTM C 40, AASHTO T 21) should be included wherever these materials are to be used in air entrained concrete.

Proper qualification of admixtures is essential to producing air-entrained concrete. This includes qualification not only of air-entraining admixtures, but other chemical and mineral admixtures which may be contemplated for use. The supplier should document the conformance

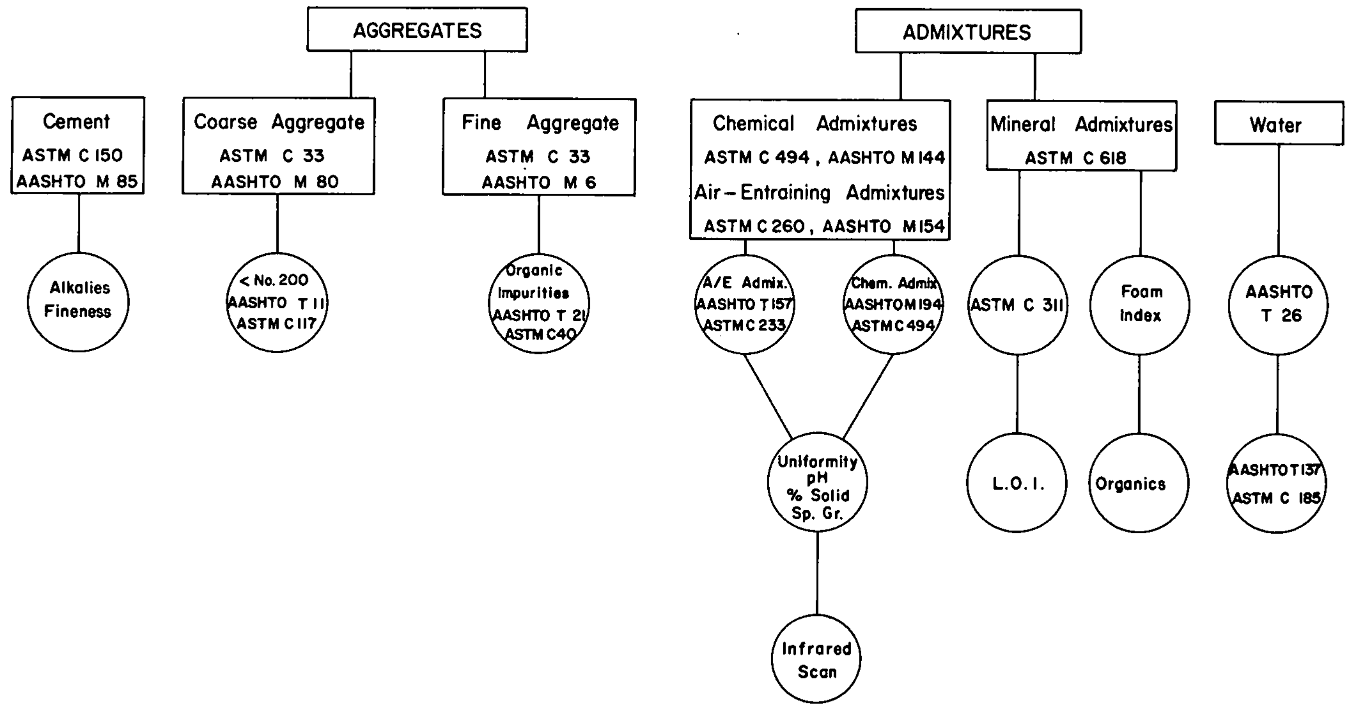

Figure D-1. Materials qualification flow chart for air-entrained concrete.

of each chemical admixture to ASTM C 494 (AASHTO M 184), and each air-entraining admixture to ASTM C 260 (AASHTO M 154). In addition, each subsequent lot of admixture should be checked for uniformity of pH, percent solids (residue by oven drying), and specific gravity, as described in these specifications. Infrared (IR) spectrophotometry, although far from being a comprehensive analytical tool, is a rapid means of documenting any major changes in chemical composition of the admixture from lot to lot. Records should be kept of the time and condition of storage of each lot of admixture which is received.

Mineral admixtures are coming into increasing use. They should meet all pertinent requirements of ASTM C 618. Sampling and testing should be carried out in accordance with ASTM C 311. Loss on ignition, which is a measure of the total carbon content, is normally the most important property affecting air entrainment. Loss on ignition generally should be limited to a maximum of 6.0 percent. Other tests currently in the developmental stage, such as the foam index test (58) and University of Maryland organics test (65), may also be useful in assessing potential problems in control of air content which might be associated with a given mineral admixture.

Mix water generally is not a major contributor towards problems with control of air content in concrete. However, instances have arisen where such problems have been traced to impurities in the mix water. AASHTO T 26 can be used to verify the general suitability of water for use in concrete. Possible effects on air content can be detected using ASTM C 185 (AASHTO T 137), and referencing the results for job water to a companion mortar batch prepared with distilled water. The most common source of contamination is algae that may be present in stagnant ponds. The above-referenced tests should always be carried out on such water prior to its use in concrete.

Trial Batching

After all concrete materials have been prequalified, it is good practice to prepare trial batches of concrete to verify mix design, establish water contents, and determine dosage rates of air-entraining agent and other admixtures to be used in the concrete. Ideally, the same batch size, mixing equipment, and procedures to be used on the job should be used for these trials. Admittedly, this is an expensive undertaking, and in most cases laboratory simulation must suffice. While it is never possible to exactly simulate field operations in the laboratory (especially with regards to mixing and batching equipment), minor deviations from established laboratory mix procedures such as ASTM C 192 still enable the mix designer to closely approximate the concrete that will be produced at the job site. A flow chart, which will aid the reader in the

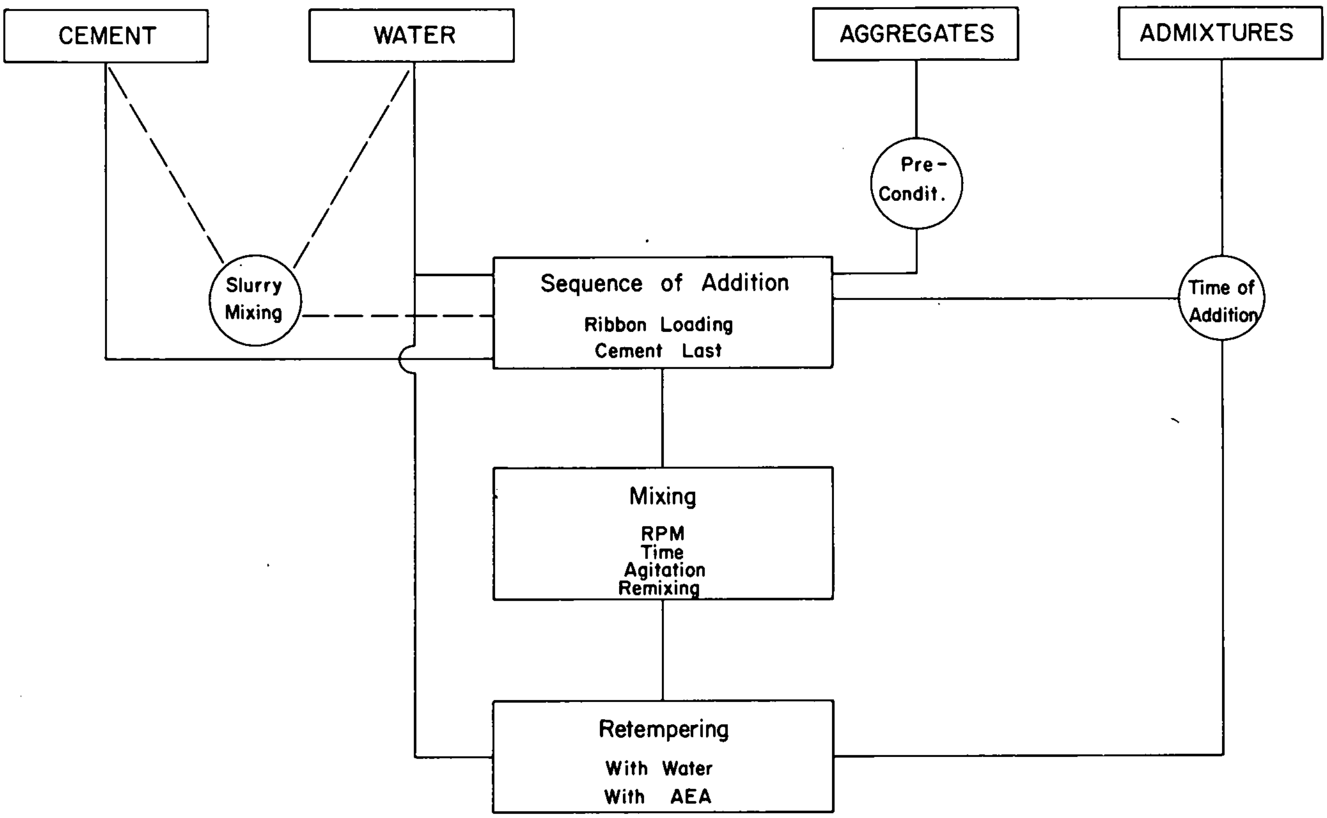

Figure D-2. Trial batching process flow chart.

trial batching process, is included as Figure D-2.

Mixers. The pan-type countercurrent mixers used in most concrete laboratories are adequate for trial batching. While it may seem that tilt-drum type mixers would more closely simulate actual equipment such as ready-mix trucks, small capacity mixers of this type are inefficient, and lengthy mix times may be needed to uniformly mix the batch and obtain the desired air content. Countercurrent pan mixers are much more efficient and can more accurately simulate the short mixing time used in modern-day concrete plants. Simulation of agitation, however, remains a problem. If such simulation is deemed essential, expedients such as special gearing and rheostat control of mixing motors, or simple interruption of mixing for preselected periods, may be employed.

Batching. Simulation of automatic batching equipment in the laboratory is rarely, if ever, done. However, preconditioning of materials and the sequence of their addition to the concrete batch can be done by manual methods. Aggregates should be used in the state in which they will be used on the actual job. For instance, if it is known that sand will be saturated, this condition should be simulated in the laboratory. If coarse aggregate is generally air-dried in the stockpiles, it should be batched in this condition. If facilities exist, the materials may be heated or cooled prior to batching.

Sequence of addition is especially important in simulating air-entrained concrete. If slurry mixing at the plant is anticipated, cement and water should be mixed together first, then admixture added. Ribbon and cement last loadings could also be simulated, although this can create problems in charging the mixer. Admixtures may be added to the sand if this is standard practice at the plant. The time of addition of admixture may be critical. To simulate simultaneous addition to a water feed line, the admixtures should be added to separate portions of the mix water, and then simultaneously added to the rotating mixing pan. Delayed addition of admixtures can have dramatic effects on slump and air content. If provisions for longer mixing times will be available at the plant, water-reducers and retarders will be more effective and should be added after a few minutes of mixing. This is generally true also for air-entraining agents.

Mixing. It is advisable to reproduce, as closely as possible, the mixing times anticipated on the actual job. For modern, high efficiency, central mixers, this may be no more than 90 to 120 seconds. For ready-mix trucks operating at 12 to 20 rpm, mixing times may vary from 4 to 8 minutes. As truck loads are often remixed briefly at the job site prior to discharge, it may be advisable to include this procedure as part of the laboratory evaluation along with an interruption (or agitation) period to simulate travel time from plant to job. Retempering with water or, less commonly, with admixtures, is discouraged by concrete technologists but often it is the only practical alternative for correcting unworkable or out-of-specification concrete. If anticipated job conditions suggest the likelihood that retempering will be necessary (i.e., hot weather or long travel), this factor may be included in the trial program.

Manipulation. In ordinary practice, consolidation and finishing will have only minor effects on the air content of concrete. With excessively fluid mixtures, however, such as those having high water contents or incorporating superplasticizers, significant air loss can occur. If these mixtures are to be used it may be prudent to include vibration in the trial program. It is preferable to vibrate concrete in forms representative of the actual volume of concrete to be placed and subsequently transfer the concrete to the air meter vessel for testing of air content. Vibration in the air meter vessel can cause unrealistically large decreases in air content. Any loss of air over 2 percent before and after vibration should be a cause for concern, and may require either redesign of the mixture or provisions for allowance of higher than normal air contents prior to consolidation in the field.

