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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM  
REPORT

**27**

**PHYSICAL FACTORS INFLUENCING  
RESISTANCE OF CONCRETE TO  
DEICING AGENTS**

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM  
REPORT

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# **PHYSICAL FACTORS INFLUENCING RESISTANCE OF CONCRETE TO DEICING AGENTS**

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SUBJECT CLASSIFICATION:

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## NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Bureau of Public Roads, United States Department of Commerce.

The Highway Research Board of the National Academy of Sciences-National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway departments and by committees of AASHO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Highway Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

This report is one of a series of reports issued from a continuing research program conducted under a three-way agreement entered into in June 1962 by and among the National Academy of Sciences-National Research Council, the American Association of State Highway Officials, and the U. S. Bureau of Public Roads. Individual fiscal agreements are executed annually by the Academy-Research Council, the Bureau of Public Roads, and participating state highway departments, members of the American Association of State Highway Officials.

This report was prepared by the contracting research agency. It has been reviewed by the appropriate Advisory Panel for clarity, documentation, and fulfillment of the contract. It has been accepted by the Highway Research Board and published in the interest of an effectual dissemination of findings and their application in the formulation of policies, procedures, and practices in the subject problem area.

The opinions and conclusions expressed or implied in these reports are those of the research agencies that performed the research. They are not necessarily those of the Highway Research Board, the National Academy of Sciences, the Bureau of Public Roads, the American Association of State Highway Officials, nor of the individual states participating in the Program.

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# FOREWORD

*By Staff*

*Highway Research Board*

This report will be primarily of interest to concrete researchers because it deals with research directed to the development of more and better information concerning the relationships between the physical characteristics of concrete and the susceptibility of the concrete to damage from deicing agents. Specifically, it presents the results of laboratory investigations which placed emphasis largely on procedures for finishing concrete and the defects which might be caused by variations in these procedures when applied to properly proportioned air-entrained concrete. Primary concentration was on the surface air-void system, while at the same time attention was given to the formation of gross structural weaknesses due to a combination of such factors as casting, finishing, and environment. The research findings are useful from the standpoint of a continuing search for answers to the very complex problem of concrete surface deterioration in the presence of freezing and thawing and deicing agents.

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Engineers generally agree that if a concrete is to remain durable in the environment of freezing and thawing and deicing agents, it must be characterized by proper air-entrainment, low water-cement ratio, adequate curing, and air drying prior to exposure to the adverse conditions. Experience in both the field and laboratory, particularly the latter, has demonstrated the durability of concrete so produced. At the same time, however, deterioration under a variety of conditions is being experienced by highway pavements and bridge decks supposedly having been constructed with the desired attributes. Scaling, spalling, crumbling, etc., are manifestations of the distress resulting from the combined effects of many variables. Because this problem persists, it is evident that more and better information is needed concerning the relationships between the physical characteristics of concrete and the susceptibility of the concrete to damage in the presence of freezing and thawing and deicing agents.

The University of Illinois has researched this issue principally by means of laboratory experiments with small- and large-scale specimens to determine the effects of finishing on the surface air-void system and the effects of adverse combinations of casting, finishing, and environmental conditions in contributing to the information of gross structural weaknesses such as weakened planes or weakened zones.

Major emphasis in this two-part approach dealt with the small-scale specimens and was placed on the effects of faulty finishing procedures because of the researchers' assertion that deterioration caused by deicing agents in combination with freezing and thawing is primarily a surface phenomenon. Support for this research direction was drawn from the fact that concrete of adequate durability has been produced in the field and laboratory; therefore, finishing procedures logically become one sus-

pect realm of contribution to inadequate durability. Other emphasis dealt with the study of large-scale specimens cast under adverse conditions of environment, casting and finishing to determine the relationships between shrinkage and bleeding and the possible formation of weakened planes and weakened zones. Support for this portion of the research was drawn from field observations indicating the possible existence of such weakened areas. Scaling tests, surface tensile strength tests, and microscopical determination of air-void parameters were performed in relation to the total study.

This document, constituting a final report on the research, contains information which will be useful in further studies of this very complex problem. Although the work was done under conditions representative of those in the field and was further compounded by the deliberate inclusion of faulty procedures, conditions of deterioration similar to those encountered in the field were not achieved. It was, therefore, not possible to evaluate the results in the desired depth. Conclusions were drawn on the basis of obtained data, and recommendations have been made for further research in this area. The reader is cautioned that the findings pertaining to excessive finishing of concrete surfaces are controversial and should be used only as a point of departure for additional verifying research.

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## **ACKNOWLEDGMENTS**

C. E. Kesler, Professor of Theoretical and Applied Mechanics and Civil Engineering, was the project director for the work reported herein. W. R. Malisch, D. A. Raecke and D. M. Fischer, Research Assistants in Civil Engineering, were responsible for most of the laboratory work and analysis of data. J. L. Lott, Assistant Professor of Theoretical and Applied Mechanics, and T. W. Kennedy, Instructor of Civil Engineering, reviewed the work and aided in the laboratory work and analysis of data.

The facilities and equipment used were those of the Civil Engineering and Theoretical and Applied Mechanics Departments of the University of Illinois, and the project was under the general administration of the Engineering Experiment Station.



# PHYSICAL FACTORS INFLUENCING RESISTANCE OF CONCRETE TO DEICING AGENTS

## SUMMARY

Studies were made of the effects of various concrete production methods on potentially durable concrete. Variations in the surface porosity, strength, and air void system produced by different finishing techniques were evaluated for typical air-entrained concretes. Large- and small-scale specimens were cast and effects of period and time of finishing, environmental conditions, and additions of water during finishing were evaluated using surface scaling tests, surface tensile strength tests, and microscopical determination of surface air void parameters.

The results indicated that the surface mortar air content is lower than the mortar air content within the concrete, but the spacing between the voids is at least as small as the void spacing within the concrete. Thus the efficiency of the air void system at the surface is not affected by the lower air content. Overfinishing and additions of water during finishing generally had no harmful effects on the surface air void system, but overfinishing did result in more severe deterioration in surface scaling tests. The addition of moderate amounts of water to the surface immediately after casting, and immediate finishing, did not result in significant decreases in surface durability. Combinations of premature finishing, heat and wind applications, and retarded concretes did not produce "weakened plane" scaling and had differing effects on surface tensile strength. The surface tensile strength did not correlate well with the surface scaling resistance.

These data indicate that adequately air-entrained, properly proportioned concrete may be adversely affected by some finishing procedures, but this adverse effect is not a result of harmful changes in the air void system. Thus it appears that field concrete found to have a deficient air void system was probably placed with this deficiency present.

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## CHAPTER ONE

# INTRODUCTION AND RESEARCH APPROACH

Surface deterioration due to freezing and thawing and the application of deicing agents has become prevalent on portland cement concrete highways and bridge decks within the past decade. This deterioration has occurred under a variety of conditions and in a variety of forms, the latter including scaling, spalling, crumbling, and popouts. The diversity of conditions producing deterioration and the many variables involved make the problem extremely complex, both in assessing the effects of these many variables and in determining the reasons for these effects. This com-

plexity has resulted in considerable research being done in an effort to pinpoint the important factors affecting concrete performance under adverse conditions.

The many investigations dealing with freezing and thawing of concrete and the use of deicing agents have provided much knowledge concerning the factors affecting concrete's resistance to such exposure, although the findings from different investigations have sometimes been contradictory. Agreement is general, however, on the relationship to the problem of several key factors, including air entrainment,

curing, and water-cement ratio. The beneficial effects of air entrainment have now been established beyond question, and the increase in freeze-thaw durability caused by an air drying period incorporated in the curing process is also agreed upon. Although a low water-cement ratio is not considered to have as much influence as the two variables mentioned, it is considered essential for good concrete performance. A composite description, then, of adequate concrete for use under freezing and thawing conditions would be an air-entrained, low water-cement ratio concrete, adequately cured but air dried before exposure to such conditions. Such a concrete has been shown, in laboratory experiments, to be highly resistant to deterioration, and some field concrete having these characteristics has shown very good performance. However, some concretes purportedly possessing these characteristics have deteriorated, and the need for more information concerning the factors causing this deterioration is emphasized.

Because concrete that can adequately resist deterioration due to freezing and thawing and the application of deicing agents has been produced both in the field and in the laboratory, it seemed reasonable to investigate the effects of varying concrete production methods on potentially durable concrete. This approach was based on the premise that defects such as loss in entrained air, low strength, or high porosity might be introduced into an otherwise adequate concrete by faulty construction practices. Thus an attempt was made to reproduce defects of this type in the laboratory, to evaluate the relative severity of deterioration due to these defects, and to develop means for minimizing their occurrence.

Deterioration caused by deicing agents in combination

with freezing and thawing is primarily a surface phenomenon. Therefore, most of the emphasis in this investigation was centered on the finishing procedure and defects which might be produced by variations in this procedure. The study was divided into two parts, one concentrating primarily on effects of finishing variables on the surface air void system and the other dealing with gross structural aspects of the problem, such as possible weakened plane or weakened zone formation due to adverse combinations of casting, finishing, and environmental conditions.

In the portion of the investigation primarily concerning surface air void parameters, small-scale specimens were used to reduce batch sizes and facilitate attainment of both uniform concrete and uniform casting and finishing procedures. As many external sources of variation as possible were eliminated. Testing consisted of microscopical determination of parameters related to the size and distribution of the surface void system and surface scaling tests. In the other portion of the investigation, much larger specimens were utilized so that bleeding and shrinkage characteristics would be more nearly representative of field conditions and the formation of gross weaknesses would be more likely. Of particular interest in these tests were the conditions which might produce a failure characterized by large relatively thick sections of the surface separating from the underlying concrete. This type of failure sometimes noted under field conditions indicates the possible existence of a weakened plane  $\frac{1}{8}$  to  $\frac{1}{4}$  in. below the surface. Testing consisted of surface strength determination and surface scaling tests. Results from these two portions were then evaluated together as a basis for the conclusions drawn.

## CHAPTER TWO

# FINDINGS

## GENERAL

In all of the small-scale specimens cast using a single mix design and one type of air-entraining admixture the theoretical mortar air content, based on the mix proportions and the pressure air content determination on the plastic concrete, was larger than the mortar air content determined microscopically at the surface. In two series in which the air content at the surface and at mid-depth in the concrete was determined microscopically, the results also indicated that the mortar air content at the surface is lower than the mortar air content in the interior of the concrete. However, the average spacing of voids was closer at the surface, thus the efficiency of the surface air void system was not reduced by the lower air content found there.

## OVERFINISHING

The effects of overfinishing on the surface strength of concrete as measured by a bond pull-off test (described in Appendix C under "Experimental Procedure") are given in Table C-5. Of nine specimens cast using the mix designs given in Table C-1, results from three indicated that overfinishing lowered the surface tensile strength. For the six other specimens the results were inconclusive. In three of these six the average surface strength of the overfinished concrete was lower than the strength of the normally finished concrete, but the scatter in results was such that this difference was not statistically significant; in the other three, the overfinished concrete had a slightly higher average surface strength than the normally finished concrete, but this difference also was not statistically significant. Visual observation of several sawed cross sections of the specimens

and observations of the depth of the fracture surface in the pull-off test revealed no cracking or other indications of the presence of a weakened plane.

The effects of overfinishing on the surface air void parameters are summarized in Tables B-7 and B-8 and in Figures B-20 through B-31. Increasing periods of finishing resulted in a decrease in the surface mortar air content and an increase in the specific surface. The net effect on the spacing of the voids was negligible.

The results of surface scaling tests on the specimens with varying degrees of manipulation are given in Tables B-6 and C-6, and in Figures B-17 through B-19. Of the six large-scale specimens tested, five indicated that overfinishing resulted in greater severity of deterioration, while the sixth indicated no effect at all. The small-scale specimens showed no adverse effects due to overfinishing.

### ENVIRONMENTAL CONDITIONS

The effects of applications of heat and wind during finishing on the surface strength of concrete are given in Table C-5. Of seven specimens tested, results from two indicated that heat and wind treatments increased surface tensile strength, while the results from one indicated that these treatments reduced surface strength. No statistically significant differences in strength were noted for the other four specimens. In one of these four the heat and wind treatment resulted in a higher average surface strength, while in the other three a lower average strength was pro-

duced. No visual evidence of a weakened plane was found.

Surface scaling tests on the specimens subjected to heat and wind treatments (Table C-6) showed that this treatment resulted in improved scaling resistance in five cases and had no effect for the other two.

### ADDITION OF WATER DURING FINISHING

The effects on the surface air void parameters of adding water during finishing are summarized in Tables B-7, B-9, and B-10 and in Figures B-5 through B-16. Addition of water generally resulted in a slightly increased surface mortar air content, decreased specific surface, and only slightly greater spacing between voids.

There was some indication that if concrete is finished after the bleed water has evaporated from the surface, the addition of water at this time may result in harmful changes in the air void system.

The results of surface scaling tests are given in Table B-5 and Figures B-1 through B-4. Adding enough water to the surface immediately after casting to increase the surface water-cement ratio from 6 to 8.4 gpc resulted in no statistically significant increase in severity of deterioration. However, there was a trend toward increased deterioration with increasing amounts of water added. When the concrete was finished after the bleed water had evaporated from the surface, the addition of water resulted in decreased scaling resistance.

## CHAPTER THREE

# INTERPRETATION

The findings for the concretes studied in this investigation indicate that there is a nonuniformity in the air void system in air-entrained concrete, the surface mortar having a lower air content than the mortar in the interior of the concrete. This was found in concretes which had very little surface manipulation, so that it appears to be a natural characteristic of the concrete. However, the average spacing of the voids at the surface was lower than the spacing of voids in the underlying concrete, so the efficiency of the system at the surface was not impaired. The effect of overfinishing is to decrease the surface air content even more, but the spacing of voids is unchanged due to a smaller average void size. Most of the findings on the effects of adding water also indicated negligible changes in void spacing due to the additions of water. These findings imply that the quality of the air void system which is incorporated in the concrete during mixing has more effect than the finishing techniques on the adequacy of the air void system at the concrete surface. Thus, closer control over variation in quality of the air-entraining admixtures and the adequacy and sequence of mixing should be exercised to insure that

the concrete as placed in the forms is adequately air-entrained.

The foregoing should not be construed as an endorsement of excessive finishing on concrete surfaces. Even though a basically adequate air void system is not adversely affected by excessive manipulation, the results of the large-scale tests show that severity of surface deterioration is increased by overfinishing. The need for careful inspection and supervision of finishing operations is thus as great as ever.

The findings are also not intended to encourage the sprinkling of water on the concrete surface during finishing. However, it would appear that light sprinkling of the surface soon after placing will not result in severe deterioration of an otherwise adequately protected concrete. There was some indication that concrete which is finished after the water sheen has left the surface (45 min after placing in these laboratory studies) may be adversely affected by the addition of water to the surface. Thus it appears that the time at which the water is added is important.



## CONCLUSIONS AND SUGGESTED RESEARCH

The following conclusions based on results from concretes used in this investigation should be applicable to similar concretes (i.e., 5- to 6-sack mixes with a water-cement ratio of 5 to 6 gpc using a similar air-entraining agent):

1. In air-entrained concrete, the air content of the surface paste and mortar is lower than the paste and mortar air content at the interior of the concrete. Even though the air content at the surface is less than the air content at the interior, the average spacing between air voids is not increased.

2. Overfinishing of concrete surfaces causes them to be more susceptible to deterioration due to freezing and thawing and deicing agents even though it has no adverse effect on the air void system near the surface.

3. Water added to the concrete surface during finishing but within a few minutes after casting does not result in any harmful changes in the surface air void system. Although there is a trend toward slightly increased deterioration with increasing additions of water, moderate amounts added do not result in a significant decrease in surface durability. It appears that water added later in the finishing process, after the bleed water has evaporated from the surface, will result in surface deterioration.

4. The conditions necessary to produce a weakened plane near a concrete surface are not easily reproduced in the laboratory. Early or excessive finishing, applications of heat and wind to the surface, and the use of retarded con-

crete produced very little evidence of a failure of the weakened plane type.

5. The surface tensile strength alone, as measured by the bond pull-off test, is not a reliable indicator of potential surface deterioration.

Research is still needed to determine the cause of the relatively deep ( $\frac{1}{8}$  to 2 in. thick) scaling of the "weakened plane" type that occurs in the field. Laboratory studies have produced a thinner flake-type scaling, but nothing of the magnitude mentioned. A surface in which  $\frac{1}{8}$ - to 2-in. deep cracks are present would possibly be necessary to "trigger" the cracking on a horizontal plane beneath the surface.

Further investigation of the surface air void system is also needed, particularly a study of the relationship between air void parameters and depth beneath the surface within the top 1 in. of concrete. Because the top surface has an air void system differing from that in the underlying concrete, the zone of transition might be of particular interest. Also of interest would be the characteristics of the void system at the boundary between the top mortar layer and the underlying coarse aggregate.

In addition, more information is needed concerning factors influencing the variability of the surface air void system. The effects on this variability of type of air-entraining admixture and different mixing techniques might be of interest.

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## APPENDIX A

### FACTORS AFFECTING SURFACE DETERIORATION

Many of the variables which affect the resistance of concrete to surface deterioration have been investigated and summaries of a number of these investigations are included in the annotated bibliography (Appendix D). The following is a brief summary of the more important factors affecting surface deterioration.

The most important of the factors is air-entrainment. Verbeck and Klieger (12), Grieb et al. (6), and Gonnerman (5) showed in laboratory studies that air-entrained concrete was far more resistant to surface deterioration than non-air-entrained concrete. Other studies of the performance of air-entrained concrete in the field verified these findings and most states now specify air entrainment for concrete which will be subjected to harsh weathering.

The curing procedure is also an important variable affecting surface deterioration. Klieger (7) and Verbeck and Klieger (12) found that a period of air-drying following the initial moist curing improved resistance to freezing and thawing and deicing agents, and Grieb et al. (6) found that concrete given no moist curing other than storage in a 50 percent relative humidity had better resistance to surface deterioration than concretes which were moist cured 3 to 28 days and given no air-drying prior to surface scaling tests. Klieger (7), however, stated that there is a minimum level of strength which must be attained to resist the effects of freezing and thawing. Closely related to the air-drying period is the moisture content of concrete when it is subjected to freezing and thawing. Whiteside and Sweet (13) found that concretes subjected to freezing and thawing deteriorated if the degree of saturation was greater than 0.91, but were highly durable if the degree of saturation was below 0.88. This moisture content is affected not only by the drying period but also by the water-cement ratio of the concrete, the presence of joints and cracks, and the drainage provided.

The importance of maintaining a low water-cement ratio is emphasized in many studies, both for increasing the strength and decreasing the porosity and permeability of the concrete. Grieb et al. (6) presented average relationships between water-cement ratio and the severity of scaling of air-entrained concrete and noted improved resistance with

decreased water-cement ratios. This factor, however, has not been considered to be as important as the previous two.

Finally, the use of frost-resistant aggregates is required to insure that the concrete surface will not deteriorate due to popouts, cracking, or other aggregate-caused distress.

Experience has shown that by utilizing the knowledge of the factors discussed in the foregoing, durable concrete can be produced. Yet some concrete structures deteriorate even when supposedly air-entrained concretes with low water-cement ratios, proper curing, and frost-resistant aggregates are used. It is possible that this deterioration is due to alterations in the concrete during the placing or finishing process, and that these alterations are responsible for the resulting deterioration. Studies have been made to investigate this problem and some evidence of deleterious effects has been found. Blandin and Larsen (2) found that freeze-thaw resistance of air-entrained concrete decreased with increasing periods of vibration, with a sudden loss of durability occurring when the air content was reduced below 3 percent. However, Backstrom et al. (1) found that excessive vibration of the plastic concrete did not consistently alter the resistance to deterioration of air-entrained concrete. The resistance remained essentially unchanged, except in the case of concretes with low initial air contents, in which decreased frost resistance was observed.

The effect of atmospheric conditions during placing was investigated by Klieger (8), who found that varying temperatures and wind velocities had little effect on scale resistance of air-entrained concrete. In the same study, Klieger found that non-air-entrained concrete struck off immediately after casting with no further manipulation during or after the bleeding period had greater scaling resistance than specimens given a second and final finish. Concretes subjected to finishing during the bleeding period showed low resistance to scaling. Krokosky and Daouk (9) reported that finished surfaces scaled at earlier ages and more severely than unfinished surfaces.

Ryell (11) noted an unusual case of bridge deck deterioration that occurred when a retarded concrete was placed during hot windy weather. Several days later large portions of the surface flaked off and investigation revealed that the bleeding characteristics of the mix and the placing

conditions had resulted in a concentration of bleed water and a weakened plane near the surface of the concrete. Although this particular case did not involve freezing and thawing, a combination of similar factors might lead to less severe conditions which would later result in freeze-thaw damage. Powers (10) has also proposed the possibility of a weakened zone formation due to overfinishing soon after casting.

Various finishing practices which had not been investigated include addition of water to the surface at the time of finishing, overfinishing under varying environmental conditions, and excessive surface vibration. These were chosen as possible causes of defects leading to deterioration and were investigated by considering their effects on the surface air void system, surface tensile strength, and scaling resistance in the presence of deicing agents.

## APPENDIX B

### SURFACE AIR VOID SYSTEM AND DURABILITY

#### EXPERIMENTAL PROCEDURE

##### Materials

Two brands of type 1 cement were used in this portion of the investigation. These cements are designated A and B and results of various chemical and physical tests on them are given in Tables B-1 and B-2.

The fine aggregate was a natural river sand of glacial origin from Covington, Ind. The coarse aggregate was a crushed limestone from near Kankakee, Ill. Both of these aggregates have good service records. Table B-3 gives the

results of physical tests on the fine and coarse aggregate, both designated A. All aggregates were air dried to a uniform moisture content in the laboratory environment and stored in covered containers until used. The coarse aggregate was divided into three different sieve sizes and recombined in the proportions given in Table B-3 prior to use. The fine aggregate was used in its natural gradation, which is given in Table B-3.

The air-entraining admixture used was a proprietary compound consisting of an aqueous solution of salts of sulfonated hydrocarbons containing a catalyst. Ordinary tap water was used for the mixing water.

