1204

TRANSPORTATION RESEARCH RECORD

Portland Cement Concrete Modifiers

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. 1988

Transportation Research Record 1204
Price: $13.00

modes
1 highway transportation
2 public transit
3 rail transportation
4 air transportation

subject area
32 cement and concrete

Transportation Research Board publications are available by ordering directly from TRB. They may also be obtained on a regular basis through organizational or individual affiliation with TRB; affiliates or library subscribers are eligible for substantial discounts. For further information, write to the Transportation Research Board, National Research Council, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.

Printed in the United States of America

Library of Congress Cataloging-in-Publication Data
National Research Council. Transportation Research Board.

Portland cement concrete modifiers.

p. cm. — (Transportation research record, ISSN 0361-1981 ; 1204)
ISBN 0-309-04774-9
1. Concrete—Additives. I. National Research Council (U.S.). Transportation Research Board. II. Series.
TE7.H5 no. 1204
[TP884.A3]
380.5 s—dc20
[666'.893]
89-38460
CIP

Sponsorship of Transportation Research Record 1204

GROUP 2—DESIGN AND CONSTRUCTION OF TRANSPORTATION FACILITIES
Chairman: David S. Gedney, Harland Bartholomew & Associates

Concrete Section
Chairman: Robert E. Philleo, Consulting Engineer

Committee on Mechanical Properties of Concrete
Chairman: V. Ramakrishnan, South Dakota School of Mines and Technology
John A. Bickley, George Calvert, Archie F. Carter, Jr., James T. Dikeou, Wilbur Charles Greer, Jr., Richard H. Howe, Charles W. Josifek, Paul Klieger, Peter A. Kopac, Louis A. Kuhlmann, Joseph F. Lamond, V. M. Malhotra, Richard C. Meininger, Edward G. Nawy, Sandor Popovics, Robert R. Santoro, Bruce Schneider, Ernest Schrader, Raymond J. Schutz, S. P. Shah, Michael M. Sprinkel, Rodney J. Stebbins, Peter C. Tatnall

Committee on Chemical Additions and Admixtures for Concrete
Chairman: H. Celik Ozyildirim, Virginia Highway and Transportation Research Council
Bernard C. Brown, John W. Bugler, Henry H. Duval, Jr., Thomas H. Ellis, Richard D. Gaynor, John S. Horn, Daniel P. Johnston, Louis A. Kuhlmann, G. John Kurgan, T. J. Larsen, Bryant Mather, Michael F. Pistilli, Joseph H. Pound, Philip A. Rosskopf, Byron E. Ruth, Raymond J. Schutz, A. Haleem Tahir

Construction Section
Chairman: Garland W. Steele, West Virginia Department of Highways

Committee on Construction of Bridges and Structures
Chairman: Edward J. Kehl, Illinois Department of Transportation
Robert M. Barnoff, Mrinmay Biswas, John K. Bright, David A. Dock, Jackson L. Durkee, Thomas H. Ellis, Allan C. Harwood, James R. Hoblitzell, Frank J. Kempf, Thomas P. McCarthy, Frieder Seible, Charles V. Slavis, Michael M. Sprinkel, Man-Chung Tang, Theunis A. Van Der Veen, J. R. Wilder, Kenneth C. Wilson, Luis Ybanez

William G. Gunderman, Transportation Research Board staff

Sponsorship is indicated by a footnote at the end of each paper. The organizational units, officers, and members are as of December 31, 1987.

Transportation Research Record 1204

Contents

Practical Considerations for Using Silica Fume in Field Concrete

TERENCE C. HOLLAND

Ready-mixed silica-fume concrete is currently used in the United States on a regular basis. During 1986, approximately 350,000 yd^3 (270,000 m^3) of silica-fume concrete were placed. The silica fume is used as a cement replacement material or as a performance-enhancing admixture. This paper reviews the practical aspects of working with silica fume in ready-mixed concrete, with emphasis on the use of silica fume in the performance-enhancement role. Availability of silica fume and of products containing silica fume is described first. The current lack of specifications for silica fume, admixtures containing silica fume, and concrete incorporating silica fume is examined. Aspects of concrete production including measuring, adding, mixing, using high-range water-reducing admixtures, and controlling concrete temperature are discussed. Transporting, placing, finishing, and curing are reviewed to determine how silica-fume concrete differs from conventional concrete in these areas. Finally, several specific considerations for using silica fume in concrete for bridge decks are discussed.

Ready-mixed silica-fume concrete has been placed successfully in a wide variety of applications. The price for a successful placement is strict adherence to the fundamentals of good concrete practice.

Silica fume is currently used in the United States as a cement replacement material and as a performance-enhancing admixture. In the first role, silica fume is added to concrete without a specific application in mind; in the latter role, silica-fume concrete is specified for a wide variety of applications where high-strength or very durable concrete is required. Recent such projects have included 14,000-psi (97 MPa) building columns and chloride-resistant concrete for parking structures and bridge decks. During 1986 in the United States, approximately 350,0000 yd^3 (270,000 m^3) of silica-fume concrete were placed, with about 60 percent being in the replacement market. In the enhancement market, most silica fume has gone into parking structure applications.

The physical and chemical properties of silica fume, the applications for which concrete containing silica fume are suited, and the properties of hardened silica-fume concrete have been described by others (*1*, *2*). Typical current uses of silica fume in both its roles have also been described elsewhere (*3*).

This paper discusses the practical aspects of specifying, making, placing, finishing, and curing concrete containing silica fume. Additionally, some special considerations for using silica fume in concrete for bridge deck overlays are considered. In essence, the lessons learned from the major placements of silica-fume concrete to date in the United States will be reviewed.

One area that has already been emphasized to the concrete community deserves mention again. Significant improvements in strength or durability cannot be achieved through the use of silica fume unless generally accepted good concrete practices are followed. No problem areas have been identified regarding the use of silica-fume concrete that do not exist, to some extent, with conventional concrete. Silica fume is not a cure for bad practice. If a concrete producer is not already following good practices, addition of silica fume to the concrete will probably result in better concrete, but the improvement may not be all that is expected or specified.

AVAILABILITY

Silica fume is available commercially in the United States in several forms. Figure 1 summarizes the types of products available at this time.

As-produced silica fume may be available in bulk or in bags. There is at least one area in the United States near a smelter where silica fume is being used as a cement replacement. However, elsewhere, very little silica fume in the as-produced state has been used in concrete in the United States. This reluctance to use the as-produced material results from difficulties in transporting and handling and the resulting poor economics.

When available in an as-produced state, bulk silica fume may be transported and handled generally like portland cement or fly ash. Bagged material has been used by emptying the bags directly into truck mixers, but because of the dust generated and the labor costs involved, the use of bagged silica fume has not been popular. Another deterrent to the use of the as-produced silica fume is the cost of transportation. The material typically has a unit weight of only 12–15 lb/ft^3 (192–240 kg/m^3), compared with 94 lb/ft^3 (1,500 kg/m^3) for cement, so very little will actually fit into a truck!

To overcome the difficulties associated with transporting and handling the dry material, producers have concentrated on marketing silica fume as a water-based slurry. These slurries typically have a unit weight of approximately 11 lb/gal or 82 lb/ft^3 (1,315 kg/m^3) and contain 45–50 percent silica fume by mass. Even when the weight of the water is considered, transportation of the slurry is more economical than transportation of the dry silica fume. The slurries are available with and without chemical admixtures and offer the major advantage of ease of use once the required dispensing equipment is available at the batch plant.

Now dry, densified silica fume products with or without chemical admixtures are also available. These products have

---

1806 Hassam Road, Coraopolis, Pa. 15108

1.0 **Dry Products**

1.1 As-produced silica fume. Availability depends somewhat on willingness of producers to supply for this application. Transportation and handling constraints also apply. Several possible suppliers, each of whom may have different capabilities to supply in bags or in bulk. Unit weight: 12 to 15 lb/ft^3 (192 to 240 kg/m^3).

1.2 As-produced silica fume with dry chemical admixtures. Chemical admixture dosage is high enough to provide water reduction for the concrete. One product is available in bags. Unit weight: same as as-produced silica fume.

1.3 Densified silica fume with dry chemical admixtures. Chemical admixture dosage is high enough to provide water reduction for the concrete. One product is available in bags. Unit weight: 35 to 40 lb/ft^3 (560 to 640 kg/m^3).

1.4 Densified silica fume without chemical admixtures. One product is available in bags. Unit weight: same as densified silica fume with dry chemical admixtures.

2.0 **Wet Products**

2.1 Silica fume slurry. Typically slurries are composed of 50 percent silica fume by mass. Not currently available commercially. Unit weight: 11 lb/gal (82 lb/ft^3 (1315 kg/m^3)).

2.2 Silica fume slurry with low dosages of chemical admixtures. The dosage of chemical admixtures is just enough to offset some or all of the increased water demand of the silica fume itself. There is no water reduction provided for the concrete. One product is available in drums and in bulk. Unit weight: same as silica fume slurry; silica fume content may be reduced by chemical admixture solids.

2.3 Silica fume slurry with high dosages of chemical admixtures. The dosage of chemical admixtures is high enough to offset the water demand of the silica fume and to provide water reduction for the concrete. Chemical admixtures may include retarders. Two products are available in drums and in bulk. Unit weight: same as silica fume slurry; silica fume content may be reduced by chemical admixture solids.

FIGURE 1 Forms of silica fume currently available for use in concrete in the United States.

a unit weight of 35–40 lb/ft^3 (560–640 kg/m^3) and are cost-effective to transport dry. Because of the densification, little dust is created when the material is used from bags. This densified material, marketed as a substitute for as-produced dry silica fume, is for small or isolated jobs where installation of dispensing equipment and use of slurry is not practical.

Depending on the type of material selected and the supplier, silica fume or products containing silica fume may be available in bulk, drums, or bags. The form of the material that is selected will have an impact on the handling of materials and the production of concrete. Available data and experience indicate that the form of the silica fume can affect the properties of the fresh and hardened concrete, particularly if a densified silica fume is substituted for one of the other forms. Therefore, changing products during a project should be avoided unless appropriate testing has been accomplished to verify mixture proportions and concrete performance using the alternate material.

Pistilli et al. have shown that variations in silica fume from a single furnace at a given source are relatively small (*4*, *5*). It is the author's experience that silica fume from different sources will behave differently in concrete, particularly in respect to water demand. It is, therefore, also inadvisable to change sources of silica fume during a project without conducting additional laboratory testing to verify the performance of the material from the new source.

SPECIFICATIONS

Specifications for silica-fume concrete must be considered on three levels: first, specifications for the silica fume itself; second, specifications for admixtures containing silica fume; and third, project specifications for concrete incorporating silica fume as an admixture. Each of these areas is currently a source of problems in the United States.

At present, no standard specification that covers silica fume as a material. The appropriate subcommittee of ASTM Committee C-9 is working on developing a specification for silica fume. Initially, the intent of the subcommittee was to include silica fume as an additional material in the existing standard for pozzolans (*6*). However, that intent was defeated, and work is under way on a stand-alone specification for silica fume. So far, the process has taken 4 yr and will probably require another 2 yr before a specification is approved and available.

Depending on the degree of sophistication of the specifier or specifying agency, the lack of a national standard has usually been addressed by developing job-specific specifications for silica fume. Users of silica fume have generally relied on product suppliers for guidance in preparing these specifications. Basically, these specifications have been patterned after ASTM C 618 and have usually included requirements for silicon dioxide content, loss on ignition, moisture content, and surface area. Most frequently, the common wisdom has been to specify a high silicon dioxide content and a high surface area.

This last property is particularly troublesome because there is not a consensus regarding the appropriate technique for determining the surface area of silica fume. It appears that the air permeability methods used for portland cement and other pozzolans are not appropriate for silica fume. A method such as nitrogen adsorption, that is well suited for such a fine material, is limited by availability of the apparatus within the concrete industry. The current draft document being worked on by the ASTM subcommittee sidesteps the fineness issue by specifying washing over a 45-micrometer (no. 325) sieve.

Standard specifications for admixtures containing silica fume or silica fume and chemical admixtures are also nonexistent. At present, there is no activity regarding the development of such a standard. This situation is complicated by the variety of types of admixtures containing silica fume plus chemical admixtures that are available. Again, users have generally relied on materials suppliers for assistance and have specified such elements as total solids and silica-fume content and that any chemical admixtures meet the requirements of ASTM C 494 (*7*). This area is further complicated for public agencies because their specifications usually must not include brand names and because different products contain different combinations of silica fume and chemical admixtures. Preparing a clear specification that does not eliminate any prospective bidders has become an extremely complex process.

Standard (guide) specifications and general guidance for projects actually employing silica fume in concrete are also lacking. There is a recently published ACI state-of-the-art document (*1*), but it deals more with suitable uses of silica-fume concrete than with how to make and place it.

Project specifications have included prescriptive and performance elements and have been based on extensive input from materials suppliers. Usually, silica-fume concrete has been treated as a separate class of concrete. The specifications then detail exceptions to normal practice or special requirements for the silica-fume concrete. A very common item in the specifications for many projects has been a requirement for test placements outside the area of the actual structure. Such placements have been particularly beneficial in flatwork construction by allowing finishers to become familiar with the concrete before they attempt to finish concrete in the structure.

Because most silica fume being used for performance enhancement is going into concrete for parking structures, performance specifications structured to include measures of the impermeability of the in-place concrete are becoming popular. The test most often specified is the Rapid Chloride Permeability Test (*8*), which has been adopted by AASHTO (*9*) and is under review by ASTM. Unfortunately, while the test has become popular among specifiers, there is little information available regarding the variability of the test method and the correlation between the results obtained and the rate of chloride penetration. Contractors have responded by bidding conservatively.

