2405

FINAL REPORT

PLACEMENT OF LOW-SLUMP CONCRETE

by

H. Celik Ozyildirim
Research Scientist

(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

Virginia Highway & Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the Virginia Department of Highways & Transportation and the University of Virginia)

In Cooperation with the U. S. Department of Transportation
Federal Highway Administration

Charlottesville, Virginia

January 1981

VHTRC 81-R33

2406

CONCRETE RESEARCH ADVISORY COMMITTEE

J. E. GALLOWAY, JR., Chairman, Asst. Materials Engineer, VDH&T

T. R. BLACKBURN, District Materials Engineer, VDH&T

C. L. CHAMBERS, Division Structural Engineer, FHWA

W. R. DAVIDSON, Asst. Maintenance Engineer, VDH&T

E. ESTES, Chairman of Civil Engineering Technology, Old Dominion University

J. G. HALL, Materials Engineer, VDH&T

F. C. MCCORMICK, Department of Civil Engineering, U. Va.

W. R. MUSTAIN, Assistant District Engineer, VDH&T

A. D. NEWMAN, District Materials Engineer, VDH&T

H. C. OZYILDIRIM, Highway Research Scientist, VH&TRC

W. T. RAMEY, District Bridge Engineer, VDH&T

J. F. J. VOLGYI, JR., Bridge Design Engineer, VDH&T

W. E. WINFREY, Assistant Construction Engineer, VDH&T

SUMMARY

Low-slump concrete is being used on bridge decks mainly to prevent or minimize spalling and delaminations resulting from corrosion of the reinforcing steel. Other beneficial effects reported include high strength and durability. This study investigated the field conditions necessary to achieve dense, impervious, good quality low-slump concrete that would provide long-lasting bridge decks. The parameters considered were consolidation, texturing, bonding, freezing and thawing durability, and permeability.

When placed under the conditions of this study, low-slump concrete retained a comparatively large number of coarse voids because of its stiff consistency. Specimens consolidated manually by rodding and vigorous tapping exhibited better consolidation than those compacted by mechanical vibrators. However, the permeability studies indicated that even though the low-slump concrete specimens contained more coarse voids than desired, they can provide a resistance to the penetration of chlorides comparable to that provided by ordinary bridge deck concretes of good quality.

To provide a satisfactory bond between the low-slump overlay and the base concrete, the surface of the latter must be sandblasted and cleaned. Conventional metal tines did not provide the deep surface texture desired for the low-slump concrete, but proper texturing could be obtained with a metal roller.

PLACEMENT OF LOW-SLUMP CONCRETE

by

H. Celik Ozyildirim
Research Scientist

INTRODUCTION

The corrosion of reinforcing bars in concrete bridge decks leads to durability problems in the form of spalling or delaminations that affect the ride quality of the decks. Later stages of corrosion result in more serious conditions, since the carrying capacities of the structures are lowered because of a decrease in the cross section of the reinforcing bars. When corrosion occurs, it is necessary that transportation agencies conduct costly maintenance programs to extend the service life of the affected concretes and structures.[1] One of the principal causes of such corrosion has been shown to be the intrusion of chloride ions into the concrete.

One of the methods used to prevent or minimize corrosion is to construct the deck with a dense, low-slump overlay to prevent the chloride from penetrating to the level of the steel. This system was used on a bridge deck at Port Royal, Virginia. In addition to the minimization of corrosion, it was expected that beneficial effects such as high strength and wear resistance and improved resistance to freezing and thawing could also be achieved. The placement of the overlay was monitored to document the procedures for placing low-slump concrete. Characteristics such as consolidation, texturing, bond between the layers, freezing and thawing durability, and permeability were determined in an attempt to establish optimum procedures.

The level of consolidation in the overlay was investigated utilizing a Troxler 3411 nuclear gage and the results are presented in another report.[2]

BACKGROUND

The corrosion of reinforcing bars is an electrochemical process that takes place in the presence of an electrolyte, moisture, and oxygen. The reinforcing bar itself acts both as the anode, where corrosion takes place, and the cathode, which provides the ionic balance.[1] Soluble chlorides, when present in sufficient concentration in concrete, act as the electrolyte. The chlorides are contributed mainly by the deicing chemicals applied to the surface of the concrete to melt ice in the winter months.[3]

During the corrosion process, rust is formed that occupies more space than the parent metal and consequently causes high tensile stresses to develop in the concrete.[4] As a result, cracks develop in the concrete and lead to delaminations and, eventually, spalling of the concrete above the reinforcing bars. Concrete with low permeability hinders the penetration of water and chlorides to the level of steel and thus provides resistance to corrosion. ACI Committee 201 recommends that the water/cement ratio should not exceed 0.40 for concrete exposed to severely corrosive environments such as high concentrations of chlorides at the water or ground line.[5] Some agencies have adopted lower values than 0.40 by attaining a w/c of 0.328 in low-slump mixtures. In addition to a low w/c, good quality materials, good consolidation and finishing practices, and proper curing are needed to achieve low permeability. Any cracks that result from poor concreting practices or from structural inadequacies also would increase the permeability.

Low-slump concrete was first used in the sixties for repairs and overlays, especially in Iowa and Kansas.[1] Widespread use in Iowa has led to the term "Iowa Method" for this system of repairs and overlays. The low-slump concrete mixtures have a low w/c of 0.328 and a slump of 3/4 in. ± 1/4 in. (19 mm ± 6 mm).[6] Air entrainment is added to protect the mixtures from cycles of freezing and thawing. When properly mixed, consolidated, and cured, the mixtures have compressive strengths of about 9,000 psi (62.1 MPa).[6] Consolidation is very critical because of the stiff consistency of the mixture requiring special equipment.[7] To assure the desired degree of consolidation, frequent checks are made with a nuclear density gage.[1]

PURPOSE AND SCOPE

The objective of this study was to study low-slump concrete in the field and in the laboratory in an attempt to provide dense, impervious, good quality concrete for long-lasting concrete decks. The parameters considered were consolidation, texturing, bonding, freezing and thawing durability, and permeability. In determining the last named parameter, tests on absorption and chloride penetration were made, petrographic examinations were conducted and the effect of curing was determined.

The study included observations and tests on field and laboratory concrete at the fresh and hardened stages. The scope of the testing program is given in Table 1. The field installation of base concrete and the low-slump overlay is described in Appendix A.

Table 1 — The Scope of the Testing Program

Type of Test	No. of Samples
1. Petrographic Examination:	
a) Air content by the linear traverse method	18
b) Visual microscopic examination for consolidation	18
c) Polished surface to study the bond area	16
d) Thin sections to study the bond area	10
e) Ultra-thin sections for the permeability study	12
2. Shear strength	48
3. Resistance to cycles of freezing and thawing	10
4. Absorption	26
5. Resistance to the penetration of chlorides	64
6. Compressive strength	53

CONSOLIDATION

Adequate Consolidation

Adequate consolidation reduces the amount and the size of entrapped coarse air voids in concrete. ACI Committee 116's definition of compaction, which is synonymous with consolidation, cites the elimination of voids other than those resulting from the use of an air-entraining agent.(8) The definition of entrapped air voids indicates that these are less useful than the purposefully entrained voids and are 1 mm or larger in size.

Approaches for evaluating adequate consolidation are described in detail in another report.(2) In the method used at the Research Council, the voids observed on a lapped surface are separated into two groups, those smaller than 1 mm (0.04 in.) in diameter and those larger. The voids less than 1 mm are considered entrained air voids and those larger are called coarse voids. The latter generally are entrapped air voids resulting from lack of consolidation or water voids resulting from excess water in the mixture. But whatever their source, the ACI definition identifies these as the voids to be eliminated by adequate consolidation. Because low-slump concretes contain no excess water to contribute significantly to the formation of coarse voids, these are attributed mainly to entrapped air generated during mixing, placement, and consolidation of the mixture.

In specification concretes considered to be properly compacted, the volume of coarse voids has been found to be less than 2%, a value that relates well to the percentage of air in the matrix of mixtures reported by Powers.(9) Powers indicates that the void content of a properly consolidated matrix without air entrainment is about 5% of the matrix volume, which converts to about 1.6% in low-slump concretes.

Consolidation in Low-Slump Concrete

Methods of Consolidation Used in Study

The low-slump concrete used in the deck overlay was consolidated using a vibratory screed at the recommended frequency of vibration of from 4,500 to 5,000 cycles per minute. To determine the level of consolidation achieved by the finishing machine, cores were obtained from the deck.

During placement of the overlay, the slump, air content, and unit weight of the fresh concrete were determined, and specimens were prepared for various tests on hardened concrete. The consolidation of the field specimens, including the concrete in the unit weight bucket, was accomplished (1) by rodding the mixture and tapping the sides of the forms vigorously to close the "postholes" (designated R in Table 2); (2) by rodding, tapping, and using an external vibrator (designated R + E); (3) by rodding, tapping, and using external vibration with a surcharge on the concrete (designated R + E + S). The surcharge provided a pressure of 50 lb./ft.^{2} (2.39 kPa) and was intended to simulate the specified 75 lb./ft.^{2} (3.59 kPa) pressure exerted by the finishing machine. In cases (2) and (3) above, the tapping was not as vigorous as in (1), since it was hoped that further vibration would close any postholes. The frequency of external vibration was 3,300 cycles per minute. The data on the w/c, slump, air content, unit weight, and compressive strength for different methods of consolidation are given in Table B-1 of Appendix B. There were small variations in the w/c as explained in Appendix A under the heading Overlay Concrete.

A limited laboratory investigation was made on the effect of the fine aggregate portion on the workability and thus the consolidation of fresh low-slump concrete. Concrete batches were prepared by varying the fine aggregate and coarse aggregate portions in ratios of 45/55, 47/53 and 50/50. The mixture proportions are given in Table C-1 of Appendix C. The materials were obtained from the bridge project, except for the fine aggregate used for the 47/53 ratio, which had a particle shape similar to that of the project sand as indicated by very close void contents of 47.8% and 47.2%, respectively. The specimens prepared from the lab mixtures were consolidated by rodding and vigorous tapping. The slump, air content, unit weight, and compressive strength of the specimens are given in Table C-2 of Appendix C.

Unit Weight vs. Method of Consolidation

Unit weight measurements were made on concretes prepared in the field and in the laboratory and consolidated by the various methods noted above. The unit weights for single samples from each of the batches corrected for the specified 5.5% total air, in descending order, and the method of consolidation are shown in Table 2. The average unit weight for rodded and vigorously tapped specimens was 146.7 lb./ft.^{3} (2,349 kg/m^3), with a coefficient of variation of 1.1%. The specimens subjected to external vibration exhibited an average value of 145.2 lb./ft.^{3} with a coefficient of variation of 0.1%. It can be seen that the specimens rodded and tapped vigorously exhibited higher unit weights than the specimens rodded, lightly tapped, and subjected to external vibration. The small change in w/c for the mixtures did not have any significant effects on the results. The one sample that utilized external vibration and a surcharge exhibited as high a unit weight as did the rodded and vigorously tapped specimens.

Petrographic Examination as a Means of Determining Consolidation

The cores obtained from the deck, the specimens prepared in the field, and the laboratory specimens were finely lapped and subjected to petrographic examination. This consisted of a linear traverse analysis to determine quantitative data and in addition a microstructural visual examination to obtain qualitative data on the void structure. In the linear traverse data the percentage of voids larger than 1 mm in diameter in a plane is assumed to be indicative of the level of consolidation. The linear traverse data on the cores, field cylinders, and laboratory cylinders are given in Appendix Tables B-2, B-3, and C-3, respectively. Table 3 lists the coarse voids in ascending order and shows their relation to the method of consolidation. The results, in general, indicate that all the cores consolidated by the vibratory screed and the field specimens subjected to external vibration had more than 2% coarse voids. The rodded and vigorously tapped specimens had a lower percentage than the specimens subjected to external vibration. The one specimen subjected to a surcharge exhibited the highest percentage of coarse voids, even though a high unit weight value was obtained when the surcharge was used.