##### Fabrication of Specimens

Essentially the same mix design was used in all series cast in this portion of the investigation, the only changes being in the initial air content and slump. The water-cement ratio was kept constant throughout, and changes in air content were accomplished by changing the amount of air-entraining admixture used. The slump was allowed to vary with these changes in air content. The basic mix design used and the properties of the concrete for each series are given in Table B-4.

Each series of specimens was prepared in essentially the

TABLE B-1  
CEMENT CHEMICAL DATA

DETERMINATION	COMPOSITION (%)		
	CEMENT A	CEMENT B	CEMENT C
Chemical:			
SiO <sub>2</sub>	20.5	20.2	21.2
Al <sub>2</sub> O <sub>3</sub>	5.7	5.7	5.6
Fe <sub>2</sub> O <sub>3</sub>	3.0	2.1	2.4
CaO	62.8	63.7	65.6
MgO	2.6	2.8	1.0
SO <sub>3</sub>	—	2.6	2.3
Loss	1.5	2.2	1.8
Free CaO	0.5	—	0.8
Insol. res.	0.1	—	0.3
Compound:			
C <sub>3</sub> S	50.0	56.9	57.6
C <sub>2</sub> S	21.1	15.0	17.5
C <sub>4</sub> A	10.0	11.7	10.4
C <sub>4</sub> AF	—	6.3	7.2
CaSO <sub>4</sub>	—	4.4	3.8
Na <sub>2</sub> O	—	0.19	0.04
K <sub>2</sub> O	0.6	0.34	0.44
Total alk.	—	0.53	0.33

TABLE B-2  
CEMENT PHYSICAL DATA

DETERMINATION	CEMENT A	CEMENT B	CEMENT C
Specific gravity	3.15	3.11	3.12
Normal consistency (%)	24.0	26.0	26.6
Time of setting, Vicat:			
Initial	2 hr 24 min	3 hr 20 min	3 hr 20 min
Final	6 hr 30 min	4 hr 35 min	5 hr 5 min
Specific surface, Blaine (sq cm/gm)	3470	3700	3360



TABLE B-3  
DATA ON AGGREGATE

AGGREGATE		RETAINED ON SIEVE (%)										FINENESS MODULUS	BULK SP. GR. <sup>a</sup>	ABSORP., 24-HR (% WT)
TYPE	DESIG.	1- IN.	¾- IN.	½- IN.	¾- IN.	NO. 4	NO. 8	NO. 16	NO. 30	NO. 50	NO. 100			
Fine	A	—	—	—	—	3.8	15.0	30.9	51.3	81.7	97.1	2.80	2.60	2.00
	B	—	—	—	—	3.8	10.3	32.4	57.0	84.2	96.7	2.84	2.65	1.92
	C	—	—	—	—	2.2	15.7	34.8	55.5	86.3	97.8	2.92	2.65	1.48
Coarse	A	0	25	—	70	100	—	—	—	—	—	—	2.66	1.70
	B	6	37	71	86	99	—	—	—	—	—	—	2.69	2.30

<sup>a</sup> Saturated, surface dry.

same manner, as described in the following. Any variations from this standard procedure in a particular series are noted in the description of each series.

Concrete for each series was mixed in one batch of 2 cu ft. Dry materials were mixed for 1 min in a horizontal tub-type mixer with a rated capacity of 2.5 cu ft, after which the water with air-entraining admixture incorporated in it was added. The concrete was mixed for an additional 3 min, and a slump test and air content determination by the pressure method were performed immediately. Four 5- by 10-in. compression cylinders and a control specimen for use in the freeze-thaw cabinet were cast, along with 18 surface scaling test specimens.

The surface scaling test specimens were cast in plastic boxes and had nominal 3-in. depth and 6- by 8-in. surface. Each box was filled with 9.5 lb concrete and placed on a vibrating table for 5 to 7 sec. After vibration the concrete surface was approximately ¼ in. below the edge of the box. Thus the surface mortar, which was of most interest, could not be screeded off during the finishing operation, and also a dike was provided for retaining the salt solution used in freezing-and-thawing tests.

Three treatments, with six replications of each treatment, were used in most series. These treatments were assigned to the 18 specimens in a random manner. After the surfaces had been given a surface treatment (the various treatments are described in a subsequent section) and final finishing was completed, covers were placed on the plastic boxes, with care being taken to avoid disturbing the surface. The specimens were left overnight at room temperature and at an age of approximately 20 hr were placed in a controlled temperature room at 70 F. The lids were removed and then replaced after 200 ml of water had been ponded on the surface. (Series E and F were submerged in a tank containing saturated limewater for 14 days, air dried for 11 days at 70 F and 50 percent relative humidity, and placed back in the tank three days prior to start of testing.)

The specimens were moist cured in this manner for 14 days, after which the water was poured off and the specimen surfaces were exposed to a 70 F and 50 percent relative humidity environment for 11 days. Then 200 ml of water were ponded on the surface for three more days immediately prior to testing.

After the 28-day curing period, one specimen from each treatment was chosen for microscopic determination of

surface air void parameters, and the others were used for surface scaling tests.

In some series only 16 specimens were cast, and microscopical air void determinations were conducted on all specimens. No surface scaling tests were run on these series.

#### *Microscopical Determination of Surface Air Void Parameters*

In the series in which both surface scaling tests and microscopical air void determinations were made, one specimen was chosen from each treatment. Four 3- by 3- by 3-in. cubes (this size was dictated by the size of the polishing equipment available) were sawed from this specimen, and a ¼-in. slice of the finished surface of each cube was taken. The finished surface of each slice was then polished on a horizontal lapping wheel until a surface suitable for microscopical observation was obtained. Lapping time was held to a minimum so as to remove as little of the surface

TABLE B-4  
MIX DESIGN AND CONCRETE PROPERTIES

Mix, by weight\*: 1:2.6:3.4  
Net water-cement ratio: 6.0 gps  
Cement factor: 5.5 sacks/cu yd

SERIES	CEMENT	SLUMP (IN.)	AIR CONTENT (%)	AVG. 28-DAY COMPRESSIVE STRENGTH (PSI)
E	A	2.50	3.8	5470
F	A	3.00	3.6	5770
H	A	3.25	4.8	5500
J	A	3.50	4.8	5900
K	A	3.50	5.0	5900
L	A	3.75	4.9	—
M	B	3.50	6.0	5300
N	B	2.00	3.7	5260
O	B	2.75	3.8	4820
P	B	2.75	3.9	5070
Q	B	3.00	5.6	4460
R	B	3.00	4.6	4800
S	B	3.50	4.6	5120

\* Saturated, surface dry, basis.

material as possible. Micrometer measurements of slice thickness before and after lapping were made on several series to estimate the average depth of material removed. Approximately 1/16 in. of material was removed from most of these slices before a satisfactory surface was obtained.

In the series in which no surface scaling tests were run, air void determinations were conducted on all 16 specimens. Two 3- by 3- by 1/4-in. slices were cut from each of the 16 specimens and polished as previously described. Micrometer measurements of depth of material removed were made on all of these slices.

Air void parameters of the prepared slices were determined microscopically by the modified point count method in accordance with ASTM C457-60T. The procedure was modified by including stops on paste with the other information recorded, thus permitting a calculation of paste content at the surface of the concrete.

Each slice from a particular specimen was traversed individually, but all of the traverses were combined in one calculation of the air void parameters for the specimen.

### *Surface Scaling Tests*

The freeze-thaw apparatus was a commercially manufactured automatic freeze-thaw cabinet modified for use with slabs. It consisted essentially of a freezing plate in an insulated cabinet, above which was mounted a row of 15 500-w heating elements. A fan within the cabinet circulated air to maintain a nearly uniform temperature distribution. A control specimen cast with each series and of the same size as the test specimens had a thermostat and recording thermometer bulb imbedded in it at a depth of 3/4 in. During cycling, the interior temperature of the control specimen ranged from  $40 \pm 5$  F to  $0 \pm 5$  F.

The testing procedure consisted of placing 200 ml of a 6 percent sodium chloride solution on the surface of each of the 15 specimens from a particular series and then placing them on the freezing plate in the cabinet, where the surfaces went through one freeze-thaw cycle approximately every 4 1/2 hr. Periodically, the specimens were removed from the cabinet during the thaw cycle, rinsed with tap water, photographed, and rated as to severity of surface deterioration. The rating method and criterion used are discussed in a subsequent section.

After rating, the specimens were put back into the cabinet and the sodium chloride solution was replaced. The position of each specimen in the cabinet was changed after each rating session so as to minimize any effects due to possible temperature differentials within the cabinet.

The total time required for removing the specimens from the cabinet, rating, and replacing them was approximately 30 min.

### *Treatments*

#### **SERIES E, H, K, M**

The treatment for Series E, H, K, and M consisted of adding 0, 5, or 10 ml of water to the concrete surface immediately after casting, these additions corresponding to

0, 1.2, and 2.4 gps (gal per sack) increases in surface mortar water-cement ratio. Surfaces of all specimens were worked with a steel screed for 40 sec, thoroughly mixing the water into the surface, and a steel trowel finish was applied.

Series E and H were tested using the surface scaling test procedure. In Series K, periodic "rest periods" were incorporated in the freeze-thaw procedure. Specimens were frozen and thawed for 15 cycles, after which they were rinsed with tap water, photographed, given surface ratings, and then air dried for three days at 70 F and 50 percent relative humidity. Following this the sodium chloride solution was replaced and 15 more freeze-thaw cycles were applied. This process of alternately freezing and thawing and air drying was repeated until the testing was completed.

In Series M, the freeze-thaw procedure was modified by placing the specimens on wires above the freezing plate, allowing the air to circulate under the specimens and increasing the time required for a freeze-thaw cycle to approximately 6 hr, the extra time being taken by the freeze cycle.

#### **SERIES P**

In Series P the specimen surfaces were lightly screeded immediately after casting, and then the specimens were allowed to stand in the laboratory environment (70 F and 20 percent relative humidity) for 45 min. until the water sheen had left the surface. The treatment then consisted of adding 0, 10, or 15 ml of water (increasing surface mortar water-cement ratio by 0, 2.4 and 3.6 gps respectively) and working each surface with a steel screed for 40 sec. All specimens were then given a steel trowel finish.

#### **SERIES R, S**

The surfaces of all specimens in Series R and S were used for determination of air void parameters, and no surface scaling tests were run. Treatments were similar to those described previously, except that 16 specimens were cast and given four treatments with four replications of each treatment. Series R treatments consisted of 0, 5, 10, or 15 ml of water worked into the surface immediately after casting. Calculated increases in surface mortar water-cement ratio were 0, 1.2, 2.4, and 3.6 gps, respectively. Series S treatments consisted of 0, 5, 10 or 20 ml of water worked into the surface 45 min after casting, resulting in calculated increases of 0, 1.2, 2.4, and 4.8 gps in the surface mortar water-cement ratio.

#### **SERIES F, J, L**

The treatments for Series F, J, L consisted of 10, 40, or 120 sec of hand manipulation of the surface immediately after casting, using a steel screed. These treatments were intended to simulate the hand floating done in the field. A steel trowel finish was given all specimens following the manipulation.

Series F and J were subjected to surface scaling tests using the procedure previously described under "Surface Scaling Tests." The Series L surface scaling test procedure was that in which the specimens were placed on wires above

the freezing plate, allowing air to circulate under the specimens (see description of Series M treatments.)

#### SERIES O

Sixteen specimens were cast for the Series O tests, and the surfaces of all specimens were used for determination of air void parameters. Both the amount of finishing and the time at which this finishing was done were varied, each of the 16 specimens representing a different combination of these two variables. The finishing treatments consisted of 10, 40, 100, or 180 sec of manipulation applied immediately or 15, 30, or 60 min after casting.

#### SERIES N, Q

Treatments for Series N consisted of 10, 30, or 60 sec of surface vibration (corresponding to 1, 3, or 6 passes with a surface vibrator having a vibration frequency of 3,600 cps at an amplitude of 0.08 in.) and a steel trowel finish. In Series Q, one treatment consisted of applying a steel trowel finish with no mechanical vibration, while the other two treatments consisted of 30 or 60 sec of vibration followed by a steel trowel finish.

#### *Methods of Analysis*

Specimens were rated at periodic intervals during freeze-thaw cycling, using a visual evaluation and the following numerical scale rating: 0, no deterioration; 1, scattered spots of very light deterioration; 2, scattered spots of light deterioration; 3, light deterioration over about one-half the surface; 4 light deterioration over most of the surface; 5, light deterioration over most of the surface, a few moderately deep spots; 6 scattered spots of moderately deep deterioration; 7, moderately deep deterioration over about one-half the surface; 8, moderately deep deterioration over the entire surface; 9, scattered spots of deep deterioration, otherwise moderate deterioration; 10, deep deterioration over the entire surface.

Photographs were also taken after each rating. At the end of the experimental program these photographs and the day-to-day ratings were used to assign the surface rating used in the analysis. This procedure reduced any variations in rating standards which might have occurred between different series.

The resulting data were evaluated by two different methods. At every cycle for which ratings were available, the mean surface ratings for the specimens from each treatment in a series were compared using an analysis of variance. A 5 percent level of significance was chosen for use in this analysis. If significant differences between treatments were noted, the time at which they became significant could be ascertained.

The comparison of surface deterioration ratings after any particular cycle does not indicate the rate at which the deterioration occurred. In order to take deterioration rate into account, the cumulative area under the curve for surface rating versus number of cycles for each specimen was computed. The area under the curve at any particular cycle (hereafter referred to as the cumulative area) is a reflection of the total performance of the specimen up to

that cycle, giving a measure of the rate of deterioration. At every cycle for which ratings were available, the cumulative area for each specimen was computed and the mean cumulative areas for each treatment were compared using an analysis of variance and a 5 percent level of significance.

The use of the analysis of variance technique might be questioned because of the subjective nature of the data and the opportunity for bias to influence the result. These possibilities were recognized early in the research program, but the analysis is still thought to be justified as an aid to interpreting the data. The spread of results within some treatments was such that comparisons of averages without taking this scatter into account could be misleading, and thus the analysis was included.

## EXPERIMENTAL RESULTS

### *Effects of Adding Water to Concrete Surface During Finishing*

#### SURFACE SCALING TESTS

The results of surface scaling tests on Series E, H, K, M, and P are given in Table B-5 and shown graphically in Figures B-1 through B-4. These results are summarized in the following.

Series E and H specimens were subjected to additions of water increasing the surface mortar water-cement ratio by 0, 1.2, and 2.4 gps, these treatments being applied immediately after casting. Results of the surface scaling tests are shown in Figure B-1. The average surface rating plotted on the ordinate is the average rating for the five specimens from each treatment. Although the specimens with the most water added exhibited the most deterioration, the difference between treatments was small, and the analysis of variance of the surface ratings showed no statistically significant differences between treatments after any cycle. The analysis of variance of the cumulative areas under the curve of surface rating versus cycle after each rating session also failed to show any statistically significant differences between treatments.

Increments of water increasing the surface mortar water-cement ratio by 0, 1.2, and 2.4 gps were added immediately after casting in Series K, and the modified surface scaling test procedure which incorporated "rest periods" was used. The plot of average surface rating versus cycle (Fig. B-2) shows only light surface deterioration of all specimens after 155 cycles and very little difference between treatments. The analysis of variance on both surface rating and cumulative area at each rating cycle indicated no significant differences between treatments.

In Series M the 0-, 1.2-, and 2.4-gps increases added immediately after casting were used again, but in the surface scaling tests the specimens were placed on wires above the freezing plate, allowing air to circulate under them. No significant differences between treatments were noted at any time during the cycling; Figure B-3 shows the slight differences that did appear.

Water increasing the surface mortar water-cement ratio by 0, 2.4, and 3.6 gps was added 45 min after casting in Series P. The specimens with water added had higher average surface ratings than the specimens with no water



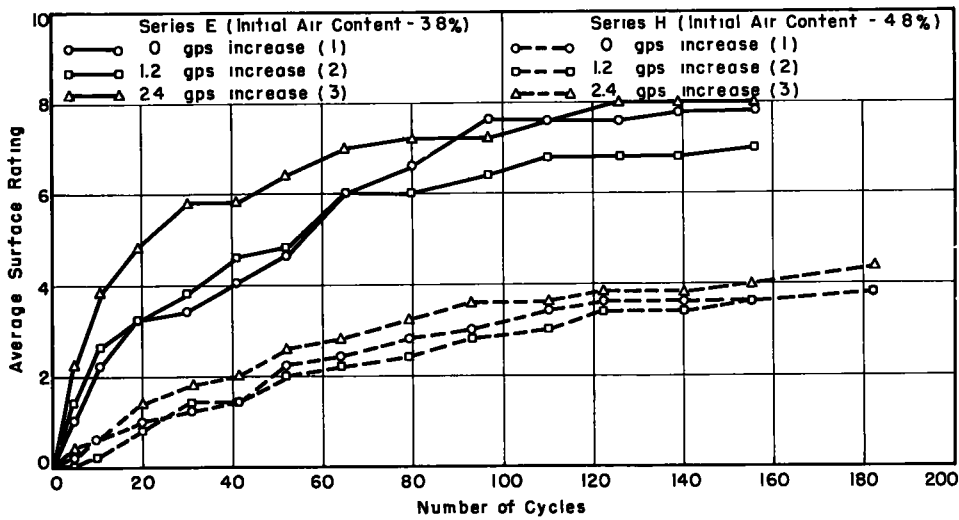


Figure B-1. Effect of additions of water on surface deterioration, Series E and H.

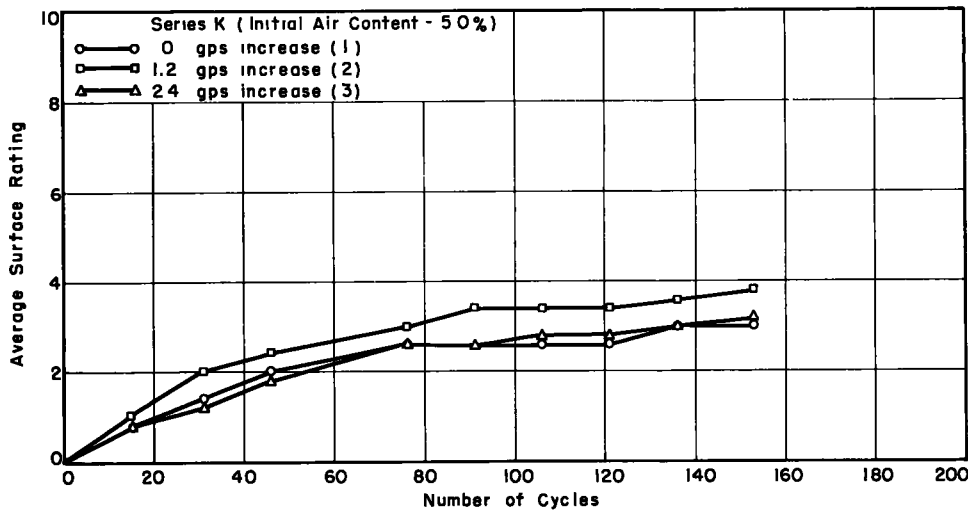


Figure B-2. Effect of additions of water on surface deterioration, Series K.

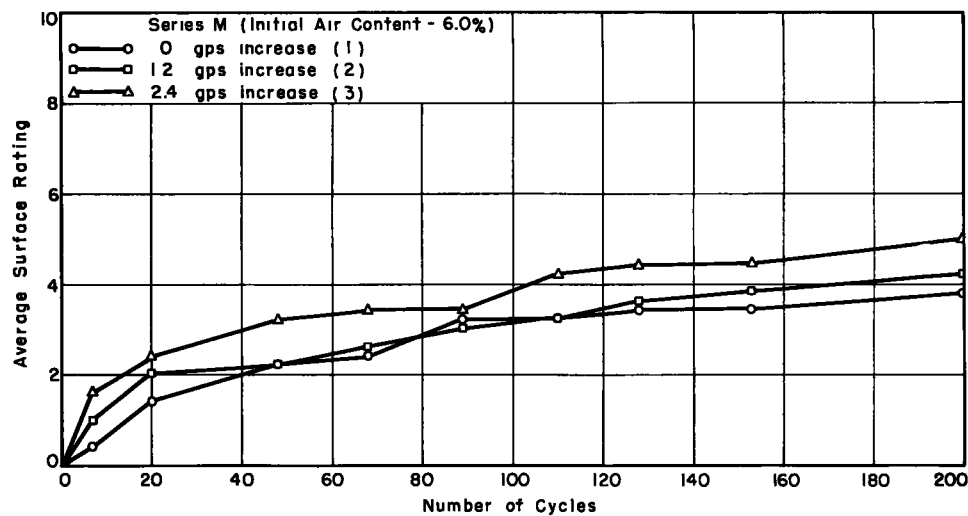


Figure B-3. Effect of additions of water on surface deterioration, Series M.

TABLE B-5  
RESULTS OF SURFACE SCALING TESTS FOR CONCRETES WITH WATER ADDED DURING FINISHING

SERIES	INCREASE IN W/c RATIO (GPS)	AVERAGE SURFACE RATING <sup>a</sup> AT									
		5 CYCLES	10 CYCLES	15 CYCLES	30 CYCLES	50 CYCLES	80 CYCLES	110 CYCLES	140 CYCLES	170 CYCLES	200 CYCLES
E	0	1.0	2.2	2.7	3.4	4.6	6.6	7.6	7.8	—	—
	1.2	1.4	2.6	2.9	3.8	4.8	6.0	6.8	6.8	—	—
	2.4	2.2	3.8	4.3	5.8	6.4	7.2	7.6	8.0	—	—
H	0	0.2	0.6	0.8	1.2	2.2	2.8	3.4	3.6	3.7	—
	1.2	0.0	0.2	0.5	1.4	2.0	2.4	3.0	3.4	3.7	—
	2.4	0.4	0.6	1.0	1.8	2.6	3.2	3.6	3.8	4.2	—
K	0	—	—	0.8	1.4	2.1	2.6	2.6	3.0	—	—
	1.2	—	—	1.0	2.0	2.5	3.1	3.4	3.6	—	—
	2.4	—	—	0.8	1.2	1.9	2.6	2.7	3.1	—	—
M	0	0.3	0.6	1.0	1.7	2.2	2.8	3.2	3.4	3.5	3.8
	1.2	0.7	1.2	1.6	2.1	2.2	2.8	3.2	3.7	4.0	4.2
	2.4	1.1	1.8	2.1	2.7	3.2	3.4	4.2	4.4	4.6	5.0
P	0	0.2	0.7	1.2	1.5	1.8	2.2	3.0	3.2	3.4	4.0
	2.4	0.2	1.0	1.8	2.4	3.2	3.4	4.0	4.3	5.4	6.0
	3.6	0.8	1.8	2.6	3.5	4.2	5.2	6.4	7.0	8.2	8.6

<sup>a</sup> Because different series were sometimes rated at different numbers of cycles, the values given are in some cases interpolated for ease of presentation (see Figs. B-1, B-2, B-3, and B-4).

added (Fig. B-4). Statistically significant differences between the surface ratings of specimens with 0 to 2.4 gps and 0 and 3.6 gps were noted after 79 cycles of freezing

and thawing. The difference for these same comparisons using the cumulative areas became significant after 143 cycles of freezing and thawing.