Overall, the specification issue is certainly unclear at present. Limited relief in terms of an ASTM specification for silica fume is on the horizon. The immediate outcome of this situation will continue to be uncertainty on the part of specifiers, extensive dependence upon suppliers for assistance, and increased costs for owners.

CONCRETE PRODUCTION

Five critical areas must be considered when producing concrete containing silica fume: measuring, adding, mixing, using a high-range water-reducing admixture (HRWRA), and controlling concrete temperature. Each of these areas is discussed below. In addition to these areas, extra care must be given to the routine aspects of concrete production. For example, the amount of wash water in the truck should be accounted for in mixture calculations; and drivers should be cautioned not to add additional water to the drum when washing dust off a truck after loading. It has been difficult, in most instances, to convince ready-mixed-concrete producers of the importance of paying attention to these details. Production of silica-fume concrete for a demanding application requires an educational effort followed by careful inspection.

Measuring

The first critical area is measuring; the correct amount of silica fume must be added. Although this point seems simplistic, measuring is complicated by the variety of forms of silica fume being marketed. The concrete supplier must understand the specifications and the mixture proportions. In some specifications, the silica fume will be shown as an addition to the portland cement; while in other specifications, it may be shown as a replacement for portland cement. The concrete producer also must understand what is being specified and what is being measured—the silica fume itself or the commercial product containing silica fume. For example, the slurried products contain about 50 percent silica fume by mass while the dry products could be 100 percent silica fume.

The silica fume should be measured with the same degree of accuracy as other concrete ingredients. Typically, accuracies of plus or minus 1 percent by mass or volume have been specified. The dispensing equipment being provided to concrete producers can meet these accuracies. If slurried silica fume is used, the amount of water in the slurry must also be accounted for in the mixture proportions; an appropriate reduction in the amount of batch water must be made.

Because of the thixotropic nature of most of the slurries and because the quantities used per cubic yard of concrete are greater, the dispensing equipment is larger and more complex than that used for chemical admixtures. For example, a typical water-reducing admixture may require only 12 fl oz/yd^3 (465 mL/m^3); a typical HRWRA, 135 fl oz/yd^3 (5.2 L/m^3); and a silica fume slurry, 11 gal/yd^3 (55 L/m^3). Clearly, the concrete supplier must be aware of the significant increase in the volume of admixture being dispensed.

Silica fume suppliers in the United States have addressed the dispensing equipment situation from two basic positions. One approach has been to develop a number of mobile dispensers that are towed to a batch plant, set up, and used for the duration of a project. This approach has the disadvantages of high capital cost for the equipment and the repeated relocation costs. Relocation costs make the use of such units uneconomical for small placements. Another approach has been to supply permanent dispensing equipment in customer batch plants. This latter approach has the disadvantage that equipment may be idle between projects because, so far, there is little economic incentive for the concrete supplier to use the silica fume admixture in day-to-day concrete.

Adding

The second critical point concerning production is determining when to add the silica-fume product. The deciding factor here is the type of material being used. Dry silica fume can usually be added at any time during the production process, particularly if the batch plant can handle the dry material in bulk. Slurried products are best added to a truck mixer first because these products will contain a portion of the batch mixing water. (For high dosages of silica fume, slurried products may contain most of the batch water.) Adding slurried products to a truck last may result in "head pack" or in poor distribution of the silica fume throughout the load. Whenever possible, concrete producers have been encouraged to make a few trial batches of the silica-fume concrete before the actual project begins to establish the appropriate batching sequence.

Mixing

The third critical area is the actual mixing; the silica fume must be uniformly distributed throughout the concrete. Compressive strength variations of 3,000 psi (21 MPa) within a single load resulting from poor mixing have been seen during mixer uniformity testing. This requirement for adequate mixing has also been difficult to get across to many producers.

Use of silica fume in central-mixed concrete has worked well and has generally caused less concern than has use in truck-mixed concrete. In this case, the only problem that has been encountered has been one of timing. The measurement of mixing time must begin after all ingredients, including the silica fume, are in the drum. On one project, no adjustment in the mixing time was made to account for the length of time required to pump the silica fume slurry into a central mixer. As a consequence, the slurry was, in some instances, passing directly through the mixer without any mixing at all.

Use of silica fume in truck-mixed concrete requires strict adherence to the requirements of ASTM C 94 (*10*). In particular, the rated mixing capacity of the truck must not be exceeded. As might be expected, this area is also one in which there have been difficulties in dealing with producers. As defined by ASTM C 94, the volume of mixed concrete should not exceed 63 percent of the total volume of the drum. This requirement has been hard to enforce because it conflicts directly with the desires of many concrete producers. On one project on which there were difficulties in obtaining satisfactory compressive strength of the silica-fume concrete, concrete was observed spilling from the truck mixers when they went up a hill between the plant and the job site. The amount of mixing achieved under such circumstances is open to question.

Although a relatively simple procedure defined in ASTM C 94 allows determination of the adequacy of mixing and the qualification of truck mixers, very few producers are interested in performing the test. The author is aware of only one silica-fume concrete project for which this testing was done. Instead, on most projects the appearance of the concrete as it has been discharged has been carefully monitored. The most common symptom of inadequate mixing has been slump variations during discharge of the concrete. For example, if during a continuous discharge the slump changes by several inches from the front to the back of the load, it is highly probable that the concrete was not properly mixed and that a uniform slump never existed in the drum. Another common symptom has been the appearance of "concrete balls" in the discharge. Usually, additional mixing or reducing the size of the load has eliminated this problem. On some projects it has been possible to determine that a specific truck mixer was more prone to producing the concrete balls (probably because of worn fins). In such a case, the truck has been disqualified from the silica-fume concrete project only to supply concrete for another, less particular user!

Adding High-Range Water-Reducing Admixtures

The fourth critical area is the use of an HRWRA. The successful use of silica fume as a performance-enhancing admixture requires the use of an HRWRA. The amount of HRWRA required and the appropriate time to add it are a function of the dosage of silica fume being used and of the nature of the silica fume product itself. For high-strength concretes with high dosages of silica fume and low water-to-powder (cement plus silica fume) ratios, it is usually necessary to add the HRWRA at the batch plant to ensure that the concrete is adequately mixed. This requirement to add HRWRA at the plant causes the usual problems and concerns regarding loss of slump between initial mixing and discharge. For some concrete applications, it may be necessary to add some or all of the chemical admixtures at the batch plant to allow initial mixing and to redose at the discharge site to achieve the workability desired for placing.

On one project, the addition of too much HRWRA too soon in the mixing cycle caused problems because the concrete became so fluid that concrete balls were formed that would not break up. Reducing the initial dose of admixture reduced the fluidity of the concrete and seemed to improve the mixing action of the truck.

Controlling Concrete Temperature

The final critical area concerning production is the control of concrete temperature during either hot- or cold-weather concreting conditions. Again, the difficulties that arise are a function of the amount of silica fume being added and of the nature of the product. The greatest problems arise from high dosages of products that are provided as a slurry. In such applications, a major portion of the batch water is typically being supplied as part of the slurry and is unavailable for use in heating or cooling the concrete. On two projects that had very strict maximum temperature requirements, liquid nitrogen was injected into the truck mixers to achieve the degree of cooling required. On another project, concrete temperature was reduced by cooling the slurry product itself by air conditioning the trailer containing the dispensing equipment.

TRANSPORTING, PLACING, AND CONSOLIDATING

In these three areas concerned with getting the concrete from the batch plant and satisfactorily into the forms, concrete containing silica fume behaves very much like conventional concrete, and there have been very few problems reported. However, several points should be mentioned, based on the nature of the silica-fume concrete itself. The fresh concrete, depending on the dosage of silica fume, will usually be more cohesive and less prone to bleeding and segregation during handling than conventional concrete. Because of the variety of silica-fume admixtures available, it is very risky to generalize further concerning the performance of fresh silica-fume concrete. Questions of slump or air stability should be addressed only by testing with project specific materials.

Silica-fume concrete has been transported in most of the equipment used to transport conventional concrete. Some difficulties in cleaning high-strength concrete from equipment have been reported.

Concrete containing silica fume has been successfully placed using all types of placement devices: buckets, pumps, tremies, etc. Because of the increased cohesiveness of the concrete, using a slump 1–2 in. (25–50 mm) higher than normally used for the same type of placement is recommended. For overall ease of placing and finishing, as high a slump as is practical should be used. Specification writers must be flexible, bearing in mind the lower tendency for segregation, and allow these higher slumps if successful placements are to be achieved.

High-slump flowing concretes containing silica fume are somewhat deceptive when it comes to consolidation. Although the concrete will flow into place well and appear to be ready for further working, it will still require thorough consolidation. The increased cohesiveness caused by the silica fume will entrap air that must be removed by vibration, even in concretes with slumps of 8–10 in. (200–225 mm).

FINISHING

The greatest differences between conventional concrete and silica-fume concrete have shown up during finishing. Up to an addition level of about 5-percent silica fume by mass of cement, there will be little difference. Above that level, the differences will become greater with increasing dosages of silica fume because of the reduced bleeding of silica-fume concrete. At low dosages of silica fume, the concrete will bleed much less than conventional concrete; at higher dosages, bleeding will be essentially eliminated.

Plastic Shrinkage Cracking

Plastic shrinkage cracking has been singled out for special attention because it has been the most common source of difficulty and complaints associated with the use of silica-fume concrete. Plastic shrinkage cracking can affect concrete, with or without silica fume, at two points: first, during the period after the initial finishing operations of screeding and bull floating but before final finishing; and second, after final finishing and before initiation of curing or final setting. Silica-fume concrete has been seen to be susceptible to problems during both of these periods.

Contractors have been urged to refer to and use the chart presented as Figure 2.1.5 in ACI 305 (*11*), or as Figure 1 in ACI 308 (*12*), that allows predictions regarding rate of evaporation to be made. For higher dosages of silica fume, the general recommendation has been to reduce the threshold for concern over potential plastic shrinkage to approximately one-half of that recommended for conventional concrete. For applications in which the chart predicts that plastic shrinkage cracking is likely, contractors have also been referred to the preventive steps included in ACI 305 and 308.

In some situations, although plastic shrinkage cracks have not occurred, the surface of the silica-fume concrete has dried and started to stiffen before the underlying concrete. This process gives the fresh concrete a spongy consistency and makes it difficult to finish. The same procedures used to prevent plastic shrinkage cracking have been effective in preventing surface drying and hardening.

A great deal of attention has been given to the tendency of silica-fume concrete to dry and suffer plastic shrinkage cracking. The problem is now well known, and all parties involved with a placement are usually made aware of the tendency beforehand. While there is no way to eliminate the tendency, the problem can be managed and it has not hindered the development of applications for silica-fume concrete. Successful preventive measures have included applying curing compound immediately after screeding, using evaporation retarding materials, the more traditional approaches of fogging and covering the concrete between finishing operations, and, when possible, waiting for a more suitable day for placing exposed slabs.

Finishing Practices

With regard to specific finishing practices of silica-fume concrete, the same tools and procedures that are normally used have been found to be satisfactory. Generalizations regarding particular types of tools are difficult to make; this decision is best left to the finishers. There may be a difference in the timing of the finishing operations because of the chemical admixtures that may be used with the silica fume and because of the lack of bleeding. The chemical admixtures will generally include retarders that will delay setting while the lack of bleeding has caused some finishers difficulty in determining when to get on the concrete.

Two general recommendations have been made to ease problems with finishing: First, silica-fume concrete should be "underfinished." Underfinishing has been advocated to mean that a greater degree of finishing than is actually necessary for the intended use of the concrete should not be specified. This concept has not always been attractive to owners and architects, particularly if a finishing technique has been selected on the basis of aesthetics rather than performance. Second, a trial placement should be conducted to allow the finishing crews to practice and get the bugs out of their approach to the silica-fume concrete. Such a trial is particularly important for finishers used to working on wetter concrete surfaces and should be mandatory for silica-fume concretes requiring a high degree of finishing.

If the concrete application requires a dosage of more than about 10-percent silica fume, a one-pass finishing procedure of screeding, bull floating, and brooming or other texturing followed immediately by curing has usually been recommended. On one parking structure the contractor used a paving train approach to placing and finishing the silica-fume concrete. According to information presented by the contractor at a 1987 World of Concrete seminar, this approach speeded placements and resulted in significant savings.

High quality, steel trowel finishes have been achieved on high-strength, high-durability silica-fume concrete flatwork. These finishes usually have been achieved by specialty contractors who were used to dealing with specialty concretes in their day-to-day placements.

CURING

Silica-fume concrete will not perform well unless it is properly cured, and proper curing is particularly important for concretes containing high dosages of silica fume in conjunction with low water contents. The general recommendation for curing has been to "overcure" the concrete. Overcuring has been emphasized to mean that to get the maximum benefit from silica fume, more curing than would be done for conventional concrete in the same placement will be required. As might be expected, this recommendation as well has not always met with an overwhelming response from contractors. Silica-fume concrete has been successfully cured using most of the generally accepted practices—wet burlap, sheets of plastic, and curing compound. As an absolute minimum, curing equivalent to 7 days of wet curing has been recommended.

Curing of silica-fume concrete can usually begin immediately after finishing, whatever the finishing process may be. Because high dosages of silica fume produce concrete that does not bleed, there is no requirement to wait for the cement to set so that the bleeding will stop before initiating curing. On projects where finishing after setting was not required, curing compound has been applied within a few minutes of the pass of a vibrating screed.

The final thought regarding curing concerns use of silica fume in concrete subjected to accelerated curing. Problems relating to strength gain have been reported in some precast operations. The problem has usually been traced to the chemical admixtures incorporated in a silica fume product rather than the silica fume itself. Because these chemical admixtures may include retarders, it may be necessary to modify the curing cycle. After the silica-fume concrete was allowed to reach an initial set before beginning the accelerated curing, strength problems were resolved.