TABLE 2

Unit Weights and Methods of Consolidation

Location	Water/Cement Ratio	Unit Weight, lb./ft.^{3}	Method of Consolidation
Field	0.328	150.9	R
Field	0.328	149.1	R
Field	0.345	146.5	R + E + S
Lab	0.328	146.4	R
Field	0.345	146.3	R
Field	0.345	146.2	R
Lab	0.328	146.2	R
Field	0.328	146.1	R
Lab	0.328	146.1	R
Lab	0.328	145.8	R
Lab	0.328	145.7	R
Field	0.345	145.6	R
Lab	0.328	145.6	R
Field	0.328	145.3	R + E
Field	0.328	145.3	R + E
Field	0.345	145.1	R + E

NOTE: 1 lb./ft.^{3} = 16.01 kg/m^3

TABLE 3

Percentage of Air Voids Larger than 1 mm in Diameter and Methods of Consolidation

Location	Air > 1 mm, %	Method
Lab	1.0	R
Field	1.2	R
Lab	1.5	R
Lab	1.6	R
Lab	1.7	R
Field	1.7	R
Lab	2.2	R
Field*	2.2	E
Lab	2.3	R
Field	2.3	R + E
Field*	2.5	E
Field*	2.6	E
Field*	2.9	E
Field*	3.0	E
Field*	3.2	E
Field*	3.3	E
Field	3.4	R + E + S

*Cores from the deck consolidated by the vibratory screed. The other field specimens were cylinders.

The laboratory mixtures that had a fine to coarse aggregate ratio of 45/55 had 1.3% coarse voids. For the 47/53 ratio, the voids were 1.6% and for the 50/50 ratio they amounted to 2.2%. These findings are consistent with the concept of an optimum ratio of fine to coarse aggregate explained by Powers.(9) The percentage of sand in the aggregate affects the paste content and the voids ratio in aggregate, which in turn would affect the level of consolidation and the volume of voids. Increasing the sand ratio above the optimum value would tend to increase the coarse voids, as was observed in the laboratory mixtures.

The microstructural examination of the cores indicated the presence of a large number of coarse voids as shown in Figure 1. The specimens that were rodded and vigorously tapped also exhibited large voids, as shown in Figure 2, but the amount was less and the size smaller than those present in the specimens subjected to vibration.

Summary and Results

The unit weight measurements indicated that denser concretes were achieved by rodding the materials in the buckets and then vigorously tapping the sides of the buckets rather than by rodding the mixtures, lightly tapping the buckets, and subjecting them to external vibration. Similarly, the petrographic examination revealed that concretes rodded and vigorously tapped exhibited a lesser amount of coarse voids than the specimens rodded and subjected to external vibration and those consolidated by the vibratory screed. For the concrete to which a surcharge was applied in addition to rodding and external vibration, a high unit weight was attained by ASTM C138 but the linear traverse data indicated a large amount of coarse voids. Because only one sample was available, this anomaly is not explained.

The variation in w/c from 0.328 to 0.345 did not significantly change the percentage of coarse voids. Therefore, it is assumed that significant improvements in workability and thus in the level of consolidation were not achieved by this small variation. Increasing the fine aggregate fraction from 45% to 50% tended to result in a larger volume of coarse voids for the materials used. These data indicate that the mixtures and materials used were incompatible with the vibration characteristics of the equipment utilized.

2416

Figure 1. Core exhibiting a large number of coarse voids. The width of the specimen is 4 in. (100 mm).

Figure 2. Polished surface of cylinder prepared in the field by rodding and vigorous tapping. The width of the sample is 4 in. (100 mm).

TEXTURING

To provide a satisfactory skid resistance and facilitate the drainage of surface water, the bridge deck overlay at Port Royal was initially textured transversely using a rake with flexible metal tines. Two textures attained by this method are shown in Figures D-1 and D-2 of Appendix D. Because of the stiffness of the low-slump concrete only a shallow, inadequate texture could generally be achieved with the flexible tines. The tines tended to lay flat on the surface of the concrete and to disturb aggregates along the sides of the grooves as they were pulled. To achieve deeper textures, nails in a piece of wood were drawn along the surface. Two textures thus attained are shown in Appendix Figures D-3 and D-4. The grooves were deep but the surface was generally torn as aggregates were pulled from the surface by the nails. Sometimes the surface was highly disturbed as shown in Figure D-4.

Subsequently, the roller shown in Figure D-5 was prepared by machining a metal rod to the dimensions given in Figure D-6. When rolled on the surface, the rod indents equally spaced grooves as shown in Figure D-7. The roller also eliminated the problem of disturbing the surface. To achieve the desired groove depth of about 1/8 in. (3 mm), it was sometimes necessary to add weights on the frame of the roller.

BONDING

In two-course bridge deck construction it is important that a good bond be achieved between the base concrete and the overlay to avoid the formation of a weak zone immediately above the top reinforcing steel. The good bond enables the layers to act as a unit. Some states, including Iowa,[6] apply a thin coating of bonding grout with stiff brooms on the cleaned, dry surface of base concrete immediately in front of the paver to ensure a satisfactory bond. However, previous work at the Research Council in relation to a satisfactory bond between fresh and hardened concretes had shown that a plain bonded interface is sufficient. This work also had demonstrated that roughening the base layer is not required.[10] While the study cited did not include low-slump concrete overlays, the findings indicated that the application of slurry or grout was not necessary. It was also reasoned that if such a coating were left to dry it would cause considerable damage to the bond. Consequently, no grout was used on the subject bridge deck.

The surface of the base concrete of the deck was textured in the fresh stage with metal tines to provide mechanical interlock between the layers. Even though this may not be necessary, it would enhance the bond strength and provide a factor of safety. Prior to the placement of the overlay the surface was sandblasted and wetted.

To investigate certain variables that affect the bond between the base concrete and the low-slump overlay, a limited laboratory study was undertaken. The variables were dry versus saturated surface dry base layers and slurry and grout bonding agents and their degree of wetness. Lab specimens were fabricated and subjected to shear tests and petrographic examination. Also, field cores were subjected to petrographic examination to investigate the quality of the bond. These laboratory and field studies are discussed in Appendix E.

Based on studies by the Portland Cement Association, a shear strength of 200 lb./in.^{2} (1.38 MPa) or even less is believed to be adequate for satisfactory bond.(11) The laboratory specimens tested indicated, as shown in Table E-3 in Appendix E, that values averaging from 602 lb./in.^{2} (4.2 MPa) to 780 lb./in.^{2} (5.4 MPa) for different variables are obtained if proper consolidation is achieved.

A petrographic examination revealed that a thin, dense carbonation layer or a coarse aggregate at the surface of the base concrete or the wet bonding agent could cause a thin layer high in water content at the bond. This finding indicates that a dry base concrete surface with no slurry or grout is the preferable condition, provided the surface temperature is not high enough to cause rapid drying of the overlay. Other than the above indications, no significant differences among variables were determined by the petrographic examination. The relatively high shear strengths obtained for all variables indicate that all of the procedures could be utilized with good results. However, it is important that all laitance be removed from the surface of the base layer by proper sandblasting, otherwise the presence of a thin layer of fine material at the bond, as shown in Figure 3, can weaken it. Wetting of the base layer is not necessary, except to clean the surface and remove small dust particles.

A petrographic investigation of field cores indicated that a good bond had been achieved, which is consistent with the laboratory findings. In many cases it was difficult to detect the bond areas as can be noted in Figure 1. Sometimes small voids resulting from deep texturing of the base concrete were observed at the bottom of the deep grooves (see Figure 4). These voids

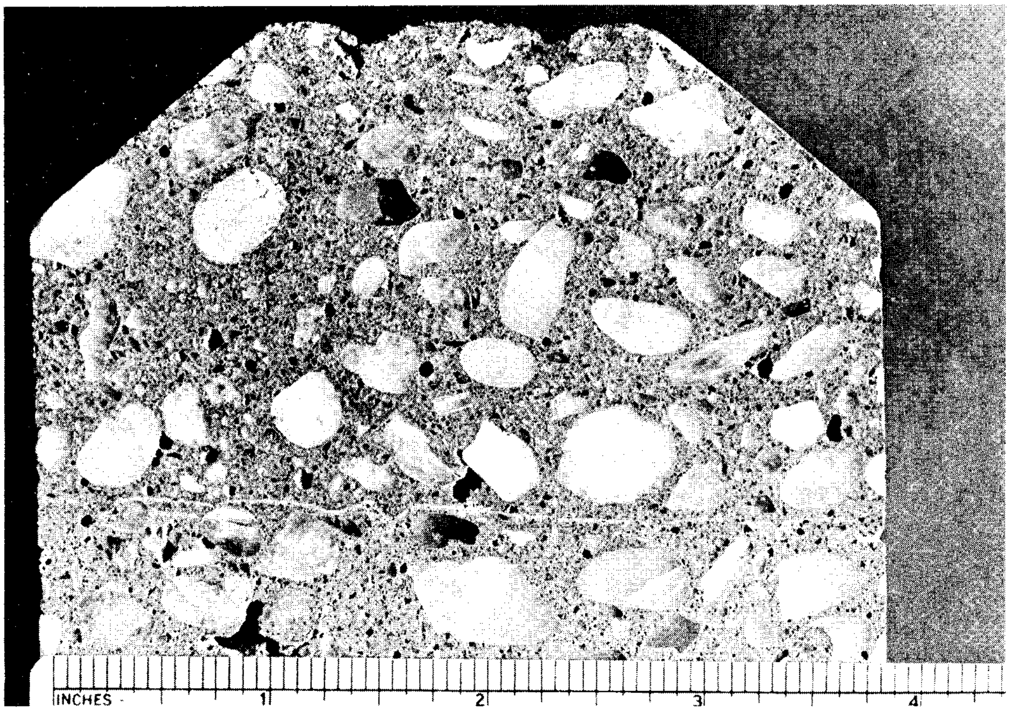

Figure 3. Thin layer of fine material in the bond area.

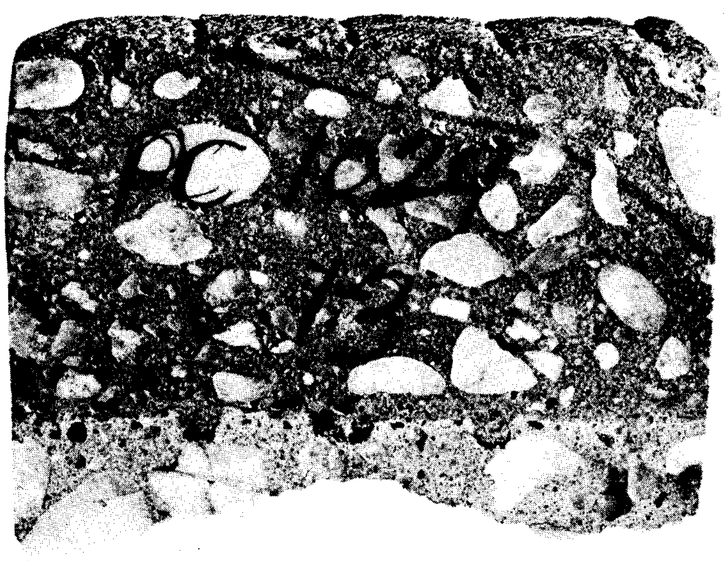

Figure 4. Core exhibiting voids at the bottom of grooves in the bond area.

could result from inadequate consolidation or the drying of excess water at the bottom of the grooves. However, in general, the bond area appeared adequately consolidated, even though numerous coarse voids were observed in the overlay concrete.

FREEZING AND THAWING DURABILITY

The presence of large amounts of coarse voids, especially those close to the surface, raised some questions as to the freezing and thawing durability of low-slump concretes. Prisms measuring 3 x 4 x 16 in. (75 x 100 x 400 mm) were prepared in the field and subjected to rapid freezing and thawing tests in accordance with ASTM C666 Procedure A, except that a 2% NaCl solution surrounded the specimens. The specimens were air dried for a week after the 2-week moist cure. As shown in Table 4, the specimens were prepared from batches for which the fresh concrete properties and the linear traverse data presented in Appendix Tables B-1 and B-2 were obtained.

The performance criteria established at the Research Council for satisfactory resistance to cycles of freezing and thawing is that at 300 cycles the specimens should exhibit a weight loss of 7% or less, a durability factor of 60 or more, and a surface rating of 3 or less. The freeze-thaw data for the subject specimens, summarized in Table 3, indicate a satisfactory resistance. This is in agreement with the satisfactory spacing factors obtained on these concretes and shown in Appendix Table B-3. However, small spalled areas were observed on the specimens as shown in Figure 5. These could have resulted from water freezing in large voids close to the surface.