TABLE B-6  
RESULTS OF SURFACE SCALING TESTS ON CONCRETES WITH VARYING DEGREES OF SURFACE MANIPULATION

SERIES	PERIOD OF MANIPU- LATION (SEC)	AVERAGE SURFACE RATING <sup>a</sup> AT									
		5 CYCLES	10 CYCLES	15 CYCLES	30 CYCLES	50 CYCLES	80 CYCLES	110 CYCLES	140 CYCLES	170 CYCLES	200 CYCLES
(a) HAND MANIPULATION											
F	10	0.4	1.4	2.1	3.6	6.0	6.6	7.8	8.0	—	—
	40	0.4	1.6	2.2	3.0	4.8	5.6	6.4	7.2	—	—
	120	1.0	1.6	2.0	3.0	4.6	5.0	5.8	6.6	—	—
J	10	0.0	0.2	0.5	1.1	2.0	2.0	2.2	2.5	2.7	—
	40	0.4	0.8	1.1	1.5	2.2	2.4	2.6	2.9	3.2	—
	120	0.2	0.4	0.8	1.2	1.6	1.6	1.8	2.4	2.6	—
L	10	0.2	0.5	0.8	1.3	2.0	2.6	3.0	3.9	—	—
	40	0.0	0.4	0.7	1.6	2.0	3.1	3.4	3.9	—	—
	120	0.0	0.4	0.7	1.4	1.8	2.9	3.4	3.5	—	—
(b) SURFACE VIBRATION											
N	10	0.0	2.4	4.2	—	—	—	—	—	—	—
	30	0.0	2.0	3.4	—	—	—	—	—	—	—
	60	0.0	3.5	6.2	—	—	—	—	—	—	—
Q	10	0.4	0.7	1.0	2.0	2.5	3.1	3.9	4.0	4.2	4.2
	30	0.0	0.2	0.4	0.8	0.9	1.6	2.0	2.2	2.2	2.4
	60	0.0	0.1	0.2	0.7	1.1	1.6	1.8	2.0	2.0	2.0

<sup>a</sup> Because different series were sometimes rated at different numbers of cycles, the values given are in some cases interpolated for ease of presentation (see Figs. B-17, B-18 and B-19).

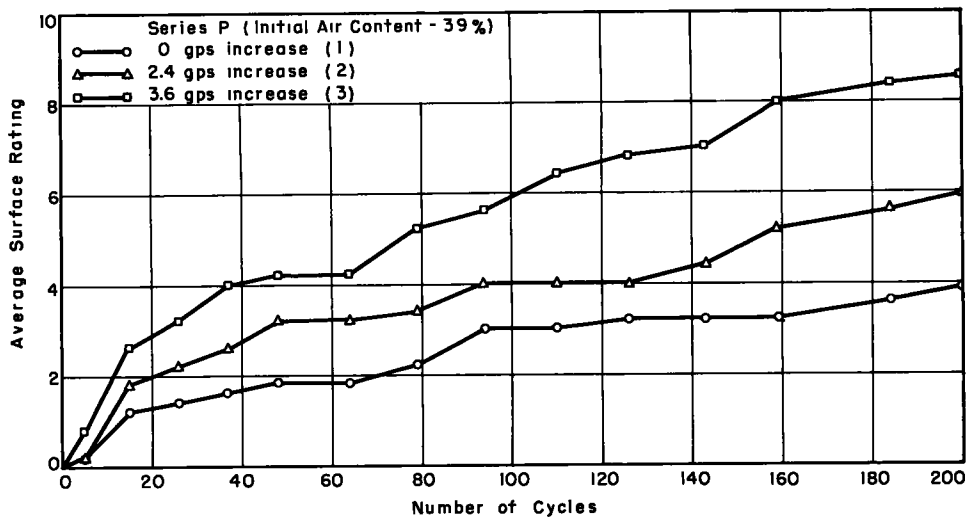


Figure B-4. Effect of additions of water on surface deterioration, Series P.

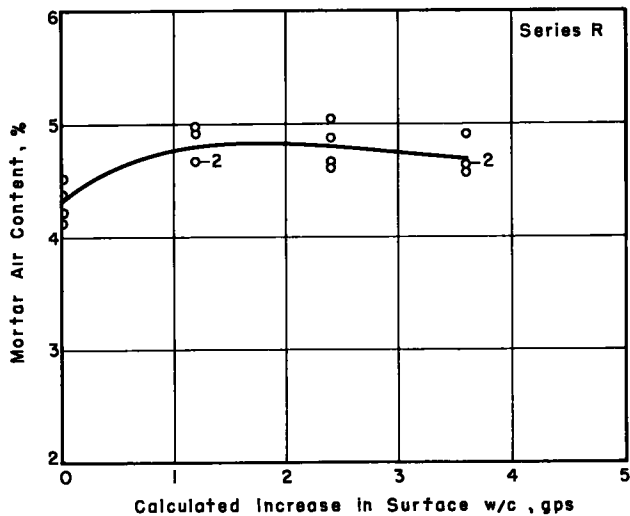


Figure B-5. Mortar air content vs increase in surface w/c, Series R.

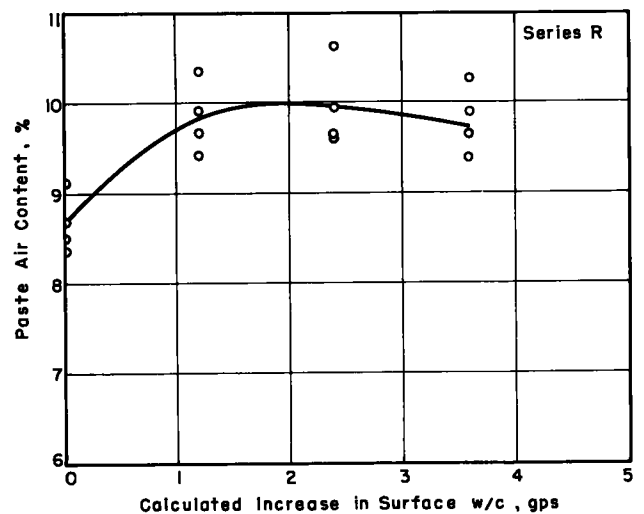


Figure B-6. Paste air content vs increase in surface w/c, Series R.

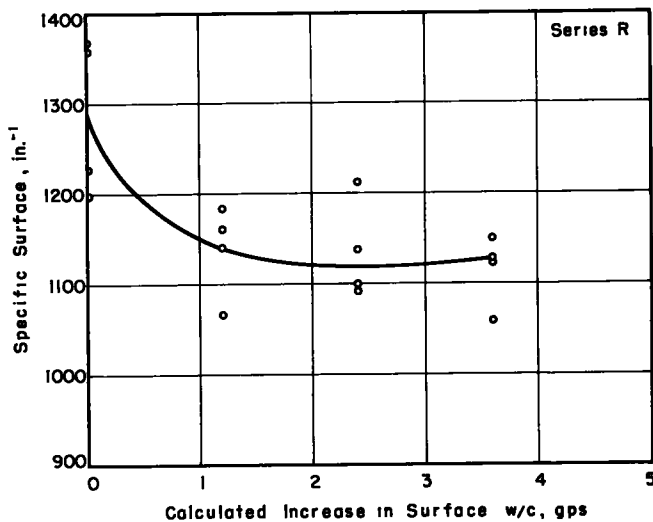


Figure B-7. Specific surface vs increase in surface w/c, Series R.

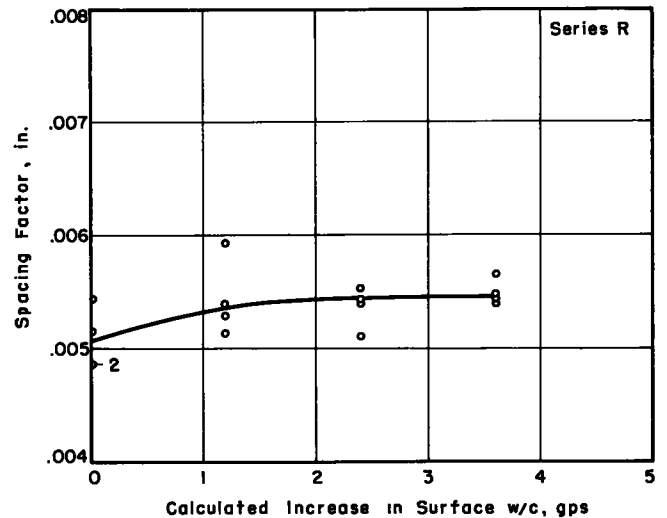


Figure B-8. Spacing factor vs increase in surface w/c, Series R.

# MICROSCOPICAL DETERMINATION OF SURFACE AIR VOID PARAMETERS

Effects on surface air void parameters and paste contents of varying amounts of water added immediately after casting are shown in Figures B-5 through B-8 for the Series R data. All comparisons of treatments' means were made using a *t*-test, and the results of those comparisons for each parameter are given in Table B-9. Also, Figures B-13 through B-16 show the trends found in data from Series E, H, K, and M, in which one specimen from each treatment within a series was examined. Summarized in the following are the effects of the changes in surface water-cement ratio on the air void parameters.

As seen in Figures B-5 and B-6 for Series R, both mortar and paste air content increased when water was added, but the increase was not proportional to the amount of water added. All of the specimens to which water had been added exhibited about the same increase in air content. Statistically significant differences were noted between treatment 1 (no water added) and each of the other three treatments (varying amounts of water added), but there were no other significant differences (Table B-11). Series E, H, K, and M (Figs. B-13 and B-14) generally showed increases in both mortar and paste air content with additions of water, although Series K and M both indicated a peak, beyond which the air content started to decrease.

Increases in the surface mortar water-cement ratio in Series R resulted in a decreased specific surface (Fig. B-7), although the decrease was not proportional to the amount of water added. As before, there was a statistically significant difference between the specimens with no water added and all of the specimens to which water had been added (Table B-11) but the amount of water was not critical. Series E, H, K, and M (Fig. B-15) showed the same trend toward a decrease in specific surface with an increase in surface water-cement ratio.

As shown in Figure B-8, the net result of the changes in air content and specific surface in Series R was a slight increase in spacing factor when water was added to the surface, but this increase was not statistically significant. The Series E, H, K, and M data (Fig. B-16) confirm this trend of only slight increases in spacing factor.

In Series S and P water was added to the surface 45 min after casting. The effects of this procedure on the surface air void parameters of Series S are shown graphically in Figs. B-9 through B-12 and the statistical comparison of treatments is given in Table B-11. Results from Series P, in which only one specimen from each treatment was examined, are shown in Figures B-13 through B-16.

In Series S (Figs. B-9 and B-10) the mortar and paste air contents exhibited no statistically significant changes (Table B-11) when varying amounts of water were added.

TABLE B-7  
SURFACE AIR VOID PARAMETERS FOR SURFACE SCALING TEST SERIES

SERIES	TREATMENT	LENGTH OF TRAVERSE (IN.)	NO. OF STOPS	AIR CONTENT (%)		SPECIFIC SURFACE (IN. <sup>-1</sup> )	SPACING FACTOR (IN.)	PASTE CONTENT (%)
				MORTAR	PASTE			
E	1	295	6051	3.47	7.56	1101	0.0063	42.4
	2	298	6117	3.81	8.06	1093	0.0061	43.5
	3	298	6120	4.11	9.05	1011	0.0063	41.3
F	1	298	6110	4.64	10.00	1049	0.0058	41.7
	2	301	6165	4.24	8.46	1120	0.0059	45.8
	3	301	6166	3.78	7.70	1278	0.0054	45.3
H	1	299	6141	4.51	9.63	1192	0.0052	42.3
	2	299	6139	4.51	9.79	1204	0.0051	41.6
	3	300	6152	4.57	9.71	1194	0.0052	42.5
J	1	299	6143	4.25	8.84	1311	0.0049	43.8
	2	297	6083	4.47	9.21	1270	0.0050	44.1
	3	299	6138	4.17	8.45	1446	0.0046	45.2
K	1	296	6070	4.46	9.04	1395	0.0046	44.9
	2	294	6038	4.84	9.79	1239	0.0049	44.6
	3	294	6038	4.70	9.64	1250	0.0049	44.1
L	1	298	6110	4.46	9.34	1346	0.0047	43.4
	2	297	6101	4.44	9.16	1322	0.0048	44.1
	3	298	6106	4.57	9.14	1365	0.0046	45.4
M	1	198	4076	5.00	10.40	1351	0.0044	43.1
	2	198	4062	5.49	11.79	1183	0.0047	41.1
	3	202	4145	4.85	10.57	1201	0.0049	41.0
N	1	150	3078	3.28	7.00	1180	0.0061	43.6
	2	199	4083	3.18	6.66	1133	0.0065	44.6
	3	199	4088	3.01	6.40	1198	0.0063	44.0
P	1	295	6059	3.15	7.14	1231	0.0058	41.0
	2	297	6081	3.34	7.52	1026	0.0068	41.1
	3	297	6093	3.22	7.27	966	0.0073	41.0
Q	1	299	6132	5.07	11.26	1194	0.0048	40.0
	2	296	6081	4.59	9.46	1329	0.0047	43.9
	3	299	6129	4.44	9.10	1361	0.0047	44.3



TABLE B-8

## SURFACE AIR VOID PARAMETERS OF SERIES O

FINISHING		LENGTH OF TRAVERSE (IN.)	NUMBER OF STOPS	AIR CONTENT (%)		SPECIFIC SURFACE (IN. <sup>-1</sup> )	SPACING FACTOR (IN.)	PASTE CONTENT (%)
PERIOD (SEC)	TIME (MIN)			MORTAR	PASTE			
10	0	149	3050	3.97	8.99	1036	0.0062	40.2
	15	151	3093	3.62	8.28	1039	0.0064	40.1
	30	147	3018	3.61	8.35	1090	0.0061	39.6
40	60	149	3048	3.41	7.69	1180	0.0061	40.9
	0	148	3032	3.66	8.01	1180	0.0057	41.6
	15	148	3032	2.90	6.66	1361	0.0054	40.7
	30	150	3085	2.95	6.57	1351	0.0055	42.0
100	60	148	3038	3.16	7.08	1238	0.0058	41.5
	0	148	3037	3.10	6.69	1282	0.0057	43.2
	15	148	3044	3.35	7.47	1235	0.0056	41.5
	30	149	3057	3.21	6.89	1246	0.0058	43.3
180	60	148	3042	2.43	5.30	1361	0.0060	43.4
	0	149	3067	3.23	7.25	1198	0.0059	41.3
	15	149	3053	2.69	5.68	1258	0.0063	44.6
	30	147	3025	2.91	6.35	1282	0.0059	42.9
	60	147	3014	2.06	4.62	1509	0.0058	42.5

TABLE B-9

## SURFACE AIR VOID PARAMETERS OF SERIES R

INCREASE IN W/C RATIO (GPS)	LENGTH OF TRAVERSE (IN.)	NUMBER OF STOPS	AIR CONTENT (%)		SPECIFIC SURFACE (IN. <sup>-1</sup> )	SPACING FACTOR (IN.)	PASTE CONTENT (%)
			MORTAR	PASTE			
0	150	3074	4.49	9.11	1225	0.0052	44.8
	149	3056	4.12	8.35	1365	0.0049	45.3
	147	3028	4.36	8.68	1196	0.0054	45.8
	149	3061	4.21	8.53	1356	0.0049	45.2
1.2	73	1503	4.92	9.92	1061	0.0059	44.7
	147	3023	4.66	9.41	1183	0.0053	44.9
	148	3044	4.96	10.34	1160	0.0051	43.0
	147	3026	4.66	9.66	1140	0.0054	43.6
2.4	149	3053	5.04	10.62	1091	0.0054	42.5
	150	3080	4.87	9.94	1100	0.0055	44.1
	150	3091	4.63	9.60	1212	0.0051	43.5
	149	3037	4.61	9.63	1138	0.0054	43.3
3.6	149	3066	4.57	9.38	1149	0.0054	44.1
	150	3089	4.63	9.64	1126	0.0055	43.4
	151	3091	4.63	9.88	1124	0.0054	42.2
	147	3020	4.90	10.26	1058	0.0057	42.9

TABLE B-10

## SURFACE AIR VOID PARAMETERS OF SERIES S

INCREASE IN W/C RATIO (GPS)	LENGTH OF TRAVERSE (IN.)	NUMBER OF STOPS	AIR CONTENT (%)		SPECIFIC SURFACE (IN. <sup>-1</sup> )	SPACING FACTOR (IN.)	PASTE CONTENT (%)
			MORTAR	PASTE			
0	147	3018	3.71	7.71	1254	0.0055	44.4
	148	3049	3.51	7.17	1418	0.0050	45.4
	150	3087	3.98	8.46	1198	0.0055	43.1
	146	3007	3.36	6.91	1515	0.0048	45.3
1.2	150	3090	3.79	7.96	1224	0.0055	44.1
	150	3073	3.84	8.19	1216	0.0055	43.0
	151	3099	3.71	7.54	1278	0.0054	45.5
	148	3045	3.84	7.69	1238	0.0056	46.1
2.4	147	3026	4.00	8.05	1160	0.0058	45.7
	149	3070	4.10	8.77	1102	0.0058	42.7
	148	3037	3.82	7.80	1201	0.0057	45.1
	148	3031	3.73	7.99	1183	0.0057	42.9
4.8	150	3085	3.11	6.73	1356	0.0054	43.1
	150	3075	3.61	7.45	1208	0.0058	44.8
	150	3073	3.68	8.24	1090	0.0061	41.0
	149	3067	3.68	7.50	1227	0.0057	45.4

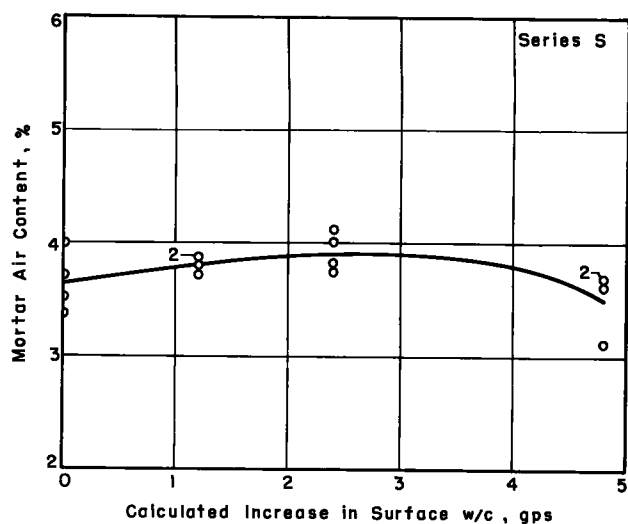


Figure B-9. Mortar air content vs increase in surface w/c, Series S.

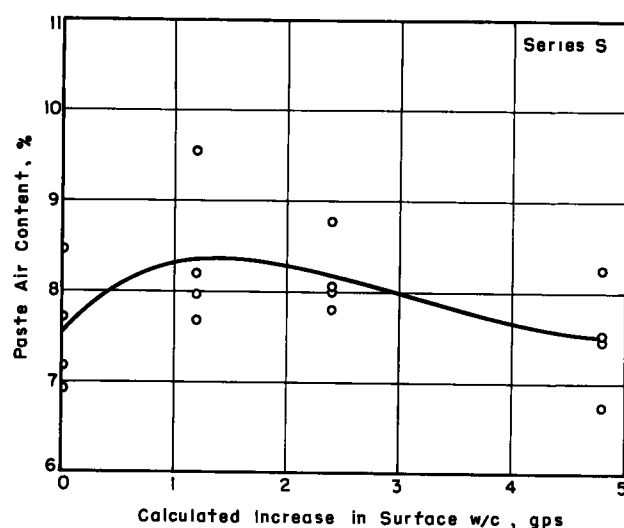


Figure B-10. Paste air content vs increase in surface w/c, Series S.

The Series P data (Figs. B-13 and B-14) were in agreement with this finding as they showed only slight changes in both of these parameters when water was added.

Specific surface in Series S specimens (Fig. B-11) decreased when water was added, and except for the specimens in which the surface water-cement ratio was increased by 4.8 gpc, the decrease was proportional to the amount of water added. The scatter between specimens of a given treatment was greater in this series than in the others, and

as shown in Table B-11, the decreases were not statistically significant. The specimens from Series P (Fig. 15) showed a much more marked effect of adding water. An increase of 2.4 gpc at the surface resulted in a 19 percent decrease in specific surface and a 3.6-gpc increase decreased the specific surface by 24 percent.

In Series S the spacing factor increased with the addition of water to the surface, as seen in Fig. B-12. The differences between treatment 1 (no water added) and both treatment 3 (2.4-gpc increase) and treatment 4 (4.8-gpc increase) were statistically significant (Table B-11), but the magnitude of these changes was small. Increases in water-cement ratio of 2.4 and 4.8 gpc both produced an 11 percent in-

TABLE B-11

SUMMARY OF STATISTICAL ANALYSIS OF SURFACE AIR VOID PARAMETERS

PARAMETER	TREATMENT COMPARISON <sup>a</sup>					
	1-2	1-3	1-4	2-3	2-4	3-4
(a) SERIES O						
Mortar air content	X	X	X			
Paste air content	X	X	X			
Specific surface	X	X	X			
Spacing factor	X	X	X	X		
(b) SERIES R						
Mortar air content	X	X	X			
Paste air content	X	X	X			
Specific surface	X	X	X			
Spacing factor						
(c) SERIES S						
Mortar air content						
Paste air content						
Specific surface						
Spacing factor		X	X			

<sup>a</sup> Significant difference between treatment means at 95 percent probability level, indicated by X under appropriate comparison.