Temperature. Temperature will have a large effect on the air content obtained with a given dosage of air-entraining agent. In general, dosages will decrease 30 to 50 percent for a 30°F drop in temperature and increase 30 to 50 percent for a 30°F rise. To obtain more precise information on the particular materials under consideration, mixing at expected job temperatures may be necessary. It may be desirable to construct a plot of concrete temperature versus dosage rate, because temperatures will generally undergo daily fluctuations, and required dosages will then change as the day progresses.

BATCH PLANT OPERATIONS

Mix Design and Materials

Table D-1 gives a format that can be used to enter all necessary information on the basic concrete mixture. This includes materials properties, proportions, and such useful parameters as w/c ratio and fine/coarse aggregate ratio. A separate form should be completed for each mix design used on a particular job.

When actual batching is underway, Table D-2 can be used to record deviations from the basic mix. If quantities are constant, a check (✓) is placed in the appropriate column. Footnotes refer to sections in the guidelines (App. C) where the user can obtain information on effects that changes in each material can have on air content. For instance, if changes in the type or amount of cement occur, Section 2 ("Portland Cement") of the guidelines can be reviewed. Reference to Table C-3 would aid in adjustment of A/E agent dosage to reflect these changes.

Batching and Mixing

Information relevant to normal batching and mixing operations can be entered in Table D-3. Mixer type, capacity, and speed (in rpm) are the first three entries. The addition sequence should then be specified; for instance, cement first, cement last, ribbon loading, etc. The mixing time and mixing cycle are then entered. Mixing time is more appropriate to central-mixing operations. Mixing cycle may be used where shrink mixing or truck mixing is used.

The admixture dispenser system which is used plays an important part in control of air content. The type of dispenser should be specified (i.e., gravity feed, flow or pulse meter, positive displacement, etc.), along with the date of last calibration.

In Table D-4 the following information can be entered for each batch: mixing time, number of revolutions, time of loading of haul vehicle, and temperature. Slump and air content can be entered as additional information if taken at the plant. Finally, deviations from the standard operations described in Table D-3 should be noted.

JOB SITE OPERATIONS

Job Description

A general description of the job plus additional information pertaining to operations having the most impact on air entrainment can be entered in Table D-5. Some information can simply be checked-off, such as whether chutes, buckets, or other types of placement techniques that are being used. Other information should be entered in detail, particularly the equipment being used for consolidation and finishing of the concrete.

Jobsite Checklist

A job site checklist is included as Table D-6. This has the advantage of including, on one form, many of those variables that are known to affect air content. Moving across the form from left to right, the following information may be entered:

1. Load No. Starting with first load of the working day (Load No. 1).

2. Truck No. Trucks should be assigned numbers because the magnitude and variability of air content may vary with the particular truck being used, especially in the case of truck mixing.

Table D-1. Basic Mixture

Material	Source	Properties	Weight* (lb)	Dosage (oz/cwt)
Cement		Type ____ Brand ________	______	
Fine Aggregate		Abs.____M.C.____Sp.G.____F.M.____	______	
Coarse Aggregate		Abs.____M.C.____Sp.G.____Max.Size____ Grading No.____	______	
Chem. Admix.		Type____Date Rec'd________ Brand ________ Lot No. ________		______
A/E Admix.		Date Rec'd________ Brand ________ Lot No. ________		______
Mineral Admix.		Type____	______	
Water			______	
Mix Properties				
w/c ratio		______		
Fine/Coarse Aggregate ratio		______		

Signed: ______________

____

Date: ______________

Abbreviations
- Abs. - 24-hour absorption
- M.C. - moisture content
- Sp.G. - specific gravity, SSD
- F.M. - fineness modulus

*Quantities per cubic yard of concrete

3. Time of arrival and haul time. Haul time is obtained as the difference between arrival time and loading time (see Table D-4).

4. Revolutions on truck. This includes all revolutions (mixing and agitation) since the truck was initially loaded at the plant.

5. Mixing on site. The number of minutes that the concrete is remixed (or initially mixed) on site are entered here.

6. Water added at site. The amount of water added to the truck at the jobsite should be noted.

7. Admixtures added at site. Admixture type and amount added at the site should be noted. This includes air-entraining agents and chemical admixtures.

8. Load sampled. Ideally every load of concrete delivered should be tested for slump and air content, the pace of construction on many large jobs often makes this impractical. Results of slump and air content testing should be noted.

9. Temperature. Temperature of both the air and concrete test sample should be recorded.

Table D-2. Mixture Checklist - (Check if no change)

Batch No.	Cement 1/	Fine Aggregate 2/	Coarse Aggregate 2/	Water 3/	Chemical Admixture 4/	Mineral Admixture 5/	A/E Admixture 6/
1	___	___	___	___	___	___	___
2	___	___	___	___	___	___	___
3	___	___	___	___	___	___	___
4	___	___	___	___	___	___	___
5	___	___	___	___	___	___	___
6	___	___	___	___	___	___	___
7	___	___	___	___	___	___	___
8	___	___	___	___	___	___	___
9	___	___	___	___	___	___	___
10	___	___	___	___	___	___	___
11	___	___	___	___	___	___	___
12	___	___	___	___	___	___	___
13	___	___	___	___	___	___	___
14	___	___	___	___	___	___	___
15	___	___	___	___	___	___	___
16	___	___	___	___	___	___	___
17	___	___	___	___	___	___	___
18	___	___	___	___	___	___	___
19	___	___	___	___	___	___	___
20	___	___	___	___	___	___	___
.							
.							
.							
.							

1/ Guidelines, Section 2, under "Portland Cement"
2/ Guidelines, Section 2, under "Aggregates"
3/ Guidelines, Section 2, under "Mix Water"
4/ Guidelines, Section 2, under "Chemical Admixtures"
5/ Guidelines, Section 2, under "Finely Divided Mineral Admixtures"
6/ See Table C-3, pg. C-36 for adjustments

Signed: ____________________

Date: ____________________

Table D-3. Batching and Mixing

Mixer Type ____________________

Mixer Capacity ____________________ cu yd

Mixer Speed ____________________ rpm

Addition Sequence ____________________

Mixing Time and Cycle ____________________

Admixture Dispensers

Type ____________________

Calibrated ____________________

Signed: ____________________

Date: ____________________

Table D-4. Mixing Checklist

Batch	Mixing Time[1/] (min)	Revolutions[1/]	Time of Loading (hr:min)	Temperature[2/] (°F)	Slump[3,4/] (in.)	Air Content[4/] (%)	Notes[5/]
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							

1/ Guidelines, Section 3, under "Mixing and Transport"
2/ Guidelines, Section 3, under "Temperature Effects"
3/ Guidelines, Section 2, under "Mix Water"
4/ If taken at plant
5/ Note deviations from normal practice as recorded in Table D-3.

Signed: ____________
Date: ____________

10. Load discharged. The time at which the load is discharged should be entered. This allows for an estimate of the delay between arrival at site and unloading.

11. Notes. Any major deviations in construction practices from those outlined in Table D-5 should be noted, especially with regards to consolidation and finishing practices.

TESTING PROCEDURES

Procedures for calibrating equipment and for performing air content tests are in appropriate ASTM and AASHTO specifications. In addition, various agencies have issued annotated reprints of these specifications which make them simpler and easier to use. However, these specifications are quite detailed, and similar detail in job records of testing procedures employed is often lacking. Tables D-7 through D-9 are offered as examples of formats that can be used to enter results obtained for pressure, volumetric, and Chace indicator tests, respectively.

Information requested at the beginning of each form is common to the meter and to the entire job. For instance, meter identification, date of last calibration, aggregate correction factors, and other items would be entered here. Specific data for each load are then entered on the remainder of the form. Cross-references to sections in the guidelines (App. C) are given in the footnotes to each table.

Table D-5. Job Description

Type of structure	________________
Location	________________
Cu yd to be placed	________________
Distance from plant	miles ______ est. travel time _________
Type of haul vehicle	R/M truck ____ Dump truck ____
	Concrete mobile ____ Other ____
Specifications	Slump ____ ± ____ in. Air ____ ± ____ %
Placement techniques	Chute ____, Bucket ____, Conveyor ____,
	Pump ____, Other ____
Consolidation	Type of vibrators: Internal ____
	Screed ____, Pan ____, Other ____
	Equipment1/ ____________________
	Frequency ____ vpm
	Amplitude ____ inches
	Vibration time2/ ____ sec.
Finishing	Type: Manual ____ Mechanized ____
	Equipment1/ ____________________

1/ Enter type of equipment, manufacturer, model no. etc.
2/ Enter only for manually inserted spud vibrators.

Signed: ____________________

Date: ____________________

Table D-6. Job Site Checklist

Load No.	Truck No.	Time of Arrival (hr:min)	Haul Time[1,2] (min)	Revolutions[2] on truck	Mixing at site[2] (min)	Water added at site[2]			Admixtures Added at site[2]				Load Sampled			Air (%)	Temperature-°F[3,4]		Load Discharged (hr:min)		Notes[5]
						No	Yes	Gal	No	Yes	Type	Amount	No	Yes	Slump (in.)		Air	Concrete	Start	Complete	
1																					
2																					
3																					
4																					
5																					
6																					
7																					
8																					
9																					
10																					
11																					
12																					
•																					
•																					
•																					
•																					
•																					

1/ Refer to Table D-4 for time of loading.
2/ Guidelines, Section 3, under "Mixing and Transport"
3/ Guidelines, Section 3, under "Temperature Effects"
4/ Enter other pertinent weather conditions (low humidity, heavy rain, etc.)
5/ Note deviations from normal practice as recorded in Table D-5.

Table D-7. Data Report Form Pressure Method[1]

Method Used ASTM ____ AASHTO ____ Other ____

Meter Identification ____________________________

Date of Last Calibration ___________ Altitude __________ ft

Operating Pressure _______ psi

Operating Altitude ___________ ft

Aggregate Correction Factor (ACF) ___________

Consolidation: Rodding _________ Vibration _________

Air Content - %

Load No.	Gross	Lag	Net[2]
1	______	____	_____
2	______	____	_____
3	______	____	_____
4	______	____	_____
5	______	____	_____
6	______	____	_____
7	______	____	_____
8	______	____	_____
9	______	____	_____
10	______	____	_____
11	______	____	_____
12	______	____	_____
.	______	____	_____
.	______	____	_____
.	______	____	_____

1/ Appendix C, Section 4, "Testing for Air Content," under "Pressure Methods"

2/ Net = Gross - ACF - Lag

Operator: __________________

Date: __________________

Table D-8. Data Report Form Volumetric Method[1]

Method Used ASTM ____ AASHTO ____ Other ____

Meter Identification ____________________________

Date of Last Calibration ___________

Load No.	Readings Initial	Readings Second	Final (B)	Cups of Alcohol[2] (C)	Air Content[3] (%)
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
.					
.					
.					

1/ Appendix C, Section 4, "Testing for Air Content," under "Volumetric Method"

2/ Isopropyl alcohol, 70% by volume, should be used.

3/ Air content = B - C

Signed: __________________

Date: __________________

Table D-9. Data Report Form Chace Indicator Method[1/]

Indicator Identification ______

Chace Factor __________

Date of Last Calibration ___________

Sampling, Trowel _____ Wet Sieving _____

Load No.	Mortar Content (cu ft)	Air Content - %[2/]					
		Test #1	Test #2	Diff.[3/]	Av.[4/]	Test #3	Av.[5/]
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
.							
.							
.							

Signed: __________________

Date: __________________

1/ Appendix C, Section 4, "Testing for Air Content," under "Chace Air Indicator"
2/ From Figure D-3.
3/ Difference between Test #1 and Test #2. If greater than 2 percentage points, run third test.
4/ Average of first two tests.
5/ Average of all three tests.