In general, the freeze-thaw resistance was good and is consistent with the linear traverse data given in Table B-3, where the spacing factors and specific surfaces are generally in the desired range. However, if these concretes become saturated and are subjected to cycles of freezing and thawing, some localized spalling like that shown in Figure 5 would be expected.

PERMEABILITY

Undesirable exposure conditions adversely affect concrete and can result in a shorter service life than intended. For example, the penetration of water into concrete that is subjected to cycles of freezing and thawing makes it susceptible to deterioration. Also, in reinforced concrete subjected to deicers

TABLE 4

Rapid Freezing and Thawing Data at 300 Cyles for Low-Slump Concrete Specimens Prepared in the Field

Specimen	Batch	Weight Loss, %	Durability Factor	Surface Rating
1	1	0.5	83	1.1
2	1	0.1	93	0.9
3	3	0.1	93	0.5
4	3	0.1	91	0.5
5	4	0.2	86	0.6
6	4	0.1	93	0.8
7	4	0.1	94	0.6
8	4	0.1	95	0.4
9	7	0.1	95	0.4
10	7	0.1	91	0.3

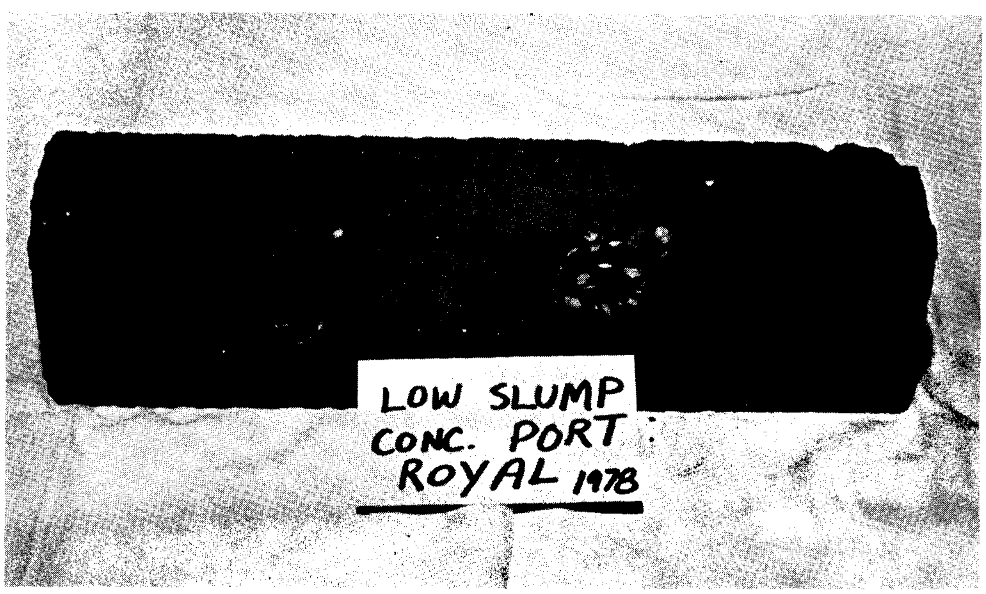

Figure 5. Freeze-thaw specimen exhibiting spalling.

containing chlorides, moisture facilitates the penetration of chlorides to the reinforcing bars and induces corrosion. Because the penetration of water or chlorides depends on the permeability of the concrete, it is desirable to achieve as low a permeability as possible.

The effectiveness of low-slump concrete in eliminating spalling and delamination of structural concrete is related to its ability to keep chlorides from reaching the reinforcing steel. However, large amounts of coarse voids found in the low-slump concretes in the present study indicate a lack of consolidation and raise questions concerning the low permeability of these concretes.

The direct determination of the permeability is difficult and requires special apparatus and sealing of specimens in containers. Tests for absorption, however, which can be made conveniently, can be helpful in determining the watertightness of specimens, even though it is recognized that the permeability of concrete is not necessarily related to the absorption, which measures the volume of accessible pore space. The permeability depends on the size, distribution, and continuity of pores in addition to the volume of pores. In this study, absorption values were obtained for field cores and cylinders. In addition, chloride penetration tests were conducted on field samples.

In the laboratory, batches of concrete were prepared with different ratios of fine to coarse aggregate by volume. Tables C-1, C-2, and C-3 of Appendix C summarize the mixture proportions, the properties, and the linear traverse data for these specimens. Specimens from these batches were used for absorption determinations, petrographic examination, and chloride penetration tests. From each batch, 3 prisms were fabricated and cured differently. The molds were removed after 1 day and one of the prisms in a batch was sprayed with a curing compound; another was put in a moist room for 2 additional days, thus undergoing 3 days of moist curing. The remaining prism was kept in a moist room for 27 days to attain the standard 28-day moist cure. Following ASTM C642, absorption data were obtained on these specimens at a later date. Also, from each of these specimens fluorescent dye-impregnated, ultra-thin sections were fabricated and a petrographic examination of the microstructure was made. It was anticipated that the observation of the microstructure would give indications of the permeability of these concretes. Further, parts of these prisms were subjected to 2% NaCl solution to determine the level of ingress of chlorides as an indirect measurement of the permeability of the concrete. These studies are described in Appendix F.

The field cylinders had absorption values averaging 3.6% compared to values averaging 4.9% for the field cores as shown in Appendix Tables F-1 and F-2. This finding is consistent with the earlier results showing the amount of coarse voids in cylinders to be lower than that found in cores representing different methods of consolidation.

The laboratory specimens had absorption values averaging 4.4% as given in Table F-3. The specimens moist cured for 28 days showed lower values than those moist cured for 3 days and the samples to which curing compound was applied. The laboratory specimens utilizing a fine to coarse aggregate ratio of 50/50 generally had higher absorption values than those with a ratio of 45/55. This finding is consistent with the results of the linear traverse analysis summarized in Table C-3, which indicated larger amounts of coarse voids in the former.

The petrographic examination showed that the 28-day-moist-cured specimens had denser hydration products at shallow depths, especially depths of 0.04-in. (1 mm) or less, than those cured under other conditions. Differences between the 3-day-moist-cured specimens and those to which curing compound was applied could not be detected in the internal structures at shallow depths. The microstructures of all specimens were similar at depths exceeding 0.2 in. (5 mm).

The chloride penetration tests on cores exhibited results comparable to those obtained on specimens made from a good quality bridge deck concrete previously prepared in the laboratory (see Appendix F-4). At the 1/4-in. (6 mm) depth, the cores averaged 102% of the laboratory specimens, and at the 3/4-in. (19 mm) depth, they averaged 82%. For the cylinders from the field and the recent laboratory specimens subjected to chloride penetration, the chloride values at the 3/4-in. (19 mm) depth were lower than the threshold value of 1.65 lb./yd.^{3} (0.98 kg/m^3).

The permeability studies indicate that even though low-slump concretes had larger amounts of coarse voids than desired, their resistance to penetration is expected to be comparable to that of good quality bridge deck concrete.

COMPRESSIVE STRENGTH

The compressive strengths of 6 x 12 in. (150 x 300 mm) cylinders prepared from low-slump concretes in the field averaged from 6,300 lb./in.^{2} (43.4 MPa) to 8,690 lb./in.^{2} (59.9 MPa) for 3 specimens as shown in Table B-1 of Appendix B. The specimens

2424

rodded and vigorously tapped had higher strengths than those rodded, lightly tapped, and subjected to external vibration. In the laboratory, specimens were prepared using different fine aggregate to total aggregate ratios by volume. Cylinders 3 x 6 in. (75 x 150 mm) prepared from low-slump concretes and tested in compression attained compressive strengths ranging from 6,600 lb./in.^{2} (45.5 MPa) to 8,840 lb./in.^{2} (61.0 MPa). Low-slump concretes were prepared for the bond study. The nine 3 x 6 in. (75 x 150 mm) cylinders tested averaged 7,260 lb./in.^{2} (50.1 MPa).

As expected, the compressive strength of low-slump concrete was high because of its w/c, but not as high as the 9,000 lb./in.^{2} (62.1 MPa) reported in the literature.(6)

CONCLUSIONS

The following conclusions are drawn from the study.

1. Low-slump field concretes consolidated by a vibrating screed had more coarse voids than desired, as indicated by the examination of cores taken from the hardened concrete. Manually prepared laboratory or field specimens of low-slump concrete could be consolidated by rodding and vigorous tapping to an extent that the amount of coarse voids was significantly lowered to desirable levels, but some large voids were visible.

2. Difficulties in achieving the desired macrotexture were observed when flexible metal tines or rigid nails were drawn on the surface of low-slump concrete; however, a roller used to indent equally spaced grooves was found to provide the desired surface texture.

3. Tests on field and laboratory specimens indicated that a slurry or grout is not necessary to bond the low-slump overlay to the base concrete. The surface of the base concrete should be sandblasted and cleaned. If water is sprayed on the surface, care should be taken not to form puddles within the indentations of the macrotexture . The macrotexture on base concrete need not be deep.

4. The laboratory investigations showed that good shear strengths can be achieved at the bond area under different moisture conditions at the surface of the base layer, with or without bonding agents. However, it is important to establish a good bond through consolidation and thereby avoid the formation of voids at the bond area.

5. Low-slump concrete with proper air entrainment exhibits satisfactory resistance to damage from cycles of freezing and thawing. However, the coarse voids close to the surface could cause popouts or spalling if the concrete is subjected to cycles of freezing and thawing when saturated.

6. The permeability studies indicate that even though low-slump concretes could exhibit larger coarse voids than desired, their resistance to chloride penetration will be comparable to that of good quality bridge deck concrete.

RECOMMENDATION

The use of low-slump concrete as a protective system, utilizing the materials and techniques available in Virginia for placement, is not recommended at this time because of costs and placement problems, particularly those with consolidation. While indications are that the permeability of low-slump concrete is satisfactory, it is not significantly less than that provided by good quality concrete prepared under Virginia Department of Highways and Transportation specifications.

ACKNOWLEDGEMENTS

The study was performed under the general direction of Jack H. Dillard, state highway research engineer. Special acknowledgement is made of the continuous assistance provided by the Fredericksburg District personnel involved in the placement of the deck overlay on the Port Royal bridge. Appreciation is expressed to Hollis Walker for the petrographic examinations; to Clyde Giannini, Bobby Marshall, Michael Burton, Sallie Miller and David Owen for the preparation and testing of the specimens for the study; and to Arlene Fewell for typing the report.

2428

REFERENCES

1. "Durability of Concrete Bridge Deck", NCHRP No. 57, National Cooperative Highway Research Program, Transportation Research Board, Washington, D. C., May 1979.

2. Ozyildirim, H. C., "Evaluation of a Nuclear Gage for Controlling the Consolidation of Fresh Concrete", VHTRC 81-R41, Virginia Highway and Transportation Research Council, Charlottesville, Virginia, January 1981.

3. Clear, K. C., "Time-to-Corrosion of Reinforcing Steel in Concrete Slabs", FHWA-RD-76-70, Vol. 3, Interim Report, Federal Highway Administration, Washington, D. C., April 1976.

4. Bailey, T., J. L. Beaton, and R. F. Stratfull, "Fundamental Factors Causing Corrosion", HRB Bulletin 182, Highway Research Board, Washington, D. C.

5. ACI Committee 201, "Guide to Durable Concrete", ACI Journal, December 1977.

6. Calvert, G., "The Iowa Method of Bridge Deck Resurfacing", Concrete Construction, June 1978.

7. "Consolidation of Concrete for Pavements, Bridge Decks, and Overlays", NCHRP No. 44, National Cooperative Highway Research Program, Transportation Research Board, Washington, D. C., 1977.

8. ACI Committee 116, Cement and Concrete Terminology, Publication SP-19 (78), American Concrete Institute, Detroit, Michigan, 1978.

9. Powers, T. C., Properties of Fresh Concrete, John Wiley & Sons, Inc., New York.

10. Tyson, S. S., "Internally Sealed Concrete for Bridge Deck Protection — Interim Report No. 1", VHTRC 79-R2, Virginia Highway and Transportation Research Council, July 1978.

11. Felt, E. J., "Resurfacing and Patching Concrete Pavements with Bonded Concrete", Proceedings, Highway Research Board, Washington, D. C., Vol. 35, 1956.