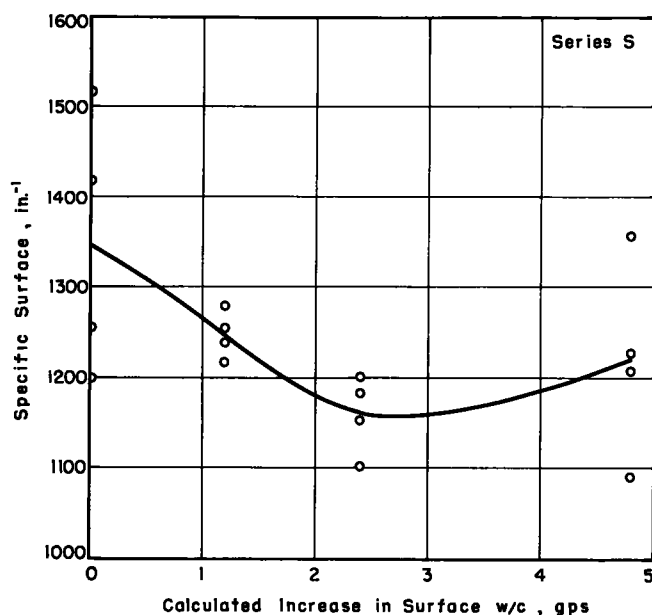


Figure B-11. Specific surface vs increase in surface w/c, Series S.

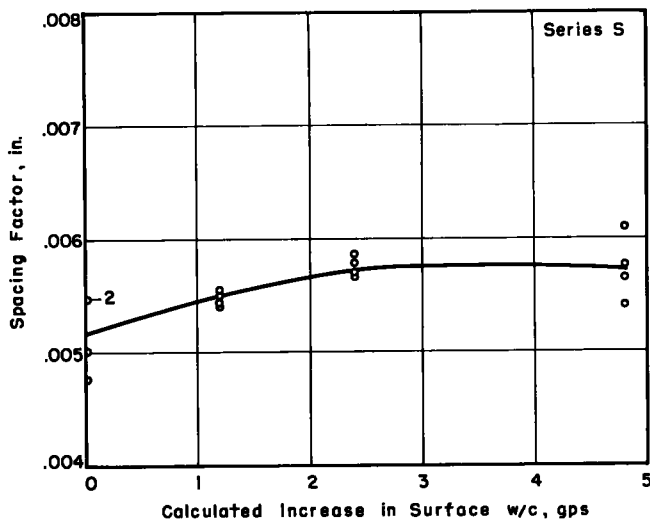


Figure B-12. Spacing factor vs increase in surface w/c, Series S.

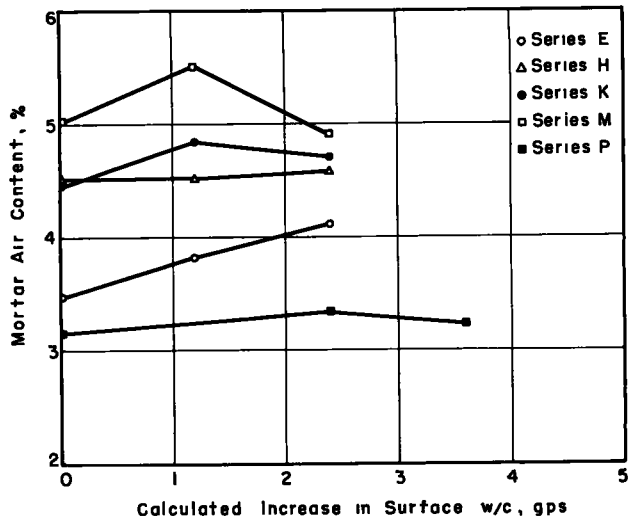


Figure B-13. Mortar air content vs increase in surface w/c, Series E, H, K, M, and P.

crease in spacing factor. In Series P (Fig. B-16) the 2.4- and 3.6-gps increases resulted in 17 and 26 percent increase, respectively, in the spacing factor.

#### Effect of Surface Manipulation

##### SURFACE SCALING TESTS

The results of surface scaling tests on Series F, J, L, N, and Q are given in Table B-6 and shown graphically in Figures B-17 through B-19. These results are summarized in the following.

Series F and J specimens were subjected to periods of hand finishing of 10, 40, and 120 sec immediately after

casting. Results from the surface scaling tests are shown in Figure B-17. There was very little difference between treatments in either series, and the analysis of variance of the surface ratings and cumulative areas after each rating cycle showed no significant differences between treatments.

Series L specimens were subjected to periods of hand finishing of 10, 40, and 120 sec immediately after casting, and the specimens were frozen and thawed on wires above the freezing plate to allow air to circulate under them. The results (Fig. B-18) showed no significant differences between treatments.

Series N and Q specimens were subjected to varying periods of mechanical vibration of the surface. Severe deterioration of all specimens in Series N occurred after very few cycles (Fig. B-19), but there were no significant

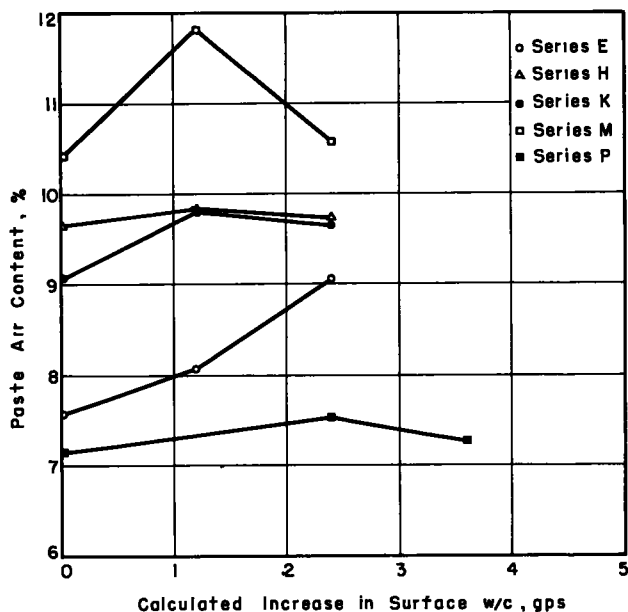


Figure B-14. Paste air content vs increase in surface w/c, Series E, H, K, M, and P.

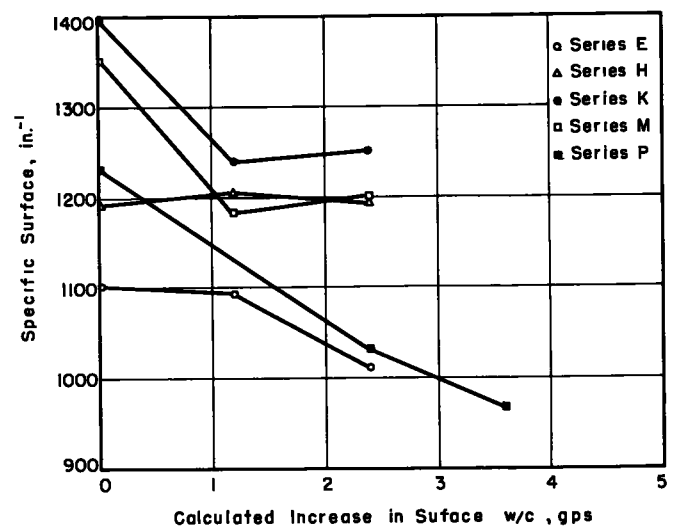


Figure B-15. Specific surface vs increase in surface w/c, Series E, H, K, M, and P.

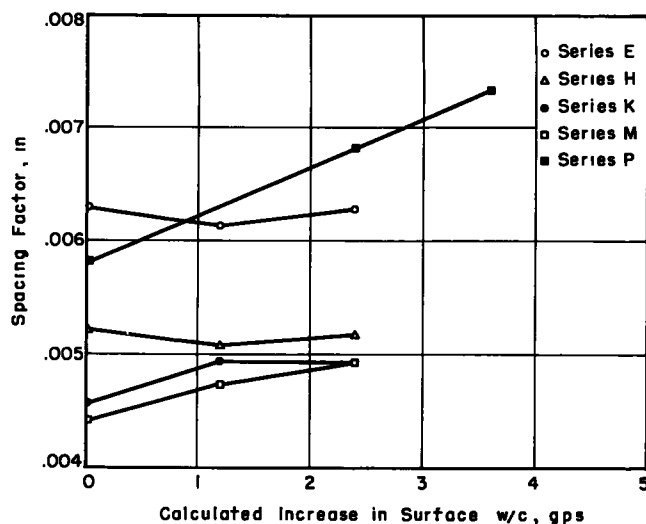


Figure B-16. Spacing factor vs increase in surface w/c, Series E, H, K, M, and P.

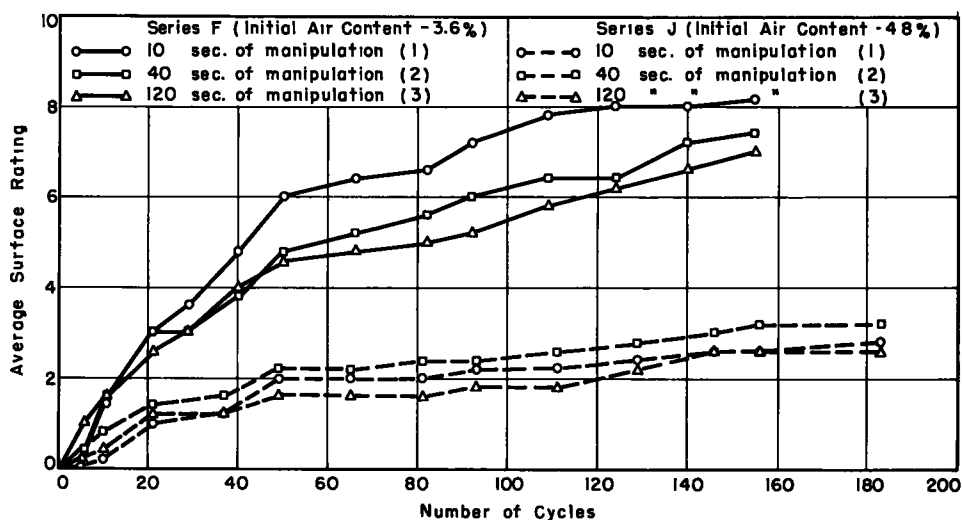


Figure B-17. Effect of surface manipulation on surface deterioration, Series F and J.

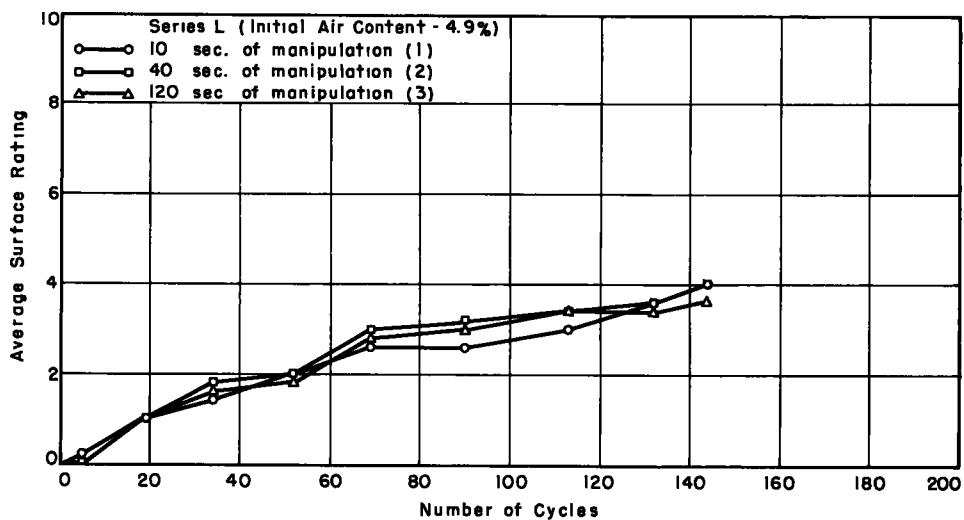


Figure B-18. Effect of surface manipulation on surface deterioration, Series L.

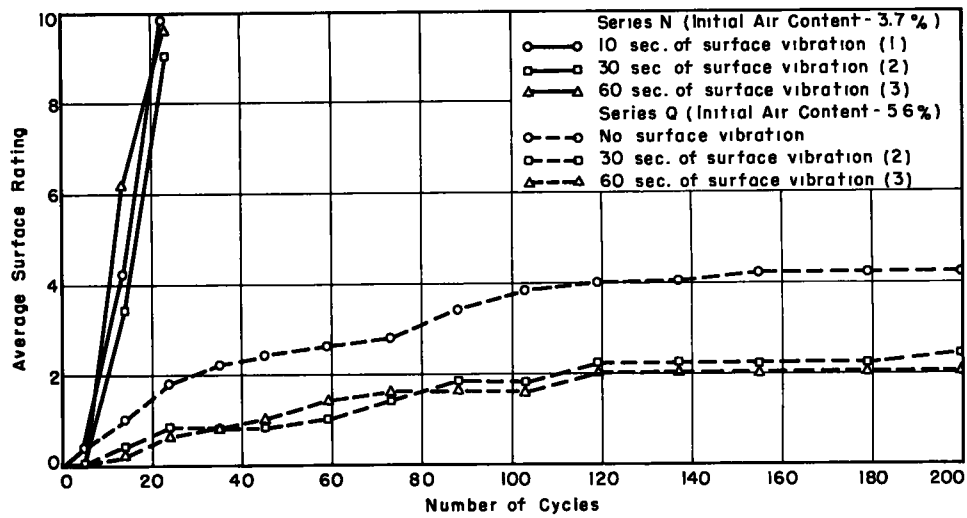


Figure B-19. Effect of surface vibration on surface deterioration, Series N and Q.

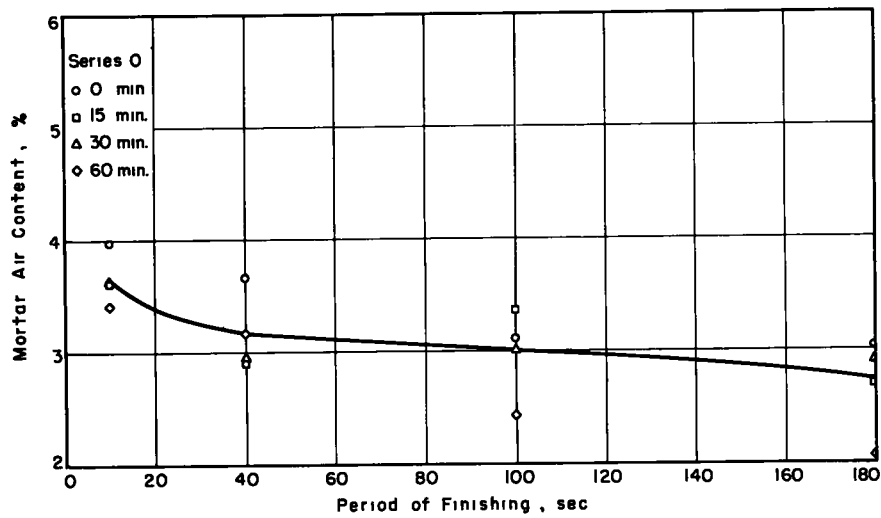


Figure B-20. Mortar air content vs period of finishing at varying times, Series O.

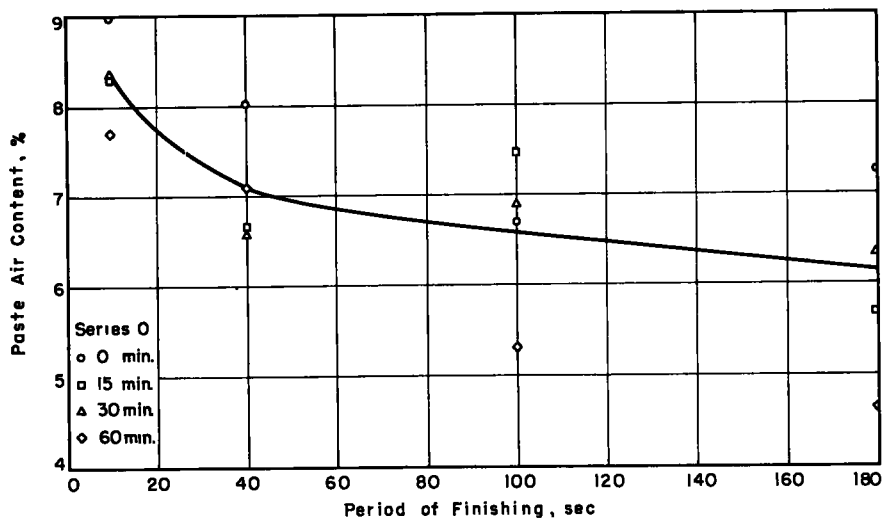


Figure B-21. Paste air content vs period of finishing at varying times, Series O.



differences between treatments. The possible reasons for this rapid rate of deterioration are discussed in a later section.

In Series Q, treatment 1 consisted of a minimum amount of manipulation with no surface vibration, whereas treatments 2 and 3 involved two degrees of surface vibration. As shown in Fig. B-19, none of the specimens exhibited severe deterioration after 200 cycles, but there was a significant difference between the vibrated and non-vibrated specimens. The vibrated specimens exhibited less deterioration than the non-vibrated specimens, and the results of these treatments differed significantly after 35 cycles.

#### MICROSCOPICAL DETERMINATION OF SURFACE AIR VOID PARAMETERS

Effects of the variable finishing efforts on surface air void parameters of Series O are shown in Figures B-20 through B-23. The means were compared between treatments using a paired *t*-test, and the results of these comparisons for each parameter are given in Table B-11. Also, Figures B-24 through B-31 show the trends found in data from Series F, J, L, N, and Q, in which one specimen from each treatment within a series was examined microscopically. Decreasing surface mortar and paste air content with increasing surface manipulation is noted in Figures B-20 and B-21

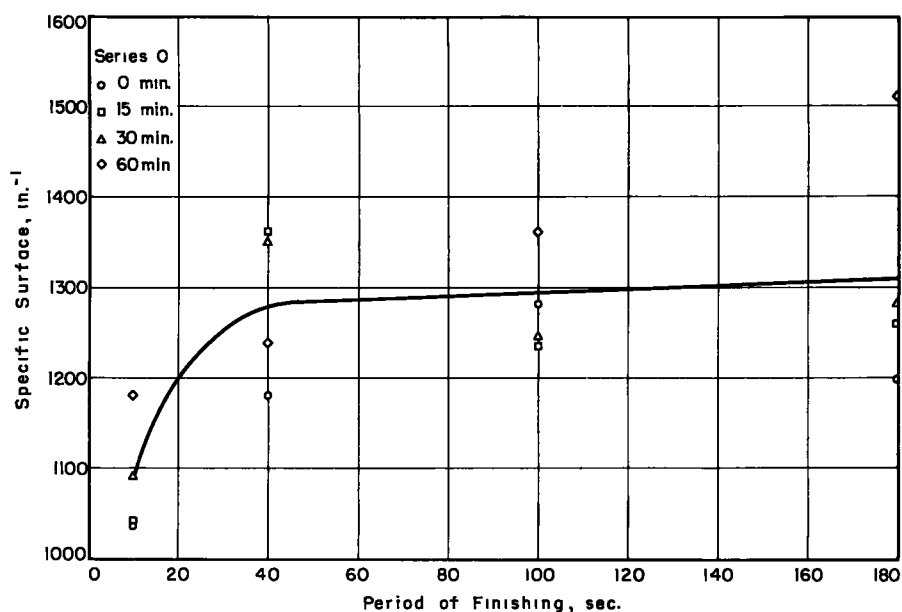


Figure B-22. Specific surface vs period of finishing at varying times, Series O.

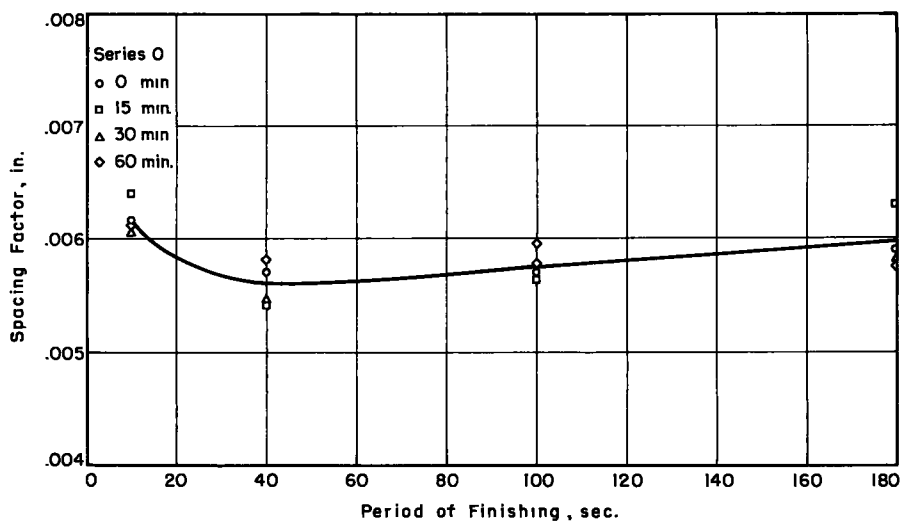


Figure B-23. Spacing factor vs period of finishing at varying times, Series O.

for the Series O data. The paste air content shows a sharper decrease than the mortar content, inasmuch as the surface paste content was increased by the manipulation. There were significant differences between the specimens with a finishing period of 10 sec and each of the specimens manipulated for longer periods, but there were no other significant differences, as shown in Table B-11. The results from Series F, J, and L (Figs. B-24 and B-25) generally follow the same trend in paste air content but show little change in the mortar air content. The same trends in both mortar and paste air contents are noted in Series N and Q (Figs. B-28 and B-29), in which surface vibration was used. Air content decreased with increasing amounts of surface vibration.