APPENDIX E

LABORATORY STUDIES

INTRODUCTION

The majority of control problems documented in this investigation apparently involved either unique interactions between given sets of materials, or more general problems that have been recognized for many years by practitioners in the field. Problems encountered with certain cements and sands by New York and New Jersey could be placed in the first group. Problems such as admixture interactions, temperature effects, and poor batching control could be placed in the second group. All are best handled at the local level by applying general principles set forth in the guidelines (App. C) to each specific instance.

Previous laboratory studies in these areas have demonstrated underlying causes and effects, but further laboratory work must necessarily be devoted to solving problems inherent in local materials, mix designs, and practices. Two areas of concern did exist where little previous research had been done, and where some preliminary laboratory study was considered useful. These problems were seen for a wide variety of materials and processes, even though the magnitude of the problems varied with particular materials and processes at any given location.

The first of these problems is the tendency of some relatively low slump mixtures to be unusually sensitive to increases in water content, as reflected in changes in slump and air content. For instance, Gaynor (44) notes that "...the phenomenon of increased slump producing an increased air content is particularly critical at slumps between 2 and 3 inches...in the critical range the addition of as little as 1/2 gallon (4 pounds) of water per cubic yard may increase slump 1 to 2 inches and air content 1 to 1.5 percent." This contrasts with the often-cited rule-of-thumb that a change in net mixing water of about 3 percent (corresponding to approximately 6 to 8 lb/ cu yd) will effect a change of only 1 in. in slump and 1/2 percent in air content. Because controlled studies appeared to be lacking, this problem was deemed sufficiently important for further investigation.

A second topic of interest was air-entrainment in low-slump dense concretes (LSDC), which form the basis of the so-called "Iowa" method of bridge deck resurfacing. In addition to restoring a high-quality riding service to severely deteriorated decks, LSDC overlays, by virtue of their very low permeability (66), can significantly reduce the rate of chloride ion penetration into the concrete and thus protect reinforcing steel from progressive corrosion.

LSDC incorporates cement factors of approximately 820 lb per cu yd, low w/c ratios of 0.30 to 0.32, and air contents specified at 6.5±1.0 percent. The most satisfactory results have been obtained in paddle or pugmill on-site mixers (67). Mobile batcher-mixers have also proven quite useful. Vigorous vibration is needed to achieve the required degree of consolidation of the concrete. Experience in placement and performance of this type of overlay has, in general, been quite good. A study by the Iowa DOT on 16 overlays, ranging from 5 to 13 years of age, indicated that none of the installations showed evidence of riding surface distress (46). Likewise, LSDC overlays installed by the Minnesota DOT from 1975 through 1977 have shown good performance (47). Previous laboratory studies (48), though not extensive, show that LSDC has excellent resistance to freeze-thaw deterioration as well as to deicer scaling. Air-void systems in this concrete meet all accepted requirements.

In spite of good laboratory and field performance, questions still arise concerning long-term durability of LSDC overlays. This is evidenced by information supplied in the Indiana interviews (App. B), and in responses to question No. 14 of the questionnaire (App. A). Apparently, many respondents believe, perhaps with some justification, that a mix prepared at a slump of less than 1 inch is simply not fluid enough to allow air to be generated. Furthermore, even if specified air contents are measured, the measurements will reflect "entrapped" rather than entrained air. Thus, the true air content will be overestimated in the pressure test. A second opinion holds that the LSDC mixture is so stiff that the pressures generated by ASTM C 231 equipment are not sufficient to overcome frictional forces in the mixture. Thus, hydraulic forces are not totally transferred to the air voids. This results in an underestimate of the true air content. It was apparent that, at the very least, some preliminary laboratory work was called for if some of these concerns were to be resolved.

BEHAVIOR OF SLUMP AND AIR CONTENT CHARACTERISTICS IN THE "CRITICAL REGION"

Materials

The cement used was a blend of three Type I cements available locally in the Chicago, Illinois, area. Physical and chemical properties of the blended cement are given in Table E-1.

Table E-1. Composition of Cement

Item	Percent
C_3S	58.6
C_2S	15.9
C_3A	7.3
C_4AF	8.5
Alkali (as Na_2O)	0.61
SO_3	2.9
MgO	2.2
Loss on Ignition	1.4
Insoluble Residue	0.2
Specific Gravity	3.11
Blaine Fineness (cm^2/gm)	3890

Aggregates used were dolomitic crushed stone from Thornton, Illinois, and predominantly dolomitic natural sand from Elgin, Illinois. Relevant properties are given in Table E-2.

Two commercially available air-entraining agents (AEA) were chosen for this study. The first, AEA-A, was a solution of neutralized Vinsol resin with a solids content of 14.8 percent by weight. The second, AEA-B, is marketed as "an aqueous solution of a complex mixture of organic acid salts," and has a solids content of 5.2 percent. Infrared analysis showed that the major component of AEA-B is an alkyl-benzyl sulfonate.

Municipal tap water was used for all batches.

Table E-2 Aggregate Properties, Thornton, Illinois, Coarse Aggregates

Mix Type	Grading - % Retained on Sieve Size Indicated: 1-1/2-in.	3/4-in.	3/8-in.	No. 4	Bulk Specific Gravity - SSD	Absorption - % by wt.
P	0	50	75	100	2.63	1.8
S	0	0	50	100	2.65	1.8

ELGIN, ILLINOIS, FINE AGGREGATE

Grading - % Retained on Sieve Size Indicated							Fineness Modulus	Bulk Specific Gravity - SSD	Absorption - % by wt.
No.	4	8	16	30	50	100			
%	2	20	38	58	84	97	3.00	2.68	1.6

Concrete Mixtures

Mix Designs. Two mix designs were used for this series. The first, mixture P, represents a design typical of that used in conventional concrete paving operations. Cement content was 564 lb per cu yd, maximum aggregate size was 1-1/2 in., and slump was 2 to 2-1/2 in. Air contents of 5±1/2 percent and 7±1/2 percent were used. Slump and air contents were held at closer tolerances than would normally be called for in practice so that effects of small changes in slump and air content could be more easily detected. The second design, mixture S, represents one that would typically be used in structural elements. Cement content was 658 lb per cu yd, maximum aggregate size was 3/4 in., slump was 2 to 2-1/2 in., and air content 6±1/2 percent.

Batching and Mixing. Coarse aggregate was weighed and then inundated with water in a closed container 18 to 24 hr prior to mixing. Immediately before mixing a measured amount of water was drained from the container, such that the water remaining would satisfy the absorption of the aggregate plus the net amount of water required for the batch. Fine aggregate was weighed and batched in a moist condition. Moisture contents were controlled at 2 to 3 percent. All mixing was carried out in a 0.75 cu ft countercurrent pan mixer. Charging sequence was coarse aggregate, cement, sand, and the remainder of the mixing water. Air-entraining agents were dispersed in 100 ml of mixing water and were added simultaneously with the remainder of the mixing water immediately following the addition of sand to the mixer. All batches were mixed for a single, 90-second period. Immediately after mixing, the concrete was tested for slump (ASTM C 143-78) and air content (ASTM C 231-81 - Type A Meter). Batch analyses and properties of fresh concrete for all mixtures prepared in this series are given in Table E-3.

Separate batches were prepared for each water content investigated. That is, although subsequent data are presented as "water added" to the batch, each point represents an entirely new, freshly mixed batch of concrete rather than a single batch to which water had been incrementally added. This was done to eliminate possible interferences from any time dependent phenomena, such as false set or slump loss.

Results

The sensitivity of slump and air content of pavement mixtures to increases in water is depicted in Figures E-1 through E-4. Data are presented in terms of water added because this more closely simulates actual production processes where water is added to increase or maintain workability and yield is not held constant. Water added is simply that amount of net water added to the laboratory concrete mixer, and is expressed on a cubic yard basis. That is

$$W = w \times \frac{27 \text{ ft}^3/\text{yd}^3}{0.6 \text{ ft}^3} \qquad \text{(E-1)}$$

where W = water added, on a cubic yard basis; and
w = water added to 0.6 ft^3 laboratory batch.

This differs from the amounts of net water given in Table E-3, which are calculated from the actual yield of each concrete batch (i.e., batch volume corrected for air content).

For the majority of the pavement mixtures shown in Figures E-1 through E-4, relationships between added water and slump and air content show a relatively high degree of sensitivity. This is particularly apparent for the mixture containing NVR prepared at high air content (Fig. E-2). In contrast, the mixture containing the alkyl-benzyl sulfonate at low air content (Fig. E-3) shows virtually linear relationships between water added, slump, and air content. The remaining two combinations (Figs. E-1 and E-4) show sensitivities falling somewhere between these two extremes.

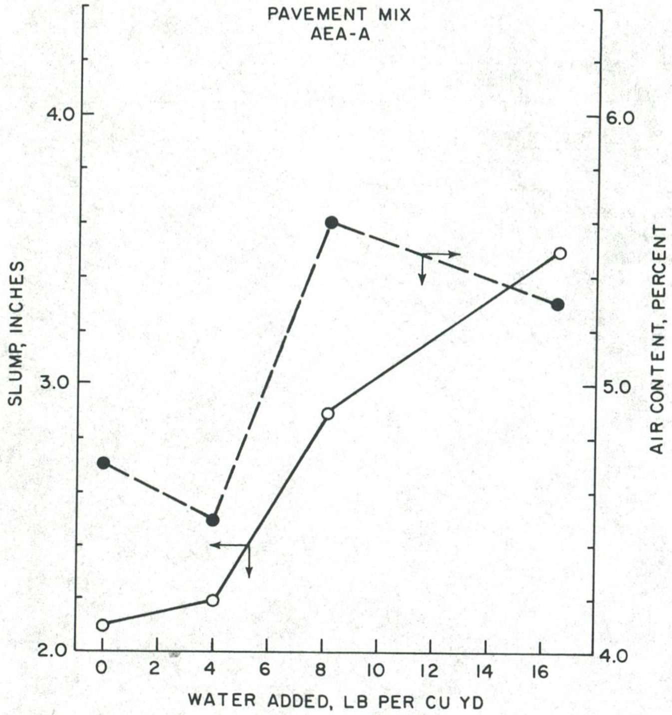

Figure E-1. Effect of added water on slump and air content of pavement mix with AEA-A. Nominal initial air content was 5 ± 1/2 percent.

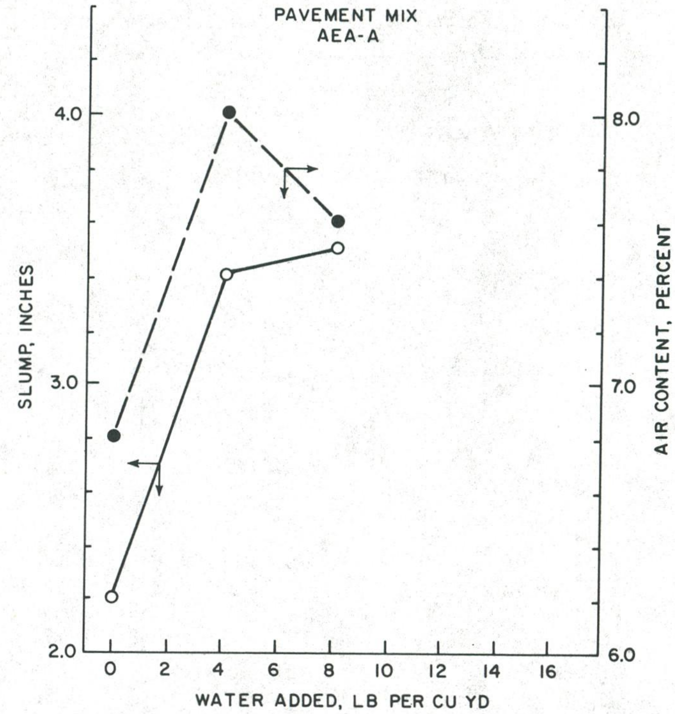

Figure E-2. Effect of added water on slump and air content of pavement mix with AEA-A. Nominal initial air content was 7 ± 1/2 percent.