12. Road and Bridge Specifications, Virginia Department of Highways and Transportation, January 1, 1978.

13. Tyson, S. S., "Bonding Fresh Concrete to Hardened Concrete", Master's Thesis, University of Virginia, 1977.

14. Walker, H. N., and B. F. Marshall, "Methods and Equipment Used in Preparing and Examining Fluorescent Ultrathin Sections of P.C. Concrete", Cement Concrete and Aggregates, Vol. 1, No. 1, pp. 3-9, 1979.

15. Walker, H. N., "Evaluation and Adaptation of the Dobrolubov and Romer Method of Microscopic Examination of Hardened Concrete", VHTRC 79-R42, Virginia Highway and Transportation Research Council, April 1979.

APPENDIX A

Experimental Field Installation at Port Royal

EXPERIMENTAL INSTALLATION

The subject bridge on Rte. 301 spans the Rappahannock River at Port Royal, Virginia. It consists of 19 spans, 16 of which are simple spans and the remaining 3 continuous, for a total length of 1,483 ft.-2 in. (451.8 m). The maximum gradient of the deck surface is 4.35%. The simple spans are 68 ft. (20.7 m) long, except the two end spans, which are 68 ft.-1 in. (20.8 m). The middle continuous span is 152 ft.-0 in. (46.3 m) long, and the two adjacent ones are 121 ft.-6 in. (37.0 m) each. An overall view of the bridge is shown in Figure A-1. The deck was built using the two-course bridge deck construction method in which an overlay of 2 in. (50 mm) is placed on a hardened base concrete.

BASE CONCRETE

The base concrete is 5.5 in. (140 mm) thick in the simple spans and 6.5 in. (165 mm) thick in the continuous spans, and meets the requirements of Class A-4 concrete of the Virginia Department of Highways and Transportation,[12] which require a minimum design strength of 4,000 lb./in.^{2} (27.6 MPa). The maximum w/c is 0.47 and the air content specified is 6 1/2% + 1 1/2%. The nominal maximum size of the aggregate is 1 in. (25 mm). Type II cement was used. The fine aggregate was a siliceous, natural sand, and the coarse aggregate either all gravel or a combination of gravel and crushed stone. The batch weights for base concrete are shown in Table A-1 for the batches with gravel (B1) and gravel and crushed stone (B2). A commercially available vinsol resin air-entraining mixture and a retarder were used in all the mixtures.

Table A-1

Mixture Proportions by Weight Ratios of Cement for Class A-4 Base Concrete

Batch	Max. w/c	Cement*	Fine Aggregate	#5 Gravel	#5 Crushed Stone	#7 Gravel
B1	0.47	1	1.55	1.52	--	1.52
B2	0.47	1	1.71	--	1.44	1.44

* Cement Content = 635 lb./yd.^{3} (375 kg/m^3).

The base concrete covered the top reinforcing bars and was textured transversely utilizing metal tines to provide mechanical interlock with the overlay. The texture on the base concrete is shown in Figure A-2. Curing was provided by polyethylene sheets; a curing compound was not used on the base concrete as this could have caused problems in bonding the overlay.

The surface of the hardened base concrete was cleaned by sandblasting and then wetted just prior to being overlaid with the low-slump concrete.

OVERLAY CONCRETE

The low-slump overlay has a higher cement content and a lower w/c compared to regular Class A-4 concrete, as can be seen in Tables A-1 and A-2. The fine and gravel coarse aggregates were similar to those used in the base concrete. However, the maximum size of the coarse aggregate was limited to 1/2 in. (13 mm). The three mixture proportions used for the overlay concrete are given in Table A-2. Initially, a w/c of 0.328 was used. However, because of the presence of a large number of coarse voids, it was increased to achieve a more workable mixture. The upper limit on the w/c was chosen as 0.350, because higher values would cause problems in the finishing process as the vibration of the finishing machine would tend to bring fine material to the surface. The changes in the w/c did not yield a noticeable improvement in the void structure. After the initial stage, a w/c of 0.345 was used. A commercially available vinsol resin air-entraining admixture and a retarder were used in all the mixtures. A slump of 3/4 in. ± 1/4 in. (19 ± 6 mm) for a w/c of 0.328 and 1.5 in. (38 mm) maximum for high ratios was specified, and an air content of 5.5% ± 1.5% was required.

Table A-2

Mixture Proportions by Weight Ratios of Cement for Low-Slump Overlay Concrete for 3 Water-Cement Ratios

w/c	Cement*	Fine Aggregate	Coarse Aggregate
0.328	1	1.54	1.86
0.345	1	1.50	1.86
0.350	1	1.48	1.86

* Cement Content = 823 lb./yd.^{3} (486 kg/m^3).

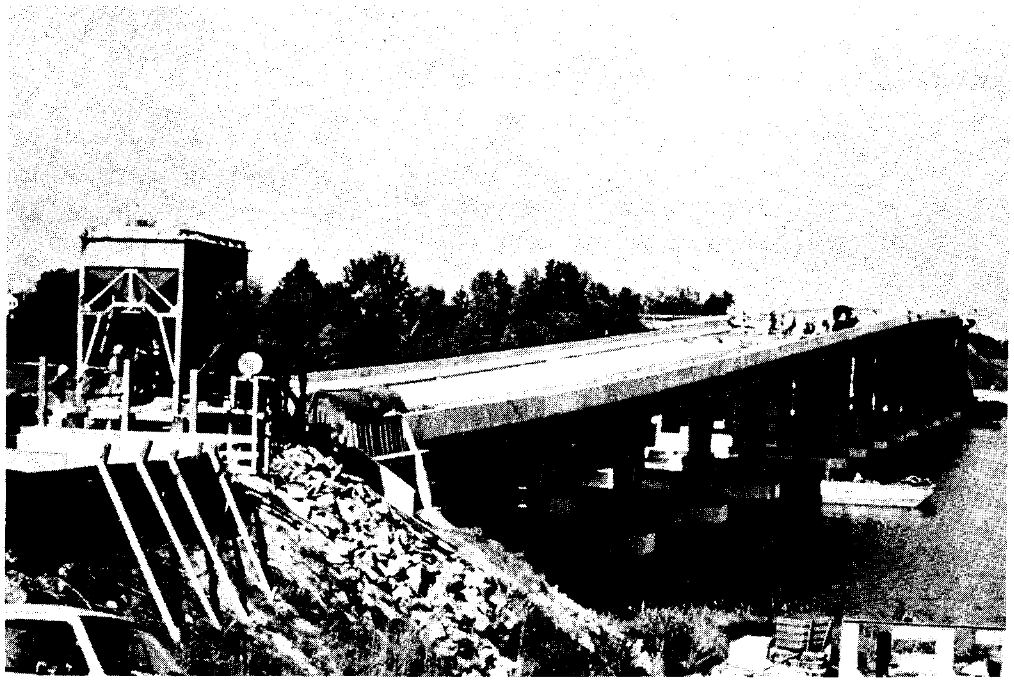

Figure A-1. Bridge on Rte. 301 at Port Royal.

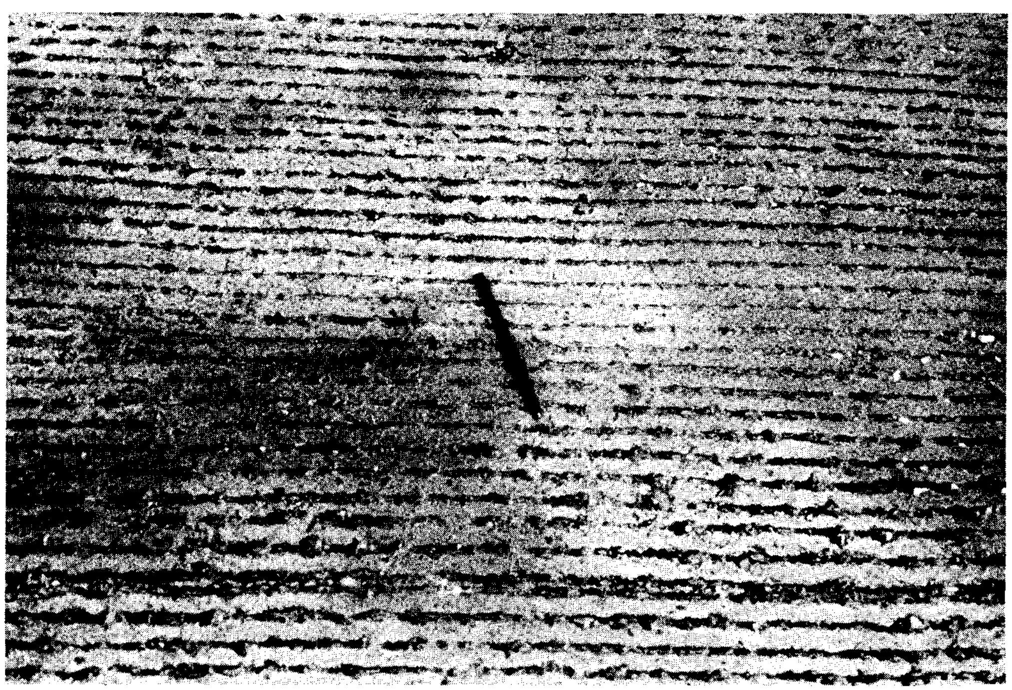

Figure A-2. Transverse texture on base concrete.

The low-slump concrete was mixed at the job site in a paddle type mixer, shown in Figure A-3, that had 1 yd.^{3} (0.8 m^3) capacity, but each time only 18.5 ft.^{3} (0.5 m^3) of concrete was batched for thorough mixing. The concrete was transported to the point of placement by the powered buggies seen in Figure A-4. A special finishing machine designed for compacting and screeding concretes to stiff consistency shown in Figure A-5 was used. The machine had two screeds with the one in the front being of the vibratory type. The concrete was distributed in front of the machine by hand and by an auger attached to the machine. Based on the information furnished by the manufacturer, the machine maintained a vertical pressure of 75 lb./ft.^{2} (3.6 kPa) and the vibratory screed had a frequency of 4,500 - 5,000 cycles per minute. Because of the stiff consistency of the mixture, surface blemishes were formed as shown in Figure A-6. Therefore, hand-finishing was provided behind the finishing machine as seen in Figure A-7.

After the screeding operation, the surface was textured transversely to impart skid resistance, as explained in the body of the report. As soon as possible after the texturing, wet burlap and polyethylene sheeting were placed as shown in Figure A-8. After 24 hours, these were removed and a white pigmented curing compound was applied to the surface. Sometimes only the burlap was removed and the polyethylene sheeting was left for an additional 6 days.

The overlay was placed on the two northbound lanes of the bridge deck in the latter part of 1978 and on the southbound lanes in the latter part of 1979.

The width of the overlay was limited by the width of the screed, and about half of the deck width was laid at a time. Before the second half was placed, a thin strip of concrete about 2 in. (50 mm) wide was cut longitudinally along the previously placed overlay section to straighten the edge and to eliminate any poorly consolidated areas along the edge.

2436

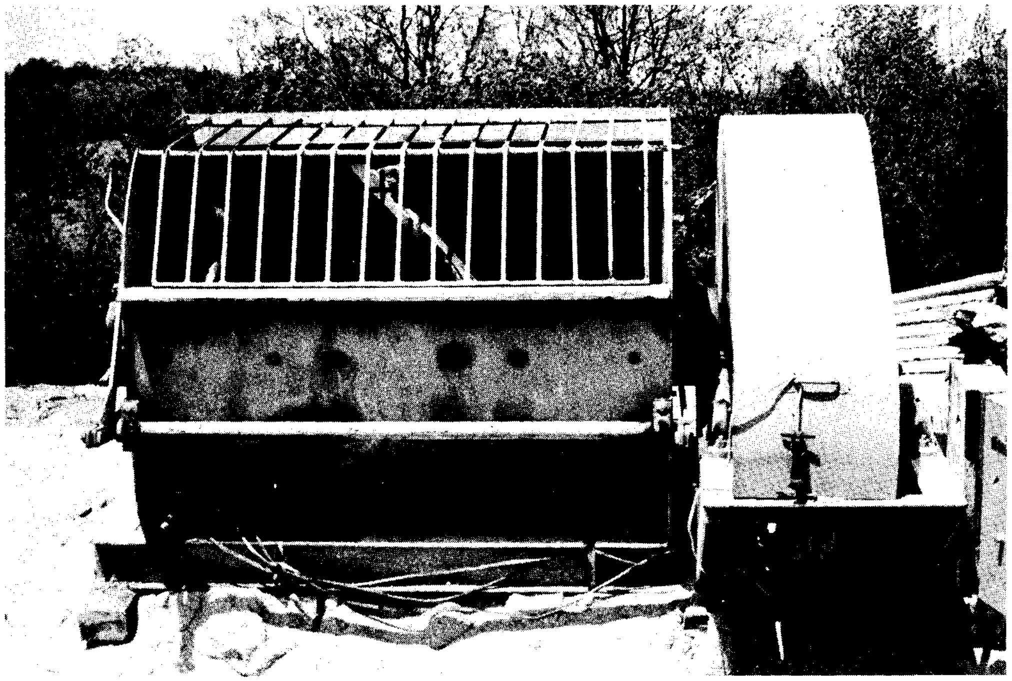

Figure A-3. Paddle type mixer used for low-slump concrete.