In Series O an 18 percent increase in specific surface was the result of increasing the period of finishing from 10 to 40 sec (Fig. B-22), but further increases in the period of

finishing did not result in commensurate increases in specific surface. Table B-11 shows that the only significant differences between treatments are those between the 10-sec period of finishing and each of the other three longer periods. The Series F data (Fig. B-26), on the other hand, show a linear relationship between period of finishing and specific surface, whereas results from both Series J and L (Fig. B-26) indicate that 120 sec of manipulation caused a more pronounced increase in specific surface than 40 sec of manipulation. Increasing amounts of surface vibration also resulted in increases in specific surface as shown in Figure B-30.

The spacing factor was only slightly changed by increasing the period of finishing (Fig. B-23). A 10 percent decrease in spacing factor resulted when the period of finishing was increased from 10 to 40 sec, and further manipu-

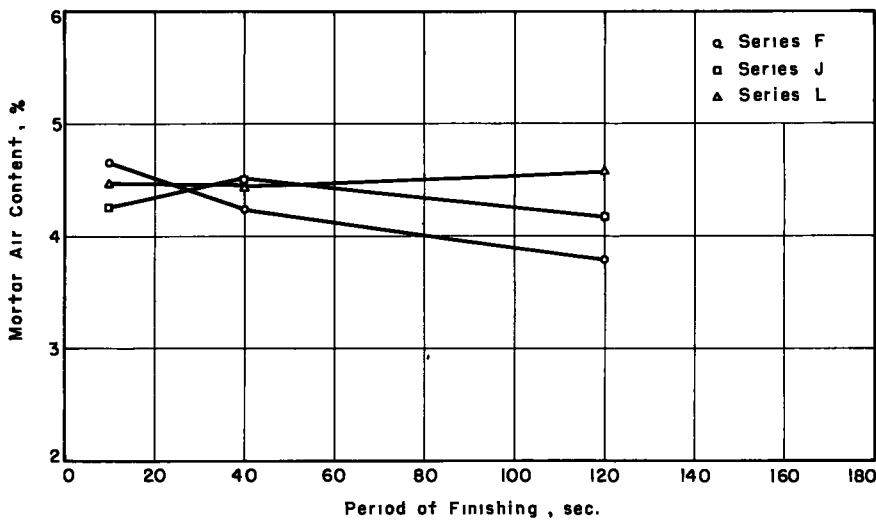


Figure B-24. Mortar air content vs period of finishing, Series F, J, and L.

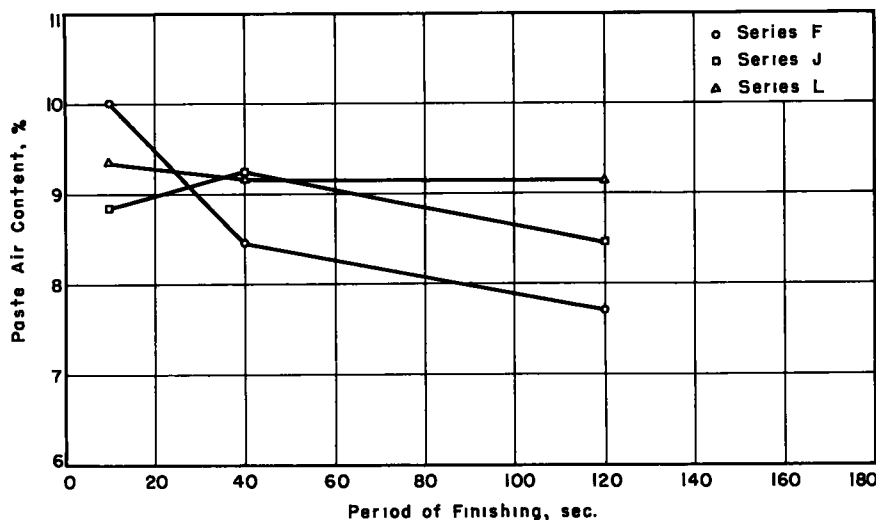


Figure B-25. Paste air content vs period of finishing, Series F, J, and L.

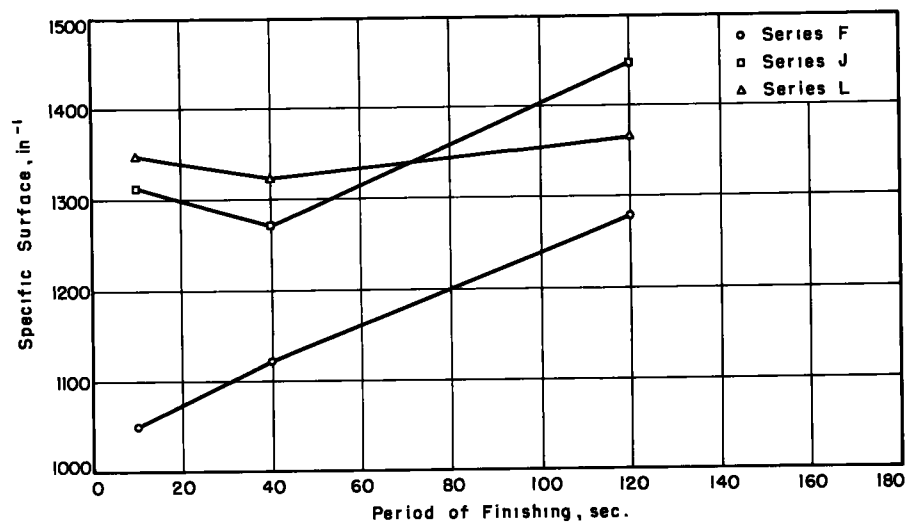


Figure B-26. Specific surface vs period of finishing, Series F, J, and L.

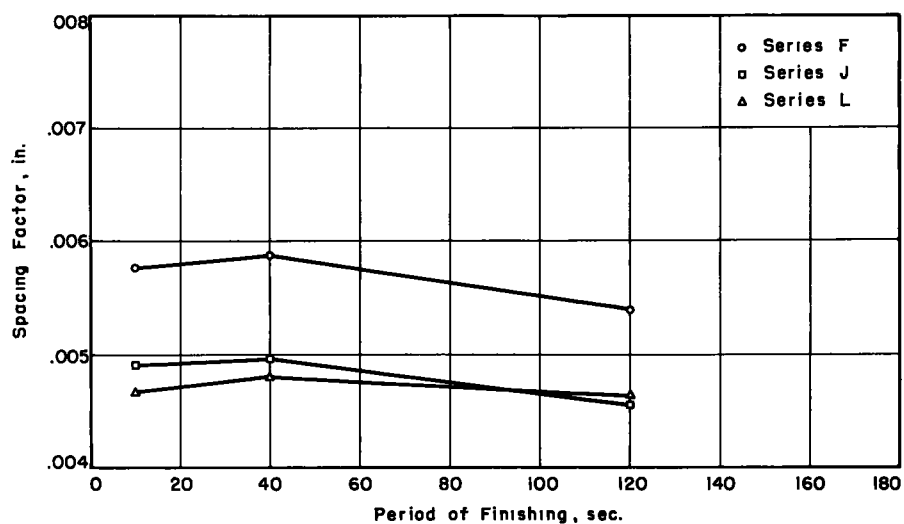


Figure B-27. Spacing factor vs period of finishing, series F, J, and L.

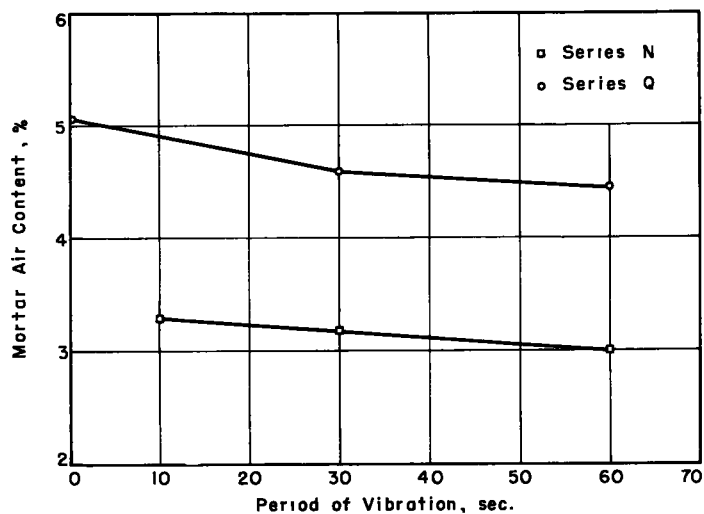


Figure B-28. Mortar air content vs period of vibration, Series N and Q.

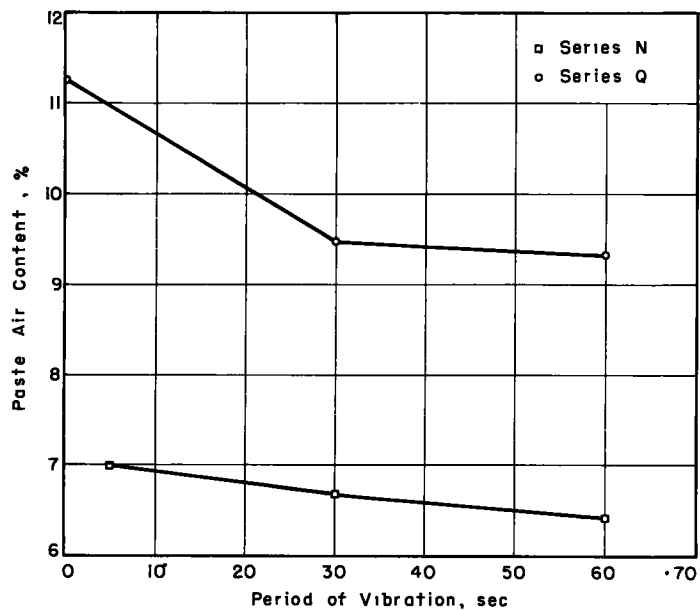


Figure B-29. Paste air content vs period of vibration, Series N and Q.

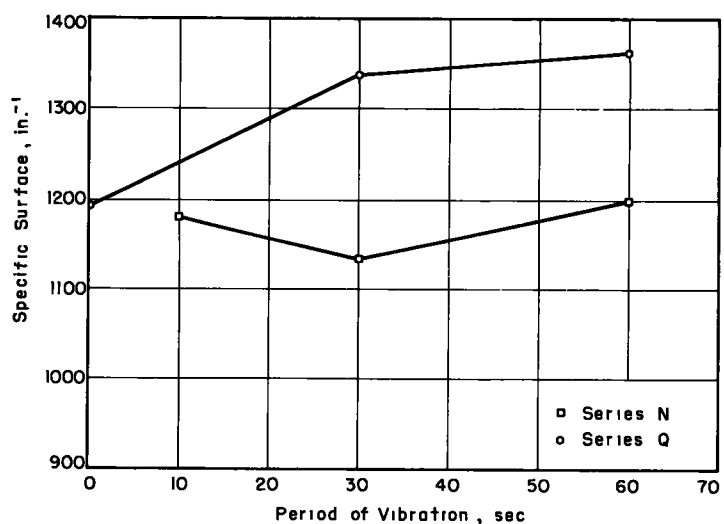


Figure B-30. Specific surface vs period of vibration, Series N and Q.

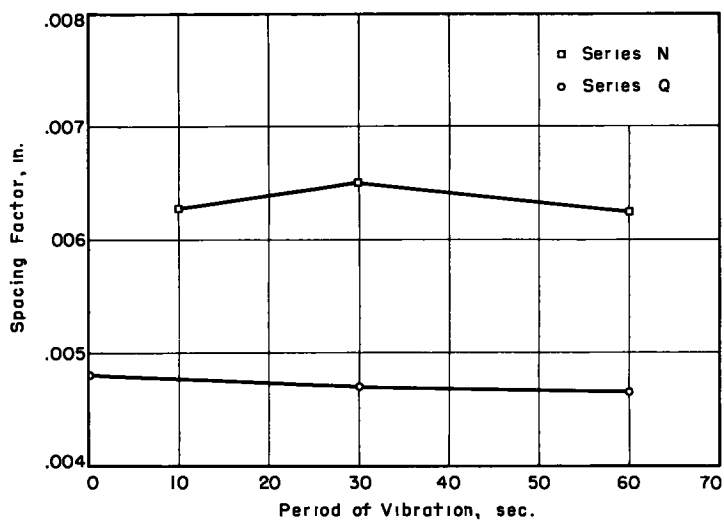


Figure B-31. Spacing factor vs period of vibration, Series N and Q.

TABLE B-12  
COMPARISON OF SURFACE AND MID-DEPTH AIR VOID PARAMETERS

SERIES	TREATMENT	DETERMINATION LOCATION	AIR CONTENT (%)	PASTE AIR CONTENT (%)	PASTE CONTENT (%)	SPECIFIC SURFACE (IN. <sup>-1</sup> )	SPACING FACTOR (IN.)
J	2	Surface	4.47	9.21	44.1	1270	0.0050
		Mid-depth	4.46	15.00	25.3	705	0.0067
K	1	Surface	4.46	9.04	44.9	1395	0.0046
		Mid-depth	4.68	16.7	23.3	723	0.0064

lation caused the spacing factor to start rising again. Due to the small amount of scatter among results between treatments, several statistically significant differences between treatment means were found (Table B-11). The magnitude of these differences is small, however. In Series F, J, L, N, and K (Figs. B-27 and B-31) only slight changes in spacing factor were effected by increasing the period of finishing or vibration.

#### *Comparison of Surface and Mid-Depth Air Void Parameters*

In all surfaces examined microscopically, the air content and paste air content were lower than would be expected. The air content at the surface would be expected to be higher than the air content of the concrete as a whole, because the surface is predominantly mortar, whereas the paste air contents would be expected to be equal. However, the air contents at the surface were of the same magnitude as those determined by the pressure method for the plastic concrete. To further investigate this, specimens from two of the series cast were sawed at mid-depth and air void parameters were determined on the sawed surfaces. Comparison of the surface and mid-depth air void parameters (Table B-12) revealed that there was a lower paste air content at the surface. The comparison also showed the air contents at the surface to be about equal to the air contents determined at mid-depth.

## DISCUSSION OF RESULTS

### *Effect of Adding Water to the Concrete Surface During Finishing*

There are several effects which might be produced by the addition of water to the concrete surface during the finishing operation. One is a possible weakening of the surface layer due to an increase in the number and size of capillary cavities present. Dykins and Blandin (4) investigated this possibility using a bond pull-off test for assessing surface strength and found that an increase in surface water-cement ratio of 3.75 gps reduced the surface tensile strength by 25 percent. No correlation with surface scaling resistance was reported. In their studies the water was added soon after the concrete had been cast, thus corresponding to the procedure used in Series E, H, K, and M in this investigation. Because in the surface scaling tests on these series

there were no significant differences between treatments, it would appear that any possible decrease in strength was insufficient to produce noticeable increases in surface deterioration. In Series P, however, where significant differences in deterioration were found between treatments, the possibility of a decrease in strength can not be discounted as a factor contributing to these differences. It is possible that water added soon after casting simply bleeds to the surface, very little of it becoming entrapped as potential capillary cavities. Water added later, however, due to the advanced stage of hydration, would have a better chance of being retained, and thus of weakening the surface layer.

The capillary cavities which might result due to the addition of water would also cause a very permeable and porous surface layer that would allow easy access of water and/or deicing solutions. This would permit faster saturation of the concrete near the surface and result in larger quantities of water present after saturation, thus increasing the vulnerability to freezing-and-thawing damage. To investigate this possibility, Series K was tested using alternating cycles of freezing and thawing and air-drying as described earlier under "Experimental Procedure, Treatments." It was felt that if the easier saturation were indeed a primary factor in the deterioration, this would show up more readily in a test where the concrete was dried and resaturated several times during freeze-thaw cycling. The results from Series K, however, showed no significant differences between treatments. Freeze-thaw tests of this type were not conducted on specimens to which water had been added later in the finishing process. If the later additions of water are more likely to be retained in the surface, as mentioned in the previous section, the surface permeability and porosity would be increased, and this might also contribute to deterioration.

A third possible effect of adding water to the surface is an alteration of the surface air void system or a "washing out" of the entrained air. This possibility is mentioned in the Kansas bridge deck study (3) as an explanation for observed low surface air contents in several cores that were studied. In the study, high water-cement ratio and excessive early manipulation are both listed as primary causes of the low air contents noted. However, the experimental results given in the earlier section on "Experimental Results, Effect of Adding Water to the Concrete Surface During Finishing" and discussed in the following do not substantiate this.



Considering first the effects on the air void system of adding water immediately after casting, it is seen from the results of Series R that additions of water caused a slight increase in air content (Fig. B-5), but a decrease in the specific surface (Fig. B-7). The net effect of these changes on the spacing factor (Fig. B-8) was a slight (less than 10 percent) increase. The air content data from the surface scaling test specimens (Table B-7) are in general agreement with the results from Series R, indicating only slight increases in spacing factor as water is added. It should also be noted that in most of these series the amount of water added had little effect on spacing factor; that is, increasing the water-cement ratio by 3.6 gps had almost the same effect as increasing it by 1.2 gps. In view of these findings, the adverse effects of water on the air void system would seem to be minor if the water is added immediately after casting. The surface scaling tests bear this out.

In Series P the addition of water at a later time during finishing had a deleterious effect on surface scaling resistance and also produced a marked trend for increasing spacing factor with increasing additions of water. In this series the specimen to which no water was added had a spacing factor of 0.0058. Increasing the surface water-cement ratio by 2.4 gps increased the spacing factor to 0.0068, and the 3.6-gps increase resulted in a spacing factor of 0.0074. Because these findings were based on the results from only one specimen chosen from each treatment, the variation between specimens was not known. To provide a better basis for drawing conclusions, Series S was cast using a mix design and casting procedure identical with the one used in Series P. Surface air void determinations were then made on all specimens so that between-specimen variations could be included in the analysis of the effects. Changes in the spacing factor of the magnitude noted in Series P did not appear in Series S, although there was a trend toward increasing spacing factor with increasing additions of water.

Because there was a lack of agreement between the results of Series P and Series S, these series were investigated further by exploring the relationships between average depth of material removed by lapping and the air void parameters at that depth. In lapping the surfaces of each slice from a specimen, the primary concern was that as little material as possible be removed, and no attempt was made to remove the same amount of material from each slice. The average depth of material removed from the Series S slices was 0.04 in.; the Series P slices had somewhat rougher surfaces, the average depth removed being 0.08 in. It was thought that this difference might be significant, and spacing factor and specific surface were computed for each of the 32 slices in Series S (two slices from each specimen) and 12 slices in Series P (four slices from each specimen). These data were plotted versus the average depth at which the air void determination was made. Within the top  $\frac{1}{8}$  in. of the surface there was no consistent relationship between depth and specific surface or spacing factor. Thus it seems unlikely that the values for specific surface and spacing factor were influenced by the varying depths at which air void determination was made.

The variations in air void parameters within the four slices from each specimen in Series P were also investigated. As previously stated under "Experimental Procedure, Microscopical Determination of Surface Air Void Parameters," four slices were removed from the surface of each specimen representing a treatment, and the traverses on all were combined in one calculation of the air void parameters. To obtain a rough estimate of the variability within a specimen, the spacing factor for each slice was computed, as follows:

<i>Treatment 1</i>	<i>Treatment 2</i>	<i>Treatment 3</i>
0.0063	0.0083	0.0084
0.0060	0.0065	0.0090
0.0054	0.0065	0.0060
0.0055	0.0062	0.0063

These data show that two of the four slices from treatment 3 had spacing factors equivalent to those found in treatment 1, but the other two slices had much higher spacing factors. This variability would seem to explain why some specimens in the surface scaling tests exhibited localized patches of deterioration while the rest of the surface remained sound or deteriorated at a slower rate. It also raises the question of the meaning of an average spacing factor, which characterizes an entire area but may not be representative of all parts of that area. In this investigation it was assumed that the relatively small specimen size and the standardized procedures used in the mixing, casting, and finishing would result in a uniform void distribution over the surface of a single specimen, but it appears that this is sometimes not a valid assumption. Because this variability among slices from the specimen was not found in other series for which four slices were used, either the treatments that were used introduced the variability or some unknown variable was the cause. The available data are insufficient to draw definite conclusions concerning this aspect of the problem, but it appears that more information concerning the causes of such variability is needed.

#### *Effect of Surface Manipulation*

Excessive manipulation of the surface concrete during finishing may result in premature densification and a weakened plane beneath the surface, or a weakened zone due to intermixing of the bleed water with the surface concrete. The primary factor of interest in this phase of the study, however, was the effect on the surface air void parameters. Increasing amounts of hand manipulation resulted in lower air contents and higher specific surfaces, so that the net effect on spacing factor was slight. These results were similar to those reported by Backstrom et al. (1) concerning the average air void parameters as affected by varying periods of internal vibration. If one accepts the spacing factor as the measure of the efficiency of the air void system in reducing deterioration, it could be concluded that although the air void system was indeed changed, the change was not a deleterious one with respect to durability. The surface scaling tests on Series F, J, and L confirmed this, as

they indicated no adverse effects due to prolonged periods of surface manipulation immediately after casting.

The only significant differences in surface deterioration which did occur were those in Series Q, where one set of specimens was given only enough surface manipulation to give a smooth surface. These specimens showed more surface deterioration than the specimens which had been given various periods of surface vibration, reemphasizing the fact that some compaction of the surface is desirable and necessary.

The Series N surface scaling test results deserve comment due to the rapid rate at which deterioration occurred. As shown in Table B-7, the spacing factor for these specimens was higher than that for most of the other series tested, so that deterioration was expected, but not at such a fast rate. It was found that due to an error in scheduling, these specimens had been air-dried only 3 days instead of 11 days, and this is believed to have resulted in a higher degree of saturation earlier in the testing. This higher degree of saturation evidently resulted in the rapid deterioration.