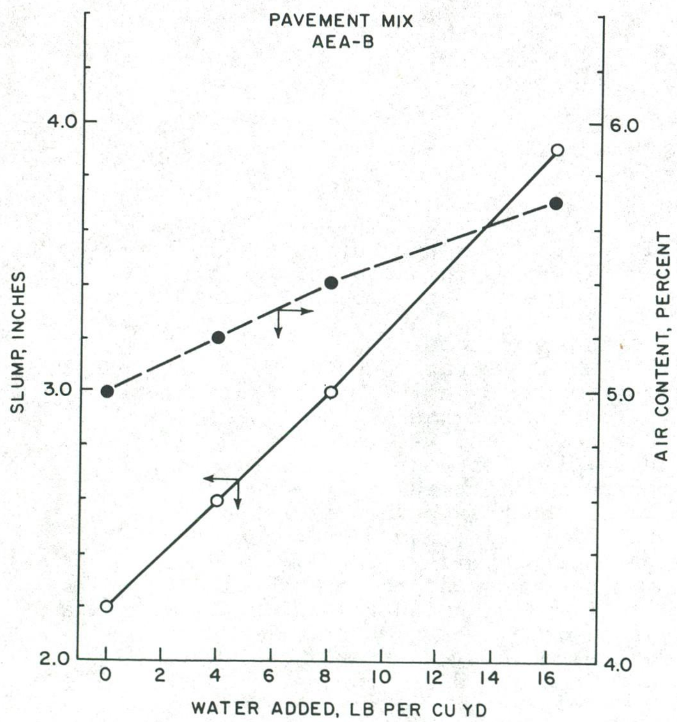

Figure E-3. Effect of added water on slump and air content of pavement mix with AEA-B. Nominal initial air content was 5 ± 1/2 percent.

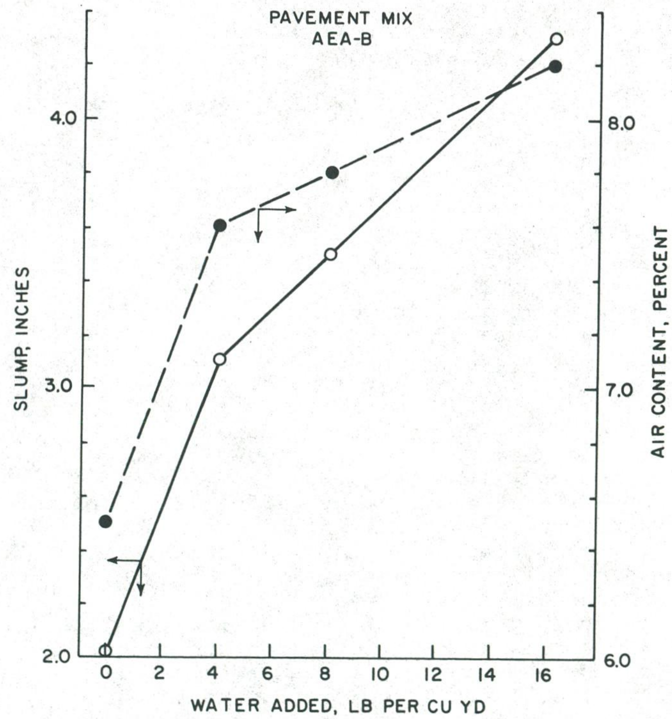

Figure E-4. Effect of added water on slump and air content of pavement mix with AEA-B. Nominal initial air content was 7 ± 1/2 percent.

Table E-3 Concrete Mix Proportions and Characteristics

Mix No.1/	Air-Entraining Agent2/	Dosage3/ (% S/C)	Proportions: Quantities, lb per cu yd — Cement	Sand (SSD)	Coarse Aggregate (SSD)	Water	Characteristics — W/C Ratio	Slump (inches)	Air Content (%)
P-A1	A	0.012	566	1205	1930	240	0.42	2.0	4.7
P-A2	"	"	566	1204	1929	244	0.43	2.2	4.5
P-A3	"	"	558	1188	1902	245	0.44	2.9	5.6
P-A4	"	"	556	1185	1898	253	0.46	3.5	5.3
P-A5	"	0.023	566	1176	1882	234	0.41	2.2	6.8
P-A6	"	"	558	1160	1856	239	0.43	3.4	8.0
P-A7	"	"	557	1158	1853	235	0.42	3.5	7.6
P-B1	B	0.012	565	1204	1928	236	0.42	2.2	5.0
P-B2	"	"	563	1199	1920	239	0.42	2.6	5.2
P-B3	"	"	560	1193	1911	242	0.43	3.0	5.4
P-B4	"	"	556	1183	1895	248	0.45	3.9	5.7
P-B5	"	0.037	565	1186	1899	229	0.41	2.0	6.5
P-B6	"	"	557	1169	1872	230	0.41	3.1	7.6
P-B7	"	"	554	1163	1863	233	0.42	3.5	7.8
P-B8	"	"	549	1153	1845	238	0.43	4.3	8.2
S-A1	A	0.028	655	1254	1712	252	0.39	2.0	6.4
S-A2	"	"	643	1231	1681	251	0.39	2.3	7.9
S-A3	"	"	636	1218	1664	253	0.40	3.0	8.6
S-A4	"	"	627	1201	1640	257	0.41	3.8	9.4
S-B1	B	0.048	656	1253	1710	255	0.39	2.0	6.3
S-B2	"	"	652	1245	1700	257	0.40	2.3	6.6
S-B3	"	"	648	1238	1691	260	0.40	2.7	6.9
S-B4	"	"	637	1217	1662	264	0.41	3.4	8.0

1/ P - pavement mix design
S - structural mix design

2/ A - neutralized Vinsol resin
B - alkyl-benzyl sulfonate

3/ %S/C - percent AEA solids by weight of cement

Results for the structural mixtures are shown in Figures E-5 and E-6. In this case NVR mixtures appear to be more sensitive to changes in water content than do mixtures containing alkyl-benzyl sulfonate.

All results are summarized in Table E-4, where those portions of the line segments having the greatest slopes were used to compute the amount of added water needed to change air content by one percentage point and slump by 1 in. For many of these mixtures, the amount of water (expressed as a percent of net mix water) needed to increase slump by 1 in. is less than the 3 percent figure commonly accepted. The amount of water needed to change air content by 1 percent is even more critical, and was as low as 1.2 percent of the net mixing water in one instance. Overall, those mixtures incorporating neutralized Vinsol resin as the air-entraining agent appear to be more sensitive to changes in water content than do those prepared with the alkyl-benzyl sulfonate. In addition, sensitivity of slump and air content to changes in water increases with increase in nominal air content. This is apparently more pronounced for the alkyl-benzyl sulfonate than for the NVR. The latter appears to be equally sensitive at all nominal air contents.

When net water contents of each batch are computed (see Table E-3) the sensitivity of slump and air content to small changes in net water content is even more dramatic. For instance, for three of the pavement mixtures, only about 1/2 percent of the net mix water is needed to change slump by 1 in. and air content by one percentage point. This implies that these mixtures respond to very small changes in water content with a concomitant increase in air content which results in an increase in slump.

In conclusion, the data obtained help to explain some of the anomalous fluctuations in air content observed for low slump mixes. On most jobs, slump is controllable within the reasonable range of ± 1 in. Normally, air content will vary ± 1/2 percent within this slump range. One can see from Figures E-1 through E-6,

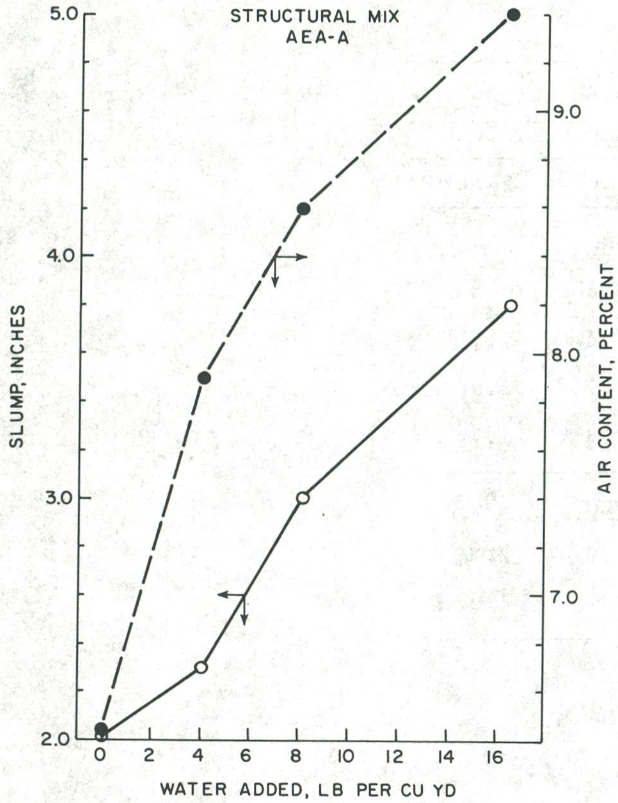

Figure E-5. Effect of added water on slump and air content of pavement mix with AEA-B. Nominal initial air content was 6 ± 1/2 percent.

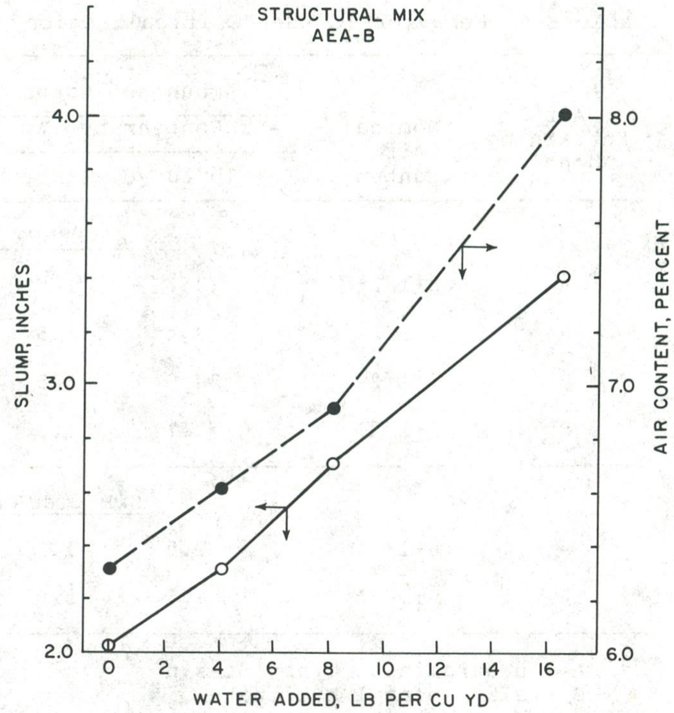

Figure E-6. Effect of added water on slump and air content of pavement mix with AEA-B. Nominal initial air content was 6 ± 1/2 percent.

however, that for mixtures initially prepared close to 2 in. of slump, an increase of 1 in. in slump may lead to an increase of more than one percentage point in air content. If air contents are initially on the high side of the target value, this increase may be enough to place them out of specification. Thus, if operations call for relatively low slump concretes, such as in slipforming, closer control of water content and increased restrictions on further additions of water may be required if good control over air content is to be obtained.

AIR ENTRAINMENT IN LOW SLUMP DENSE CONCRETES

Materials

The cement used for these concretes was the same blend of three Type I cements used in the previous series (see Table E-1). Aggregates used were Elgin, Illinois sand (see Table E-2), and a crushed diabase from Dresser Junction, Wisconsin (Table E-5).

Four commercially available air-entraining agents were used. The first two (AEA-A and -B) were from the same lots as those used in the previous laboratory studies described above. The third, AEA-C, is an alkali-stabilized, saponified natural wood resin (not NVR) with a solids content of 7.3 percent. The fourth, AEA-D, is marketed as "an aqueous solution of a complete mixture of organic acid salts." It consists predominantly of tall-oil derivative, and has a solids content of 17.3 percent. No other types of admixtures were used.

Concrete Mixtures

Mix Designs. A single mix design which follows that recommended by the Iowa Dept. of Transportation (45) was used in this study. Cement content was 823 lb per cu yd, maximum aggregate size was 1/2 in., and slump was 3/4 to 1 in. The ratio of fine to coarse aggregate was 50:50. Air content was held to 6±1/2 percent for the initial mixtures.