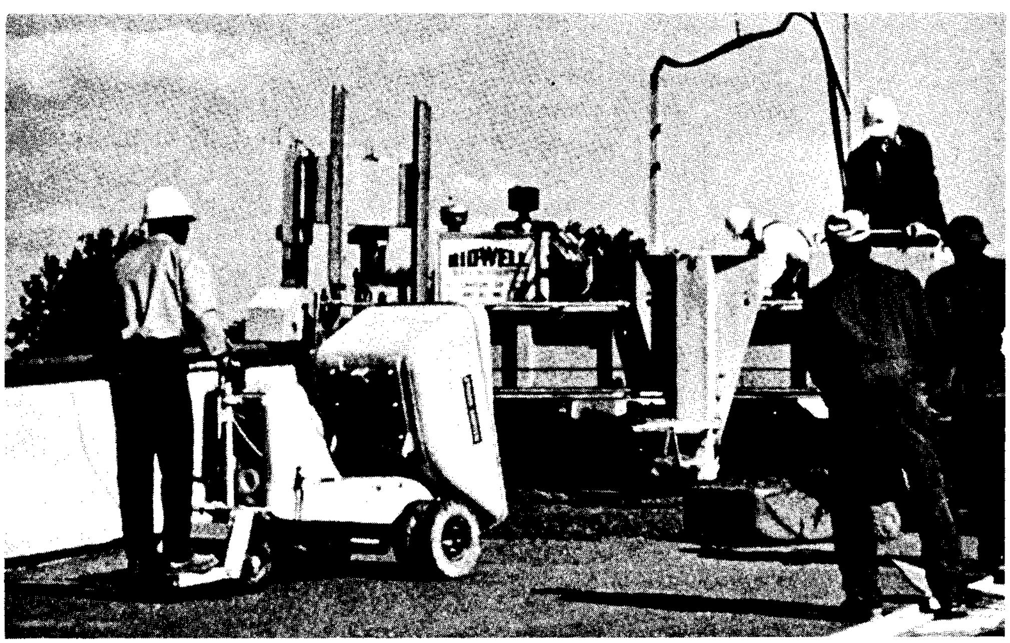

Figure A-4. Powered buggy used to transport concrete.

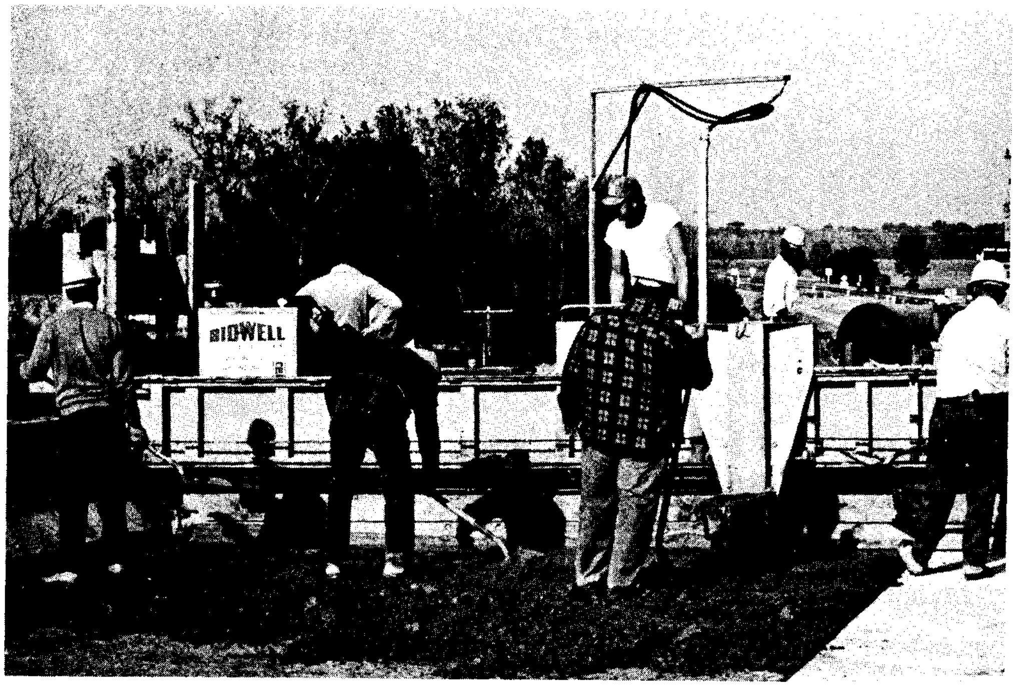

Figure A-5. Finishing machine used for compacting and screeding the low-slump concrete.

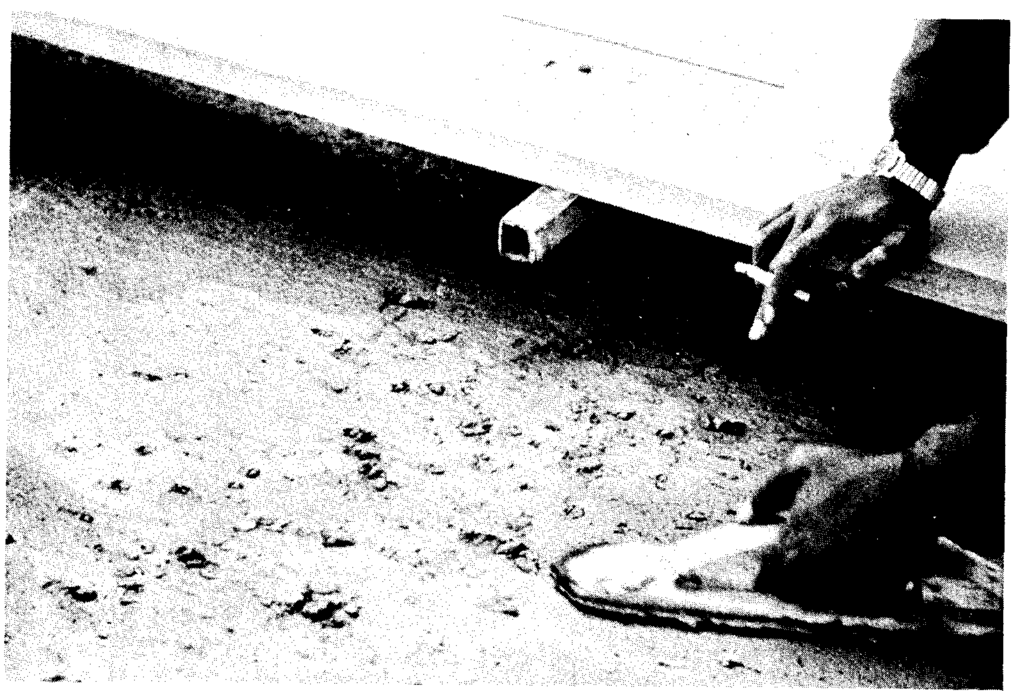

Figure A-6. Surface irregularities observed behind the finishing machine.

2438

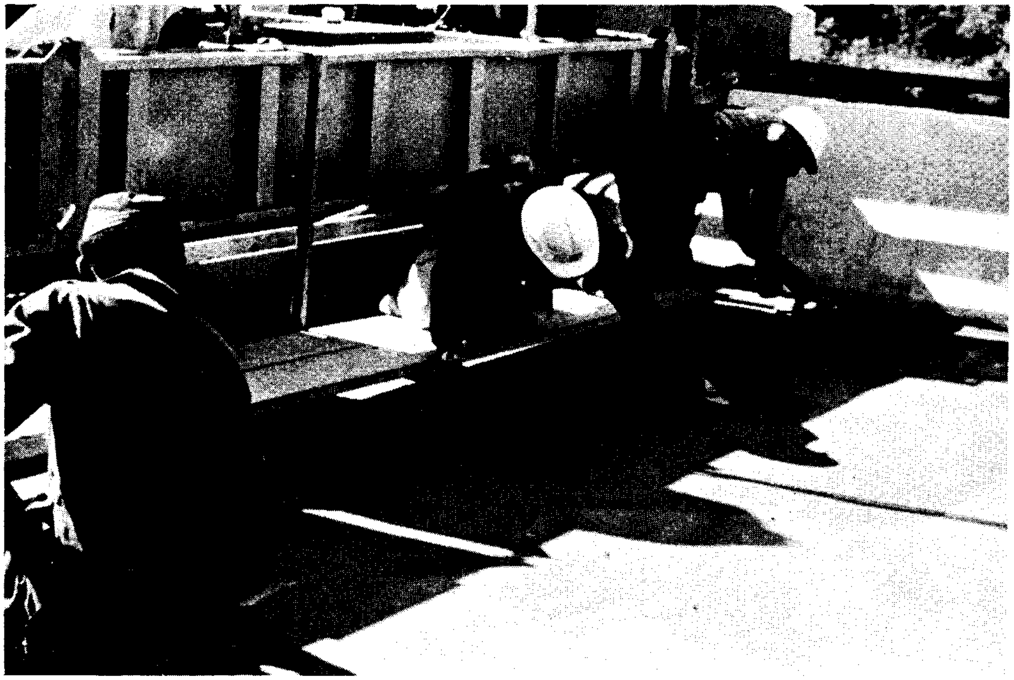

Figure A-7. Hand-finishing behind the finishing machine.

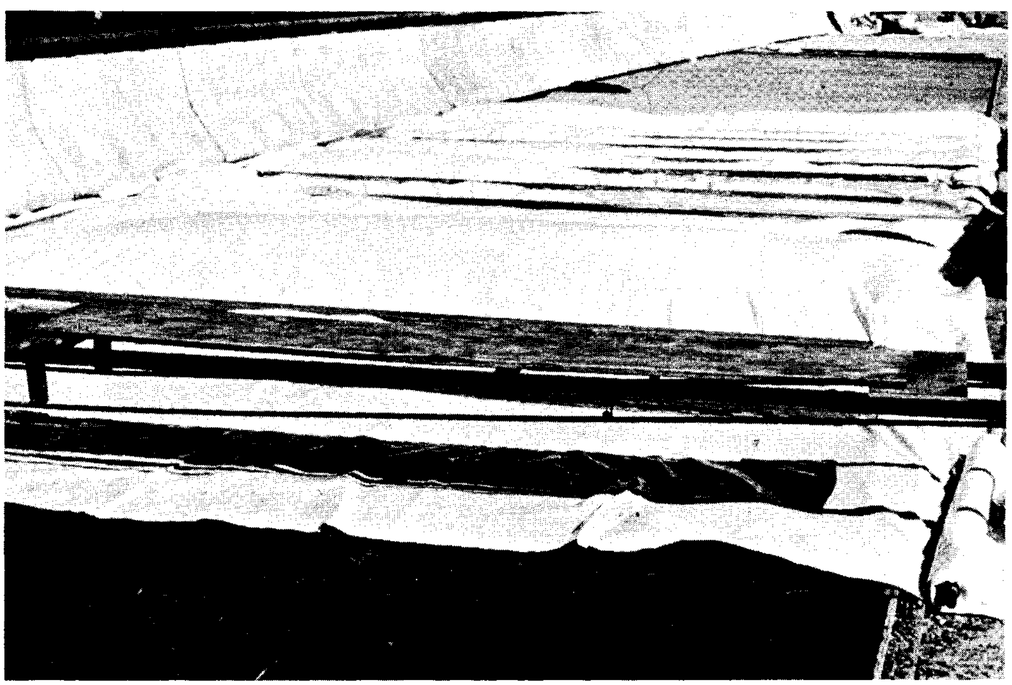

Figure A-8. Wet burlap and polyethylene sheets provided the initial curing.