TESTING

Testing of concrete containing silica fume, particularly for high-strength concrete, has been covered elsewhere (*13*). For the purposes of this paper, it is sufficient to note that difficulties with testing procedures have certainly been encountered. The same attention to detail required for making and placing silica-fume concrete is absolutely required for its testing.

SPECIAL CONSIDERATIONS FOR BRIDGE DECKS

Because of its impermeability, silica-fume concrete has attracted a great deal of interest for its possible application in bridge decks. Several points concerned with the use of silica fume in concrete for bridge decks deserve special mention.

First, bridge deck placements (overlays) tend to require relatively small amounts of concrete. Because of the low volumes, the silica fume suppliers have been reluctant to set up a mobile dispenser at a local ready-mixed concrete supplier for a deck placement. Therefore, until recently, when the dry, densified silica-fume products became available, a slurried silica-fume product would have been supplied in drums. Using drummed material requires pumping and drum-handling equipment and, possibly, additional inspectors to verify that the correct amount of silica-fume product has been used. One state DOT was very reluctant to enter into such an arrangement.

Second, at least one deck has been placed with silica-fume concrete produced in a volumetric measuring continuous mixing (VMCM) system. The unit was modified to use silica-fume slurry rather than latex. It has been the author's experience that it is difficult to obtain a satisfactory air-void system in VMCM units in conjunction with a silica-fume admixture. Trial batches along with appropriate testing of hardened concrete are certainly recommended. Obviously, this recommendation implies testing well before actual placements are to take place.

Third, finishing machines used for other types of concrete overlays have been successfully used for silica-fume concrete. As with any piece of equipment using a new material, test placements are desirable. Because of the small volumes of concrete involved in an overlay, one or two truckloads of concrete used to calibrate the finishing machine may very well complete a major portion of the deck. One agency currently involved in a full-depth deck replacement using silica-fume concrete has overcome this problem by requiring test placements in a toll plaza area away from the actual deck.

Finally, bridge deck overlays have usually used high silica fume contents and low water contents: an ideal combination for increasing the potential for plastic shrinkage cracking. The precautions usually taken for placing latex-modified concrete, such as placing in the evenings, have also worked well for silica-fume concrete.

CONCLUSIONS

Silica fume is a material that offers significant potential for improvements in some properties of concrete. It is not a cure-all for bad practices, and it is not a laboratory curiosity that cannot be placed in the field under field conditions. Silica-fume concrete is being successfully manufactured and placed on a wide variety of projects. However, the author's experience to date is that many producers and contractors generally want to obtain the benefits of high strength or high durability without paying any price other than that of the silica fume itself. The additional price that must be paid is strict attention to detail and careful adherence to good practices.

No difficulties have been identified in the use of silica fume in field concrete that cannot be overcome by proper planning before the problems occur. The one difference that cannot be overcome is that silica-fume concrete will be less forgiving than conventional concrete of any attempts to cut corners.

REFERENCES

1. ACI Committee 226. Silica Fume in Concrete. *ACI Materials Journal*, Vol. 84, No. 2, March-April 1987, pp. 158–166.
2. V. M. Malhotra and G. G. Carette. Silica Fume Concrete—Properties, Applications, and Limitations. *Concrete International: Design and Construction*, Vol. 5, No. 5, May 1983, pp. 40–46.
3. T. C. Holland and M. D. Luther. *Improving Concrete Quality with Silica Fume*. Louis H. Tuthill International Symposium on Concrete and Concrete Construction, ACI SP–104, American Concrete Institute, Detroit, Mich., 1987, pp. 107–122.
4. M. F. Pistilli, G. Rau, and R. Cechner. The Variability of Condensed Silica Fume from a Canadian Source and Its Influence on the Properties of Portland Cement Concrete. *Cement, Concrete, and Aggregates*, Vol. 6, No. 1, 1984, pp. 33–37.
5. M. F. Pistilli, R. Wintersteen, and R. Cechner. The Uniformity and Influence of Silica Fume from a U. S. Source on the Properties of Portland Cement Concrete. *Cement, Concrete, and Aggregates*, Vol. 6, No. 2, 1984, pp 120–124.
6. ASTM C 618, Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete. In *Current Annual Book of ASTM Standards*, Volume 04.02, American Society for Testing and Materials, Philadelphia, Pa.
7. ASTM C 494, Standard Specification for Chemical Admixtures for Concrete. In *Current Annual Book of ASTM Standards*, Volume 04.02, American Society for Testing and Materials, Philadelphia, Pa.
8. D. Whiting. *Rapid Determination of the Chloride Permeability of Concrete*. FHWA Report No. FHWA/RD-81/119. FHWA, U. S. Department of Transportation, 1981, 174 pp.
9. Standard Method of Test for Rapid Determination of the Chloride Permeability of Concrete. T 277-83. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, Part II, AASHTO, Washington, D.C., 1986, pp. 1229–1234.
10. ASTM C 94, Standard Specification for Ready-Mixed Concrete. In *Current Annual Book of ASTM Standards*, Volume 04.02, American Society for Testing and Materials, Philadelphia, Pa.
11. ACI 305R-77, Hot Weather Concreting. *ACI Manual of Concrete Practice*, American Concrete Institute, Detroit, Mich.
12. ACI 308–81, Standard Practice for Curing Concrete. *ACI Manual of Concrete Practice*, American Concrete Institute, Detroit, Mich.
13. T.C. Holland. Testing High-Strength Concrete. *Concrete Construction*, Vol. 32, No. 6, June 1987, pp. 534–536.

Publication of this paper sponsored by Committee on Chemical Additives and Admixtures for Concrete.

Addressing Parking Garage Corrosion with Silica Fume

THOMAS G. WEIL

Because it reduces chloride penetrability, silica-fume concrete is gaining popularity as a corrosion-protection system for parking garages, bridge decks, and other structures. This paper provides an overview of experience with silica-fume concrete in the United States.

Twenty-two hundred parking areas were built between the years 1979 and 1984 in what would be considered the frost belt of the United States. Of these, 630 contained 150 spaces or more (according to the McGraw-Hill Construction Group). With more than 100 of the larger structures being constructed on an annual basis, it is important that precautions be taken to protect them against deicing salt-induced corrosion. The latest exciting product to enter the corrosion protection market is silica fume (microsilica).

Concrete in a nonaggressive environment is a very strong, durable, and long-lasting building material. In aggressive environments, some precautions may be needed to protect the concrete or embedded steel. With the use of deicing salts since the early 1960s to keep our roads clear of snow and ice, concrete transportation-type structures are now under attack. Bridges and parking garages are deteriorating at an alarming rate due to chloride-induced corrosion. Bridge decks have deicing chemicals deposited directly on the surface where the chemicals affect not only the deck but also the supporting structural members due to leakage. Although deicing chemicals are used only sporadically in parking garages, cars carry salt-infested snow into the garages. Much of this salt remains after the cars leave.

Unlike bridges, however, which are washed by spring rains, parking garages are rarely washed down in the spring. The salts deposited in the winter remain all year. Indeed, when comparing concrete chloride contents of bridge decks and parking garage decks in the same location, and all other parameters being equal, the garage decks usually show a higher chloride content at all slab depths. This chloride content is due to the presence of larger amounts of chlorides on the slab surface during warmer weather. As ambient temperatures rise, chlorides are able to diffuse through the concrete pores at a greater rate of speed.

The highly alkaline environment of concrete creates a protective passivating layer on steel that inhibits the electrochemical reaction of corrosion under normal conditions. Chlorides will move through the concrete pores as well as through the transition zone between the paste and aggregate and eventually reach the embedded steel. Penetration of the passivating layer takes place, and corrosion of the steel begins. As the chloride content around the rebar increases, so does the corrosion rate. The corrosion product will expand in size by roughly four times its original volume, creating tensile pressures on the concrete up to 10,000 psi. The concrete eventually ruptures, causing cracking and spalling which allows more chlorides to enter at an even faster rate. Eventually, the concrete will deteriorate, requiring expensive rehabilitation or causing structural failure.

Obviously, steps must be taken to protect these structures against chloride-induced corrosion. Because it is very unlikely that the use of deicing salt will cease, design engineers must rely on corrosion protection methods to protect their structures. Corrosion protection in many other industries is a normal part of the design package. For reinforced concrete structures, however, it is a fairly new feature. Even so, many types of corrosion protection products are already available on the market, and most have proven their worth.

Surface sealants and membrane systems attempt to physically block chlorides from entering the concrete and prevent them from reaching the rebar. Coated reinforcing steel attempts to place a physical barrier between the concrete and steel, thus preventing the chlorides from attacking the steel. Calcium nitrite corrosion inhibitor promotes the stabilization of the steel's natural passivating layer, thereby controlling the corrosion rate. And finally, latex modifiers and silica fume reduce the permeability of the concrete, considerably slowing the ingress of chlorides. Each of these systems has a different operational mechanism, but all help extend the service life of the structure.

Silica fume is a by-product of silicon, ferrosilicon, or other silicon alloy production in a submerged arc electric furnace. It contains a silica (SiO_2) content of 85 percent or greater and has as an extremely fine particle size, which has caused some researchers to call it a "super pozzolan." The ultra-fine particle size of roughly 0.1 micrometers allows the silica fume to fill the voids in the cement paste and between the cement paste and aggregate while the pozzolanic feature causes reaction with the excess calcium hydroxide ($Ca(OH)_2$). This process results in a far less permeable microstructure matrix that appears homogeneous and that has no gaps and no large crystals of $Ca(OH)_2$ (*1*).

Fairly long-term studies (*2*) have shown that silica fume reduces the apparent diffusion coefficient of concrete by at least an order of magnitude. Other long-term salt water ponding studies at H. R. Grace & Co.'s Construction Products Division, Cambridge, Massachusetts, are beginning to corroborate these results.

W. R. Grace & Company, Construction Products Division, Cambridge, Mass.

TABLE 1 CHLORIDE PERMEABILITY BASED ON CHARGE PASSED

Charge Passed (coulombs)	Chloride Permeability	Typical Description
4,000	High	High water-cement ratio (0.6); conventional PCC
2,000–4,000	Moderate	Moderate water-cement ratio (0.4–0.5); conventional PCC
1,000–2,000	Low	Low water-cement ratio (0.4); conventional PCC
100–1,000	Very Low	Latex-modified concrete, internally sealed concrete
100	Negligible	Polymer-impregnated concrete; polymer concrete

Actual concrete permeability is a feature that cannot, unfortunately, be measured quickly for upcoming projects. In response to this problem, the Federal Highway Administration has produced a rapid test method for determining the apparent chloride permeability of various concretes (*3*). The 4-in.-diameter by 2-in.-thick specimens are subjected to a 60-V potential for 6 hr to measure the charge passed in coulombs. At least a dozen parameters affect the final coulomb reading, so five chloride permeability categories were created (Table 1). Coulomb readings from different samples that fall in the same category are considered to be equivalent as far as chloride permeability is concerned. Design engineers who have specified silica fume thus far required concrete coulomb readings to be in the 100–1,000 coulomb category (very low).

Some engineers believe inaccuracies exist in the FHWA test and are not specifying coulomb levels, but rather "percent silica fume by weight of cement." Usually a specified silica fume quantity is based on prespecification testing at a local laboratory to see what amount will attain a coulomb level of 1,000 or less. As an example, tests (*4*) run on a 550-lb cement factor mix with a water-cement ratio of 0.45 yielded a coulomb reading of 3,600. When 7.5 percent silica fume by weight of cement was added, a coulomb reading of 850 was produced; while a 15 percent silica-fume addition gave 200 coulombs. It is not uncommon to see silica-fume specifications of 7.5 percent by weight of cement.

Besides reducing concrete chloride permeability, silica-fume concrete has many other benefits: increased abrasion and erosion resistance; increased resistance to aggressive chemical acid attack; and most importantly, compressive and flexural strength enhancement. Silica fume develops higher strength in concrete due to the same factors that reduce chloride permeability—by combining with the excess calcium hydroxide to produce more calcium silicate hydrate paste and filling the pores between the aggregate and cement grains. More paste with fewer voids creates a better bond between the aggregate, producing higher strengths. To continue the earlier example (*4*), the concrete mix containing a cement factor of 550 lb of type I cement with a water-cement ratio of 0.45 will produce a 28-day compressive strength of 5,500 psi. Adding 7.5 percent silica fume by weight of cement and a high-range water reducer to insure workability produces a 28-day strength of 9,500 psi. When 15 percent silica fume is added, the 28-day strength reaches 10,300 psi (Table 2). The engineer should take advantage of this increased compressive strength and design not only for reduced concrete chloride permeability but for high concrete strengths as well.

TABLE 2 CONCRETE 28-DAY COMPRESSIVE STRENGTH AND RAPID CHLORIDE PERMEABILITY

Microsilica Content (%)	Compressive Strength (psi)	Coulombs Passed
0	5,500	3,600
7¼	9,500	850
15	10,300	200

NOTE: Data refer to 550 lb type I cement, water-cement ratio 0.45.

Due to reduced concrete chloride permeability, silica-fume concrete is gaining popularity as a major corrosion-protection system for parking garages, bridge decks, and other structures. To date, the two major silica-fume admixture suppliers have participated in the construction of 39 parking garage projects (both completed and under construction). The first silica-fume parking garage was completed in 1984, while 27 were either completed in 1986 or under construction in 1987. The average-size project contained 3,500 yd^3 of concrete, with the smallest containing 150 yd^3. The largest, 45,000 yd^3, is under construction. Dosage rates ranged from 3.75 percent silica fume by weight of cement to 16 percent with an average of 7.5 percent. Types of projects include less permeable overlays, toppings on prestressed double tees, rehabilitation ranging from large-scale patching to completed deck replacement, and standard cast-in-place new construction.