Batching and Mixing. Materials conditioning, batching, and mixing procedures were essentially the same as those employed in the previous "critical slump" series. A 3-minute mix period was used, with air-entraining agents being added after an initial 20 seconds of mixing. Immediately following the 3-minute mix period, the concrete was tested for slump (ASTM C 143-78) and air content (ASTM C 231-81-Type A meter). As in the previous series, new batches were prepared at each dosage rate of AEA and at each water content investigated. Exceptions are those batches that were retempered. These are denoted by "-R." Batch analyses and properties of fresh concrete for all

Table E-4 Behavior in the "Critical Region"

Air Entraining Agent[1/]	Nominal Air Content	Amount of Water Needed to Change- Air Content by 1% lb/cu yd	Air Content by 1% % Net	Slump by 1-inch lb/cu yd	Slump by 1-inch % Net
		PAVEMENT MIXTURE			
A	5±1/2%	3.7	1.5	5.8	2.4
A	7±1/2%	3.4	1.5	3.4	1.5
B	5±1/2%	20.0	8.5	9.2	3.9
B	7±1/2%	3.7	1.6	3.8	1.7
		STRUCTURAL MIXTURE			
A	6±1/2%	2.9	1.2	5.6	2.2
B	6±1/2%	7.6	3.0	10.2	4.0

1/ A - neutralized Vinsol resin
B - alkyl-benzyl sulfonate

Table E-5
Dresser Junction, Wisconsin, Coarse Aggregate

Grading - % Retained on Sieve Size Indicated: 1/2-in.	3/8-in.	No. 4	Bulk Specific Gravity - SSD	Absorption % by wt.
0	50	100	2.95	0.6

mixtures prepared in this series are given in Table E-6.

Specimen Preparation. Specimens prepared for this program were used for subsequent measurement of air content in the hardened concrete. For Series I, these were 3x3x11-1/4-in. prisms cast from mixtures A-1 and B-1. Rodding and external vibration were used to compact companion specimens from each batch into steel molds. A table vibrator with a frequency of 7000 vpm, and an amplitude of 0.004 in., was used for vibration of the molds. In Series II, concrete in the 0.22 cu ft air meter vessel was internally vibrated immediately after measurement of air content. A spud-type vibrator with a frequency of 8000 vpm and an amplitude of 0.03 in. (in air) was inserted three times for each of three lifts. Insertion times were 0, 8, and 20 seconds per insertion for specimens cast from mixtures AII-1, AII-2, and AII-3, respectively. Because the mixtures were relatively stiff, concrete was removed from the air meter vessel immediately after vibration, and was placed under wet burlap and allowed to harden. After moist curing for approximately 4 weeks, all specimens were sawed to obtain a 9-in.x3-in.x1-in. slice from each casting. These slices were lapped to a smooth finish using 1800 and 2600 silicon carbide grits in an oil-based lapping vehicle.

The slices were dried to remove lapping oil, and then subject to linear traverse analyses (ASTM C 457-80). After linear traverse tests were completed, a water-based paste consisting of zinc oxide was worked into the surface of each specimen to fill all the voids. Specimens were then subjected to the entrapped void measurement technique described next under "Experimental Techniques." After these tests were completed, the specimens were packaged and shipped to the New York State Department of Transportation Materials Bureau Laboratories for determination of hardened air content using a high pressure air meter. They were subsequently returned to CTL where, as described later, additional linear traverses were carried out.

Table E-6 Concrete Mix Proportions and Characteristics Dense Overlay Concretes

Mix No.[1/]	Air-Entraining Agent[1/]	Dosage[2/] (% S/C)	Proportions: Quantities, lb per cu yd: Cement	Sand (SSD)	Coarse Aggregate (SSD)	Water	Characteristics: W/C Ratio	Slump (inches)	Air Content (%)
A-1	A	0.057	828	1409	1551	267	0.32	0.8	5.7
A-2	A	0.057	824	1389	1529	277	0.34	1.3	6.3
A-3	A	0.057	818	1363	1501	286	0.35	1.7	7.0
A-4	A	0.057	833	1433	1577	258	0.31	0.4	5.3
A-5	A	0.029	838	1426	1570	271	0.32	0.5	4.8
A-5R	A	0.029	828	1409	1551	281	0.34	0.8	5.1
A-6	A	0.086	826	1421	1564	256	0.31	0.5	6.1
A-7	A	0.143	819	1394	1534	265	0.32	1.0	6.9
A-7R	A	0.143	798	1360	1497	273	0.34	1.9	8.3
B-1	B	0.099	822	1383	1523	275	0.33	0.7	6.7
B-2	B	0.099	806	1333	1468	287	0.36	1.7	8.5
B-3	B	0.099	831	1414	1557	261	0.31	0.5	6.0
B-4	B	0.198	798	1355	1492	270	0.34	0.8	8.6
B-4R	B	0.198	771	1297	1428	262	0.34	1.3	12.3
B-5	B	0.049	834	1403	1544	279	0.33	1.0	5.4
B-5R	B	0.049	809	1361	1498	293	0.36	1.1	6.9
C-1	C	0.120	833	1418	1560	275	0.33	0.7	5.0
C-2	C	0.240	831	1415	1557	276	0.33	0.8	5.1
C-3	C	0.480	830	1413	1555	283	0.34	0.6	4.8
D-1	D	0.100	845	1421	1565	283	0.33	0.9	4.1
D-2	D	0.200	843	1418	1561	283	0.34	0.7	4.3
D-3	D	0.400	845	1421	1565	283	0.33	0.4	4.2
AII-1	A	0.057	823	1402	1543	271	0.33	0.9	6.0
AII-2	A	0.057	823	1402	1543	271	0.33	0.8	6.0
AII-3	A	0.057	827	1408	1549	272	0.33	0.8	5.6

[1/] A - neutralized Vinsol resin
B - alkyl-benzyl sulfonate
C - alkali-stabilized wood resin
D - tall-oil derivative

[2/] %S/C - percent AEA solids by weight of cement

Experimental Techniques

Linear Traverse. Equipment and techniques used for the linear traverse measurements followed those specified in ASTM C 457-80. The traverses were carried out at magnifications of 75X using the equipment shown in Figure E-7. Traverse lines are approximately 8-in. long and were spaced 0.25-in. apart on a standard 9 x 3-in. section. This provided a total of 100 in. of traverse for each specimen.

The following expressions were used to calculate the various parameters of interest:

$$\text{Percent Air (A)} = \frac{\text{Sum of void chord lengths} \times 100}{\text{Total distance traversed}} \qquad \text{(E-2)}$$

$$\text{Voids per Inch (n)} = \frac{\text{Total number of voids traversed}}{\text{Total distance traversed}} \qquad \text{(E-3)}$$

$$\text{Specific Surface } (\alpha)\ (\text{in.}^2/\text{in.}^3) = \frac{400n}{A} \qquad \text{(E-4)}$$

Spacing Factor ($\bar{L}$)

If P/A ≤ 4.33   If P/A > 4.33

$$\bar{L} = \frac{25p}{n} \qquad \bar{L} = \frac{3}{\alpha} \times \left[1.4 \times \left(\frac{100p}{A} + 1\right)^{1/3} - 1\right] \qquad \text{(E-5)}$$

where p = paste content expressed as a fractional amount of the total volume of concrete.

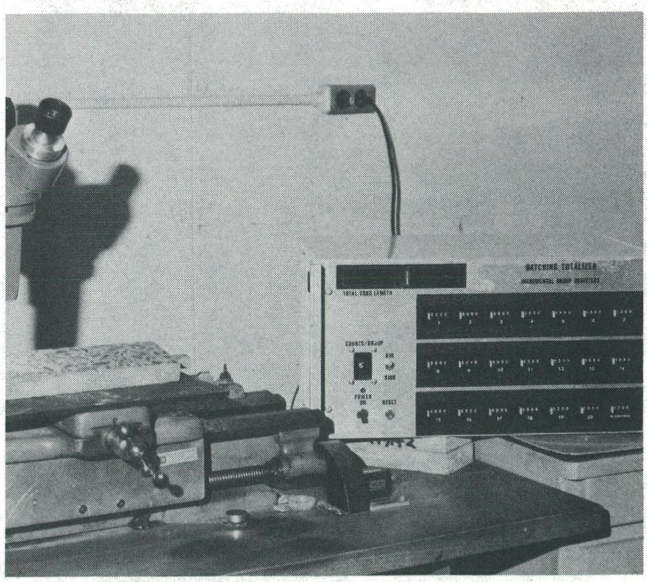

Figure E-7. Linear traverse apparatus with void count totalizer.

Entrapped Void Measurements. The percent air content contributed by so-called entrapped voids (i.e., those voids with diameters greater than about 1 mm) was determined using a computer-assisted areal traverse technique. Photographs were taken of each lapped surface such that one-half of the surface area just filled the lens field. Negatives (35-mm format) were then used to produce enlargements on a 6 x 9-in. format

(Fig. E-8A). A scale was placed on at least 1 surface for each series so that the instrument could be calibrated directly in millimeters. Prints were analyzed using a graphics tablet device available with a 64K laboratory microcomputer system (Fig. E-8B). Void areas were determined by circumscribing each void with a pressure-actuated pen interfaced with the graphics tablet. A proprietary software program (68) was used to compute void areas, average diameters, group statistics, and frequency distributions.

Traverses were performed by securing each print to the graphics tablet, then calibrating the computer at 0 and 50 mm on the scale. The scaled print was then removed and the print to be analyzed was affixed to the tablet. A mask was placed over the print such that a horizontal strip 1-in. wide was left exposed, while the remainder of the area was covered by the mask. All voids within this strip were then traced. Operator experience was used to judge which voids were significantly less than 1 mm. Those voids judged to be "borderline" were included in the limited data set. Later, after average diameters had been calculated, they were eliminated if they were less than 0.9 mm in average diameter. (After a number of trial measurements had been made, it was found that a sizeable number of voids lay between 0.9 and 1.0 mm in average diameter. Because the resolution of the technique was judged to be no better than 0.1 mm in this size range, 0.9 mm was used as the cut-off point to avoid excluding a significant number of voids. Voids less than 0.9 mm were difficult to resolve and thus were not included in the analysis). After all voids had been tallied, the pen was used to circumscribe the entire area of the specimen, thus yielding a basis for computing total air content. The following calculations were then carried out:

$$\underset{(A)}{\text{Percent Air}} = \frac{\text{Sum of void Areas} \times 100}{\text{Total specimen surface area}} \quad \text{(E-6)}$$

$$\underset{\text{(each void)}}{\text{Average Diameter}} = \frac{4 \times \text{void area}}{\text{Void perimeter}} \quad \text{(E-7)}$$

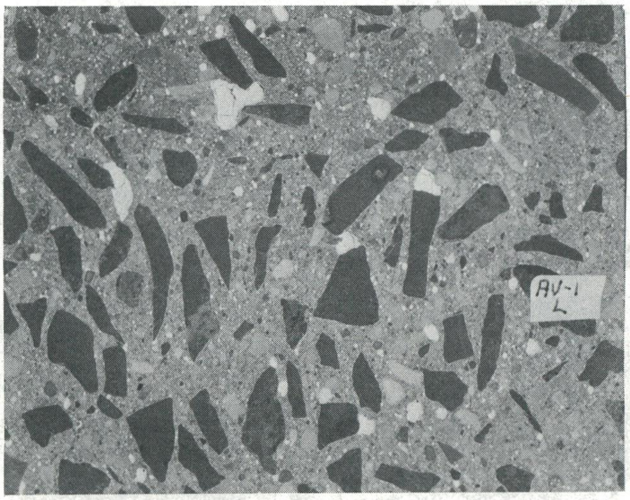

Figure E-8A. Specimen prepared for entrapped void area measurements.