APPENDIX B

Test Results for Field Specimens

Table B-1

Properties of Manually Prepared Specimens from the Low-Slump Field Concretes. The Method of Consolidation is indicated as R for Rodding and Tapping, E for External Vibration and S for Application of a Surcharge

Batch	w/c	Slump, in.	A, %	Unit Weight, $lb./ft.^3$	Corrected Unit Weight* $lb./ft.^3$	Compressive Strength** $lb./in.^2$	Method of Consolidation
1	0.328	3/4	14.0	137.3	150.9	6,300	R
2	0.328	1/4	4.9	147.0	146.1	8,690	R
3	0.328	1/4	5.8	148.6	149.1	8,690	R
4	0.328	1/4	6.2	144.2	145.3	6,830	R + E
5	0.328	1/4	7.2	142.7	145.3	6,600	R + E
6	0.345	1/8	5.8	145.8	146.3	--	R
7	0.345	5/8	7.0	144.2	146.5	7,520	R + E + S
8	0.345	3/4	7.4	142.2	145.1	6,430	R + E
9	0.345	1 1/4	5.0	147.0	146.2	--	R
10	0.345	1 1/8	4.6	147.0	145.6	--	R
11	0.345	1/4	4.4	148.0	146.3	--	R

NOTE: 1 in. = 25.4 mm   1 $lb./ft.^3$ = 16.01 kg/m^3 1 $lb./in.^2$ = 6.89 kPa

* Unit weight corrected for the specified air (5.5%).

** Average of three 6 x 12 in. (150 x 300 mm) cylinders.

2440

Table B-2

Linear Traverse Data on Cores from Port Royal

Sample No.	Description	w/c	Voids, % >1 mm	Voids, % <1 mm	Voids, % Total	Specific Surface, in.$^{-1}$	Spacing Factor, in.
S1	Cut strip	0.328	2.2	5.1	7.2	742	0.0057
1, 2, 3	Avg.-3 cores	0.328	3.3	4.6	7.9	633	0.0060
1A	Core	0.350	3.2	3.4	6.6	462	0.0097
2A	Core	0.350	2.5	5.1	7.6	615	0.0064
3A	Core	0.328	2.9	5.2	8.1	606	0.0061
13	Core	0.345	2.6	3.7	6.3	550	0.0084
18	Core	0.345	3.0	4.3	7.3	517	0.0084

NOTE: 1 in. = 25.4 mm

Table B-3

Linear Traverse Data on Low-Slump Concrete Cylinders Prepared in the Field

Sample No.	Batch	w/c	Method of Consolidation	Voids, % >1 mm	Voids, % <1 mm	Voids, % Total	Specific Surface, in.$^{-1}$	Spacing Factor, in.
1	1	0.328	R	1.7	7.8	9.5	782	0.0053
2	2 + 3	0.328	R	1.2	3.5	4.7	902	0.0058
3	4 + 5	0.328	R + E	2.3	4.9	7.2	702	0.0060
4	7	0.345	R + E + S	3.4	4.4	7.8	589	0.0068

APPENDIX C

Test Results for Laboratory Specimens

Table C-1

Mixture Proportions by Weight Ratios of Cement for Laboratory Specimens

Batch	w/c	Cement*	Fine Aggregate	Coarse Aggregate	F.A./C.A.
1, 2	0.328	1	1.54	1.86	45/55
3, 4	0.328	1	1.59	1.80	47/53
5, 6	0.328	1	1.70	1.70	50/50

* Cement Content = 823 lb./yd.^{3} (486 kg/m^3).

Table C-2

Slump, Air Content, and the Unit Weight of Batches given in Table C-1. Compressive Strength Values are an Average of Two 3 x 6 in. (75 x 150 mm) Cylinders, Except as Noted

Batch	Slump, in.	Air, %	Unit Weight lb./ft.^{3}	Compressive Strength lb./in.^{2}	Method of Consolidation
1	1/2	4.7	146.8	8,310	R
2	3/4	5.0	146.6	7,850	R
3	3/4	5.0	147.2	6,600*	R
4	1 1/4	6.4	144.8	6,930*	R
5	1/4	4.0	148.4	8,840	R
6	1/2	5.8	145.2	8,190	R

NOTE: 1 in. = 25.4 mm

1 lb./ft.^{3} = 16.01 kg/m^3

1 lb./in.^{2} = 6.89 kPa

* Average of 3 specimens

Table C-3

Linear Traverse Data on Laboratory Specimens

Batch	Sand	Void Content, %	F.A./C.A.	Voids, % >1 mm	Voids, % <1 mm	Voids, % Total	Specific Surface $in.^{-1}$	Spacing Factor, in.
1	1	47.2	45/50	1.6	2.1	3.7	614	0.0097
2	1	47.2	45/50	1.0	3.3	4.3	544	0.0101
3	2	47.8	47/53	1.7	3.8	5.5	470	0.0105
4	2	47.8	47/53	1.5	3.7	5.2	605	0.0102
5	1	47.2	50/50	2.3	2.6	4.9	289	0.0179
6	1	47.2	50/50	2.2	3.0	5.2	595	0.0084

NOTE: 1 in. = 25.4 mm

2445

2448

APPENDIX D

Texturing Low-Slump Concrete

TEXTURING OF LOW-SLUMP CONCRETE AT PORT ROYAL

The bridge deck overlay at Port Royal was initially textured using flexible metal tines (a rake). The textures attained by this method are shown in Figures D-1 and D-2. The texture in Figure D-2 is not as deep as that in Figure D-1. However, because of the stiffness of the low-slump concrete, a shallow texture was generally achieved with the flexible tines. The tines tended to lay flat on the surface of the concrete and also to disturb aggregates along the sides of the grooves as they were pulled. To achieve deeper textures, long nails in a piece of wood were drawn along the surface. The texture thus attained is shown in Figures D-3 and D-4. The grooves were deep but the surface was generally torn as aggregates were pulled from the surface by the stiff nails. Sometimes the surface was highly disturbed as shown in Figure D-4.

Subsequently, the roller shown in Figure D-5 was prepared by machining a metal rod. The geometry of the roller is given in Figure D-6. When rolled on the surface it indents equally spaced grooves as shown in Figure D-7. The roller also eliminated the problem of disturbing the surface. To achieve the desired groove depth of about 1/8 in., it was sometimes necessary to add extra weights on the frame of the roller, depending upon the consistency of the concrete.

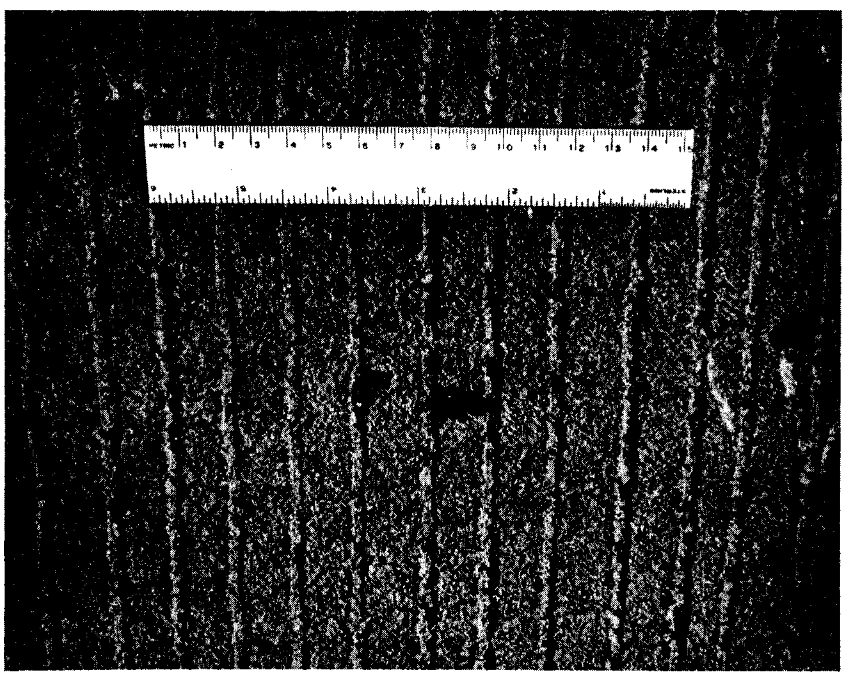

Figure D-1. Texture #1 imparted by flexible metal tines.

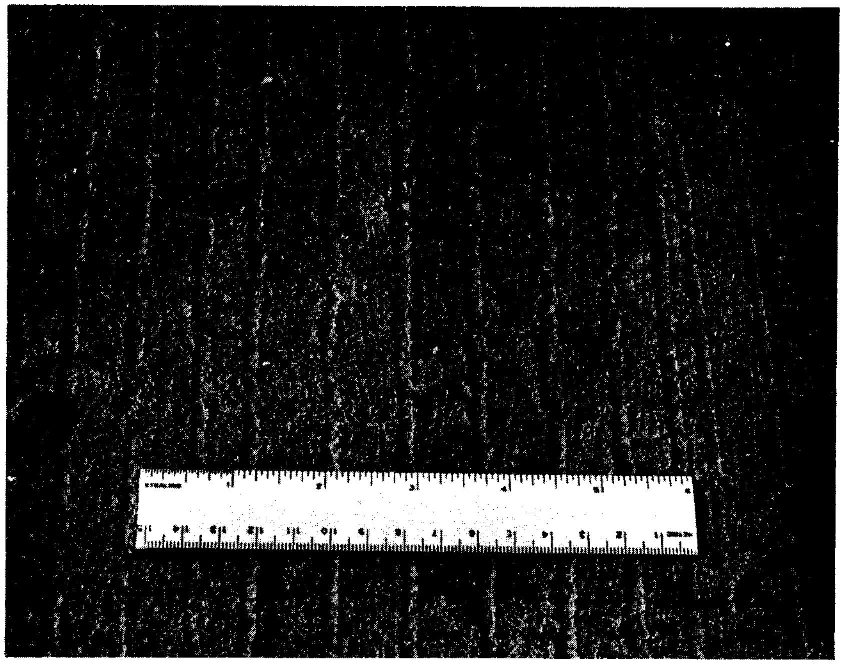

Figure D-2. Texture #2 imparted by flexible metal tines.

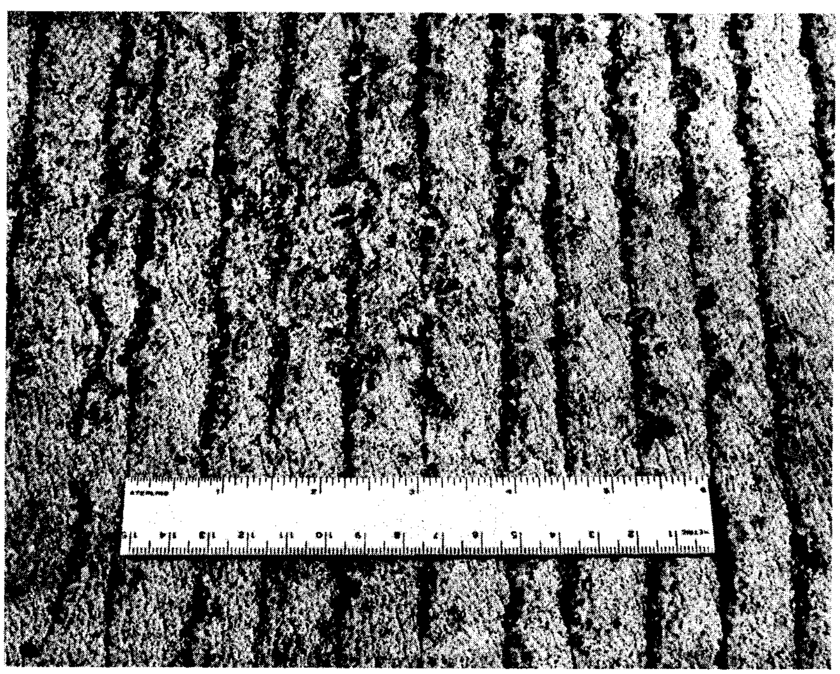

Figure D-3. Texture #1 imparted by nails pulled along the surface.