Even with all its advantages, silica-fume concrete does require extra attention during finishing and curing. Due to the cohesiveness of silica-fume concrete, it is recommended that slumps at least an inch higher than normally placed be used. Another area of caution is the reduced amount of bleed water after a slab is placed. Above a dosage rate of 5 percent silica fume by weight of cement, the bleed rate drops dramatically. As the silica-fume content increases, the bleed rate correspondingly decreases. ACI 302, Guide for Concrete Floor and Slab Construction, or ACI 30B, Standard Practice for Curing Concrete, should be followed to reduce the possibility of plastic shrinkage cracks. Recommended procedures include fogging during finishing and wet burlap or the use of curing compounds during curing.

In 1986, a 5,000-yd^3 parking structure owned by Crown Center Redevelopment was built in Kansas City, Missouri, to hold roughly 800 cars. A concrete mix consisting of 611 pounds of cement, water-cement ratio of 0.40, 0.75-in. aggregate, 10 percent silica fume, and 7 percent entrained air was used. A superplasticizer was added to produce a 6-in. slump. The 28-day compressive strength averaged 8,000 psi, and coulomb readings averaged 400 at 90 days. The finishing and curing procedure reflected bleeding characteristics of silica-fume concrete. Screeding was performed with an aluminum screed 2 in. × 4 in. The two passes with a vibratory bullfloat were followed by two passes with a regular bullfloat; an evaporation retardant was then applied; and finally, a hand-swirl finish.

The largest silica fume-protected parking structure is presently under construction. The Capitol South parking garage in Columbus, Ohio, will have spaces for 3,000 cars and needs 45,000 yd^3 of concrete. Silica-fume concrete will be used in the slabs for corrosion protection and is being combined with a calcium nitrite corrosion inhibitor in the columns for high strength (8,000 psi) and corrosion protection. The slab mix contains a 610-lb cement factor, 90 lb of fly ash, a water-cement ratio of 0.40, and 7.5 percent silica fume by weight of cement. A superplasticizer is added to attain slump. Construction is cast-in-place posttensioned. The 28-day strengths range from 7,600 to 9,000 psi, and 28-day coulomb readings average 500. Here again, care is taken during finishing and curing. Screeding is with a 2 in. × 4 in. screed followed by a wood float and then a steel float. Fogging is then applied to maintain a moist surface until a power float is used. A broom finish is applied and then fogged until burlap can be laid down and moistened.

Although new construction is a perfect application for silica-fume concrete, its use in rehabilitation of existing structures is growing in popularity. After 20 yr of use, Old Kent Bank & Trust Company parking garage in Grand Rapids, Michigan, required rehabilitation. Two levels of parking are located below grade, and one at street level. The top deck is a 6-in.-thick, cast-in-place posttension design spanning 25 ft between supporting precast single tees. Chloride content in the top 1 in. of concrete was roughly equivalent to 8 lb of chlorides per yd^3. Reinforcing steel had between 1 in. and 1.5 in. concrete cover. A rehabilitation program called for the removal of distressed concrete, repairing or replacing damaged posttensioning and reinforcing, and a silica-fume concrete overlay. To ensure proper bonding, the surface was first shot-blasted. A bonding grout consisting of cement, water, and silica fume was then applied. The 1.5-in.-thick overlay mix consisted of 650 lb of cement, 10 percent silica fume by weight of cement, 7 percent air content, 0.625-in. maximum aggregate, a high-range water reducer, and a water-cement ratio of 0.40. Concrete strengths were 4,500 psi in 24 hr, and 8,000 psi in 28 days.

Due to the lack of bleed water in a 10 percent silica-fume mix, the finishers bull-floated the overlay directly behind the screed. Water fogging was constantly used to protect against plastic shrinkage cracks. Wet burlap was then put down for curing purposes.

It is now apparent that most transportation-type concrete structures must be protected from deicing-salt-induced corrosion. Silica-fume concrete has quickly become one of the major corrosion protection systems available to protect parking garages due to improved strengths and reduced chloride permeability. It must be remembered, however, that one must first start with quality concrete mix designs as recommended by ACI. Silica fume can then deliver those extra properties that will help the concrete structure perform for its full design life.

REFERENCES

1. M. Regourd. Microstructure of Cement Based Materials Containing Silica Fume, Its Relationship with Some Properties. Presented at the International Workshop on Condensed Silica Fume in Concrete, Montreal, Quebec, Canada, May 4–5, 1987.
2. K. P. Fischner, O. Bryhn, and P. Aagaard. Corrosion of Steel in Concrete: Some Fundamental Aspects of Concrete with Added Silica. Presented at the NACE CORROSION/83 Meeting, Anaheim, Calif., April 18–22, 1988.
3. D. Whiting. *Rapid Determination of the Chloride Permeability of Concrete*. Report FHWA/RD-81/119. FHWA, U.S. Department of Transportation, 1981.
4. M. Gee. Microsilica Concrete. *The Construction Specifier*, December 1986.

Publication of this paper sponsored by Committee on Chemical Additives and Admixtures for Concrete.

Silica-Fume (Microsilica) Concrete in Bridges in the United States

MARK D. LUTHER

This paper reviews silica-fume-concrete (SFC) use in bridges in the United States. Although the focus is on bridge-deck overlays, other bridge-related applications are discussed, including full-depth decks, approach slabs, and piles. The reasons for using SFC include providing a chloride barrier, developing high early strength, achieving high ultimate strength, obtaining abrasion resistance, and improving bond strength. The concretes, representing silica-fume dosages between 5 and 15.5 percent, were placed successfully, although some difficulties were encountered. These dificulties, along with their solutions, are discussed. One silica-fume-concrete feature that required particular attention was the need to take measures to prevent plastic shrinkage cracking. An attempt is made to characterize the performances of the concretes, which are generally acceptable and encouraging. Further experimental work with silica-fume concrete is being done, and the material is now being specified in bridges.

Silica-fume concrete (SFC) has been used in bridges outside the United States since the 1970s (*1*); in some countries it is commonly specified to provide generally improved durability. Silica-fume concrete has been used with increasing frequency in bridge decks and associated structures in the United States since 1983, and this work is reviewed herein.

Many articles have described silica fume (SF) and its effect on portland cement concrete (*2–4*). Briefly, silica fume—a term often used interchangeably with the term microsilica—is collected from exhaust gases during the production of silicon or ferro-silicon alloys. Most SFs contain at least 85 percent amorphous silicon dioxide (SiO_2) and have a specific surface above 20 m^2/g. Silica fume is a highly reactive pozzolan that refines the portland cement paste pore structure. Usually, addition of SF to concrete significantly reduces permeability and improves many of the more significant concrete properties.

Silica-fume dosages used in bridges commonly lie at 5–15.5 percent, expressed as an addition by weight of the cement. Most of the bridge-related projects to date have used SF supplied from wet (sometimes called slurry-type) SF-based admixtures. Commercially available formulations of these wet SF admixtures usually contain, by weight, 45–50 percent SF, 47.5–51 percent water, and 2–4 percent other components, which may include chemical water-reducing admixtures (WRA) and/or high-range water-reducing admixtures (HRWRA). The dry SF-based admixtures typically contain at least 85 percent SF.

BRIDGE-DECK OVERLAYS

The experiences of owners that have investigated using SFC as a bridge-deck-overlay material are presented here. The slab-type placements shared many similar operations: preparing the base to a moist-surface condition; applying bonding grout (for overlays); consolidating with internal vibration; screeding, and in the case of roller screeds, further closing the surface with a drag pan and a wet burlap drag; floating; applying a tine surface texture; and curing by immediately covering with wet burlap and plastic. This series of operations is designated by the phrase "in the standard manner" in this paper, and exceptions to this procedure are noted.

Ohio Department of Transportation

The Ohio Department of Transportation (ODOT) placed an experimental 15.5 percent SFC overlay in October 1984 during rehabilitation of Bridge No. ASD–511 along State Route 511 about 2 mi north of Ashland. It is believed that this placement represents the first of its kind in the United States. Silica fume concrete was investigated as a potential alternative to latex-modified concrete (LMC) (*5*). One lane of this bridge received an LMC overlay, and 15.4 yd^3 of SFC were placed on the other lane. The minimum overlay depth was 1.5 in., and the average depth was 2.3 in. The non-air-entrained concrete (Table 1) was supplied from a mobile mixer, with the wet SF-based admixture being pumped from drums. After a trial run, concrete was placed in the standard manner using mortar from the concrete for bonding grout and using a roller screed of the type commonly used to place LMC. A portion of the lane was covered with curing compound, and the remaining part was covered with wet burlap and plastic. After 2 days, the burlap and plastic were removed; and the lane was opened to traffic on the fourth day. An ODOT inspection at 1 week showed a blemish-free surface.

Rapid freezing-and-thawing results were poor (Table 1) because, as expected, the air-void spacing factor was high. The spacing factor was nearly four times greater than the 0.008-in. figure commonly associated with achieving good frost resistance, and the specific surface, at 168/in., was lower than the minimum 600/in. figure that is clearly acceptable. A bridge inspection by the author in July 1985, though, found no cracks; and it revealed generally blemish-free surfaces in both lanes. An ODOT inspection during July 1987 again found the concrete to be performing satisfactorily even though several cracks were seen in the LMC lane, and two were observed in the SFC lane. The largest crack was 16 in. long, 0.03 in. wide,

---

Elkem Chemicals, Inc., 10 Parkway View Drive, Pittsburgh, Pa. 15205.

TABLE 1 CONCRETE PROPORTIONS FOR ODOT, KyDOH, AND NYSDOT OVERLAYS

State Agency	ODOT			KyDOH		NYSDOT	
Year	1984		1987	1985	1985	1984	1985, 1986
Bridge	Ashland		Avery Rd.	Three Rivers Power Plant	N/A	N/A	The Syracuse Project
Trial, Overlay, or Lab	Overlay		Overlay	1st Overlay	Lab	Lab	Overlays
Silica Fume Dose[a] (%)	15.5		15.0	15.5	15.5	13.9	14.0
Cement, Type 1 (lb/cu yd)[b]	658[c]		698[c]	658[c]	658[c]	694[h]	680[h]
W/(C+SF)[b]	0.35		0.34	0.33	0.33	0.31	0.30±
Slump (in.)	4.0-11.0[d]		6.5-8.0	7.0-8.5	10	7.5	6.5-8.0
Air Content, Fresh (%)	5.2		9.1-9.8	8.5	8.8	2.2	5.0-9.0
Strength: (psi)							
Compressive	6880		6060-6380	10800	8190 @ 7d	11000	9000 @ 7d
Flexural	940		990-1080				
Hardened Air system	ODOT	W.Dolch[e]	ODOT	P.D. Cady[e]	KyDOH		
Air Content (%)	5.5	4.7	--	6.71	9.02		
Specific Surface (1/in.)	168	162	620	525	623		
Spacing Factor (in.)	0.030	0.032	0.004	0.0083	0.0052		
Freezing and Thawing							
Durability Factor:							
@ 300 cycles	5.5[f]		97.5-103.1	85[fg]			
@ 352 cycles				60-70[fg]	95		
Weight Loss[i] (%)			0.03-0.05			0.55	0
Chloride Content at all depths[j] (%)						0	

Note a: SF dose is expressed as a percentage, by weight, added to the cement. Note b: W/(C+SF) - water-to-(cement plus silica fume), by weight. Note c: 3/8-in. limestone. Note d: Slump was varied deliberately. Note e: W. Dolch is a professor of Civil Engineering at Purdue University. P. D. Cady is a professor of Civil Engineering at Pennsylvania State University. Note f: ASTM C666, procedure B. Note g: Limestone had a history of D-cracking in concrete. Note h: 1/2-in. limestone. Note i: 25 cycles at one cycle per day in a 10% sodium chloride solution. Note j: 3% and 10% sodium chloride solutions, 95-day ponding.

and about 1.25 in. deep (cored). Chain dragging indicated good bond.

A second SFC overlay was placed on the two-lane Avery Road Bridge over Route 33, near Dublin. This time the concrete (Table 1) was air-entrained to improve frost resistance. Subsequent to placing a trial slab, the southbound lane was constructed in April 1987, and the northbound lane was cast in May. The concrete was truck-mixed prior to the 45-min trip to the job site where it was discharged without further slump adjustment. Concrete was placed in the standard manner using a cement-sand bonding grout and a roller screed. The placement proceeded smoothly. The finish was acceptable, and at 3 mo no cracks were seen. Rapid freezing-and-thawing tests were acceptable, and the hardened concrete air-void tests revealed the presence of a traditionally acceptable air-void system.

ODOT is expanding the use of SFC overlays. Approximately 120 yd^3 of air-entrained 15-percent SFC was placed in a full-depth application in August 1987 for the Plain City Bridge on Route 161 in Madison County. Again, rapid freezing-and-thawing tests were acceptable. Durability factors ranged between 95.5 and 101.1, the spacing factor was 0.008 in., and the specific surface was 550/in. The Route 422 extension project in Cleveland (ODOT Project No. 462) will require approximately 500 yd^3 of SFC in 10 bridges. For each bridge, one lane will receive an SFC overlay, and one lane will receive a high-density overlay. This work was planned for spring of 1988. Also, two other ODOT bridge deck overlays are currently being bid in Barnesville, Ohio.

University of Cincinnati

During May 1986 the University of Cincinnati placed overlays on two pedestrian walkways using about 25 yd^3 of 5-percent SFC. Also, one 65-ft-long three-span full-depth pedestrian bridge was cast. These placements were successful, and the university subsequently constructed a parking garage with SFC.