#### *Comparison of Surface and Mid-Depth Air Void Parameters*

It is of interest to note that the mortar and paste air contents at the concrete surface were not as high as might be expected, based on the air content of the concrete as a whole and the assumption that the surface mortar air content is the same as the air content of the interior mortar. The comparison between air void parameters at the surface and mid-depth in Series J and K specimens (Table B-12) revealed that both the mortar and paste air contents were lower at the surface than in the interior of the concrete. This was found in all specimens examined in this portion of the investigation and seems to reflect a tendency for elimination of large voids at the surface. However, these low air contents did not result in an inadequate spacing factor at the surface or in poor performance of the concrete in the surface scaling test. Thus it would seem that low surface air contents alone are not the cause of surface deterioration.

#### **CONCLUSIONS AND SUGGESTED RESEARCH**

The following conclusions were drawn from this portion of the investigation:

1. Increases in the surface water-cement ratio up to approximately 2.4 gps in a 6-gps concrete, caused by adding water to the concrete surface immediately after casting,

have little or no adverse effect on the scaling resistance of the surface.

2. Increases in the surface water-cement ratio up to approximately 3.6 gps in a 6-gps concrete, caused by adding water to the concrete surface immediately after casting, result in a slight increase in surface air content, a decrease in specific surface, and little change in the spacing factor at the surface. The changes in surface air void parameters are not proportional to the amount of water added within this range.

3. Increases in the surface water-cement ratio of approximately 2.4 and 3.6 gps in a 6-gps concrete, caused by adding water to the surface after the bleed water has evaporated, both result in decreased scaling resistance of the surface.

4. Increases in the surface water-cement ratio up to approximately 4.8 gps in a 6-gps concrete, caused by adding water to the surface after the bleed water has evaporated, result in decreased specific surface and slightly increased spacing factor in the surface air void system.

5. Excessive manipulation or overfinishing of the surface of small-size (negligible bleeding and shrinkage effects) specimens immediately after casting has no adverse effect on the scaling resistance of the surface.

6. Increasing amounts of surface manipulation result in decreased surface air contents, increased specific surface, and little change in spacing factor at the surface.

7. The air void system at the concrete surface is finer than the interior void system, and the air content of the surface paste and mortar is less than the interior paste and mortar air content.

The study of the air void system in this investigation was confined to the top  $\frac{1}{8}$  in. of the surface and no attempt was made to investigate the variations which might occur at greater depths. Inasmuch as deterioration in many cases may reach depths of  $\frac{1}{2}$  in. or more, a study of the vertical distribution of air in the top 1 in. of the concrete surface would be of value. Because the top surface has a lower air content than the underlying concrete, the zone of transition might be of interest, as would the air void characteristics at the boundary between the surface mortar and the underlying coarse aggregate.

The study of the adequacy and variability of the surface air void system as influenced by the type of air-entraining admixture, type of mixing, and sequence of mixing, would also contribute to a better understanding of surface durability.

## APPENDIX C

### SURFACE STRENGTH AND DURABILITY

#### EXPERIMENTAL PROCEDURE

An experimental program was designed to investigate the surface soundness of concrete and the possible formation of a weakened plane in particular. The effects of excessive finishing and environmental conditions during the bleeding period upon surface soundness were of major interest. One-half of the surface of concrete slab specimens was subjected to either application of heat and wind during the bleeding period or was finished excessively; the remainder was finished only once at the end of the bleeding period and in a laboratory environment. Differences in surface soundness of the treated and untreated halves were investigated by means of pull-off tests and surface scaling tests.

The tests were conducted using differing specimen sizes, differing mix designs, and normal and set-retarded concretes.

#### Materials

Type 1 cement from a single lot was used in all concrete cast in this portion of the investigation. This cement is designated C in Tables B-1 and B-2, which give the results of typical chemical and physical tests performed on it.

The aggregates used were Wabash River sand and gravel from near Covington, Ind. The origin of the aggregates is a glacial outwash. The coarse aggregate consisted mainly of dolomite and limestone with minor quantities of quartz, granite, and chert. The fine aggregate consisted mainly of

quartz. The fine aggregate was from two different lots; however, only aggregate from a single lot was used in any one concrete. The coarse aggregate is designated B, and the fine aggregates are designated B and C in Table B-3, which gives the results of physical tests on the aggregates. The aggregates were used in their natural gradation, which is also given in Table B-3.

Two air-entraining agents were used. The agent used in most batches was a proprietary compound consisting of an aqueous solution of salts of sulfonated hydrocarbons containing a catalyst. The other agent was a neutralized vinsol resin. An organic-acid retardant in powder form was used in the set-retarded concrete and ordinary tap water was used in all batches.

Two basic mix designs, one lean and one rich, were used for all batches with the exception of one intermediate mix. Mix designs are given in Table C-1.

#### Fabrication of Specimens

The concrete for each specimen was mixed in a single batch of 5.5 cu ft, using a free-fall, non-tilting drum mixer of 6-cu-ft rated capacity. The air-entraining agent was mixed thoroughly in the mix water, and the set-retarding admixture was added to the sand prior to mixing. A slump test and an air content determination by the pressure method were made immediately following mixing. The results of these tests are given in Table C-1.

TABLE C-1  
PROPERTIES OF PLASTIC CONCRETE AND MIX DESIGNS

SPECI- MEN	TREAT- MENT	RETARDED	SLUMP (IN.)	NET AIR CONTENT (%)	INITIAL BLEEDING RATE (IN./SEC $\times 10^6$ )	EFFECTIVE W-C RATIO	NOMINAL MIX, BY WEIGHT <sup>1</sup>			
							CEMENT	WATER	SAND	GRAVEL
L2	1	No	5.25	2.5	17	0.62	1	0.66	2.92	5.05
L5	1	Yes	5.00	5.0	5.4	0.58	1	0.66	2.92	5.05
L6	3	No	4.00	3.0	7.3	0.62	1	0.66	2.92	5.05
M1	3	No	3.00	3.5	—	0.62	1	0.66	2.92	5.05
N1	1	No	4.50	2.0	7.3	0.53	1	0.53	2.14	4.09
M2	3	Yes	4.00	4.5	—	0.44	1	0.47	2.11	3.32
M3	2	Yes	4.00	3.9	—	0.44	1	0.47	2.11	3.32
M4	3	No	6.00	1.4	—	0.52	1	0.47	2.11	3.32
M5	2	No	3.50	3.1	—	0.47	1	0.47	2.11	3.32
M6	3	No	3.75	5.3	—	0.47	1	0.47	2.11	3.32
N2	3	Yes	5.00	5.0	5.9	0.46	1	0.47	2.11	3.32
N3	2	Yes	2.50	4.4	3.5	0.44	1	0.47	2.11	3.32
N4	3	No	2.75	2.5	5.9	0.47	1	0.47	2.11	3.32
N5	2	No	3.50	3.0	5.8	0.47	1	0.47	2.11	3.32
N6	3	No	3.25	3.1	8.3	0.47	1	0.47	2.11	3.32
N7	3	No	7.00	6.3	—	0.50	1	0.47	2.11	3.32

<sup>1</sup> Saturated, surface dry, basis.

Two specimen sizes were used. The specimens of Series L and N were 64 by 15 by 8 in.; those of Series M were 48 by 24 by 6 in. The specimens were cast in plywood forms. The forms were filled in one lift, and the concrete was vibrated uniformly for 10 to 15 sec with an immersion vibrator. The surface was then screeded and floated lightly for 1 to 2 min. Following this initial floating, bleeding measurements using the float method were initiated on the half of the specimen that was to be untreated, and special treatments were initiated on the other half. Results of the bleeding tests are given in Table C-1.

Time-of-set tests were conducted on samples taken from several batches of both normal and set-retarded concretes. Results of these tests are given in Table C-2.

### Surface Treatments

Three types of surface treatments were used. Treatment 1 consisted of finishing the concrete immediately after screeding and then applying heat and/or wind with no further finishing. Treatment 2 was similar to treatment 1 except the surface was subjected to further finishing during the application of heat and wind. In treatment 3 the concrete was finished excessively with no application of heat and wind. Within each general type of surface treatment various combinations of duration of heat and wind, amount of finishing, and time of finishing, were used. Details of the treatment for each specimen are given in Table C-3.

Heat was supplied by four 500-w infrared lamps suspended 10 to 12 in. above the surface. The temperature at the treated surface was approximately 90 F. The wind force was supplied by an electric fan; wind velocity was 13 to 15 mph.

Upon completion of bleeding measurements, the untreated surface was given a final finish with a steel trowel.

### Curing

The specimens were covered with two layers of wet burlap and a layer of polyethylene as soon as the surface was firm enough to prevent marring. The specimens were cured with the wet burlap for either four or five days before being removed from the forms and prepared for the pull-off tests. After this initial curing the specimens were air-dried in laboratory environment until three days before the start of surface scaling tests, at which time water was ponded on the surface. Some variation occurred in the age of the specimens at the start of surface scaling tests, and consequently in the length of the air-drying period, due to limited freezer space. Table C-4 gives the curing schedule and age at initiation of testing for each specimen.

### Pull-Off Tests

The pull-off tests were run on the end quarters of the specimens, generally at an age of seven days. To reduce the shearing stresses in the failure zone, annular cores were drilled in the surface to a depth of  $\frac{1}{4}$  to  $\frac{1}{2}$  in. using a  $2\frac{1}{8}$ -in. I.D. diamond core bit.

One day after coring, the surfaces of the cored disks were wire-brushed to remove dust and laitance, and 2 in. diam-

TABLE C-2  
TIME OF INITIAL AND FINAL SET

SPECIMEN	TIME* (HR: MIN)		TYPE OF CONCRETE
	INITIAL SET	FINAL SET	
M1	4:36	6:09	Normal
M4	4:26	5:51	Normal
M2	6:23	7:39	Retarded
M3	5:33	6:49	Retarded
N2	6:48	9:06	Retarded
N3	6:18	7:18	Retarded

\* Time measured from initial water-cement contact; initial set = 500 psi, final set = 4,000 psi.

eter steel heads were bonded to the surface of the disks using a room-temperature-curing epoxy compound adhesive. Figure C-1 shows the cored disks and the bonded pull-off heads. The adhesive was allowed to cure a minimum of 15 hr before the pull-off tests were run.

The pull-off apparatus consisted of a 2-ton hydraulic pull ram connected to a strain-gage dynamometer, both housed in a  $1\frac{1}{2}$ -in. I.D., 2-in. O.D. steel pipe, as shown in Figure C-2. The lower end of the pipe was threaded to receive a  $2\frac{1}{4}$ -in. I.D.,  $2\frac{3}{4}$ -in. O.D. loading collar. The lower end of the dynamometer was provided with a threaded coupling for connecting the pull-off heads.

The four-arm bridge of the dynamometer was connected to an electronic recorder, which provided a continuous record of load vs time. The pull-off apparatus was calibrated by placing it in the tension jaws of a hydraulic testing machine and loading the pull-off apparatus with a portable hydraulic pump. The load was read on the testing machine, and the corresponding deflection of the recorder stylus was noted. Subsequent recalibration showed no change from the original.

The pump of a hydraulic testing machine was used to supply the pressure for the pull-off tests. The loading rate was approximately 100 lb/sec. The test set-up is shown in Figure C-1.

### Surface Scaling Tests

Upon completion of the pull-off tests, the end quarters of the specimens were sawed off to facilitate handling. Two sets of precast air-entrained mortar dikes (one enclosing a portion of the treated surface, the other a portion of the untreated surface) were bonded to the specimen with a synthetic latex rubber adhesive.

The surface scaling test procedure consisted of placing a  $\frac{1}{4}$ -in. depth of 3 percent sodium chloride solution over the diked surface and placing the specimen in a room maintained at  $-30$  F for 15 hr. The specimens were removed from the freezer and thawed for approximately 9 hr at room temperature (70-85 F). Once a week the specimens were rinsed off and the sodium chloride solution was replaced.

The surfaces of the specimens were inspected periodically to note any differences in the surface deterioration of the

TABLE C-3  
SURFACE TREATMENTS<sup>a</sup>

SPECIMEN	WIND		HEAT		FINISHING
	START (MIN)	DURATION (HR)	START (MIN)	DURATION (HR)	
L2	26	6	26	6	1 min metal float at 25 min
L5	23	5	None	None	1 min wood float at 20 min
N1	27	7			1 min wood float at 22 min
M3	33	7	33	5	2 min metal float at 45 min
					4 min metal float at 60 min
					1 min metal float at 75 min <sup>b</sup>
M5	29	7	29	5	2 min metal float at 56 min
					2 min metal float at 71 min
					1 min metal float at 90 min <sup>b</sup>
N3	29	7	29	5	2 min metal float at 45 min
					2 min metal float at 60 min
					1 min metal float at 75 min <sup>b</sup>
N5	36	7	36	5	2 min metal float at 50 min
					2 min metal float at 65 min
					1 min metal float at 95 min <sup>b</sup>
L6	None		None		5 min wood float at 32 min
M1	None		None		5 min wood float at 20 min
M2	None		None		3 min metal float at 24 min
					3 min metal float at 39 min
M4	None		None		3 min metal float at 30 min
					3 min metal float at 45 min
					2 min metal float at 60 min
M6	None		None		3 min metal float at 18 min
					3 min metal float at 37 min
					2 min metal float at 70 min
N2	None		None		3 min metal float at 23 min
					3 min metal float at 38 min
					2 min metal float at 55 min
N4	None		None		3 min metal float at 20 min
					3 min metal float at 35 min
					2 min metal float at 50 min
N6	None		None		3 min metal float at 21 min
					3 min metal float at 36 min
					2 min metal float at 66 min
N7	None		None		3 min metal float at 25 min
					3 min metal float at 40 min
					2 min metal float at 70 min

<sup>a</sup> All times measured from time of water-cement contact. <sup>b</sup> Lightly.

treated and untreated surfaces and to look for any evidence of weakened plane deterioration. Each surface was rated using the numerical rating scale given in Appendix B under "Experimental Procedure, Methods of Analysis." Inasmuch as the purpose of this portion of the investigation was to look for gross defects that would result in surface deterioration within a relatively small number of cycles of freezing and thawing, the surface scaling tests were discontinued after approximately 30 cycles.

#### EXPERIMENTAL RESULTS

The results of the pull-off tests showed a great deal of scatter. Therefore, no definite conclusions can be drawn from them. However, it is felt that the results are still useful in pointing out general trends. The results of the surface scaling tests are somewhat more consistent and show more clearly defined trends.

TABLE C-4  
MOIST CURING TIME AND TEST TIME-TABLE

SPECIMEN	DAYS OF MOIST CURING	AGE AT TIME OF PULL-OFF TEST (DAYS)	AGE AT START OF F-T TESTS (DAYS)
L2	4	7	29
L5	4	10	31
N1	5	7	35
M3	5	7	28
M5	4	6	32
N3	5	7	30
N5	5	8	35
L6	5	7	31
M1	5	8	28
M2	5	7	28
M4	5	8	44
M6	5	8	—
N2	4	6	28
N4	5	7	42
N6	5	8	—
N7	5	10	—



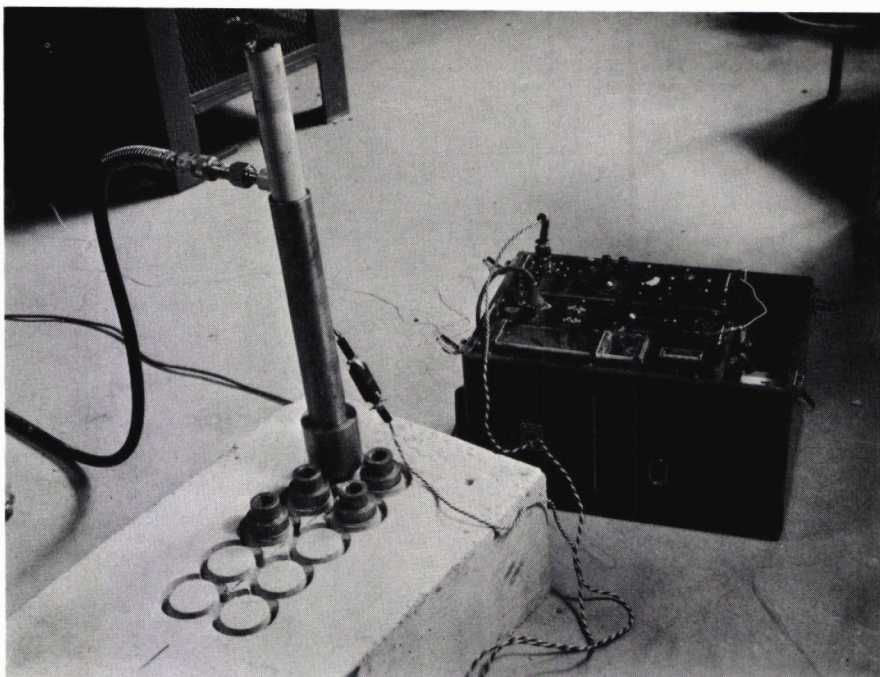


Figure C-1. Pull-off test setup.

### Pull-Off Tests

The average pull-off strengths of the treated and untreated surfaces of each specimen, as well as pertinent statistical data, are given in Table C-5.

For the specimens subjected to treatment 1 (heat and wind with no finishing during the bleeding period), the average pull-off strength of the treated surfaces was greater than that of the untreated surfaces. This phenomenon was also noted in preliminary tests on smaller specimens designed to develop the pull-off apparatus and procedure.

For the specimens subjected to treatments 2 and 3 (heat and wind plus finishing, and overfinishing only, respectively), the results show a trend for the average pull-off strength of the treated surfaces to be less than that of the untreated surfaces.

### Surface Scaling Tests

The rate of deterioration of the treated and untreated surfaces of each specimen is given in Table C-6. The rate of deterioration is equal to the surface deterioration rating divided by the number of cycles at which it was assigned. Thus a high rate of deterioration indicates poor durability.

For the specimens subjected to treatments using heat and wind, the surface scaling tests indicated that the treated surfaces were somewhat more durable than the untreated surfaces.

For the specimens subjected to treatments involving only overfinishing, the treated surfaces were generally less durable than the untreated surfaces.

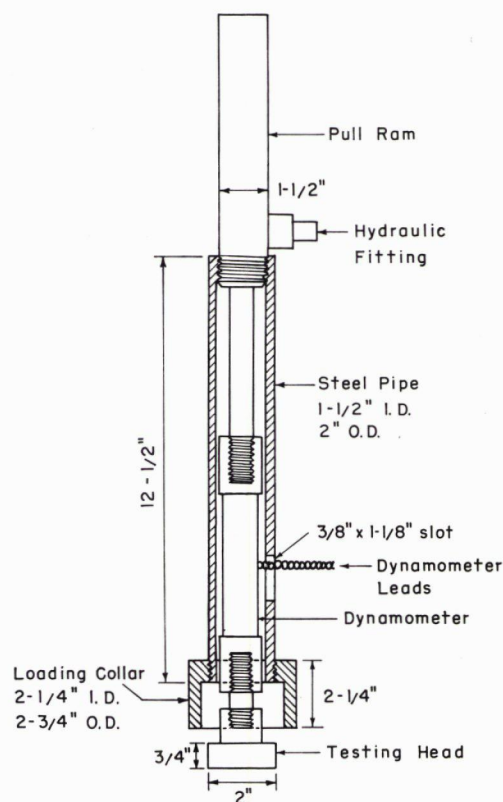


Figure C-2. Functional sketch of pull-off apparatus.

TABLE C-5  
PULL-OFF TEST RESULTS

SPECIMEN	TREAT- MENT TYPE	AVG. PULL-OFF STRENGTH (PSI)		STANDARD DEVIATION (PSI)		COEFF. OF VARIATION (%)		SIGNIFICANT DIFFERENCE AT 0.95 PROBABILITY LEVEL
		NOT TREATED	TREATED	NOT TREATED	TREATED	NOT TREATED	TREATED	
L2*	1	375	476	70.9	77.6	18.9	16.3	Yes
L5	1	116	179	41.2	106.7	35.5	59.6	No
N1	1	108	152	43.5	60.5	40.5	39.7	Yes
M3	2	226	207	83.2	90.4	36.8	43.7	No
M5	2	255	162	89.7	68.6	35.1	42.2	Yes
N3	2	195	165	76.1	55.0	39.1	33.4	No
N5	2	243	200	88.9	97.5	36.6	48.9	No
L6	3	181	138	53.3	80.4	29.4	58.3	No
M1	3	144	175	52.4	68.9	36.4	39.4	No
M2	3	160	169	42.7	66.5	26.8	39.3	No
M4	3	226	176	105.3	51.1	46.5	30.7	No
M6	3	166	132	66.4	56.9	40.0	43.1	No
N2	3	158	88	71.9	50.4	45.6	57.3	Yes
N4	3	227	143	93.0	68.9	40.9	48.2	Yes
N6	3	130	158	65.3	62.1	50.1	39.4	No
N7	3	175	111	105.4	49.6	60.2	44.9	Yes

\* Surface not cored for pull-off tests.

## DISCUSSION OF RESULTS

Powers (10) has suggested that a weakened plane near the surface of concrete might form if, during the bleeding period, the surface somehow becomes more dense than

the underlying concrete, causing bleed water to collect under this dense surface layer and increasing the water-cement ratio of the concrete below the surface. Such an increase in the water-cement ratio would weaken the con-

TABLE C-6  
RESULTS OF SURFACE SCALING TESTS ON LARGE-SCALE SPECIMENS

SPECIMEN	TREAT- MENT TYPE	RATE OF DETEIORATION*		COMMENTS
		UNTREATED SURFACE	TREATED SURFACE	
L2	1	0.032	0.032	Discontinued at 31 cycles
L5	1	0.258	0.194	Discontinued at 31 cycles
N1	1	0.588	0.353	Low air content, rapid deterioration, discontinued at 17 cycles
M3	2	0.000	0.000	No noticeable deterioration at 29 cycles, discontinued
M5	2	0.161	0.065	Discontinued at 31 cycles
N3	2	0.065	0.032	Discontinued at 31 cycles
N5	2	0.226	0.194	Discontinued at 31 cycles
Avg.	1 & 2	0.124	0.086	
L6	3	0.077	0.231	Discontinued at 26 cycles
M1	3	0.240	0.240	Discontinued at 25 cycles
M2	3	0.177	0.294	Discontinued at 34 cycles
M4	3	0.161	0.833	Treated surface had rating of 10 at 12 cycles; specimen discontinued at 31 cycles
M6	3	—	—	No freeze-thaw tests
N2	3	0.236	0.370	Discontinued at 34 cycles
N4	3	0.258	0.667	Treated surface had rating of 10 at 15 cycles; specimen discontinued at 31 cycles
N6	3	—	—	No freeze-thaw tests
N7	3	—	—	No freeze-thaw tests
Avg.	3	0.192	0.426	

\* Rate of deterioration = surface deterioration rating divided by number of cycles at which it was assigned. The number of cycles used is that at which the freeze-thaw test was discontinued or that at which a rating of 10 was assigned.

crete in this zone. The surface may become more dense than the underlying concrete if the rate of evaporation of water from the surface exceeds the rate of bleeding or if the surface is manipulated excessively during finishing.