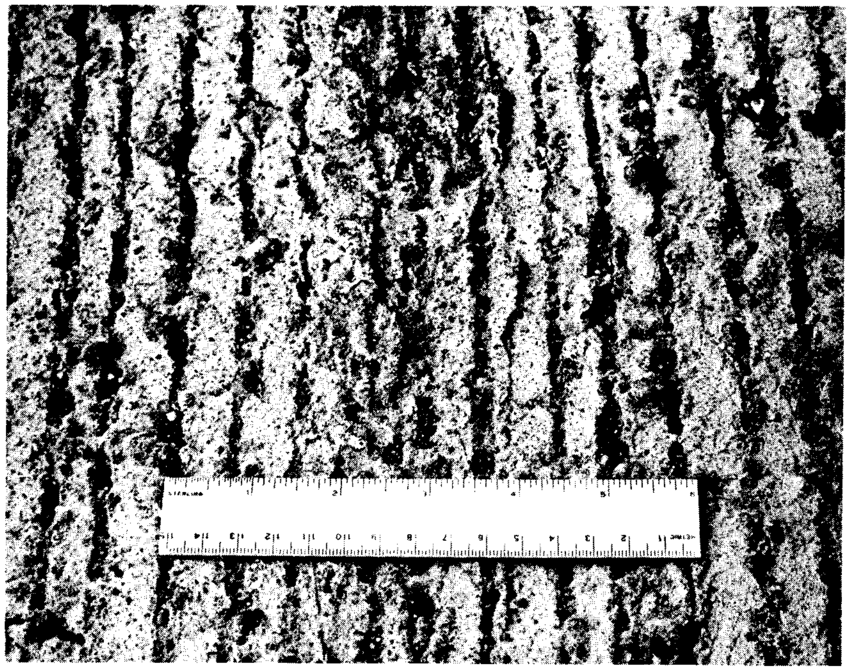

Figure D-4. Texture #2 attained by nails pulled along the surface.

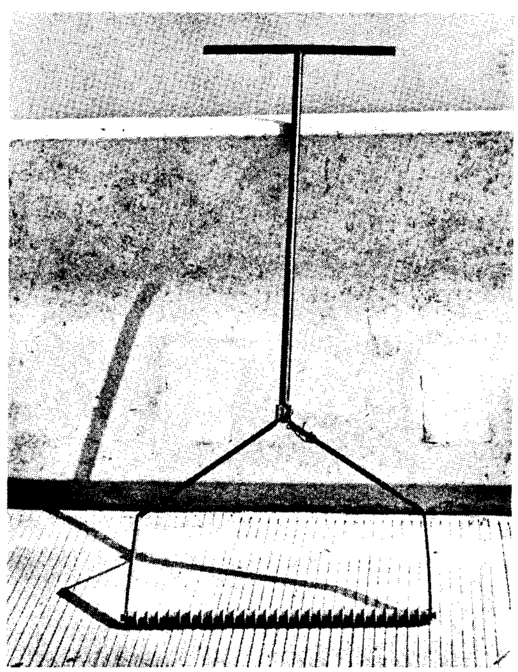

Figure D-5. Roller used in texturing.

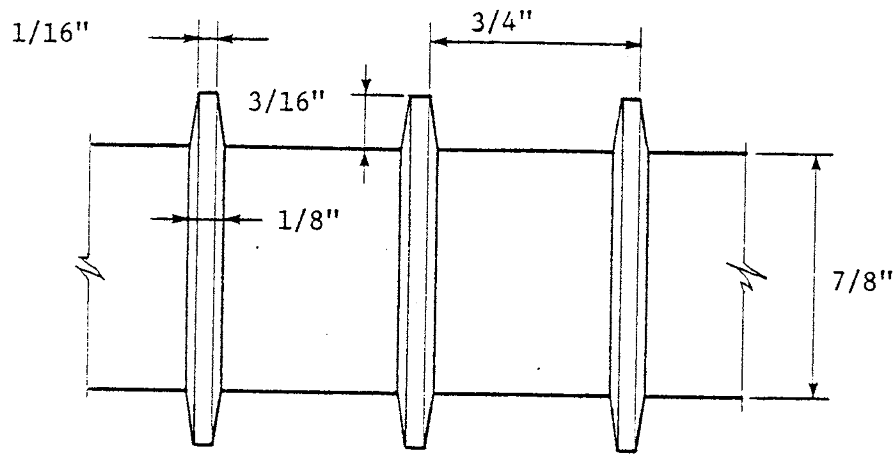

Figure D-6. Approximate geometry of the roller used.

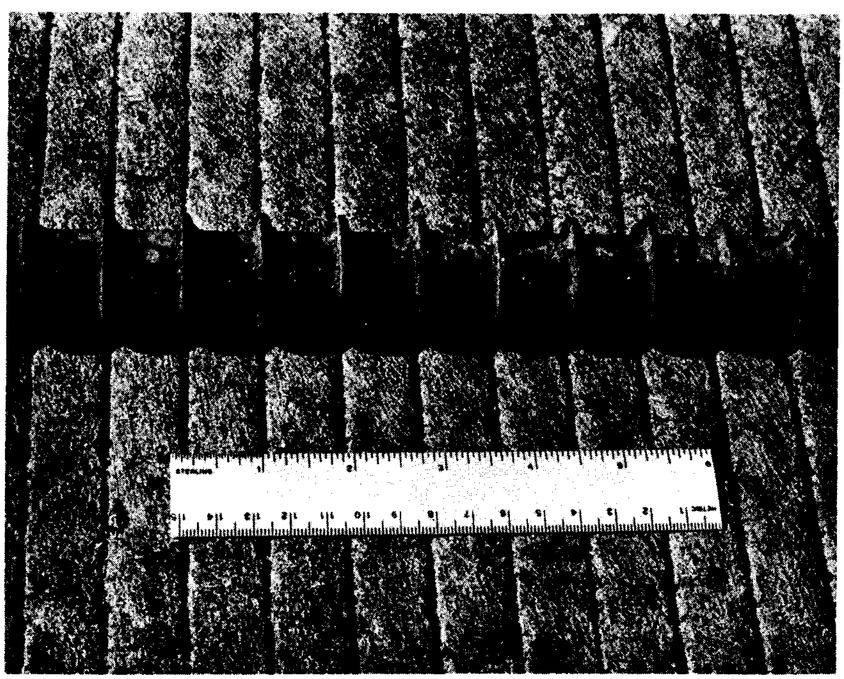

Figure D-7. Texture attained with the roller.

2452

APPENDIX E

Bonding of Low-Slump Concrete

BOND STUDIES IN THE LABORATORY

A limited laboratory study was made to investigate the effect of the variables given in Table E-1 on the bond between low-slump overlays and a base concrete. The slurry used consisted of cement and water with a w/c of 0.39. The grout consisted of cement, sand (that used in base concrete), and water and had a w/c of 0.42. In some specimens, the slurry or grout was left to dry so as to simulate an undesirably extreme case that can occur in the field.

Table E-1

Variables in Bond Study

Base Layer	Bonding Agent
Dry	None
SSD	None
Dry	Wet Slurry
SSD	Wet Slurry
Dry	Dry Slurry
Dry	Wet Grout
SSD	Wet Grout
Dry	Dry Grout

To determine the bond strength a shear strength test reported by the PCA in the 1950's and conducted at the Research Council in the mid-1970's was followed.[11, 13] Laboratory specimens measuring 6 x 7 in. (150 x 175 mm) by 4 in. (100 mm) were overlaid with 2 in. (50 mm) of low-slump concrete, and the overlay was sheared from the base using the testing apparatus shown in Figure E-1.

The specimens were fabricated from 6 laboratory batches, 3 for the base concrete and the remainder for the overlay. The mix proportions, slump, and air content for the fresh concrete are given in Table E-2. From each batch, three 3 x 6 in. (75 x 105 mm) cylinders were prepared for compressive strength tests. The 9 samples from the 3 batches of base concrete averaged 5,220 lb./in.^{2} (35.99 MPa) and the 9 from the low-slump concrete averaged 7,260 lb./in.^{2} (50.06 MPa).

Eight variables were considered, and for each variable a set of 7 specimens were fabricated. Six specimens from each set were subjected to the shear test and the remaining specimen was cut, lapped, and examined under a microscope.

The base concrete for the specimens was prepared utilizing materials available in the laboratory. The overlay concrete was made of materials brought from the bridge project.

The base layer of specimens was cast by placing concrete in two layers and consolidating each layer by rodding and then tapping the sides of the molds. The surfaces were screeded with wood but not textured. The base concrete samples were moist cured for a month and then air dried for a week. The surface was wire brushed and the variables shown in Table E-1 were employed.

The concrete was put into a saturated surface dry condition by wetting the wire brushed surface with water about an hour before the placement of the overlay and then keeping the specimens in a moist room till the casting of the overlay. For the case where the bonding agent was left to dry, the base concrete was kept in an oven overnight at 120°F (49°C) and then the bonding agent was applied. Subsequently, the specimens were placed in a forced air oven for half an hour at 120°F (49°C). This procedure provided a dried surface when a grout or slurry was applied.

Table E-2

Mix Proportions, as a Ratio of Cement by Weight, and Slump and Air Content Used in Bond Studv

Batch	Layer	Cement	Water	F. A.	C. A.	Slump, in.	Air, %
1	Base	1*	0.439	1.73	2.94	4.0	8.2
2	Base	1*	0.439	1.73	2.94	3.7	6.8
3	Base	1*	0.439	1.73	2.94	3.7	6.6
4	Overlay	1**	0.328	1.54	1.86	0.9	5.9
5	Overlay	1**	0.328	1.54	1.86	0.8	5.1
6	Overlay	1**	0.328	1.54	1.86	1.2	6.9

NOTE: 1 lb. = 454 g

1 in. = 25.4 mm

* Cement Content = 635 lb./yd.^{3} = 375 kg/m^3.

** Cement Content = 823 lb./yd.^{3} = 486 kg/m^3.

The overlay was placed on the prepared surfaces and consolidated by tapping and providing external vibration with a vibrator attached to a plate as shown in Figure E-2. The plate was laid on the surface to compact the overlay from the top. The specimens were cured in a moist room for a month and then tested to determine the shear strength. During the testing it was noticed that some overlays were not compacted satisfactorily and that honeycombs had formed in the bond area. Such samples yielded low values of shear strength and were excluded from the experiment. The test data, summarized in Table E-3, show shear strengths averaging from 602 lb./in.^{2} (4.2 MPa) to 780 lb./in.^{2} (5.4 MPa) for the different variables.

For each variable, a sample was fabricated for microscopic examination. Two finely lapped surfaces were prepared on each of the specimens. The microscopic examination did not indicate any significant differences among the variables in Table E-1. It was observed that when a large piece of aggregate was at the surface of the base concrete the bond was weak and that a thin layer of mortar at the surface of base concrete provided a good bond. Entrapped air voids noted at the interface indicated the difficulty of consolidating low-slump concretes. Since differentiation of the variables was not possible by studying lapped surfaces, thin sections of some specimens were prepared to study the bond area at high magnification with transmitted light. This examination indicated that a dry base concrete surface without a slurry or grout is the preferable condition.