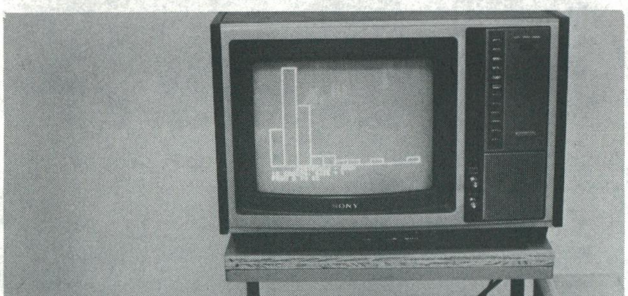

Figure E-8B. Computer-assisted entrapped void measurement equipment.

High Pressure Air Meter. Tests for hardened air content by a high pressure method were conducted by the New York State Department of Transportation Materials Bureau. Because their device has been described in detail elsewhere (69), only a brief description will be given here.

A photograph of the device is shown as Figure E-9. It consists of an air-actuated hydraulic pump which supplies 4,000 psi pressure to the test specimen. After the test, an overflow valve allows for exudation of water through a rubber hose into a pan situated on a digital balance. Prior to starting the test, the specimen is brought to an equilibrium moisture content through immersion in water at atmospheric pressure.

The test sample is placed in the chamber, submerged in water, and the pressure is applied. When pressure has stabilized, it is reduced to atmospheric by opening the overflow valve. A time-weight curve for the amount of water in the container on the scale is established, starting 10 seconds after atmospheric pressure is reached. This curve is continued until there is a minimal amount of water being expelled by the sample. At this point the time is recorded and the sample is taken from the pressure chamber and transferred to a conventional apparatus for determining weight in water. A time-sample weight tabulation is started and continued for several minutes. The time-weight curve is then extrapolated from 10 to 0 seconds, and from the last scale reading of the overflow to the first conventional weight in water. Subsequent conventional weights in water are plotted relative to the first conventional weight on the graph. The difference in weight between the last conventional sample weight in water and the zero time on the graph is added to the difference between the last conventional sample weight in

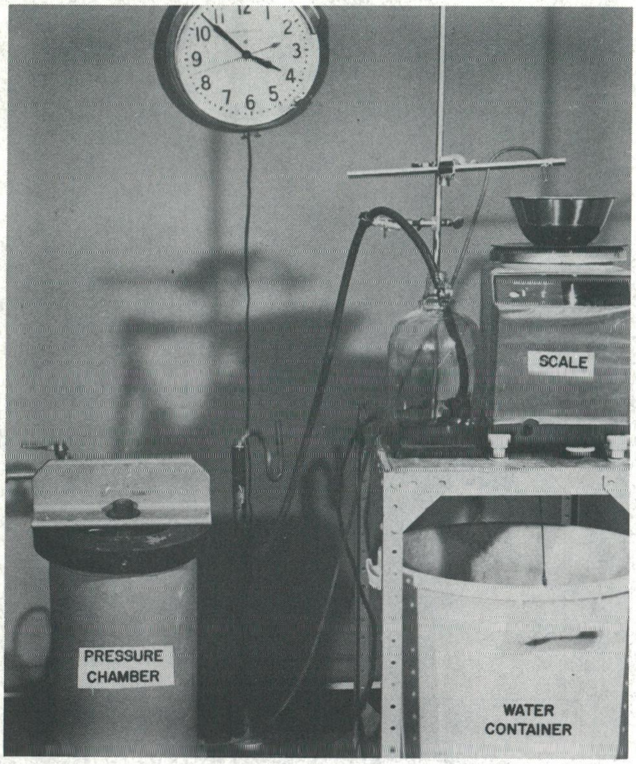

Figure E-9. High pressure air meter (69).

water on the graph and the sample weight in water before pressure is applied. This represents the amount of water forced into the sample, and it can be assumed to be equivalent to the volume of air voids in the sample.

The air content is then calculated as follows:

$$\text{Percent Air} = \frac{\text{Volume of air voids} \times 100}{\text{SSD wt. in air} - \text{initial wt. in water}} \quad (E\text{-}8)$$

Results

Air Contents in Fresh Concretes. Air contents for each batch prepared are given in Table E-6. The effects of increasing dosages of AEA and increasing water content at constant dosage of AEA for neutralized Vinsol resin and alkyl-benzyl sulfonate are shown in Figures E-10 through E-13. The most obvious items of note are the extremely high dosages of AEA needed to achieve the specified air content. For both air entraining agents this ranges between 0.05 and 0.10 percent of active ingredients on a cement weight basis. This is approximately one order of magnitude higher than dosages needed to obtain comparable air contents in conventional concretes. Also, as seen from Figures E-10 and E-12, the sensitivity of air content to changes in AEA dosage is greatly reduced in comparison with conventional concretes. For instance, in the case of the NVR, 0.062 percent s/c is needed to change air content by one percentage point. This corresponds to a dosage of about 6 fl oz/cwt of cement simply to increase air content by a single percentage point! The situation is similar for the alkyl benzyl sulfonate, although in this case proportionately more agent is needed. This is due to the higher dilution factor employed by this manufacturer.

The relationships between water content and air content (Figs. E-11 and E-13), however, follow more closely those of conventional concretes. The amount of net mixing water needed to effect a change of one percentage point in air content ranges from 10.5 lb per cu yd for the alkyl benzyl sulfonate to 16.5 lb per cu yd for the neutralized Vinsol resin. These amounts correspond to approximately 4 and 6 percent of the net mixing water, respectively.

With the other two AEA studied, it was not possible to achieve the specified air content, even at dosages approaching 1/2 percent by weight of cement. As an example, it can be seen from Table E-6 that the initial dosage of agent D (tall-oil derivative) yielded an air content of 4.1 percent. Increasing this dosage to 0.2 percent by weight of cement yielded an air content of 4.3 percent. Quadrupling the initial dosage to 0.4 percent effected no change in air content. These two agents, then, appear to be ineffective in generating the specified amounts of air in these stiff, high cement content mixtures.

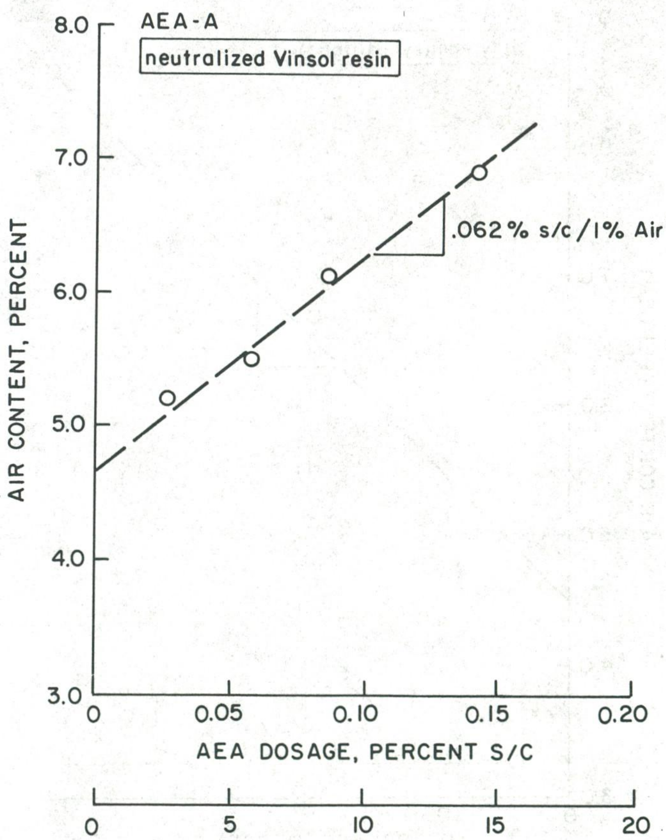

Figure E-10. Relationship between dosage of neutralized Vinsol resin and air content in dense concrete mixtures.

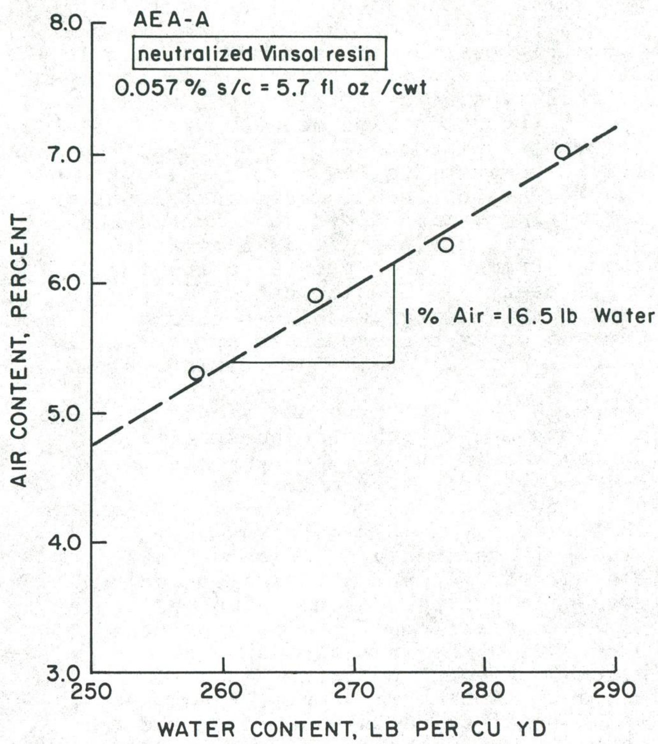

Figure E-11. Relationship between water content of dense concrete mixtures and air content using neutralized Vinsol resin.

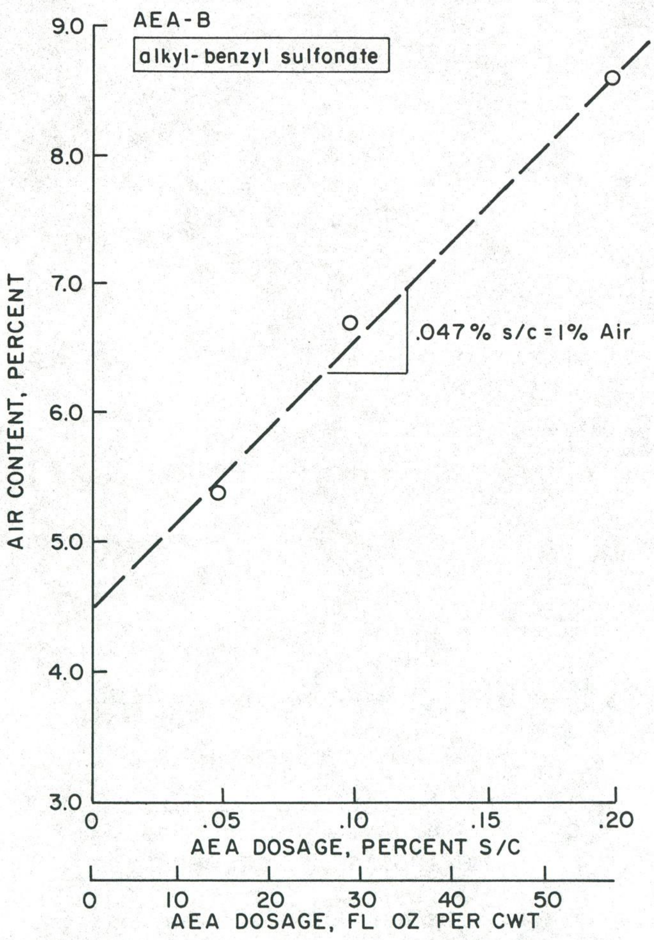

Figure E-12. Relationship between dosage of alkyl-benzyl sulfonate and air content in dense concrete mixtures.