Kentucky Department of Highways

On the evening of May 30 and the morning of May 31, 1985, a 15.5 percent SFC (Table 1) minimum 1.25-in.-thick overlay was placed by the Kentucky Department of Highways (KyDOH). The three-span structure (Bridge No. 1120–44) services an access road to the Three Rivers Power Plant near Seebree. At least one loaded coal truck per minute travels toward the plant on what is now the SFC lane. Concrete was produced in a mobile mixer, and the wet SF- based admixture was supplied from drums. On May 30, concrete was placed in the standard manner using mortar from the concrete for bonding grout and using a roller screed initially. The roller screed was in disrepair, and the initial overlay surface closure was unacceptable. Bull-floating improved the surface, and a fine-broom texture was applied. Due to various delays some plastic shrinkage cracks developed in the segment over the second pier before the concrete was covered with wet burlap and plastic. Only two spans were placed on May 30. On May 31 a reciprocating beam vibrator—the type commonly used for high-density concrete—was used for the third span with excellent results. In addition to the finishing equipment change, the fine aggregate-to-aggregate percentage was increased from 50 on May 30 to 55 on May 31.

Durability factors as defined by ASTM C666, procedure B (Table 1) for the overlay concrete were around 85 at 300 cycles; but after 352 cycles, performance dropped off. The air-void spacing factor was 0.0083 in., which just exceeded the traditionally acceptable 0.008-in. maximum figure. It was noted that the limestone was known to cause D-cracking in concrete. Subsequent laboratory tests (Table 1) with a different coarse aggregate and batching in a drum mixer produced durable SFC, having a durability factor over 95 at 352 cycles. This concrete, incidentally, showed a spacing factor of 0.0052 in.

The bridge was inspected regularly. At 4 mo, no changes were seen. At 9 mo, a few cracks were seen in the May 31 concrete near the second pier, and more were seen there after 2 yr. Although the cracking was disappointing, the overlay appeared to be functioning well as a chloride barrier. There were no spalls or delaminations, and the original surface texture was still visible, indicating high wear resistance. It was noted that there were no cracks seen in the outbound lane that was made with high-density concrete. There was interest in placing future overlays with a higher air content to improve frost resistance.

New York State Department of Transportation

Beginning in February 1984, the New York State Department of Transportation (NYSDOT) studied in the laboratory a non-air-entrained 13.9-percent SFC (Table 1) and concluded that the SF-based admixture could enhance strength and decrease water and chloride permeability of concrete. Silica-fume concrete was considered to be a potential alternative to LMC and high-density concrete. By June 1985, several 2-in. minimum thickness experimental air-entrained SFC overlays were scheduled into bridge repair work on the east side of Syracuse (Project No. D251436) along with more than a dozen LMC overlays.

During 1985 two bridges received SFC. One was a 4.5-yd^3 base repair (Bridge No. BIN 1093550), and the other was an overlay (Bridge No. BIN 1093562). Wet SF-based admixture, added first to the truck mixers, was dispensed from a 6,000-gal-capacity mobile dispenser. Typically the 6-yd^3 loads (Table 1) were mixed 100 revolutions before being discharged at about 25 min, often after slump adjustment. Concrete was placed in the standard manner using a vibratory screed for the base repair, which worked well, and using a roller screed for all other placements. There were cases of poor surface closure and plastic shrinkage cracking with both SFC and LMC when the roller screed was used. The SFC, though, did show good workability retention. Also, the grooves that were saw-cut into all the SFC overlays were made without raveling or spalling.

Silica fume concrete placements in 1986 proceeded smoothly. The previously experienced plastic shrinkage cracking was eliminated because these overlays were cast in the evenings when evaporation rates were lower and more favorable for placement. Additionally, proper adjustment of the roller screed, increased consolidation, absence of delays, and a higher fine aggregate-to-aggregate ratio served to improve results. After further trial batch work, the northbound east lane of bridge number BIN 1093562 was placed on May 14. On June 24, the one-lane exit ramp from Route I–690 eastbound to Route I–481 northbound (Bridge No. B191093520) was placed. A small portion of BIN 1093562 was cast on July 15, and the last placement under this contract (Bridge No. 1093520), on August 2, used 21 yd^3 of SFC with no problems. Typically, the concrete was cured under wet burlap for 1 day, then the burlap was removed and the concrete was cured under plastic for 3 more days.

An NYSDOT inspection in 1987 showed that one lane of the BIN 1093520 overpass was unblemished and the other lane showed reflection cracks. There was a question about whether the affected lane received adequate curing. Visual inspection indicated wear resistance better than normally seen, and no scaling or popouts were observed. Freezing-and-thawing tests on cores from the last SFC placement showed only insignificant weight loss (Table 1). The NYSDOT construction report for the Syracuse overlays (*6*) concluded that SF overlay concrete can be handled and finished, and the material appears to be a viable alternate to LMC and low slump concrete. The report encouraged the use of SFC in future overlays.

NYSDOT is considering SFC as an alternate overlay material, and further SFC bridge deck work is being planned. NYSDOT specifications now require initiation of curing within 5 min if the theoretical evaporation rate according to Figure 2.1.5 of ACI 305R–77 exceeds 0.05 lb/ft²/hr. Focus is on precautions to eliminate plastic shrinkage cracking.

Tennessee Department of Transportation

In June 1986, the Tennessee Department of Transportation (TDOT) began using 11.2-percent SFC (Table 2) in a minimum 4-in.-deep repair of the 1,228-ft-long Landon B. Hassler Memorial Bridge (Bridge No. 69–SR42–3–27), located where State Route 42 crosses the Obey River. Silica-fume concrete was included as an add-on material that was expected to achieve 4,500 psi within 3 days. On remarkably short notice, a 6000-gal-capacity mobile dispenser was set up at the concrete plant, located 40 min from the job. There was no trial batch. Typically, no slump adjustments were necessary. The truck-mixed concrete was placed in the standard manner using a vibratory tandem wooden screed, bull-floating, water-misting to prevent plastic shrinkage cracking, and wet-burlap (no plastic cover) curing. The approach spans also received overlays which were full depth in places.

The concrete was uniform and exhibited good workability retention. Although the concrete was somewhat sticky, the desired finish was achieved. The SFC developed 5,220 psi at 3 days. The surface was acceptable even though after 10 days transverse cracks were seen on about 5-ft intervals—roughly the same as in the adjacent conventional concrete lane, and apparently a common occurrence. A 6-mo inspection revealed no changes in the surface. The TDOT considered SFC to be an acceptable material for use in high early strength applications.

A second SFC overlay is scheduled for late fall of 1987 for

TABLE 2 CONCRETE PROPORTIONS FOR TDOT, MiDOT, AND MeDOT OVERLAYS

State Agency		TDOT	MiDOT	MeDOT		
Year		1986	1986	1986		1987
Bridge		Landon B. Hassler Memorial	Fontenac	Passadumkeag &	Dresden	Ohio St.
Silica Fume Dose	(%)	11.25	10.0	7.2	7.2	10.0
Cement	(lb/cu yd)	620[ab]	658[a]	658[a]	658[d]	635[d]
W/(C+SF)		>0.34	0.39	0.40	0.35-0.37	0.50
Slump	(in.)	5	5.25[c]	4.25-7.50	3.5-4.75	6.0
Air content, fresh	(%)	6	5.3[c]	5.9-7.8	6.5-5.9	6.5
Compressive strength	(psi)					
@ 3 days		5220	4740			
@ 7 days		6550 @ 5d	6450	4110-5180	5440-6610	6260
@ 28 days			7840	5540-6730	5870-7160	
Flexural Strength	(psi)					
@ 7 days			1180			
@ 28 days			1230	980	1170	
Modulus of Elasticity	(psi)		5,200,000			
Rapid chloride charge passed	(coulombs)					
Dryiing shrinkage:	(%)					
@ 28 days			0. 35			
@ 6 months			0.53			
Rapid chloride (charge passed)	(coulombs)			548[e]		

Note a: Type 1. Note b: 1-in. limestone. Note c: Mean of all results. Note d: Type 2.

Note e: Tested at 148 days. Charge passed level for 658 lb/cu yd of cement, w/c = 0.35, 4880 psi @ 28 days conventional concrete placed on the same deck was 5060 coulombs @ 148 days.

the Broad Street Bridge over I–40 near Nashville. This 4.5-in. overlay will be placed on the 203-ft-long by 76-ft-wide deck on weekends, one lane per weekend. Again, the SFC is being used primarily to achieve high early strength and thereby minimize the time that lanes are closed to traffic.

Michigan Department of Transportation

The State of Michigan Department of Transportation (MiDOT) began SFC laboratory tests in May 1985 (*7*). This work suggested that a 658 lb/yd^3 of cement mixture with 10-percent SF could develop "very low" AASHTO T277 rapid chloride permeability (RCP) (*8*), which was comparable to the 658 lb/yd^3 LMC mixture currently used. MiDOT considered SFC to be a potential economically competitive alternate to LMC for bridge decks.

By late June 1986, two four-span bridges—Fontenac Ave. Bridge and Mt. Elliott Ave. Bridge (Bridge Nos. S12 and S10, respectively, of contract number 82024), both over I–94 in Detroit—received experimental thin-bonded overlays. The overlays were 2 in. thick, although in some places the repair was full depth. Wet SF-based admixture was dispensed from a remote-controlled 6,000-gal-capacity mobile dispenser to a central mixer. After a 15-min trip to the job, concrete (Table 2) was placed in the standard manner using a cement-sand bonding grout and a roller screed. During the first placement, the fine aggregate content was increased to improve surface closure. Workability retention was good, and surface closure was acceptable, although it could have been better.

No plastic shrinkage cracking was experienced. The hardened concrete surfaces showed no spalls or popouts, and they were blemish free with the exception of some tight cracks that appeared within 2 weeks. These cracks were generally rectangular, and both thick and thin depth areas were affected. It should be mentioned that in Michigan low slump high-density placements some years earlier showed heavy cracking (*7*), and local LMC overlays generally showed little cracking. An initial MiDOT report (*9*) indicated that at 6 mo the average SFC shrinkage was 0.53 percent, whereas LMC from the Ferry Avenue Bridge nearby was 0.41 percent. Rapid chloride permeability tests on both job cylinders and cores from the overlays revealed that the SFC consistently achieved RCP results near the low end of the "very low" range (this included one core with a full-depth crack), and the LMC specimens showed results near the upper end of the "very low" range. The 90-day 3 percent sodium chloride solution ponding tests found no chlorides at the 1.5-in. depth for SFC, whereas LMC showed 0.3 lb/yd^3 at the same depth.

MiDOT is continuing laboratory study of SFC, and another experimental bridge deck overlay placement is being planned.

MiDOT is also investigating the use of a dry densified SF-based admixture for making SFC for bridge deck overlays.

Maine Department of Transportation

The Maine Department of Transportation (MeDOT) investigated using SFC wearing courses as an alternative to LMC, primarily to achieve good bond and to act as a chloride barrier. Two bridges were selected for experimental work during the latter half of 1986. The two-lane bridges—Passadumkeag (Bridge No. 264950–0–990), located where State Route 2 crosses the Passadumkeag River, and the Dresden (Bridge No. 334), spanning the Eastern River—received 2.5-in.-thick minimum design wearing surfaces. The SF-based admixtures, added first to the truck mixers, were transferred from pre-weighed drums. The 7.2 percent SFC (Table 2) was mixed 100 revolutions at the plant, driven 20 mi to the job, and mixed at least 20 revolutions just before discharge, sometimes after on-site water addition. Concrete was placed in the standard manner using a cement-sand bonding grout, a vibratory tandem wooden screed, and bull-floating. The concrete was wet-burlap-cured for seven days, and the lane was opened within 9 days. The concrete was uniform, achieved the desired properties, and was easy to place and finish. No cracks or delaminations were observed. AASHTO T277 RCP tests on SFC specimens from the Dresden Bridge showed that the charge passed level was improved (reduced) by a factor of 10 relative to that of the conventional concrete that was also placed in the deck. MeDOT placed a minimum 3-in.-thick wearing surface during the summer of 1987 on the two-lane Ohio St. Bridge over I–95 in Bangor. Approximately 100 yd^3 of 10 percent SFC (Table 2) were placed as previously described. The first MeDOT contract job using SFC will be a minimum 2-in.-thick overlay for the Sandy River Bridge in Farmington. Specifications currently being written for this project will call for a maximum water-to-cement-plus-SF ratio of 0.40, and will require at least 65 lb/yd^3 of a wet SF-based admixture.

Virginia Department of Transportation

In 1984 the Virginia Department of Transportation (VDOT) conducted SFC laboratory work (*10*) and concluded that 5 percent SFC having a water-to-cement ratio of 0.40 or lower would be suitable for overlays as thin as 1.25 in. The SFC provided satisfactory strength, low permeability, a 90-day ponding chloride content at the 0.25–0.75-in. depth that was half the level of the control concrete, and satisfactory rapid freezing-and-thawing durability even though a high air-void spacing was observed (attributed to use of HRWRA).

In May 1987, a four-span bridge near Winchester received the first VDOT SFC overlay—a minimum 1.25-in.-thick placement in the traffic lane using both 7- and 10-percent SFC (Table 3). Three weeks later the passing lane was placed. The wet SF-based admixture was added to the truck mixers at the plant along with HRWRA, and in two of the seven truckloads additional HRWRA was added at the job. The time from batching to discharge was about 35 min. Concrete was placed in the standard manner using mortar from the concrete for the bonding grout and using a roller screed. Portions of the decks were covered with wet burlap and plastic, and other areas received a curing compound only. The hardened concrete surface was acceptable. Only one foot-long crack was seen, associated with a joint where the overlay depth changed abruptly. Also, a zone that was poorly consolidated with the internal vibrator soon delaminated and was replaced. Air contents in the fresh concrete were generally low, and, as expected, some of the air-void spacing factors were high. Although the rapid freezing-and-thawing results were mixed, those concretes having air contents within the specification performed satisfactorily. Future VDOT SFC overlay placements are expected.