Table E-3

Shear Strength of Bonded Specimens in lb./in.^{2}

Variables		Shear Strength of Samples							
Base Layer	Bonding Agent	1	2	3	4	5	6	Avg.	Std. Dev.
Dry	None	711	614	724	773	700	824	724	71
SSD	None	599	629	315	771	696		602	174
Dry	Wet Slurry	739	706	677	774	895	889	780	93
SSD	Wet Slurry	743	694	700	745	746	602	705	56
Dry	Dry Slurry	612	577	721	720	855	784	712	104
Dry	Wet Grout	532	655	745	717	780	706	689	88
SSD	Wet Grout	745	545	524	770	705		658	115
Dry	Dry Grout	596	480	664	919	619		656	162

NOTE: 1 lb./in.^{2} = 6.894 Pa

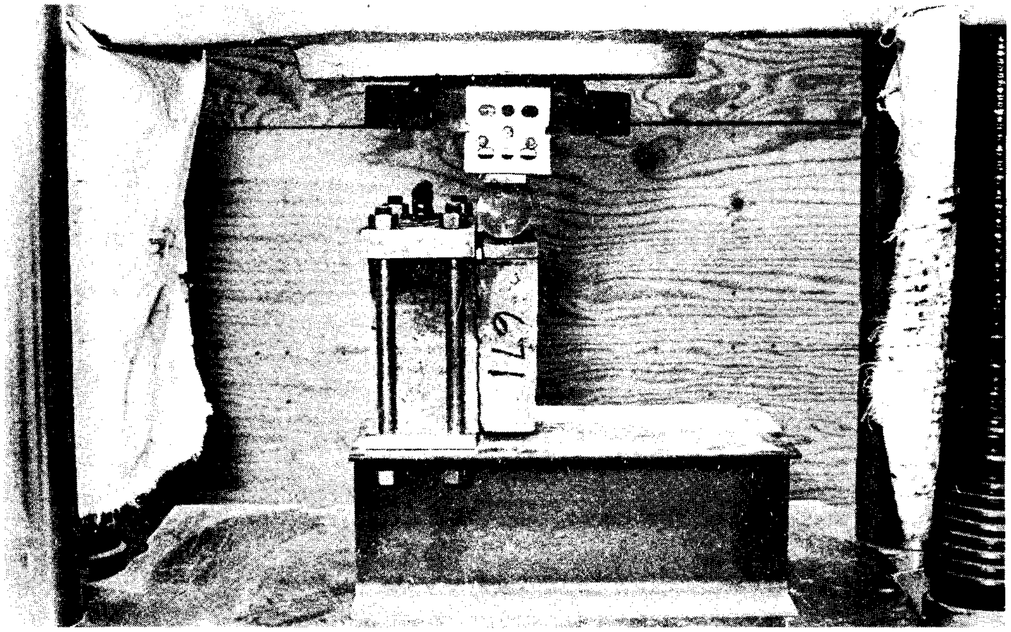

Figure E-1. Apparatus used to determine shear strength.

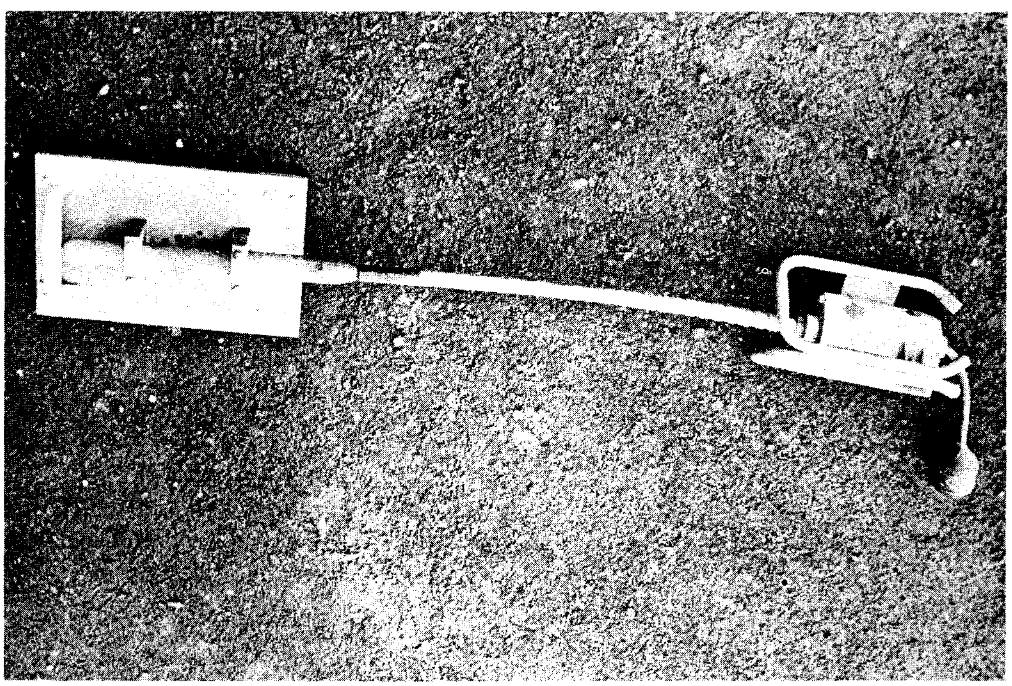

Figure E-2. Device used to consolidate overlays in bond study.

2458

APPENDIX F

Tests Related to the Permeability of Concrete

ABSORPTION

The cores and cylinders from the field and the specimens fabricated in the laboratory were subjected to absorption tests in accordance with ASTM C642. The results are given in Tables F-1 through F-3. The absorption values include those determined after immersion and those calculated after immersion and boiling. The values after immersion and boiling were slightly higher or equal to those after immersion in all cases. The results given in Table F-1 show that the cores obtained from the field had higher absorption values than both the cylinders prepared in the field and the laboratory specimens. The field cylinders had the lowest absorption.

In Table F-3 it can be seen that the laboratory specimens with 28-day moist curing displayed the lowest absorption values. These were followed by those with 3-day moist curing, and then those with the curing compound. In general, the laboratory mixtures with a fine to coarse aggregate ratio of 50/50 showed higher absorption values than those with a ratio of 45/55.

PETROGRAPHIC EXAMINATION

From each of the laboratory prisms obtained from the batches described in Table C-1 and cured under different conditions, fluorescent dye-impregnated, ultra-thin sections were fabricated.[14, 15] The microscopic examination at 400x did not reveal any differences in quality of hydration between the two mix designs with varying fine to coarse aggregate ratios. The results indicate that the microstructures in all specimens at depths exceeding 0.2 in. (5 mm) were similar. However at shallower depths, especially 0.04 in. (1 mm) or less, differences were evident. Dense, interwoven hydration products with dense carbonation were present in specimens that had been given 28-day moist curing compared to a less dense surface layer in those cured moist for 3 days and those with curing compounds. Differences in structure at the surface between the specimens moist cured for 3 days and those to which a curing compound had been applied were difficult to detect.

Table F-1

Absorption Data on Cores from Bridge Deck

Sample	w/c	Absorption after Immersion, %	Absorption after Immersion and Boiling, %
17	0.345	5.3	5.6
19	0.345	5.0	5.2
1B	0.345	4.9	5.2
2B	0.345	4.7	5.0
3B	0.345	4.6	4.6
4B	0.350	5.0	5.3
5B	0.328	4.6	4.7

Table F-2

Absorption Data on Field Cylinders. Average of two Specimens (See Tables A-2 and B-1 for information on batches)

Batch	w/c	Absorption after Immersion, %	Absorption after Immersion and Boiling, %
1	0.328	3.7	3.8
2	0.328	2.9	3.0
3	0.328	3.3	3.4
4	0.328	3.8	4.0
5	0.328	4.0	4.0
7	0.345	3.4	3.4
8	0.345	4.1	4.2

Table F-3

Absorption Data on Laboratory Specimens; Averages of Two Samples one from each Batch (See Tables C-1 and C-2 for information on batches)

Batch	F.A./C.A.	Curing	Absorption after Immersion, %	Absorption after Immersion and Boiling, %
1, 2	45/50	Curing compound	4.6	4.7
1, 2	45/50	3-day moist cure	4.4	4.4
1, 2	45/50	28-day moist cure	4.2	4.2
3, 4	50/50	Curing compound	4.8	4.8
3, 4	50/50	3-day moist cure	4.6	4.6
3, 4	50/50	28-day moist cure	4.1	4.1

2462

CHLORIDE PENETRATION

To determine the resistance of concretes to chloride penetration, cores, cylinders or parts of prisms were ponded continuously for 90 days in a 2% NaCl solution. The top finished surfaces of the specimens were cleaned of loose materials, dikes were built around them as shown in Figure F-1, and they were ponded with a 2% NaCl solution and covered with plastic. Periodic checks were made to ensure that the surfaces had a continuous supply of chloride solution. After 90 days, the solution was removed from the specimens. After drying, the surfaces of the samples were wire brushed to remove salt crystals.

The samples for chloride ion analysis were obtained by dry coring the concrete specimens with a percussion hammer. The chloride contents were obtained for two average depths of 1/4 in. (6 mm) and 3/4 in. (19 mm) from the surface. The tests were made in accordance with AASHTO T260-78.

In the first series of tests summarized in Table F-4, a comparison was made between the penetration of chlorides into the cores of the low-slump concrete and 2 specimens representing normal bridge deck concrete that had been previously prepared in the laboratory, moist cured for a month and kept in an air-dry condition for a considerable time, about 4 years. At which time the absorption values were 4.0% and 4.1%. The chloride contents at the 1/4-in. (6 mm) depth and 3/4-in. (19 mm) depth for both field cores and lab specimens in this series of tests were higher than expected. The average for the laboratory concrete was 13.0 lb/yd.^{3} (7.7 kg/m^3) at the 1/4-in. (6 mm) depth and 6.8 lb/yd.^{3} (4.0 kg/m^3) at the 3/4-in. (19 mm) depth. The cores yielded comparable values as indicated by the ratios in Table F-4. It is possible that either the soak period was inadvertently extended beyond 90 days or that some change occurred in the salt concentrations during the test for both types of specimens. However, since both types of specimens were exposed to the same conditions and the laboratory specimens are known to represent concretes that give satisfactory service, the behavior of the low-slump specimens as compared to that of the laboratory specimens is considered the important criterion for this series of tests. The values for the low-slump cores at the 1/4-in. (6 mm) depth averaged 102% of the average values for the laboratory concrete and at the 3/4-in. (19 mm) depth the similar comparison was 82%. On this basis, the resistance to salt penetration of the low-slump cores would be judged satisfactory.

The results of later tests on field cylinders of the low-slump concrete and laboratory specimens made for comparison purposes in the investigation are shown in Table F-5 and F-6. As shown, all of these specimens showed satisfactory performance; the chloride contents at 3/4 in. (19 mm) were less than the threshold value of 1.65 lb/yd.^{3} (0.98 kg/m^3) for low-slump concrete. At the 1/4-in. (6 mm) depth, recently prepared specimens cured with a compound and others given 28-day moist curing showed similar chloride contents; but the 3-day moist cured specimens exhibited higher chloride contents. Neverthele s, as mentioned above, all these concretes were able to resist the chloride penetration at the 3/4-in. (19 mm) depth.

Figure F-1. Specimen prepared for ponding with 2% NaCl solution.

2464

Table F-4

Chloride Contents of Cores and Laboratory Specimens made with Regular Bridge Deck Concrete

Specimen	No.	w/c	Chloride Contents, % of Lab Specimens 1/4-in. Depth	3/4-in. Depth
Core	17	0.345	93	40
Core	19	0.345	95	81
Core	1B	0.345	127	162
Core	2B	0.345	89	82
Core	3B	0.345	108	66
Core	4B	0.350	93	50
Core	5B	0.328	107	91
Lab Concrete	*	0.44	100	100

NOTE: 1 lb./yd.^{3} = 0.59 kg/m^3

1 in. = 25.4 mm

* Average of 2 specimens. The average chloride values for lab concrete were 13.0 lb/yd.^{3} at the 1/4-in. depth and 6.8 lb/yd.^{3} at the 3/4-in. depth.

Table F-5

Chloride Contents of Field Cylinders
(For information on Batches see Tables A-2 and B-1)

Batch	Chloride Contents in lb./yd.^{3} 1/4-in. Depth	3/4-in. Depth
1*	2.7	0.6
2	4.8	1.4
3	1.8	0.5
4	1.2	0.6
5	1.2	0.2
6	1.8	0.6
7*	3.9	0.6
8*		

* Average of two specimens

NOTE: 1 lb./yd.^{3} = 0.59 kg/m^3

1 in. = 25.4 mm

Table F-6

Chloride Content of Laboratory Specimens Given Different Curings
(For information on Concretes see Tables C-1 and

Batch	Curing	F.A./C.A.	Chloride Contents in lb./yd.^{3} 1/4 in. Depth	Chloride Contents in lb./yd.^{3} 3/4 in. Depth
1	Curing compound	45/50	5.5	0.4
2	" "	45/50	7.0	0.2
3	" "	50/50	4.5	0.4
4	" "	50/50	3.2	0.2
1	3-day moist cure	45/50	9.0	1.3
2	" "	45/50	9.4	0.6
3	" "	50/50	10.4	0.3
4	" "	50/50	10.5	0.7
1	28-day moist cure	45/50	3.9	0.3
2	" "	45/50	9.4	0.6
3	" "	50/50	6.0	0.6
4	" "	50/50	3.4	0.2

NOTE: 1 lb./yd.^{3} = 0.59 kg/m^3

1 in. = 25.4 mm