A high evaporation rate is generally the result of hot and/or windy weather during placing. Such an environment is also conducive to the formation of plastic shrinkage cracks in the concrete. Because the possible formation of a weakened plane and/or plastic shrinkage cracking is considered to be detrimental to surface scaling resistance, it has been axiomatic in the concrete industry to avoid these environmental conditions during placing and finishing whenever possible.

Klieger (8), however, has presented evidence that the surface scaling resistance of small-scale non-air-entrained laboratory specimens was improved by subjecting the surface of the concrete to a wind force during the bleeding period. A slight trend toward increased durability with an increase in the air temperature during bleeding was also noted although it was not well defined. Furthermore, it was found that non-air-entrained concrete given a single final finish immediately after strike-off was more durable than concrete given a second finish either during or at the end of the bleeding period. Air-entrained concrete specimens were also tested by Klieger in the same manner. No scaling developed on any of the air-entrained specimens up to 250 cycles of freezing and thawing. However, Klieger believed that if the specimens were to scale, the trends would probably be the same as for the non-air-entrained specimens.

#### *Effects of Heat and Wind*

For the specimens subjected to treatment 1 (application of heat and wind during bleeding), the results seem to corroborate those of Klieger. For each of the three specimens, the average pull-off strength of the treated surface was greater than that of the untreated surface of the same specimen. In two cases (L2, N1), the difference in pull-off strength was statistically significant. The surface scaling resistance, as given by the rate of deterioration, of the treated surface was greater than that of the untreated surface in two cases (L5, N1). In the third case (L2), the durability of the treated and untreated surfaces was approximately the same. In general, the application of heat and wind during the bleeding period with no finishing taking place during bleeding increased the pull-off strength and

surface scaling resistance of the treated surface of the specimens. There was no evidence of a noticeably consistent failure surface that could be interpreted as a weakened plane, from either pull-off or surface scaling tests.

#### *Effects of Overfinishing*

The results from the specimens subjected to treatment 3 (finishing during bleeding without heat and wind) generally agree with the results reported by Klieger. All of the finishing took place during the bleeding period, which was the worst case reported by Klieger. Six specimens (L6; M4,6; N2,4,7) showed an average pull-off strength of the treated surface which was less than that of the untreated surface. Three of these six specimens (N2,4,7) showed statistically significant differences in the pull-off strength. The remaining three specimens (M1,2; N6) showed a slightly greater average pull-off strength for the treated surface than for the untreated surface, but the differences were not statistically significant.

Six of the specimens (L6; M1,2,4; N2,4) were subjected to surface scaling tests. All specimens except M1 showed that the treated surface was less durable than the untreated surface. The two surfaces of specimen M1 had about the same durability. In specimen N2, after only three cycles of freezing and thawing, large patches of a very thin layer of mortar scaled off of the treated surface. After this initial flaking, however, the deterioration progressed at a slower rate and at the end of 27 cycles the treated surface was only slightly more deteriorated than the untreated surface. This was the only specimen which exhibited any type of weakened plane failure.

The foregoing findings show that overfinishing generally resulted in poorer performance of specimens in the surface scaling tests. Results from Appendix B indicated that excessive manipulation did not have a harmful effect on the air void system of small-scale specimens. Because larger specimens and different finishing procedures were used in this portion of the investigation, however, samples from the surfaces of two of the specimens (M2 and M4) were used for microscopical determination of air void parameters. The results, summarized in Table C-7, indicate that the spacing factor was not adversely affected by the overfinishing. Thus, it appears that the lowered scaling resistance caused by overfinishing is due to a weaker surface rather than a harmful change in the air void system.

TABLE C-7  
SURFACE AIR VOID PARAMETERS FOR LARGE-SCALE SPECIMENS

SPECIMEN TREATMENT		LENGTH OF TRAVERSE (IN.)	NO. OF STOPS	MORTAR AIR CONTENT (%)	SPECIFIC SURFACE (IN. <sup>-1</sup> )	SPACING FACTOR (IN.)	PASTE CONTENT (%)
M2A	Normal	149	3046	2.46	1493	0.0055	44.0
M2B	Overfinish	225	4606	3.06	1674	0.0046	48.2
M4A	Normal	296	6090	2.40	1389	0.0062	47.5
M4B	Overfinish	224	4591	2.48	1370	0.0061	47.4

### *Effects of Both Heat and Wind and Overfinishing*

Specimens M3,5 and N3,5, subjected to treatment 3, combined heat and wind and overfinishing, showed surprising and contradictory results. In all cases the average pull-off strength of the treated surface was less than that of the untreated surface. In three specimens (M5; N3,5) the surface scaling resistance of the treated surface was greater than that of the untreated surface. The fourth specimen (M3) showed approximately equal durability for the two surfaces. Specimen M5 showed the most perplexing behavior. Although the difference in pull-off strength between the treated and untreated surfaces was statistically significant, with the treated surface being weaker, the surface scaling resistance of the treated surface as given by the rate of deterioration was much greater.

One possible explanation for these contradictory results is that there was no real difference in the pull-off strengths of the treated and untreated surfaces, and that the lower indicated strength of the treated surface is the result of extreme scatter in the pull-off test data. However, the significant difference shown by specimen M5 and the consistent trend of the results (i.e., all treated surfaces showing lower pull-off strength) seem to make this explanation unlikely.

A more probable explanation is that pull-off strength and surface scaling resistance are not necessarily directly related and might be affected in a different manner and/or to different degrees by the various treatments. Thus, perhaps the pull-off strength of the treated surface was lowered so greatly by overfinishing (the trend of treatment 3) that the beneficial effects of heat and wind (the trend of treatment 1) were negligible. Conversely, the freeze-thaw durability of the treated surface may have been improved enough by the heat and wind (the trend of treatment 1), that the detrimental effects of overfinishing (the trend of treatment 3) were overcome.

A visual examination of the pull-off failure surfaces indicated that the pull-off strength and surface scaling resistance may not be directly related. In many cases, scattered throughout all of the specimens, it was noted that a coarse aggregate particle near the surface had been included within the cored disk on which the pull-off tests were made. In such a case, a large portion of the failure surface consisted of the mortar-aggregate interface. The failure of the bond between the mortar and aggregate greatly reduced the nominal pull-off strength of such a test as compared to the pull-off strength of an adjacent area in which no coarse aggregate appeared. However the same coarse aggregate particle lying in the same position near the surface might have no appreciable effect on the surface scaling resistance of the concrete. Thus it seems inadvisable to put too much emphasis on the raw data of the pull-off test as an indicator of potential surface scaling resistance.

### *General Observations*

In general, little evidence of a weakened plane or zone was found using either pull-off tests or surface scaling tests. The use of retarded concrete under the conditions described did not result in the phenomenon reported by Ryell (11), in

which the bleed water collected under a prematurely set surface, and there was no apparent relationship between the initial bleeding rate of the concrete and the pull-off strength or surface scaling resistance. Some cracking occurred at the surface of most specimens cast, but the cracks were all very fine and less than 1/16 in. deep. There was no indication that these cracks impaired the durability of the concrete. Thus, it appears that the conditions producing relatively deep scaling indicative of a weakened plane in the field were not reproduced in the laboratory. Perhaps the presence of reinforcing steel alters the settlement rate enough to produce the plane of weakness and also provides restraint so that cracking is more severe in the field situation. The need for further investigation of this phenomenon is apparent.

As mentioned earlier, the results of the pull-off tests exhibited a great deal of scatter. There are several probable reasons for this. The pull-off test is a form of direct tension test and thus includes all of the inherent weaknesses of such a test, particularly the difficulty encountered in obtaining a truly axial tensile force. Coarse aggregate particles lying near the surface of the cored disk can exert a large influence on the nominal tensile strength due to bond failure at the mortar-aggregate interface, and it is also possible that the coring produced defects in the concrete. Any or all of these, in addition to the heterogeneous nature of concrete itself, could have caused the large amount of scatter. This scatter is possibly the reason for the poor correlation between the pull-off tests and the surface scaling tests.

### **CONCLUSIONS AND SUGGESTED RESEARCH**

The following conclusions based on this portion of the investigation appear to be valid:

1. Excessive surface manipulation lowers the surface scaling resistance of concrete, especially if the manipulation occurs during the bleeding period. Therefore, the amount of finishing should be kept to a minimum, and as little finishing as possible should take place during the bleeding period.
2. For the specific conditions imposed by the procedures in this investigation, the surface scaling resistance of the treated surfaces was improved by the application of heat and wind. In the field, however, the same conditions might have detrimental effects due to the increased possibility of plastic shrinkage cracking.
3. The pull-off test is not a reliable indicator of potential surface scaling resistance. The pull-off test might be developed as a laboratory procedure for investigating the effects of various surface treatments on the nominal tensile strength of the concrete, but surface scaling tests are still necessary for an indication of the effects on durability.
4. No evidence of the formation of a weakened plane was found under the laboratory conditions that were used. This does not exclude the possibility that such a plane might form under slightly different conditions.

As previously noted, the formation of a weakened plane has often been proposed as a possible cause of deterioration of concrete, although little experimental evidence has been

presented to confirm the hypothesis. It seems profitable to continue investigation in this area using concrete with reinforcing near the surface. This would perhaps alter the settlement rate of the concrete near the surface and also provide restraint to shrinkage, which could cause deeper cracking than was produced in previous investigations.

With regard to cracking in the surface, an hypothesis for a failure of the weakened plane type is proposed. Microscopic studies of concrete have shown that a region of micro-cracks exists at the coarse aggregate-mortar interface. If, during finishing, a more or less continuous layer of

coarse aggregate were to form beneath the top layer of mortar, a weakened plane might be present due to the micro-cracks. This plane might not be detectable with surface pull-off tests, due to the random nature of the bond cracking, but a crack propagating through the surface might, upon reaching such a weakened plane, expend its energy in the direction of the plane, increasing and extending the micro-cracks and perhaps ultimately leading to failure. An investigation of the possible formation of such a weakened plane would be useful.

## APPENDIX D

### ANNOTATED BIBLIOGRAPHY

#### 1930

1. "Progress Report of Committee on Curing of Concrete Pavement Slabs." *Proc. HRB*, Vol. 10, pp. 370-408 (1930).

A survey of surface conditions of selected highways resulted in the following conclusions being drawn: (1) Calcium chloride surface applications used as a curing method under normal conditions is not a primary cause of scaling; (2) If conditions conducive to scaling are present, the scale will probably occur to some extent under either earth and water or calcium chloride surface methods of curing. The data also indicate strongly that (a) the percentage of scaling increases as the silt content of the fine aggregate increases when the final finishing operations and general construction methods are similar, (b) too much and too late finishing are contributory causes of scaling that are independent of the laitance removal operation and materials used, and (c) the extent of scaling was greater where hand finishing was employed than where mechanical finishers were used.

#### 1932

2. LAWTON, E. C., "Progress in Determining Suitability of Concrete Pavement Aggregates." *Proc. 8th Ann. Conv., Assoc. of Highway Officials of North Atlantic States*, p. 175 (1932).

Scaling in concrete occurs in the mortar and thus must be caused by deficiencies in either the sand or the cement. In all probability, absorption of moisture by the sand particles causes a change in the volume of the particle, hence in the concrete itself. Such volume changes tend to disintegrate the concrete and thus, in order to check scaling, careful acceptance tests for sands are necessary.

#### 1933

3. COMMITTEE ON MAINTENANCE, "Treatment of Icy Pavements." *Proc. HRB*, Vol. 13, Part 1, pp. 330-339 (1933).  
Laboratory tests were run to determine the effects

of calcium and sodium chloride on the surfaces of concretes subjected to repeated freezing and thawing. Also, an attempt was made to evaluate means of pretreating the surface with various coatings to protect the concrete from scaling when deicing salts are used. Conclusions are that (1) the disintegration that may occur in connection with the treatment of icy pavements with chlorides is not due to the action of the chlorides, but rather to the repeated freezing-and-thawing action produced by the treatment; (2) the use of sodium chloride is more detrimental than the use of calcium chloride, although both increase the pitting and scaling occurring due to repeated freeze-thaw cycles; (3) the amount of chert, shale, or soft stone existing near the surface of the concrete is one of the most important factors controlling the severity of pitting and scaling; and (4) coating the concrete did not prove of value in protecting it.

#### 1934

4. BOGUE, R. H., LERCH, W., and TAYLOR, W. C., "Portland Cement Pastes—Influence of Composition on Volume Constancy and Salt Resistance." *Ind. Eng. Chem.*, Vol. 26, No. 10, p. 1049 (1934).

The effects of cement composition on the volume changes of pastes stored in water and in air and on their resistance to the action of solutions containing salts were investigated. Volume changes are considered from the viewpoint of hydration, colloidal swelling, and the formation of secondary products. Salt action is considered from the viewpoint of the formation of addition products and reactions of base exchange.

#### 1937

5. GONNERMAN, H. F., TIMMS, A. G., and TAYLOR, T. G., "Effect of Calcium Chloride and Sodium Chloride on Concrete When Used for Ice Removal." *Progress Report, Proc. Amer. Conc. Inst.*, Vol. 33, p. 107 (1937).

Tests were run to find methods of treating the

surface of existing concrete pavements to prevent their scaling and to discover ways to reduce the tendency of concrete surfaces to scale when subjected to calcium and sodium chloride applications. Freeze-thaw and wetting-and-drying methods were used to test the usefulness of surface treatments. The results showed that boiled linseed oil and soybean oil were superior to other treatments, including stearic acid and crankcase oil. Where the use of sodium or calcium chloride is considered necessary, either for ice removal or in combination with granular materials to provide traction, it is recommended that the pavement be thoroughly brushed and then treated with boiled linseed oil thinned by an equal volume of turpentine.

6. "Surface Scaling of Concrete Roads." *Contr. and Eng. Monthly*, Vol. 34, No. 5, p. 27 (1937).

The causes of scaling are not easy to determine, but it is generally agreed that proper curing will partially alleviate the problem. Improper finishing techniques, shrinkage cracking, freezing and thawing, and the addition of deicing salts may also promote scaling.

#### 1938

7. BRATT, A. V., "A Preliminary Report of an Investigation of the Behavior of Blended Cement Concrete Road Surfaces." *Proc. 14th Ann. Conv.*, Assoc. of Highway Officials of North Atlantic States, p. 186 (1938).

Cores taken from test sections of a highway, after going through freezing and thawing in a calcium chloride solution, revealed that concrete made with natural cement blends was more resistant to deterioration than concrete made with straight portland cement.

8. MATTIMORE, H. S., "Chloride-Salts-Resistant Concrete in Pavements—Discussion." *Proc. 14th Ann. Conv.*, Assoc. of Highway Officials of North Atlantic States, p. 168 (1938).

More detailed comparison of cements would be of value in the investigation concerning effects of natural cement blends on scaling resistance of concrete. Some further tests should be carried out to try to determine the differences in the cores under test which were made with cement of apparently identical composition.

9. PAUL, I., "Chloride-Salts-Resistant Concrete in Pavements." *Proc. 14th Ann. Conv.*, Assoc. of Highway Officials of North Atlantic States, p. 144 (1938).

An extensive field and laboratory study of the effects of variations in cements on scaling resistance of concrete reveals that concretes made with a blend of natural cement and portland cement are markedly superior to concretes made with straight portland cement. Results from test roads in New York State and freeze-thaw tests on concrete cores both confirm this.

10. TRAVER, R. B., "Chloride-Salts-Resistant Concrete in Pavements—Discussion." *Proc. 14th Ann. Conv.*, Assoc. of Highway Officials of North Atlantic States, p. 173 (1938).

Field tests have shown that blended-cement concrete is highly resistant to both sodium and calcium chloride in normal and highly concentrated treatments. Also, straight portland cement

concrete does not develop immunity to chloride attack in three years if the attack is in concentration sufficient to melt the ice.

#### 1940

11. MOORE, O. L., "Pavement Scaling Successfully Checked." *Eng. News-Rec.*, Vol. 125, No. 15, p. 471 (1940).

Study of concrete scaling caused by use of chlorides to clear icy roads led to the discovery that minute amounts of grease in the cement account for the superior resistance of some concretes. Further laboratory work indicated that scaling could be prevented by grinding a rosin product into the cement. A test road subjected to intensified calcium chloride attack during two winters confirmed the finding that portland cement containing 0.05 percent of this material does not scale. Fineness of the cement had little effect, and amount of mixing water, although important, was not the major factor.

12. "Utah Studies Scaling of Concrete Pavements." *Western Constr. News*, Vol. 15, No. 12, p. 407 (1940).

In a field test, the Utah State Road Commission is studying a new method for reducing the scaling of concrete pavement during winter weather, and especially after the application of deicing agents. Vinsol resin is added to the cement immediately before its final grinding. On the lane where this resin-treated cement was used, the concrete was highly workable and handled well under the finishing process. Excess surface moisture was eliminated at the conclusion of the finishing work.

13. WICKESBERG, A. W., "Pavement Spalling, Causes and a Suggested Remedy." *Pub. Works*, Vol. 71, No. 6, p. 26 (1940).

Extensive and ever-increasing use of deicing agents on concrete pavements has caused deterioration of the concrete. The fact that older pavements do not suffer nearly as much as newer ones suggests that the concrete is vulnerable to this deterioration only during its first few years. If some protection were given the pavement during its early life, the problem would be solved. Such protection might be a protective coating of boiled linseed oil applied right after the curing process.

#### 1941

14. ANDERSON, A. A., "Experimental Test Data in Connection with the Development of Chloride Resisting Concrete by the Use of Treated Portland Cements and Blends with Natural Cement." *Proc. 71th Ann. Conv.*, Assoc. of Highway Officials of North Atlantic States, p. 67 (1941).

Field and laboratory tests show that concrete having excellent durability can be produced with portland cements ground with minute quantities of certain fatty or resinous materials. The durability is even better than that of concretes made with natural cement blends. The increased durability attained by the use of treated cements seems to be a function of the air entrained in the concrete during mixing. The resulting concrete is cohesive and practically free from bleeding and segregation. The optimum air content is 3 to 6 percent by volume.



ways, which should provide a wide base for field observation of the effectiveness of the method.

#### 1950

34. JACKSON, F. H., "A Way to Better Pavement Concrete." *Proc. Amer. Conc. Inst.*, Vol. 46, p. 489 (1950).

The lack of durability of much of present-day concrete may be due to construction methods. The author does not believe that air entrainment is necessarily the final answer to the problem of surface deterioration and suggests that construction practices in general should be overhauled, as well as the present method of controlling aggregate gradation. This conclusion was reached through comparison of construction methods in the United States with those of Germany and Great Britain.

35. SWAYZE, M. A., "Finishing and Curing: A Key to Durable Concrete Surfaces." *Proc. Amer. Conc. Inst.*, Vol. 47, p. 317 (1950).

After a comparison of past and present pavement curing and finishing techniques, the significance of timing and character of finishing and the timing and mode of curing is discussed. Laboratory tests are cited to show the effect of time at finishing and curing on surface durability to freezing and thawing. It is recommended that all concrete exposed to frost contain entrained air, have a low water-cement ratio, and be thoroughly compacted after placing. A finishing and curing procedure is suggested which is adapted to the ambient conditions and to the hydration needs of the cement.

#### 1954

36. *Experimental Use of Oil-Solvent Treatment to Control Salt Scale of Concrete Pavement.* Illinois Div. of Highways, Bur. of Res. and Planning, Illinois Highway Res. Proj. No. 17, Progress Report No. 1 (Apr. 1954); *Highway Res. Abstr.* (July 1954).

A comprehensive field experiment was undertaken by the Illinois Division of Highways in 1951 to obtain more positive information concerning the effectiveness of the oil-solvent treatment in Illinois. The test sections and treatment procedures are described and a tabulation is presented showing the number and amount of applications of sodium and calcium chlorides for the winter of 1951-52. By late 1952, scale had not occurred on either the treated or untreated sections.

Concurrent with the oil-solvent treatment studies, a laboratory study has been under way to determine the air content of cores taken from several Chicago pavements, portions of which showed salt damage even though air-entrainment had been specified. The results have shown that where scaling did occur, the hardened concrete did not contain the proper amount of entrained air, and in undamaged sections the proper amount of air was present in nearly all cases.

37. HANSEN, W. C., "Effect of Age of Concrete on Its Resistance to Scaling Caused by Using Calcium Chloride for Ice Removal." *Proc. Amer. Conc. Inst.*, Vol. 50, p. 341 (1954).

Field tests were made to determine the effect of concrete age, at the time of first application of deicing salt, on frost resistance and salt action. Specimens were made with Types I and IA and a mix-

ture of the two cements, yielding concretes with air contents of 1.5, 3.0, and 5.0 percent. Ice was removed with flake calcium chloride. Fifty-five cycles of freezing and thawing were obtained.

Except for specimens 117 and 91 days in age at the first freeze, those made with concrete containing 1.5 percent air were completely scaled in from 5 to 15 cycles. Complete scaling was obtained in less than 55 cycles with concrete containing 3 percent air only in specimens of 29 days or less in age at the time of first freeze, and with concrete containing 5 percent air only on specimens 8 days or less in age at the first freeze.

#### 1955

38. KIEGER, P., "Effect of Atmospheric Conditions During the Bleeding Period and Time of Finishing on the Scale Resistance of Concrete." *Proc. Amer. Conc. Inst.*, Vol. 52, p. 309 (1955).

Specimens of both non-air-entrained and air-entrained concrete were subjected during the bleeding period to variations in wind velocity and temperature, and given final finishes at different times during bleeding.

Test results indicated that air-entrained concrete scale resistance after 250 cycles of freezing and thawing was not influenced by any of the treatments.