TABLE 3 CONCRETE PROPORTIONS AND PROPERTIES FOR VDOT OVERLAY

		Traffic Lane May 13, 1987		Passing Lane June 6, 1987	
Silica fume dose	(%)	7.0	10.0	7.0	10.0
Cement, type 2ᵃ	(lb/cu yd)	658	658	658	658
Slumpᵇ	(in.)	1-1/2 - 7 1/2			
Air content: fresh concrete	(%)	3.7	5.2	4.5	6.0
Compressive strength:	(psi)				
@ 28 hrs.		4340	5880	3730	5370
@ 7 days		6850	6770	6090	6100
@ 28 days		9180	7800	7890	6950
Flexural strength psi @ 28 days		760 - 960			
Hardened concrete air void system:					
Air contentᶜ	(%)	5.2	5.8	6.5	7.2
Specific surface	(1/in.)	539	582	489	455
Spacing factor	(in.)	0.0088	0.0077	0.0085	0.0082
Durability factorᵈ		33	60	79	80

Note a: Coarse aggregate was a nominal 3/8-in. stone. Estimated fine aggregate-to-aggregate ratio was 0.45. Maximum water-to-cementitious materials ratio was 0.40. Note b: Specified slump was 6 in. ± 2 in. Note c: Coarse void content was around 1%. Note d: ASTM C666, procedure A, modified with addition of 2% sodium chloride.

Illinois Department of Transportation

In 1987 the Illinois Department of Transportation (IlDOT) used 11.1-percent SFC in minimum 3-in.-thick overlays near Stauton (in March), which carries Route 4 over I–55, and in Mascoutah on the Silver Creek Bridge (in June). Concrete (Table 4) was placed in the standard manner using a 15-percent SF-modified bonding grout, a reciprocating beam vibrator, a fresno-float, a longitudinal astroturf drag, and a transversely tined surface texture. At Stauton, the SFC was covered with wet burlap and plastic for 4 days; and at Mascoutah, curing compound was used. The SFC was somewhat easier to place and finish than high-density concrete. The ready-mixed concrete was also cheaper than alternate concretes that required mobile mixers. The first Route 4 bridge inspection, made at 3 mo, revealed about four short transverse cracks and a few still-shorter ones near the drains, but these were not considered significant. It was noted that an adjacent high-density deck placed in October 1986 showed seven transverse cracks that were on 6–8-ft centers.

In June 1987, the IlDOT placed approximately 15 yd^3 of 11.2 percent SFC in an abrasion-resistant overlay for the approach lane of the two-lane Wood River Bridge, located along State Route 3 in East Alton. The overlay thickness ranged between 1.5 in. and 4 in. The concrete was truck-mixed, using a bagged densified SF-based admixture that was added first to the mixers. The placements were successful. In this case, SFC was used instead of LMC primarily because of the simplicity of production.

City of Milwaukee, Wisconsin

The city of Milwaukee placed 36 yd^3 of 10-percent SFC overlay on the 60th and Hampton Bridge during 1987. Reportedly, the placement was successful, although detailed information is not yet available.

Pennsylvania Department of Transportation

During May 1984, the Pennsylvania Department of Transportation (PaDOT) began testing a non-air-entrained 14.8-percent SFC that was made with a wet SF-based admixture (Table 4). A product evaluation report from August 1984 (*11*) was favorable. The rapid freezing-and-thawing results were excellent even though the air content was only 3.8 percent. Negligible RCP was reported. The SF-based admixture was approved for use as an experimental overlay material. An overlay is being planned.

Indiana Department of Highways

The Indiana Department of Highways (IDOH) conducted a laboratory evaluation of SFCs (*12*) that achieved air contents

TABLE 4 IlDOT, PaDOT, IDOH, VDOT, AND OHIO TURNPIKE COMMISSION CONCRETE PROPORTIONS AND PROPERTIES

State Agency		IlDOT	PaDOT	IDOH	VDOT	Ohio Turnpike Commission
Year		1987	1984	1984	1986	1985
Concrete Description		March field trial	Lab	Lab	Lab	I-77 overpass Placement[b]
Silica fume dose	(%)	11.1	14.8	15.2	4.5-12.5	6.8
Cement	(lb/cu yd)	630[a]	700	700[a]	660-705	658
W/(C+SF)		0.35	0.33	0.31	0.40-0.41	0.43
Slump	(in.)	6	6.5	4-6.5	2.0-4.75	4.25
Air content of fresh concrete	(%)	7.5-8.1	3.8	3.6-5.0	6.6-10.5	6.0
Compressive strength	(psi)					
@ 1 day					3280-5140	2180
@ 3 days				7340	5130-7580	
@ 7 days			8740	9930	5800-9400	6310
@ 28 days			10920	11880	7400-11720	8170
Flexural strength	(psi)					
@ 1 day						350
@ 3 days						600
@ 28 days			2080	1310		
Hardened concrete system						
Air content	(%)			3.6-5.6		
Specific surface	(1/in.)			276-336		
Spacing factor	(in.)			0.017-0.018		
AASHTO T277-831 charge passed	(coulombs)	539[c]	0			
ASTM C666[d]						
Durability factor			106.8	91.0-94.1	101.5-107.5	
Bond strength performance indicator @ 28 days[e]	(%)			101		

Note a: 3/8-inch limestone. Note b: 1.5 lb/cu yd polypropylene fibers were added. Note c: Test age was 49 days. n=3. Note d. VDOT and PaDOT use procedure A with VDOT using a 2% sodium chloride solution and VAOT using a 3% solution. VAOT results are for 500 cycles. IDOH used procedure B. Note e: The bond strength performance indicator expresses the ratio of the flexural strength of a reference base concrete-test concrete composite (joined vertically near the center of the beam) divided by the flexural strength of the base concrete.

significantly below the desired levels. The SFCs developed high ultimate strength, high early strength, and good bond (Table 4). Durability factors were acceptable (in the 90s), and the material appeared to limit the depth of chloride penetration to around 0.5 in. In July 1985, field tests were recommended.

Vermont Agency of Transportation

A Vermont Agency of Tranportation (VAOT) laboratory investigation preliminary report dated December 1986 (*13*) indicated that significant strength increases were seen in air-entrained 4.5-percent and 13.8-percent SFC (Table 4) relative to those of reference concretes. The SFCs also showed acceptable frost resistance. The durability factors consistently exceeded 100 at 500 cycles. Most encouraging was the observation that the SFCs were significantly better than the reference concretes in regard to screening chloride ions from the top inch portions of ponding test specimens. An experimental field placement was recommended, and VAOT has scheduled an SFC bridge overlay during 1988.

State of Washington Department of Transportation

The Washington State Department of Transportation has plans to place experimental SFC nominal 1.5-in.-thick bridge deck overlays on two structures. One bridge is north of Seattle, and the other is in the Spokane vicinity. Ready-mixed concrete will be used.

APPLICATIONS OTHER THAN OVERLAYS

Although great attention has been given to bridge deck overlays, SFC has been used in several other bridge-related applications. Work identified in other (non-overlay) applications is summarized as follows.

Full-Depth Bridge-Related Applications

In October 1985, the Ohio Turnpike Commission used 6.8-percent SFC (Table 4) in an approach slab at the west end of the westbound lane of an I–77 overpass. Silica-fume-based admixture was pumped from drums into truck mixers, added first along with polypropylene fibers. After a 35-min trip to the job, the concrete was pumped to the slab, leveled with an adjustable vibratory screed, and bull-floated and darbied. Although surface texturing and curing were delayed, the fibers prevented plastic shrinkage cracking. No differences were seen between this placement and previous conventional concrete placements. However, the impressive high early strength development of the SFC was noted.

The new Delaware River Gap Bridge along I–80, operated by the Delaware River Joint Toll Commission, has specified approximately 5,000 yd^3 of SFC in a full-depth deck to provide a chloride barrier. Initial placements began in late 1987. Traffic lane construction was scheduled to begin in April 1988. The specifications require the SFC to achieve RCP charge passed levels no greater than 750 coulombs. A maximum water-to-cement ratio of 0.40 is specified along with a cement content between 635 and 705 lbs/yd^3. Only wet SF-based admixtures will be allowed, and a wet burlap cure is specified.

During the summer of 1986, roughly 1,000 yd^3 of 5.8-percent SFC were used on an experimental basis throughout the Vondale Road Bridge, which is owned by Jefferson County, Alabama. Dry undensified SF was dispensed from a silo into a central mixer. The results were favorable. In October 1987, placement of 4,800 yd^3 of a similar SFC began for the Blue Lake Bridge, located in Birmingham. The SFC was used throughout the structure to improve generally the concrete performance.

Bridge-Related Marine Applications

The Florida Department of Transportation (FDOT) began laboratory testing of SFC in November 1984. Initial tests with 14.9-percent SFC using local aggregates developed around 10,000 psi and showed low shrinkage and good corrosion protection properties. Fourteen prestressed piles were cast during early 1987 using a 10-percent SFC. The results showed that SFC can be placed with the same degree of effort as conventional concrete, and corrosion tests revealed that the SFC was significantly better than the typically specified concrete. There were plans to use SFC in a bridge by the end of 1988 (*14*).

On May 19, 1987, the Massachusetts Bay Transit Authority (MBTA) used about 24 yd^3 of 15.8-percent SFC to achieve high early strength for an urgent railroad bridge repair in Sandwich, Massachusetts. A 5,000-psi 3-day strength was specified for two pile caps that were partially submerged in sea water during high tide. Achieving good workability and bond strength was important. The job was 45 min from the concrete plant, and there was no time for a trial batch. Fortunately, the concrete (wet SF-based admixture was supplied from drums) performed as desired. Workability retention was excellent, and the concrete was pumped. Although temperatures were unseasonably low (evening air temperatures in the low 40s, and water temperatures in the 50s) the concrete achieved nearly 6,000 psi within 3 days, and the structure opened on schedule.

The Texas Department of Transportation (TxDOT) is evaluating the use of SFC to achieve better corrosion protection for bridges in marine environments and to reduce the size of some precast elements by achieving high strength. Some test piles have recently been cast.

The Alabama Highway Department (AHD) has specified about 8,100 yd^3 of 11.1-percent SFC in precast piles for the Perdido Pass Bridge, located near Mobile. Up to another 6,871 yd^3 of cast-in-place SFC has been specified for portions of the substructure. The SFC is being used to improve corrosion protection of the steel and to increase abrasion resistance of the submerged concrete.

The MeDOT is currently using SFC in the piles for the Fairbanks Bridge located near Farmington. Again, SFC is expected to improve corrosion protection of the reinforcing steel.

Miscellaneous Bridge-Related Applications

The Elk River Bridge, in Charleston, West Virginia, where the Elk River enters the Kanawha River, was repaired in the summer of 1985. The sidewalks and monolithically cast-in-place traffic barriers were made with no problems using truck-mixed 7-percent SFC. Wet SF-based admixture was pumped to the truck mixers from a 2,000-gal tank. The traffic barrier forms could usually be removed within 1.5 hr, then the concrete was covered with curing compound. Inspection in July 1987 showed no significant changes in the concrete surfaces.

During 1986 the Pennsylvania Turnpike Commission used truck-mixed 12-percent SFC in parapet walls and traffic barriers associated with two bridges, primarily to achieve better frost resistance.

The IlDOT has specified SF in bonding grout since 1986 for various types of overlays (*15*). A 15-percent SF dose is also specified for use in grouts for partial patches.

Perhaps the first bridge-related placement of SFC in the United States took place on January 6, 1983. An approach lane to a weighing platform at a quarry near Roaring Springs, Pennsylvania, used 2.75-in.-thick 11-percent SFC overlays to improve abrasion resistance and to develop high early strength. The 2 yd^3 of concrete were central-mixed. The concrete was hand-screeded; bull-floated; and cured under burlap, straw, and plastic. Nearly every truck leaving the quarry traverses the weighing platform, often decelerating and accelerating over the debris-covered approach lanes. The SFC has performed very well—significantly outlasting previously tried wearing surfaces, which typically lasted only 2 yr. In 1987, at least one other weighing platform received a wear-resistant SFC surface.

DISCUSSION OF RESULTS

Several SF dosages were used—from 5 percent (University of Cincinnati) to 15.5 percent (KyDOT). A sound approach is to use the lowest SF dose that will still provide the desired concrete performance while maintaining a comfortable margin of safety. For example, the VDOT used 7- and 10-percent doses in the field when laboratory investigations suggested that a 5-percent dose coupled with a water-to-cementitious materials ratio below 0.40 would work.

Most of the jobs were small (the quarry job was only 2 yd^3), and many were supplied with wet SF-based admixtures supplied from drums. In some cases, the drum volumes were sized to fit the load sizes (MeDOT, IlDOT). Mobile dispensers provided wet SF-based admixtures for several jobs (NYSDOT, TDOT, MiDOT), but unless a job is large enough to economically justify installing a mobile dispenser, or unless admixture is supplied from a plant with permanent dispensing capability, future wet SF-based admixture bridge work will probably use drummed material. Dry undensified SF was used successfully (AHD), although it is believed that transportation costs will limit the use of this form of the material to regions near SF sources. One placement (IlDOT) successfully used a dry-bagged densified SF-based admixture that was developed for small jobs. It is likely that dry densified products will play a more important role in future SFC bridge work, especially on small jobs.

Some of the earlier placements used mobile mixers (ODOT, KyDOH), but either central-mixed or truck-mixed concrete is now generally preferred. Ready-mixed concrete costs less than mobile-mixed concrete, and the good workability of the SFCs is maintained long enough to make ready-mixed concrete use feasible.

Many different types of screeds were used satisfactorily, but initial surface closure was most acceptable when vibratory screeds were used. Roller screeds worked well, too, but sometimes required the equipment to be adjusted and the aggregate proportions modified. Well-maintained equipment and experienced operators are as important to SFC work as they are to conventional concrete placements.