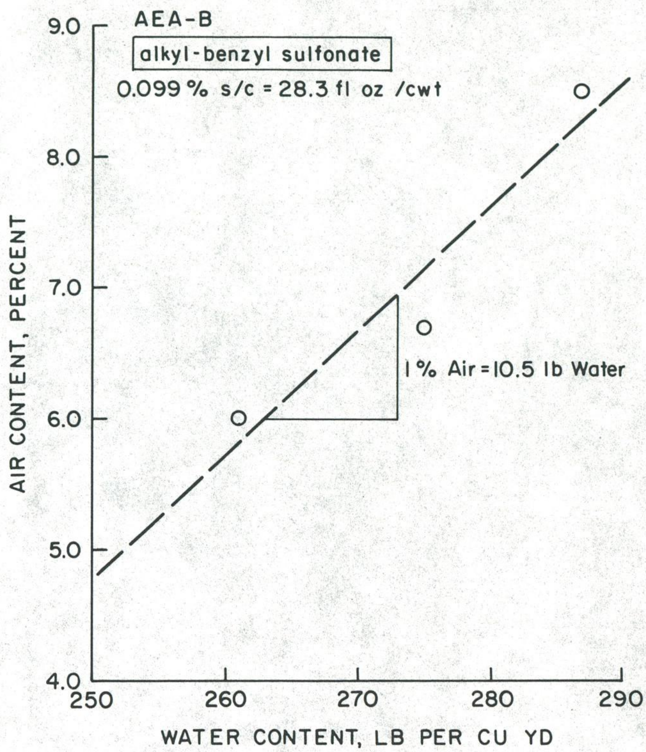

Figure E-13. Relationship between water content of dense concrete mixtures and air content using alkyl-benzyl sulfonate.

Linear Traverse Analyses. The four specimens that were cast from mixtures A-1 and B-1 and were consolidated by rodding and external vibration were subject to an initial series of linear traverse analyses. Results showed very large differences in total air content compared to results of pressure meter measurements on plastic concrete. Examination of void size distributions indicated that an unusually high proportion of voids, which were difficult to detect in many instances, fell into very small size classes. To improve resolution, all specimens were reanalyzed after measurements of entrapped voids. At this point in the process, the voids had been filled with the zinc oxide paste which makes them easier to distinguish.

Results on these specimens are given in Table E-7. In all cases, a large number of voids intersected per inch of travel, a high specific surface, and a low spacing factor were encountered. The difference in air contents between plastic and hardened concretes is somewhat greater than one would anticipate for so stiff a mixture. In one instance, B-IV, loss in air content is close to 3 percentage

Table E-7 Linear Traverse Analyses Dense Concrete Mixtures

Specimen[1/]	Air Content - %			Voids/in.	Specific Surface (in.^{2}/in.^{3})	Spacing Factor (in.)
	Plastic	Hardened	Diff.[2/]			
A-1R	5.9	4.5	1.4	13.2	1173	0.0046
A-1V	5.5	4.8	0.7	17.0	1417	0.0037
B-1R	6.7	5.1	1.6	17.0	1333	0.0038
B-1V	6.6	3.8	2.8	11.3	1189	0.0049
ARII-1	6.0	4.5	1.5	13.7	1218	0.0045
AII-2[a/]	6.0	5.3	0.7	13.8	1041	0.0048
AII-3[b/]	5.6	4.4	1.2	17.4	1582	0.0035
C	6.9	5.8	1.1	8.8	607	0.0071

[1/] A - neutralized Vinsol resin
B - alkyl-benzyl sulfonate
R - consolidated by rodding
V - consolidated by external vibration
C - conventional concrete mixture

[2/] Difference between plastic and hardened air contents

[a/] 24 seconds of internal vibration per layer
[b/] 60 seconds of internal vibration per layer

points. It is difficult to assess the comparative effects of the two types of air entraining agents because of differences in both initial and final air contents. However, void characteristics are virtually identical for the two specimens with the closest hardened air contents (A-IV and B-1R). Vibration, at least for the NVR mixtures, appears to increase the number of voids and to decrease spacing factors, as would be expected.

Differences among the various dense concrete mixtures, however, pale in comparison to differences between dense concretes and a conventional paving mixture (Table E-7, mixture C). For the most part, these differences arise from the shift in air void size distributions in the dense concretes, as can be seen from Figure E-14. The dense concretes display a sharp peak in the distribution over the range of 50 to 200x 10^{-5} in. Indeed, over 50 percent of the air voids measured exhibit chord intercepts less than 150x10^{-5} in. In comparison, the conventional concrete shows a broad distribution over the range of 100 to 300x10^{-5} in. In this case the 50th percentile was not reached until a chord length of approximately 300x10^{-5} in. had been exceeded.

Entrapped Void Measurements. After filling with zinc oxide paste, all specimens were subjected to the entrapped void measurement procedure described earlier. Results are given in Table E-8. Shown are the total percentage area of void sections, mean area, and mean average diameter. Standard deviation and 95 percent confidence limits on the mean are also included. Total percentages of entrapped voids range from 0.8 percent for AII-3 to 1.6 percent for A-IV and B-IR. One might approach the problem of determining percentage of entrained air simply by subtracting the entrapped air values in Table E-8 from total air content, as determined via linear traverse in Table E-7. However, this is not as straightforward as might be expected. Because of their relatively large size and relatively small number (as compared to entrained air voids), linear traverse analysis most likely underestimates the true contribution of entrapped voids to total air content. (Consider any random line of traverse across a concrete specimen. The entrained air chord intercepts will, taken over a very large number of voids, gradually approach the actual void diameter. However, if only a few large voids are present along the line of traverse, the fact that most of these intercepts may intersect only a very small portion of each void is easily appreciated. Further complicating the relationship is the fact that entrapped voids often display irregular rather than spherical shapes.)

Thus, the total air contents given in Table E-7 for hardened concrete, while including the contribution from entrained air, would actually be greater if entrapped air could be subtracted out and independently measured. Unfortunately, the linear traverse equipment used in this study was such that the contribution of each size class could be measured only in number of voids and not in summation of length. Therefore, the best estimate of total air content which can be given is that it lies somewhere between the values in Table E-7, and the sum of the values in Tables E-7 and E-8. These estimates are presented in the final column of Table E-8. Not considered in this estimate is

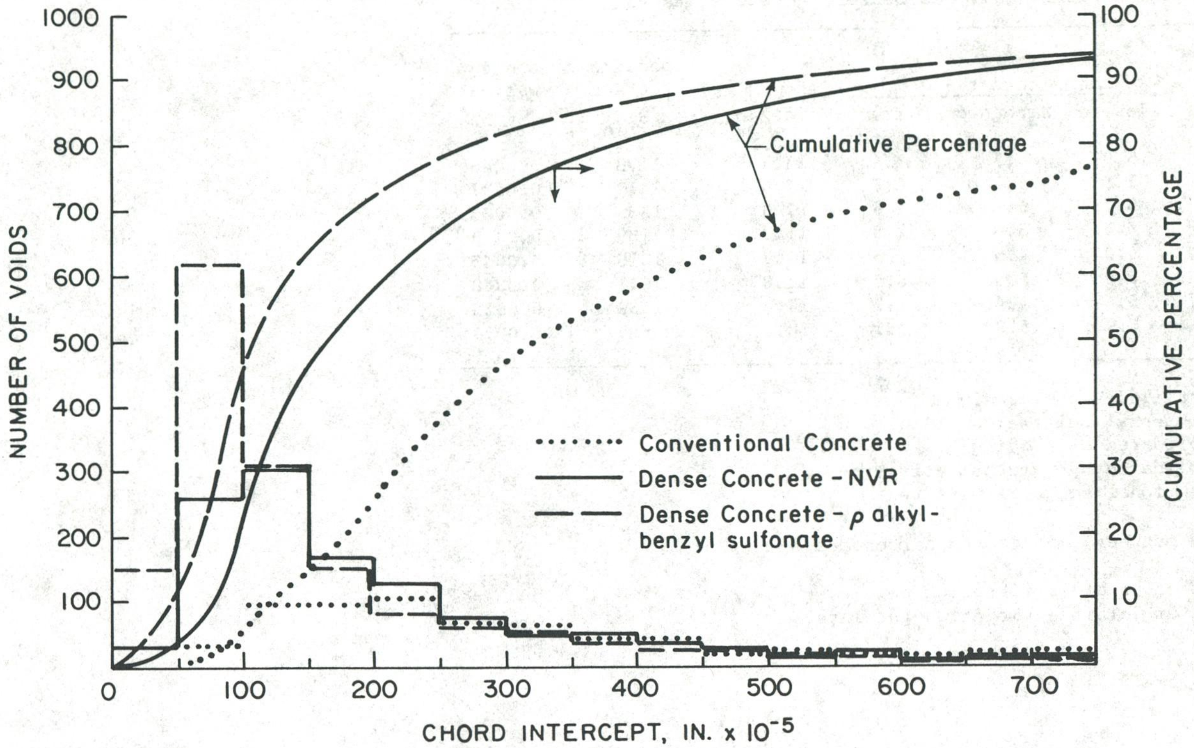

Figure E-14. Comparison of air void size distributions in conventional and dense overlay concrete mixtures.

Table E-8 Entrapped Void Measurements

Specimen[1/]	Void Area-%	Void Area-mm² Mean	Void Area-mm² Std. Dev.	Void Area-mm² 95% C.L.	Average Void Diameter-mm Mean	Average Void Diameter-mm Std. Dev.	Average Void Diameter-mm 95% C.L.	Total Estimated[2/] Air Content-%
A-1R	1.5	3.3	3.2	6.4	1.7	0.8	1.6	4.5 - 6.0
A-1V	1.6	3.0	2.8	5.6	1.7	0.6	1.2	4.8 - 6.4
B-1R	1.6	2.8	2.1	4.3	1.6	0.6	1.2	5.1 - 6.7
B-1V	0.9	2.3	1.6	3.1	1.5	0.5	1.0	3.8 - 4.7
ARII-1	1.4	3.1	4.0	8.1	1.6	0.7	1.4	4.5 - 5.9
AII-2[a/]	1.3	3.2	4.0	8.1	1.5	0.8	1.6	5.3 - 6.6
AII-3[b/]	0.8	2.3	2.0	4.1	1.5	0.5	1.1	4.4 - 6.2

[1/] A - neutralized Vinsol resin
B - alkyl-benzyl sulfonate
R - consolidated by rodding
V - consolidated by external vibration

[2/] See text for assumptions used in this estimation

[a/] 24 seconds of internal vibration per layer
[b/] 60 seconds of internal vibration per layer

the possibility that some air voids entrained in these concretes were too small to resolve, or that operator strain induced during the tedious measurement of such a large number of very small voids induces errors in the results.

Other parameters derived from the entrapped void measurements are also of interest. The average entrapped air void area is approximately 3 mm^2. This area was somewhat smaller for those specimens subjected to the greatest amounts of vibration. Average void diameter, which was about 1.5 mm, is essentially the same for all specimens.

The distribution of these parameters can be seen from examination of Figures E-15 through E-17. Distributions for neutralized Vinsol resin and alkyl-benzyl sulfonate are essentially similar, with perhaps a slight tendency towards a coarser void area and diameter distribution for the specimens utilizing NVR. Vibration, both internal and external, tends to shift the distribution to somewhat smaller sizes. In all cases, the proportion of voids having areas greater than 5 sq mm and corresponding average diameters greater than about 3 mm is relatively small. This suggests that the majority of voids classified as "entrapped" in this series have their origins in mechanisms akin to the formation of entrained air, rather than in other mechanisms which would tend to produce much larger void sizes.

High Pressure Meter and Comparison of Air Contents. After entrapped air void measurements were completed, samples were tested for total air content using a high-pressure air meter (HPM). Results are presented in Table E-9, and are compared to plastic, linear traverse, and the estimated air content discussed previously. In all but one case, AII-2, HPM results exceed those determined using linear traverse. In two cases, ARII-1 and AII-3, HPM results exceed the air contents of plastic concrete. In the majority of cases, however, HPM results fall in the range estimated to represent the total air content.