Both the rate and amount of bleeding and resistance to surface scaling of non-air-entrained concrete increased with an increase in surface air velocity. Temperature at pouring had little effect on scaling resistance.

Non-air-entrained concrete struck off immediately after casting showed greater scale resistance than that given a second and final finish during the bleeding period. Concrete finished only once near the end of the bleeding period also showed greater scale resistance than that finished twice during the bleeding period.

#### 1956

39. TIMMS, A. G., "Resistance of Concrete Surfaces to Scaling Action of Ice-Removal Agents." *HRB Bull.* 128, pp. 20-50 (1956).

A resume is given of the investigations conducted to test materials and procedures for protecting concrete pavements against scaling and disintegration caused by calcium chloride and other thawing agents used for ice removal. A laboratory investigation by the Bureau of Public Roads was started in 1948 on methods of protecting the wearing surface of concrete against the action of calcium chloride. Later a similar study was made of the effect of outdoor weather conditions on small slabs on the ground. It was found that resistance to scaling is affected by air content, type of air-entraining admixture, surface treatments or coats, admixtures of oils, inhibitors, flyash as a replacement for portland cement, rate of application of calcium chloride, curing methods, thawing agents other than calcium chloride or common salt, and vacuum methods of placing concrete.

1957

40. HARTMAN, E., "Über die Wirkung von Frost und Tausalzen auf Beton ohne und mit luftporenbildenden Zusatzmitteln." *Zement-Kalk-Gips*, Vol. 10, p. 265 (1957).

The increasingly extensive use in recent years of deicing salts in winter road maintenance in some cases has given rise to damage to the surfaces of concrete roads. Tests to determine the cause of damage yielded no indication that the deicing salts affect the concrete by chemical attack, osmosis, or crystallization pressure. It was shown, however, that the damage was caused by the consumption of melting heat and the consequent rapid cooling of the upper layers of the concrete. The sharp changes in temperature produce stresses in the inelastic and already frozen layer of fine mortar which cause disintegration. At temperatures only a little below the freezing point unfrozen water may still be present in a deeper zone parallel to the surface of the concrete. The rapid cooling of the concrete causes this water to freeze very quickly, producing spalling of the whole layer above it. Both types of damage are thus due to the very rapid cooling of the concrete. This sudden cooling constitutes a danger, even to concrete which is otherwise frost-resistant.

41. KLIENER, P. "Curing Requirements for Scale Resistance of Concrete." *HRB Bull.* 150, pp. 18-31 (1957).

Freeze-thaw tests were run on samples of air-entrained and non-air-entrained concrete cured at different temperatures and for different lengths of time. Results showed that non-air-entrained concrete has little resistance to surface scaling resulting from the use of deicers. Increased time of curing helps, but not much. Air-entrained concrete has a high resistance to surface scaling resulting from the use of calcium chloride as a deicer. However, adequate curing is required before a deicer may be safely used. At temperatures above freezing this curing time is little more than the time needed to develop a level of strength sufficient to carry traffic loads. At lower temperatures an accelerator will reduce the curing period. A curing temperature below freezing results in an excessively long curing period. The development of a certain level of strength has merit as an index to the amount of curing required for air-entrained concrete prior to permitting the use of deicers.

42. VERBECK, G., and KLIENER, P., "Studies of 'Salt' Scaling of Concrete." *HRB Bull.* 150, pp. 1-13 (1957).

Tests at the Portland Cement Association research laboratories were run to provide new information on the effect of deicers on the surface scaling of non-air-entrained and air-entrained concretes, each made with two different coarse aggregates, cured differently, and tested under a variety of scale test procedures. Chemically dissimilar materials caused "salt" scaling and low concentrations of deicer produced more surface scaling than higher concentrations or the absence of deicer. On this basis it appears that the scaling mechanism is primarily physical rather than chemical. No scaling was produced when the concrete surface had no free water on it during the freeze portion of the cycle, and a period of air drying

prior to the start of scaling tests increased the resistance to surface scaling. Surface scale test procedures greatly influenced the rate of scaling and differences in resistance to scaling were noted for concretes made with different sand and gravel.

1958

43. BRITTON, H. B., "New York State's Experience in Use of Silicones." *HRB Bull.* 197, pp. 13-23 (1958).

The New York State Highway Department carried on both laboratory and field testing to study the rate of absorption of water, freezing-and-thawing resistance, resistance to sodium chloride action, and light reflectance of concrete pavements treated with silicone or petroleum distillates in comparison with like specimens having no treatment. Results indicate pavements treated with silicone to be superior in all cases.

In laboratory freeze-thaw tests, blocks treated with silicone showed no failures for either air-entrained or non-air-entrained concrete. Field data on ten bridge structures support the laboratory results.

44. ODEMARK, N., and ENGMAN, S., *Experiments with Protective Coatings and with Methods of Repairing a Scaled Concrete Road*. State Road Inst., Stockholm, Sweden, Report 31 (1957) (Summary in English); *Highway Res. Abstr.* (July 1958).

Experimental work was done with various surface coatings used to prevent further scaling on roads in Sweden subjected to deicing agents. The coatings tested included concentrated water glass, diluted water glass and calcium chloride, a mixture of diesel fuel and white spirit, a water-repelling silicone product, and a plastic product. It was found, in comparison with untreated slabs, that treatments of the kind tested have no noticeable effect on the development of scaling.

Experimentation with methods of repairing scaled concrete is also reported.

1959

45. BERGSTROM, S. G., *Deterioration of Concrete Pavements Due to Salting in Winter Time*, Swedish Cement and Conc. Res. Inst. (Royal Inst. of Technology, Stockholm, Sweden), Applied Studies No. 3 (1959). (In Swedish: summary in English); *Highway Res. Abstr.* (Oct. 1959).

Salt treatment in winter has repeatedly caused damage to concrete pavements, and also to other concrete structures in Sweden. During the years from 1954 to 1958 extensive field and laboratory investigations were made to find out how concrete roads should be constructed to resist scaling. Investigated were the effects produced by air-entrainment, cement content, aggregate gradation, vibration, post-compaction, vacuum treatment, and curing.

1960

46. ADAMS, A., "Durability of Concrete in Maine Bridges Built Since 1947." *Highway Res. Correlation Serv. Circ.* 411, pp. 1-8 (Feb. 1960).

A survey revealed that air-entrained concrete bridges showed a large improvement in durability over bridges built with non-air-entrained concrete. In the deteriorated bridges the low side on super-

elevated bridge decks usually had more deterioration than the high side.

47. MIESENHELDER, P. D., "Effect of Design and Details on Concrete Deterioration." *Proc. Amer. Conc. Inst.*, Vol. 56, p. 581 (1960).

Deterioration is often thought of as a consequence of the number of times freezing and thawing occurs, but in the examples pictured the major factor is the high degree of saturation which existed at the time of freezing. This high degree of saturation is usually a consequence of inadequate or no drainage provisions at critical points.

48. RHODES, C. C., and FINNEY, E. A., "Final Report on Durability Project, Michigan Test Road." *Proc. HRB*, Vol. 39, pp. 217-309 (1960).

A test road was designed to study the effect on the durability of concrete of (a) proportioning and grading of aggregates, (b) admixtures, (c) natural cement blends, (d) limestone aggregates, and (e) finishing and curing. Supplementary laboratory studies preceded and accompanied the construction and evaluation of the pavement. A pattern set in earlier accelerated durability tests was followed in that the air-entrained concretes exceeded all others in durability and the sections with limestone aggregates were the first to require resurfacing.

#### 1961

49. DILLON, R. M., and EDWARDS, P. H. D., "The Inspection, Repair and Maintenance of Highway Bridges in London, Ontario." *Eng. Jour. (Canadian)*, Vol. 44, No. 11, p. 39 (1961); *Highway Res. Abstr.*, (Feb. 1962).

In the fall of 1959, a section of deck collapsed on the Dundas St. Bridge in London, Ont. The investigations described in this paper revealed that the condition of many of the bridges was worse than might have been expected. The cause in part is attributed to the increasing use of deicing chemicals.

50. LAWRENCE, M., and VIVIAN, H. E., "Action of Calcium Chloride on Mortar and Concrete." *Jour. Appl. Chem.*, Vol. 11, pt. 7, pp. ii-10 (July 1961); *Highway Res. Abstr.* (Oct. 1961).

Severe disruption of hardened cement paste, mortar, or concrete when 30 percent aq.  $\text{CaCl}_2$  penetrates deeply into these is ascribed to a reaction between  $3\text{CaO}$ ,  $\text{Al}_2\text{O}_3$ ,  $n\text{H}_2\text{O}$ , and  $\text{CaCl}_2$  to form calcium chloride aluminate. With high  $\text{Al}_2\text{O}_3$  cement disruption is negligible in dense mixes, but there is rapid collapse of porous mortars and concretes; chlorine probably reacts with the hydrated ferrite phase. The effect is analogous to sulfate attack and is prevented by exclusion of solutions from contact with concrete, use of dense mixes or impermeable surface films, or rapidly modifying the susceptible hydration products to insure absence of reactive material after set.

51. MCGOVERN, J. F., "Water Is the Number One Enemy in the Maintenance of Structures." *Better Roads*, Vol. 31, p. 15 (1961).

Water is a primary enemy of concrete and chlorides used in snow and ice removal act as water attractors. The freezing and thawing of this aqueous solution has a detrimental effect on concrete surfaces. Several methods have been suggested to keep water out of concrete and thus reduce frost

action. These include membrane waterproofing, surface coatings on curbs and fences, coal tar emulsions, crack patching with epoxy materials, urethane resins, and oil treatments.

A new method of interest in the protection of bridge decks is the use of polyurethane foam to insulate the underneath side of the bridge. This reduces heat loss in the pavement and the need for excessive amounts of deicers.

52. ROBERTS, J. A., and VIVIAN, H. E., "Further Studies on the Action of Salt Solutions on Cracked Mortar." *Austral. Jour. Appl. Sci.*, Vol. 12, No. 3 (1961); *Jour. Amer. Ceramic Soc.*, *Ceramic Abstr.*, Vol. 45, No. 1 (Jan. 1962); *Highway Res. Abstr.* (July 1962).

The widening of cracks by the action of salt solutions was studied in mortars containing surface-active agents that entrain air. In many instances the presence of the surface-active agents tended to reduce the expansive action of the salt solutions on the cracks. Cracks treated with water-repellent silicone solutions were also less affected by subsequent treatment with salt solutions. Other important effects studied included the slow positive expansion of specimens subjected to cycles of wetting by salt solution and drying; the expansion of cracked mortar specimens subjected to salt solution penetration when restrained by superincumbent loads; and the expansions induced by ions of different size and charge.

#### 1962

53. ATEN, C. E., "Visual Examination of Structural Damage in Wisconsin." *HRB Bull.* 323, pp. 15-18 (1962).

Maintenance reports of the Wisconsin Highway Department indicate an obvious lack of any set pattern or factor than can be pinpointed as the major cause of surface deterioration in highway bridges. Since the institution of a wholesale program of pavement deicing in 1956, the concrete pavements have undergone more serious deterioration than before. The more vulnerable spots for deterioration are described and possible reasons for this deterioration are presented with the theory that air-entrainment, together with an increase in cement content, will provide the maximum resistance to surface scaling.

A discussion concerns observations made at the PCA Research and Development Laboratories on the effect of variations in air entrainment on surface scaling of concrete.

54. AXON, E. O., GOTHAM, D. E., and CONCH, R. W., "Investigation Techniques Used or Contemplated." *HRB Bull.* 323, pp. 3-11 (1962).

The Missouri State Highway Department is carrying on a detailed study of the deterioration of bridge deck concrete, including both a field survey and laboratory testing of cores taken from bridges. A rather extensive terminology of types and stages of deterioration used by the Missouri Highway Department in the survey of damaged decks is presented. The tests presently being used to evaluate core samples are discussed, with no specific data being presented or discussed.

55. FAUL, A. F., and MCELHERNE, T. E., "Survey Technique and Iowa Experience." *HRB Bull.* 323, pp. 19-22 (1962).

The bridge survey instituted by the Iowa State

Highway Department produced the observation that scaling was not a serious problem, due primarily to the localized nature of the problem. A series of construction recommendations was made to minimize future problems. The data were summarized as to the frequency of each defined detrimental characteristic, and the practice of treating pavements with linseed oil emulsion was discussed.

56. FINNEY, E. A., "Preventive Measures for Obtaining Scale-Free Concrete Bridge Structures." *HRB Bull.* 323, pp. 26-42 (1962).

The use of proven control procedures is suggested as the logical approach to scale-free structures. The procedures are divided into those undertaken before construction, during construction, and after construction.

Essential factors related to construction control of air-entrainment, aggregate soundness, excess water, and protection are discussed, based on the experiences of the Michigan Highway Department. Experience has shown that linseed oil is a satisfactory surface treatment superior to any water repellents and surface penetrants. Adequate maintenance of bridges is emphasized as being one of the major deterrents to scaling.

57. GRIEB, W. E., WERNER, G., and WOOLF, D. O., "Resistance of Concrete Surfaces to Scaling by Deicing Agents." *HRB Bull.* 323, pp. 43-62 (1962).

Results of tests conducted on slabs produce an insight into the effects of forming methods, surface finishing, air-entrainment, cement type, fly ash, cement alkali content, and protective treatments on surface scaling. The slabs were subjected to freezing and thawing in a climate similar to that of Washington, D. C.

Deep scaling was produced on all non-air-entrained slabs; with some exceptions, air-entraining admixtures gave excellent resistance to calcium chloride action.

A limited number of laboratory specimens showed calcium chloride to be more desirable than sodium chloride or urea as a deicing agent.

58. KIEGER, P., and FOUNTAIN, R. S., "A Cooperative Bridge Deck Study." *HRB Bull.* 323, pp. 23-25 (1962).

A bridge study undertaken by the Bureau of Public Roads, a number of state highway departments, and the Portland Cement Association is discussed in terms of organization and purposes. The method of data reduction and the random sampling procedure is presently just beyond the planning stage.

59. LANG, C. H., "Restoration and Protection of Damaged Concrete." *HRB Bull.* 323, pp. 63-65 (1962).

The New York State Thruway Authority has done considerable work in restoring disintegrated concrete structures. New methods and materials have been developed that are both satisfactory in their results and flexible in their application. One such material is "jet-crete" a coal tar-pitch emulsion applied to the surface of deteriorating concrete structures.

60. LINDSAY, J. D., "A Survey of Air-Entrained Structures in Illinois." *HRB Bull.* 323, pp. 12-14 (1962).

A general discussion of the results of an inspection of all bridges built from 1947 to 1959 in Illinois discloses that bridges subjected to lesser amounts of ice removal salts showed the same amount of dam-

age as did bridges in the northernmost districts of the state. These observations are contrasted with laboratory tests showing increased scaling due to sodium chloride and calcium chloride applications.

The investigations are to be followed by testing of specimens obtained from selected bridge sites and a study of protective coatings.

The procedure followed in the bridge investigations is presented, including the terminology used in reporting the observations of disintegration.

61. SMITH, P., "Observations on Protective Surface Coatings for Exposed or Asphalt-Surfaced Concrete." *HRB Bull.* 323, pp. 72-96 (1962).

Results of inspection of treated structures and pavements, controlled field trials, and laboratory evaluations performed by the Ontario Department of Highways indicate that the more conventional surface coatings, such as linseed oil and bituminous products, prove to be more effective than certain epoxy resins and silicones as protective surface coatings for concrete.

The testing program is not finished, but sufficient data are available to allow certain observations to be made.

Effects of using permanently installed steel deck forms, polyurethane foam coatings as insulation, and complete covering of all concrete surfaces are discussed in terms of their effect on the critical problem of ensuring a low moisture content in the material. Control of air-entrainment during construction is emphasized.

#### 1963

62. "Better Roads Forum: Protection and Repair of Bridge Decks." *Better Roads*, Vol. 33, No. 9 (Sept. 1963).

Vermont reports successful use of bituminous concrete pavement on bridge decks, as well as use of granite curbing instead of concrete. Linseed oil has been used successfully in some cases, but epoxy gave poor results in a trial application.

Wisconsin has repaired scaled concrete with asphalt sealcoats and aggregate chips. However, they claim adequate drainage to be most significant in preventing deterioration. Experiments with epoxy have not been satisfactory.

63. CORDON, W. A., and MERRILL, D., "Requirements for Freezing-and-Thawing Durability for Concrete." *Proc. ASTM*, Vol. 63, p. 1026 (1963).

Specification requirements for concrete durability have not changed commensurate with increased knowledge and research developed during the past 20 years. This paper is a short review of current thinking on the causes of concrete deterioration due to freezing-and-thawing action. Laboratory test results made with a wide variety of materials and mix proportions are reported. A method for arriving at required cement contents and air contents based on required strength and required durability is discussed.

64. HANSEN, W. C., "Crystal Growth as a Source of Expansion in Portland Cement Concrete." *Proc. ASTM*, Vol. 63, p. 932 (1963).

Research shows that a salt crystal can grow under pressure if it is supported on a film of solution which can receive salt molecules from a solution that is supersaturated with respect to the crystal under pres-

sure. It also shows that an ice crystal can grow under pressure if it is supported on a film of water in contact with a reservoir of water in which ice crystals cannot nucleate at the temperature at which the ice crystal is growing. Also outlined are the conditions under which ice and salt crystals can grow and produce pressures in concrete and similar porous materials.

65. HAVENS, J. H., and DRAKE, W. B., *Concrete Bridge Decks: Deterioration, Coatings and Repairs*. Highway Materials Res. Lab., Lexington, Ky. (Feb. 1963).

An historical account is given of damage sustained by both new and old concrete bridge decks under the action of deicing agents and freezing and thawing. Relief from scaling is being sought through improved construction practices, air-entrainment, and protective coatings. A special construction technique which minimizes excess working of concrete in finishing bridge decks is described. Coatings and methods of repair for bridge decks are also discussed.

66. KROKOSKY, E. M., and DAOUK, A. M., *Bridge Deck Scaling and Organic Inhibitors*, Massachusetts Inst. of Tech. Res. Rep. R63-33 (July 1963).

A general review has been made of some of the factors that affect bridge deck scaling, such as air content, concrete age, finishing, and deicing agents. The theoretical aspects of concrete bridge deck scaling are discussed, with specific reference to physical factors such as capillary structure and ice formation. Models were developed to explain the method of deterioration of pavements due to over-finishing and deicing agents.

This report also presents results on a series of laboratory tests in which latex water-based emulsions of polymers (butadiene styrene, polyvinylidene chloride, polyvinyl acetate, etc.) were employed to inhibit scaling. In addition, tests were conducted to check the relation between strength and durability of these organic modified concretes.

67. MCGOVERN, R. W., "Protection of Concrete from Deteriorous Effects of Ice Removal Chemicals." *Highway Res. Record No. 14*, pp. 24-28 (1963).

Some experiences using a coal tar compound to protect portland cement concrete from the harmful effects of chlorides are described. Test slabs with and without this treatment were subjected to freeze-thaw tests and calcium chloride solutions. The treated specimen in both tests showed no signs of distress. Experience with several field applications of the coal tar sealer during the past five years show that it definitely retards or prevents damage from ice removal chemicals to portland cement concrete used in highway and bridge deck construction.

#### 1964

68. *A Review of Literature Treating Various Aspects of Bridge Deck Concrete Durability*. Intermediate Report, Pennsylvania State Univ., Dept. of Civil Eng., Materials Research Report (Apr. 1964), p. 18.

Severe exposure coupled with often inferior concrete has caused bridge deck concrete deterioration to be a matter of national concern. This report presents a review of recent literature treating subjects closely related to concrete bridge deterioration and summarizes important findings to date on basic prop-

erties and design of concrete, construction procedures, corrosion of steel reinforcement, and surveys of service environment, treatment, and condition.

69. DYKINS, F. A., and BLANDIN, F. H., "Field and Laboratory Air-Content Studies of Salt-Damaged Concrete Structures." *Highway Res. Record No. 62*, pp. 7-12 (1964).

To determine the uniformity and effectiveness of air-entrainment, and the extent of damage to air-entrained concrete bridges attributable to the action of salt, an investigation of all structures constructed in Illinois with air-entrained concrete was started in 1960. Of the 879 bridges surveyed, 503 were studied in some detail and 67 were given a thorough investigation, including drilling of cores for air-content studies. The adequacy of the entrained air and preventive measures and treatments are discussed.

#### 1965

70. *Durability of Concrete Bridge Decks*. Report 1, A Co-operative Study. State Highway Commission of Kansas, U.S. Bureau of Public Roads, Portland Cement Association (1965).

Field investigations were made on 18 bridge decks in Kansas and cores from these decks were examined in the laboratory using air content measurements, chloride analyses, pulse velocity measurements, and petrographic examination. Cracking of the bridge decks and variations in surface air void parameters are discussed in detail.

71. LARSON, T. D., and MALLOY, T. J., "Durability of Bridge Deck Concrete." *Durability Studies of Structural and Paving Concretes*. Pennsylvania State Univ., Dept. of Civil Eng., Materials Research Report (Jan. 1965).

Tests were made on samples taken from various bridge decks throughout Pennsylvania. Void analysis and petrographic examination of samples showed that deterioration was usually associated with low air contents. Other factors observed to affect deterioration were shrinkage cracking, excessive mix water, bleeding channels, and poor compaction. Exposure to excessive amounts of moisture and deicer solution due to poor drainage seemed to accelerate deterioration of the surface concrete.

72. RYELL, J., "An Unusual Case of Surface Deterioration on a Concrete Bridge Deck." *Proc. Amer. Conc. Inst.*, Vol. 62, p. 421 (1965).

Set-retarded concrete placed in a bridge deck and finished with conventional equipment exhibited a severe surface deterioration in the form of flaking several days after paving. Similar concrete placed in the approach slab on a granular subgrade did not flake. Laboratory and field investigations showed that the flaking was due to the formation of a weak plane immediately below the surface of the concrete and was closely connected with bleeding characteristics of the mix.

The solution was found in reducing the bleeding rate of the concrete by a change in the type of set-retarding admixture.

From test specimens cast, finished, and cured under simulated conditions in the laboratory, it was found that bleeding was reduced and flaking prevented if the specimens were cast on a permeable base or if a cover protected the test specimens from the wind and heat.

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