Clearly, SFC has been placed successfully in a variety of bridge-related applications. In all cases only off-the-shelf equipment was needed to batch, place, finish, and cure the concrete. Laboratory and field tests were often conducted, and they helped develop effective placement procedures and minimize construction problems. Although some jobs proceeded smoothly without trials (Ohio Turnpike Commission; TDOT; MBTA), most were preceded by trial work, which is recommended.

It is clear that plastic shrinkage cracking precautions must be taken, and more attention is now being paid to them. Although a few of the earlier placements experienced plastic shrinkage problems, these seem now to have been eliminated. Routine preventive measures include minimizing delays, beginning curing immediately, working with the weather to minimize the evaporation rate (e.g., evening placements by NYSDOT), and using polypropylene fibers (Ohio Turnpike Commission). Several of the structures were entirely crack free, and cracking was generally light. More extensive cracking could usually, but not always, be attributed to problems such as delayed curing, interrupted curing, or thermal effects. In the case where a 7-day continuous wet burlap cure was used (MeDOT), no cracking was observed. It is believed that immediately started and extended wet curing is an important factor in eliminating cracking.

Some of the earlier studies did not use air-entrained concrete, and although some of these freezing-and-thawing results were clearly acceptable (IDOH, PaDOT), others were only marginally acceptable or poor. Frost resistance field performance of the SFC has been acceptable as have been the available laboratory freezing-and-thawing results of the air-entrained concretes that showed void spacing factors under 0.008 in. The trend has been to use air-entrained SFC, and this practice is recommended strongly.

Although SFCs are noted for high strength, and there were cases where this was at least one of the motives for considering its use (TxDOT; Ohio Turnpike Commission), the most prevalent reason for using the material was to provide a chloride barrier. Various agencies (PaDOT, IDOT, MiDOT, MeDOT, VDOT, VAOT) reported good resistance to chloride intrusion; and as a chloride barrier, the SFC overlays appear to be performing well. Bond was good, and with the exception of one poorly consolidated zone (VDOT) no delaminations have been reported. In at least three instances (TDOT; MBTA; the quarry) SFC was used to achieve high early strength. In several cases SFC was used to provide abrasion resistance (the quarry, IlDOT, ADH), and among those placements old enough to assess fairly, good wear resistance has been reported (the quarry, KyDOH).

The performance of the various SFCs are now resulting in increasing interest in this relatively new construction material. For example, the volume of SFC used in bridge-related applications has steadily increased from year to year, as follows: 2 yd^3 in 1983, 15.4 yd^3 in 1984, about 270 yd^3 in 1985, at least 1,480 yd^3 in 1986, at least 3,500 yd^3 in 1987, and there are now contracts for about 23,000 yd^3 in 1988. The results have been encouraging enough either to merit further study of SFC on an experimental basis or to prompt specification of the material in new bridge construction.

CONCLUSIONS

- SFC at dosages between 5 and 15.5 percent can be manufactured, placed, finished, and cured using conventional equipment. Measures must be taken to prevent plastic shrinkage cracking.

- There are several motives for using SFC: to provide a chloride barrier, to develop high-early strength, to achieve high-ultimate strength, to provide abrasion resistance, and to improve bond strength. Expectations in regard to the original motives for using SFC appear to have been met.
- Interest in SFC is increasing, and SFC is now being specified in bridges.

ACKNOWLEDGMENTS

Portions of the work reported herein were supported by the Federal Highway Administration. The author expresses his gratitude to the materials suppliers, agencies, and other owners whose cooperation enabled him to write this paper. He also wishes to acknowledge the financial support of Elkem Chemicals, Inc., of Pittsburgh, Pa., and to thank those who offered encouragement and advice.

REFERENCES

1. P. Fidjestol. Use of Condensed Silica Fume Concrete in *Scandinavia: Case Histories*. Presented at International Workshop on Condensed Silica Fume in Concrete, Montreal, Canada, May 4–5, 1987.
2. E. Sellevold and T. Nilsen. Condensed Silica Fume in Concrete: A World Review. Presented at International Workshop on Condensed Silica Fume in Concrete, Montreal, Canada, May 4–5, 1987.
3. Condensed Silica Fume. In *Les Editions de l'Université de Sherbrooke* (P. Aitcin, ed.), 1983. pp. 25–27.
4. ACI Committee 226. Silica Fume in Concrete. *ACI Materials Journal*, Vol. 84, No. 2, March-April 1987.
5. Dense Mix Fights Road Salt. *Engineering News Record*, Vol. 213, Nov. 8, 1984, p. 16.
6. D. Graves. *Microsilica Concrete (Rockbond) Overlay*. Construction Report. FHWA Experimental No. NY76-06C. Materials Bureau, State of New York Department of Transportation; FHWA, U.S. Department of Transportation, Sept. 1986, 2 pp.
7. *Experimental Resurfacing of Concrete Bridge Decks with Micro-Silica Modified Concrete*. Research Project 85B-102, Work Plan No. 100. Michigan Transportation Commission, Lansing, July 1985.
8. Rapid Determination of Chloride Permeability of Concrete. AASHTO T277-831. In *AASHTO Materials*, Part II, 14th ed., Washington, D.C., 1986.
9. H. Patterson. *Experimental Resurfacing of Concrete Bridge Decks with Microsilica Modified Concrete—Initial Report*. Research Report No. R-1282. Michigan Department of Transportation, Lansing, April 1987, 17 pp.
10. C. Ozyildirim. Laboratory Investigation of Concrete Containing Silica Fume for Use in Overlays. *ACI Materials Journal*, Vol. 84 No. 1, Jan.-Feb. 1987, pp. 3–7.
11. *Product Evaluation Report of EMSAC-B (PE84-111)*. Materials and Testing Division, Pennsylvania Department of Transportation, August 1984, 4 pp.
12. R. Smutzer and A. Zander. *A Laboratory Investigation of EMSAC-B Modified Portland Cement Concrete*. NPEC I.D. No. 252-K-84-02. Indiana Department of Highways, Indianapolis, July 1985, 21 pp.
13. C.C. Benda. *Preliminary Report on EMSAC F-100 Microsilica Additive For Concrete*. Work Plan No. 85–C–24. Materials and Research Division, State of Vermont Agency of Transportation, December 29, 1986.
14. Silica Fume May Save Bridge Piles. *Civil Engineering*, February 1987, p. 12.
15. *Bridge Special Provisions No. 16: Bridge Deck Concrete Overlays*. Illinois Department of Transportation.

Publication of this paper sponsored by Committee on Chemical Additions and Admixtures for Concrete.

Microsilica and Concrete Durability

N. S. BERKE

Results from experiments to determine the effects of microsilica on concrete freeze-thaw resistance and on the permeability to chlorides and subsequent early corrosion rates of steel in the concrete are described. The results to date show that air-entrained microsilica concretes pass laboratory freeze-thaw tests and demonstrate reduced chloride permeability and corrosion rates. ASTM C 666 testing was performed on concretes with no entrained air, below-normal entrained air, and normal air-entrainment levels on numerous mix designs with and without microsilica slurry additions. In all cases, properly air entrained microsilica mixes behaved as well as or better than control mixes. When air entrainment was not added, all mixes failed. Chloride permeabilities were determined using ASSHTO 277. Results show that silica fumes significantly reduced chloride permeability. Concrete resistivity measurements were performed using the A. C. impedance method. Microsilica significantly increased concrete resistivity over that of the control concretes, indicating that macrocell corrosion should be reduced. Corrosion-rate measurements show reduced rates (essentially noncorroding) for silica-fume concretes at 0.43 and 0.5 water-cement ratios, whereas some controls have gone into corrosion. Chloride analyses are to be performed to determine whether reduced permeability, increased electrical resistivity, or a combination of the two is responsible for the better corrosion performance.

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

EXPERIMENT

Materials

A normal type I portland cement (ASTM C 150) and silica fume were used; their chemical compositions and physical properties are given in Table 1. The silica fume was added in a water slurry. The coarse aggregate consisted of an ASTM size 67 (19–4.75 mm) trap rock. The fine aggregate was a natural sand, which met the requirements of ASTM C 33.

A modified naphthalene sulfonate formaldehyde condensate high-range water reducer was used to maintain a minimum slump of 4 in. (10 cm). A Vinsol resin air-entraining agent was used.

Concrete Design

The mix proportions and physical properties of the fresh and hardened concretes are presented in Table 2. The mix proportions are based on two overlapping factorial designs consisting of 12 different mix designs and one repetition for a total of 13 mixes. Cement factor was kept at approximately 600 pcy, and w/c ratios were 0.38, 0.43, and 0.48. Silica fume was proportioned as an additive (rather than as cement replacement) at 3.75, 7.5, and 15 percent by weight of cement. Note that sand decreased as silica fume was added to maintain yields. Minor variations in cement factor and coarse aggregate were caused by variations in air content.

The concrete mixtures were prepared at 22°C. Samples for concrete mechanical testing and rapid chloride permeability testing were cast into 4-in. × 8-in. metal cylinder molds. The cylinders were demolded at 24 hours and cured at 22°C and 100 percent relative humidity. Cylinders for rapid chloride permeability testing were removed at 28 days.

Freeze-thaw beams were cast in 4-in. × 5-in. × 16-in. steel molds. They were cured for 14 days before initiating the tests.

Resistivity samples were cast as 3-in. × 6-in. cylinders with an embedded no. 3 reinforcing bar (0.375-in. diameter) positioned 1.5 in. from the cylinder bottom and with the top 0.5 in. protected with electroplaters tape to expose 4 in. These "lollipop" samples were demolded at 24 hr and cured to 28 days as above.

Corrosion samples include the above resistivity samples plus minislabs 11 in. × 4.5 in. × 6 in. with top and bottom no. 4 reinforcing bars. The top concrete covers were 0.75, 1.38, or 2.0 in. The bottom bar was 1.0 in. from the bottom. The reinforcing bars were taped with electroplater's tape to expose 7.0 in. of bar. A 2-in.-high plastic dam with inside dimensions of 9 in. × 2.75 in. was caulked on top, and the four sides and top surface outside of the dam were coated with a concrete epoxy. Ground clamps were used to attach a 100-ohm resistor between the top and bottom bar.

Test Methods

Compressive strengths were determined in accordance with ASTM C 39. Freeze-thaw testing was in accordance with ASTM C 666, Method A. Rapid chloride permeability tests were conducted in accordance with the AASHTO T–277 test method on samples cut from 4-in. × 8-in. cylinders. Total acid soluble chloride was determined as outlined in the Florida DOT Research Report 203 PB 289620.

Electrochemical tests were used to determine concrete resistivity and corrosion rates as a function of time. Concrete resistivities were determined by measuring the A. C. impedance of steel rebars in the 3-in. × 6-in. cylinders at 20 KHz.

W. R. Grace and Company, Construction Products Division, 62 Whittemore Avenue, Cambridge, Mass. 02140.

TABLE 1 CHEMICAL COMPOSITION OF PORTLAND CEMENT AND CONDENSED SILICA FUME

Chemical Analysis	Portland Cement 170 (ASTM Type I)	Microsilica
Silicon Dioxide (SiO_2)	20.78	95.75
Aluminum Oxide (Al_2O_3)	4.44	0.35
Ferric Oxide ($(Fe_2)_3)$)	2.88	0.21
Calcium Oxide (CaO)	64.20	0.17
Magnesium Oxide (MgO)	3.66	0.09
Sulfur Trioxide (SO_3)	2.75	0.42
Alkali as Na_2O	0.46	0.51
Loss on Ignition	0.61	1.44

Each cylinder was submerged in a 3-percent NaCl solution to within 1 in. of the top surface to provide a high conductivity environment and to minimize resistance drops outside of the concrete.

The A. C. impedance measurements involved the use of a potentiostat to provide the current necessary to sinusoidally vary the potential between a calomel reference electrode and the steel rebar. The current was provided through graphite auxiliary electrodes in the NaCl solution. At high frequencies, any capacitive effects were eliminated as the impedance of a capacitor is inversely proportional to the frequency, and thus quite low relative to the resistance. This is a fast (less than 5 min) nondestructive test. A detailed explanation of the technique can be found in Dawson et al. (*1*), and a description of the PAR Model 368 Corrosion System used to make the measurements is in Scali et al. (*2*).

Corrosion-rate measurements consisted of polarization resistance and macrocell corrosion techniques. Both methods have been successfully used to measure corrosion rates of steel in concrete (*1, 3–10*).

The polarization resistance method is a nondestructive means of determining the corrosion rate, and thus one can monitor the corrosion rate as a function of time on the same specimen. The technique uses a potentiostat to supply the current necessary to vary the potential between a reference electrode and the specimen away from the corrosion potential (typically ±20 MV). The voltage versus current curve is plotted on a linear scale.

The polarization measurements were performed using a PAR Model 351 system with current interrupt circuitry (eliminates concrete resistivity errors) as described in Berke (*3*). Specimens tested included the 3-in. × 6-in. cylinders with embedded rebars. These samples are continuously ponded in 3 in. of 3 percent NaCl to stimulate wicking action. Measurements were also performed on the minislabs.

Macrocell corrosion measurements are performed by measuring the voltage drop across the 100-ohm resistor connecting the top and bottom bars of the minibeams. The specimens are ponded with 3 percent NaCl for 2 weeks, vacuumed, allowed to room-dry for 2 weeks, and then reponded. Macrocell currents are measured at the beginning of the second week of ponding. The method is very simple and determines the galvanic corrosion susceptibility of a top salt-rich rebar mat coupled to a salt-free bottom mat with good access to oxygen.

RESULTS AND DISCUSSION

Compressive Strength

As can be seen in Table 2 and Figure 1, compressive strength increases substantially when silica fume is added to concrete. Lowering the w/c ratio also increases strength. However, at any given w/c ratio silica-fume additions increase strengths.