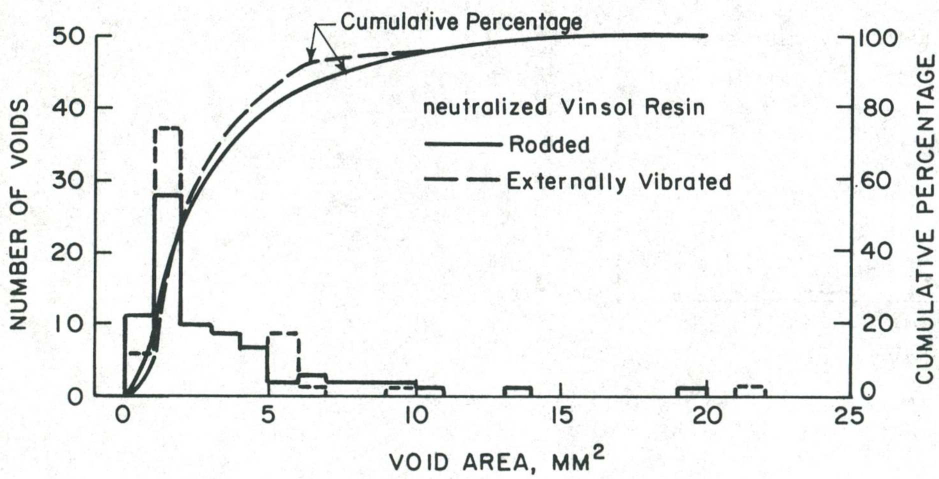

Figure E-15A. Distribution of entrapped void areas in dense concretes prepared with neutralized Vinsol resin.

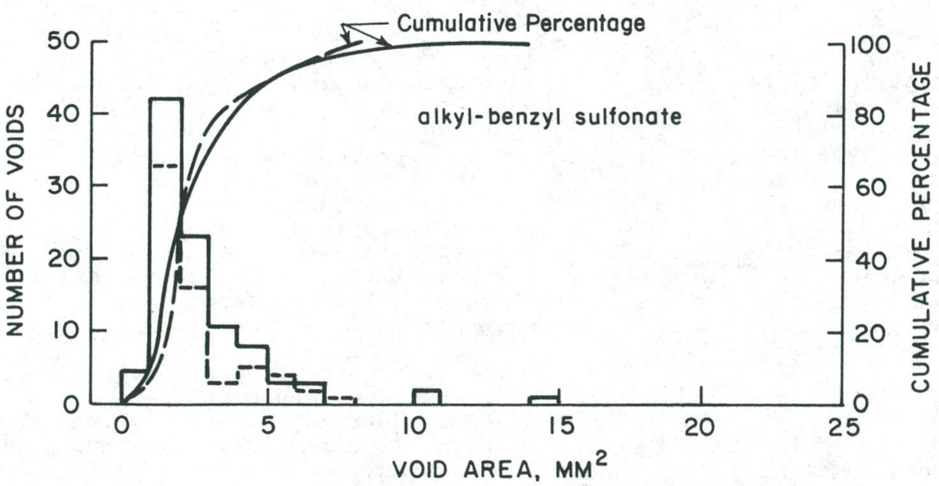

Figure E-15B. Distribution of entrapped void areas in dense concretes prepared with alkyl-benzyl sulfonate.

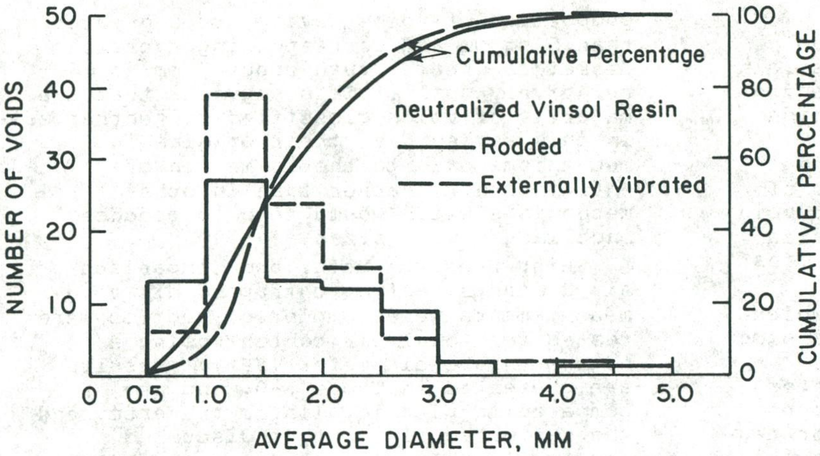

Figure E-16A. Distribution of entrapped void average diameters in dense concretes prepared with neutralized Vinsol resin.

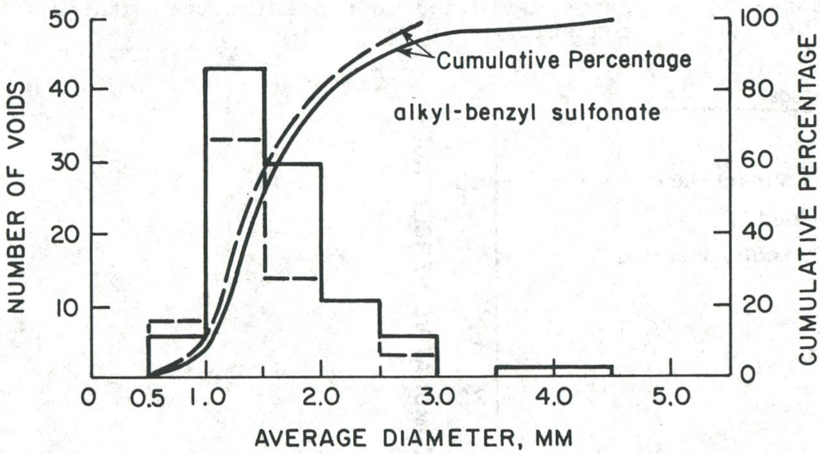

Figure E-16B. Distribution of entrapped void average diameters in dense concretes prepared with alkyl-benzyl sulfonate.

These results indicate that, although minor discrepancies do exist, there is general agreement between results of pressure meter, linear traverse (modified to include entrapped voids), and high pressure meter measurements. Considering the low spacing factors together with the high specific surfaces measured using linear traverse, the general conclusion can be drawn that if the proper type and amount of air-entraining agent is used, air content can be measured accurately with presently available techniques. In addition, properly air-entrained dense concrete mixtures should have adequate long term durability in freezing and thawing and deicer scaling environments.

CONCLUSIONS

The laboratory studies carried out during this project have helped to clarify some of the questions and concerns encountered during review of the questionnaire and raised in subsequent interviews with agency personnel. Based on results of these laboratory investigations, the following conclusions can be drawn:

1. There is a certain consistency range of concrete which lies roughly between 2 and 3 in. of slump, in which relatively small changes in water content can cause abnormal fluctuations in both slump and air contents. This phenomenon is most apparent when Vinsol-resin-type air-entraining agents are used, especially if air contents in the range of 7 to 8 percent are specified.

2. To obtain specified air contents in low-slump dense concrete ("Iowa" overlay mixtures), the amount of air-entraining agent needed may be up to ten times more than that needed in a conventional concrete. For certain types of air-entraining

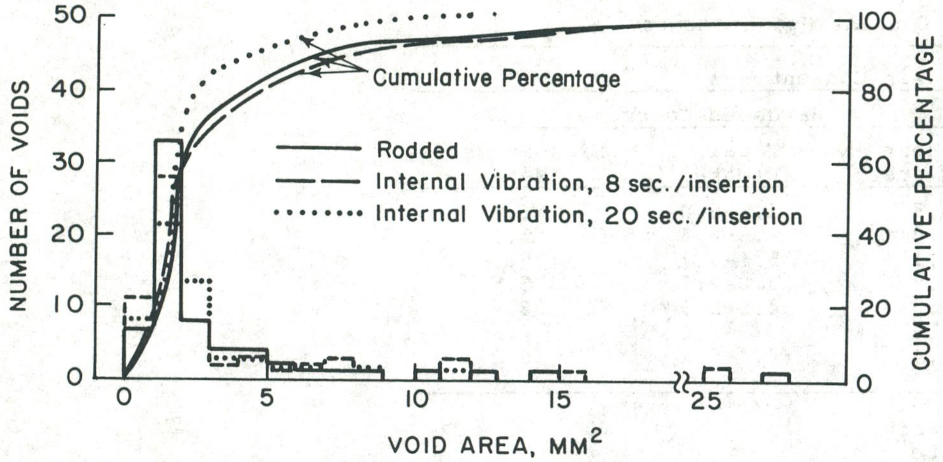

Figure E-17A. Effect of internal vibration on distribution of entrapped void areas.

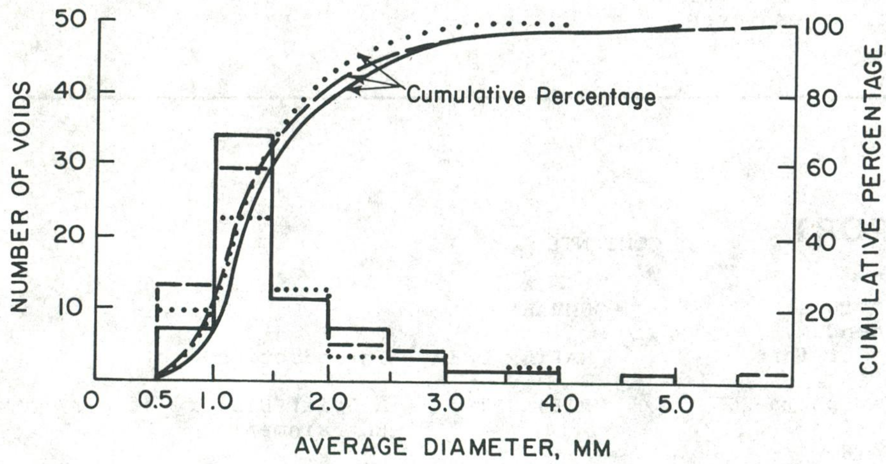

Figure E-17B. Effect of internal vibration on distribution of entrapped void average diameters.

agents, notably alkali-stabilized wood resins and tall-oil derivatives, even these high dosage rates may not be sufficient.

3. The sensitivity of air contents to additions of mixing water in dense concrete mixtures is similar to that of conventional concrete. That is, an increase of about 4 to 6 percent in net mixing water will increase air content by about 1 percentage point.

4. If specified air contents are achieved in fresh dense concrete mixtures, the final air content of the hardened concrete, when measured by either microscopic or high pressure techniques, should be in reasonable agreement with pressure meter (ASTM C 231) tests on the original concrete. Some amount of entrapped air (i.e., voids having average diameter greater than 1 mm), which may range up to 2 percent of the volume of concrete in some instances, is to be expected. However, if the concrete is properly mixed and consolidated, characteristics of the air void system, generally regarded as indicative of ultimate durability of the concrete, should be within acceptable limits.

Table E-9 Comparison of Air Content Measurements

Specimen[1/]	Air Content - %			
	Plastic Concrete	Hardened Concrete		
		Linear Traverse	Total Estimated[2/]	High Pressure Meter
A-1R	5.9	4.5	4.5-6.0	5.6
A-1V	5.5	4.8	4.8-6.4	5.1
B-1R	6.7	5.1	5.1-6.7	5.9
B-1V	6.6	3.8	3.8-4.7	5.5
ARII-1	6.0	4.5	4.5-5.9	6.4
AII-2[a/]	6.0	5.3	5.3-6.6	4.6
AII-3[b/]	5.6	4.4	4.4-6.2	6.2

1/ A - neutralized Vinsol resin
B - alkyl-benzyl sulfonate
R - consolidated by rodding
V - consolidated by external vibration

2/ See text, pg 79 for assumptions used in this estimation
a/ 24 seconds of internal vibration per layer
b/ 60 seconds of internal vibration per layer

APPENDIX F

A STATE-OF-THE-ART REPORT

Appendix F is not published in this report but is reproduced in an addendum, which is available on a loan basis or for the cost of reproduction from the Cooperative Research Programs, Transportation Research Board, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.

ABSTRACT

A state-of-the-are report was prepared which represents a compilation of currently available knowledge concerning the use and effects of air entrainment in portland cement concrete. Its objectives were to critically review the literature in the area of air entrainment and, from this review, to suggest directions which might be taken to find solutions to current problems in the field. The report includes: a brief historical review of the development of air entrainment and relevant specifications, and a discussion of the chemical composition and classification of air-entraining agents, the mechanism by which entrained air is developed in concrete, the influence of materials and construction procedures on entrainment of air, the relationships between entrained air and concrete durability, strength, and other properties, and a detailed discussion of current test procedures.

Only the table of contents of the literature review is included in this report. Much of the information presented in Appendixes C and D, however, has been taken from the report.

CONTENTS

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