Freeze-Thaw Resistance

The freeze-thaw data summarized in Table 2 show that all properly air-entrained concretes with or without silica fume offer good resistance to freeze thaw. This finding is in good agreement with others who have properly air-entrained concretes with silica fume (*11, 12*).

Chloride Permeability

The FHWA rapid chloride permeability test is a qualitative test for estimating the chloride ion permeability of concrete. The test method assumes that the total electrical charge (coulombs), which passes through the concrete, is directly related to chloride ion permeability.

Figure 2 graphically depicts the rapid chloride data in Table 2 as a function of w/c and silica-fume content. Clearly, silica-fume additions are more influential than is lowering the w/c ratio.

At this time, chloride data are available on six of the mixes (Table 2). On a gross scale, the rapid chloride test values agree with the chloride contents, e.g., mix 13 (75 coulombs/0.53 pcy chloride) vs. mix 1 (3,663 coulombs/4.9 pcy chloride) and mix 10 (3,485 coulombs/1.63 pcy chloride), even though the latter two rapid chloride values are similar. Nevertheless, both of these high-coulomb-value mixes have higher chloride concentrations then mix 13 (75 coulombs/0.53 pcy chloride).

TABLE 2 CONCRETE PROPERTIES

		Mix Proportions (pcy)				Properties of Fresh Concrete				Properties of Hardened Concrete					
Mix ID	% Silica Fume by Mass of Cement	Portland Cement	MS	Fine Agg.	Coarse Agg.	w/c	Slump (in)	% Air	Unit Weight (pcf)	28-Day Comp. Strength (psi)	28-Day Chloride Perm. (coulombs)	28-Day Resistivity (kohm-cm)	300 Cycles Freeze Thaw (RDME)	Scale Factor	10 Month Total Chloride 0.5-1.0 inch (pcy)
1	0	587	0	1194	1819	0.48	6.0	7.0	144	5160	3663	7.7	105	1	4.90*
2	3.75	588	22.0	1197	1822	0.48	5.4	7.0	144	5417	3175	16.3	—	—	ND
3	7.5	585	44.6	1268	1813	0.48	6.75	9.0	147	6346	348	45.4	100	0	ND
4	15.0	591	89.0	1204	1834	0.48	5.75	7.0	145	7357	198	94.7	102	1	0.43
5	0	556	0	1205	1723	0.43	9.75	10.5	138	5264	2585	9.3	—	—	ND
6	3.75	593	22.2	1261	1838	0.43	4.0	7.4	147	6547	2210	22.1	—	—	ND
7	7.5	573	43.0	1167	1779	0.43	8.25	8.0	140	7214	213	67.7	100	0	0.54
8	7.5	575	43.1	1246	1782	0.43	9.1	10.0	143	6751	—	67.0	—	—	ND
9	15.0	598	91.2	1295	1853	0.43	7.0	6.0	149	8582	98	118.0	—	—	ND
10	0	571	0	1312	1770	0.38	8.75	8.0	144	5782	3485	10.8	104	1	1.63*
11	3.75	585	21.9	1344	1814	0.38	3.5	8.0	147	9312	736	24.3	—	—	ND
12	7.5	591	44.3	1358	1832	0.38	8.25	7.0	149	9288	132	73.9	104	1	0.41
13	15.0	599	90.0	1377	1858	0.38	6.0	6.0	151	12119	75	161.0	102	1	0.53*
Mean Values		584	39.3	1264	1811	0.43	6.8	7.8	145	7318	1410	55.0	102	1	ND

Notes: RDME is the relative dynamic modulus of elasticity. Scale Factor ratings: 1 = Very slight scaling (no coarse aggregate visible); 2 = slight to moderate scaling; 3 = moderate scaling (some coarse aggregate visible).

* These chloride values are at 18 months.

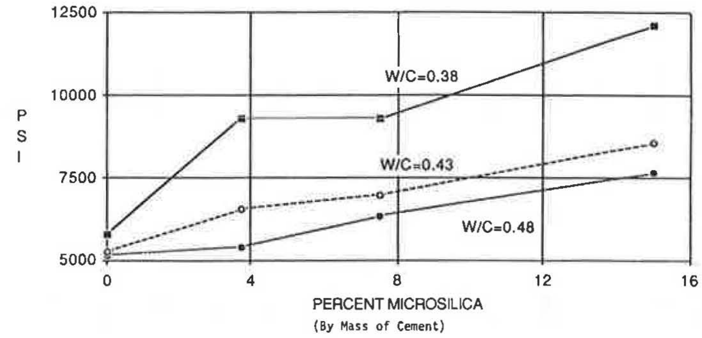


FIGURE 1 **Compressive strength vs. microsilica and w/c.**

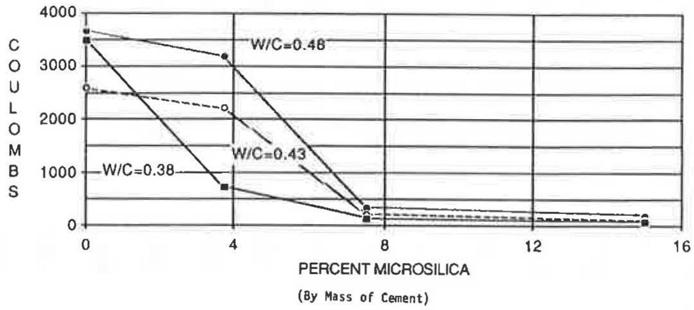


FIGURE 2 **Rapid chloride permeability vs. microsilica and w/c.**

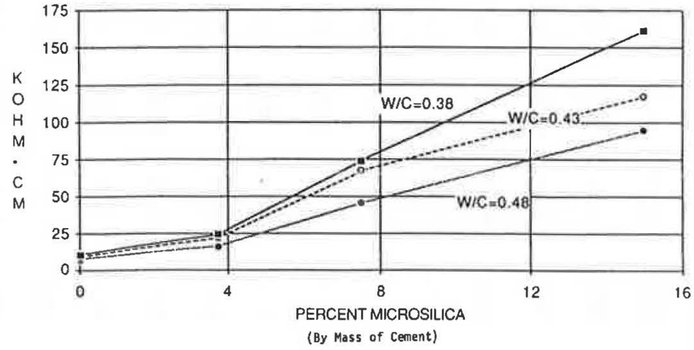


FIGURE 3 **Resistivity vs. microsilica and w/c.**

Thus, the rapid chloride method appears to give a qualitative indication of chloride permeability, but should not be used as a quantitative test. Note that chloride ponding is still in progress, and long-term results will be reported when available.

Resistivity

Resistivity data at 28 days is plotted in Figure 3 as a function of w/c ratio and silica-fume content. Silica fume plays the predominant role in increasing resistivity as was the case for the rapid permeability test. At any given silica-fume content, resistivity increased as w/c decreased. Note that in several cases, resistivity is substantially above 30 kohm-cm.

Corrosion processes, which are electrochemical in nature, can be affected by concrete resistivity. In general, concretes having resistivities greater than 30 kohm-cm do not exhibit evidence of corrosion (*13*). As will be shown below, this finding appears to hold for the concretes in this study.

Corrosion Studies

Corrosion data to date are summarized in Table 3. The lollipop data were determined by use of the polarization resistance method. Previous experiments in our laboratory indicate that severe corrosion is occurring at 1/Rp (Rp = polarization resistance) values above 20 umho/cm^2 (*3–5*). Note that 1 umho/cm^2 is approximately 0.01 mpy (*3*). Thus, only the control

TABLE 3 CORROSION-RATE DATA FOR LOLLIPOPS AND MINIBEAMS

					Lollipop Data 18 Months			Minibeam Data			
Mix ID	% Silica Fume by Mass of Cement	CF (pcy)	Silica Fume (pcy)	w/c	Ecorr (mV vs SCE)	1/Rp (umho/cm^2)	Cover (in)	Ecorr (mV)	12 Months Macrocell Current (uA)	Ecorr (mV)	21 Months Macrocell Current (uA)
1	0	587	0	0.48	-456	22	1 3/8	-79	0.1	-287	10.3
							3/4	-50	0		
2	3.75	588	22.0	0.48	-71	7	1 3/8	-47	0	—	—
3	7.5	585	44.6	0.48	-40	3	1 3/8	-32	0.2	—	—
4	15.0	591	89.0	0.48	-26	4	1 3/8	-35	0.1	-45	0.2
5	0	556	0	0.43	-55	5	1 3/8	-71	0.05	—	—
6	3.75	593	22.2	0.43	-83	5	1 3/8	-9	0.1	—	—
7	7.5	573	43.0	0.43	+7	4	3/4	-36	0.1	—	—
8	7.5	575	43.1	0.43	-13	4	2.0	-23	0.2	—	—
9	15.0	598	91.2	0.43	-53	3	1 3/8	-30	.1	—	—
10	0	571	0	0.38	-286	7	1 3/8	-63	0	-69	0.1
							3/4	-10	0.1		
11	3.75	585	21.9	0.38	-58	3	1 3/8	-13	0.1	—	—
12	7.5	591	44.3	0.38	-38	1	1 3/8	-32	0.1	—	—
13	15.0	599	90.0	0.38	53	4	1 3/8	-32	0.1	-46	0.1

Note that 1/Rp is proportional to the corrosion rate. Values above 20 umho/cm^2 are indicative of the onset of severe corrosion.

lollipops at 0.48 w/c are into corrosion at 18 mo of accelerated testing.

The minibeam macrocell current data indicate that, once again, only the control samples at 0.48 w/c are corroding. Note that these beams started to corrode at 17 mo.

Polarization resistance and macrocell current measurements show that the steel reinforcement in the highest w/c ratio mix without silica fume is corroding, whereas additions of silica fume have delayed the onset of corrosion. Based on previous experiments, we expect the controls at lower w/c ratios to begin to show corrosion activity at 2–2.5 yr of testing (*3*). Nevertheless, at this point, we clearly see that silica fume has prevented the onset of corrosion at 0.48 w/c.

The improved corrosion resistance with silica fume is probably due to the noted reductions in chloride permeability and to the increase in concrete resistivity. A prior study of microstructure by our laboratory (*2*) showed that silica fume significantly reduced the porosity of concrete, especially at the paste-aggregate interface. We believe that this reduced porosity is responsible for the reduced chloride permeability and increased resistivity.

CONCLUSIONS

- The addition of silica fume to concrete improves the compressive strength and resistivity while reducing chloride permeability.
- Silica fume improves the resistance to the onset of chloride-induced corrosion of steel in concrete.
- Lowering the w/c ratio of concrete improves the performance gain of adding silica fume.
- Properly air-entrained concretes with silica fume have excellent resistance to freeze-thaw damage as measured by ASTM C 666.

ACKNOWLEDGMENTS

The author wishes to thank his colleagues for their assistance in carrying out this investigation. Special thanks are due to P. Scheiner, D. F. Shen, A. Dressler, R. Hoopes, and P. Toner. The author also would like to thank W. R. Grace for permission to publish this paper.

REFERENCES

1. J. L. Dawson, L. W. Callow, K. Hardky, and J. A. Richardson. *Electrochemical Impedance Measurements Applied to the Corrosion of Reinforcing Steel in Concrete*. Paper No. 125. NACE Corrosion 78, National Association of Corrosion Engineers, Houston, Tex., 1978.
2. M. J. Scali, D. Chin, and N. S. Berke. Effect of Silica Fume and Fly Ash Upon the Microstructure and Permeability of Concrete. In *Proc., Ninth International Conference on Cement Microscopy*, Duncanville, Tex., 1987, p. 375.
3. N. S. Berke. *The Effects of Calcium Nitrite and Mix Design on the Corrosion Resistance of Steel in Concrete. Part 2: Long-Term Results*. Paper No. 132. NACE Corrosion 87, National Association of Corrosion Engineers, Houston, Tex., 1987.
4. N. S. Berke. Corrosion Rates of Steel in Concrete. *ASTM Standardization News*, March 1986, p. 57.
5. N. S. Berke. *The Effects of Calcium Nitrite and Mix Design on the Corrosion Resistance of Steel in Concrete. Part 1*. Paper No. 273. NACE Corrosion 85, National Association of Corrosion Engineers, Houston, Tex., 1985.
6. J. A. Gonzalez, A. Molina, M. Esadero, and M. C. Andrade. *A Comparison of Linear Polarization and A.C. Impedance in the Determination of Corrosion Rates of Reinforcements Embedded in Concrete*. Paper No. 257. NACE Corrosion 85, National Association of Corrosion Engineers, Houston, Tex., 1985.
7. J. A. Gonzales, S. Algaba, and C. Andrade. *Bridge Corrosion Journal*, Vol. 15, 1980, p. 135.
8. J. L. Dawson. Corrosion Monitoring of Steel in Concrete. In *Corrosion of Reinforcement in Concrete Construction* (A. P. Crane, ed.), Ellis Horwood Ltd., London, England, 1983, p. 175.
9. Y. P. Virmani, K. C. Clear, and T. J. Pasko. *Time-to-Corrosion of Reinforcing Steel in Concrete Slabs*, Vol. 5: *Calcium Nitrite Admixture and Epoxy-Coated Reinforcing Bars as Corrosion Protection Systems*. Report FHWA/RD-83/012. FHWA, U.S. Department of Transportation, Sept. 1983.
10. D. W. Pfeifer, J. R. Landgren, and A. Zoob. *Protective Systems for New Prestressed and Substructure Concrete*. Report FHWA/RD-86/193. FHWA, U.S. Department of Transportation, Sept. 1986.
11. P. C. Aitcin, and P. Vezing. Resistance to Freezing and Thawing of Silica Fume Concrete. *Cement, Concrete, and Aggregates*, Vol. 6, No. 1, 1984, p. 38.
12. A. Bilodeau and G. G. Curette. Resistance of Condensed Silica Fume Concrete to the Combined Action of Freezing and Thawing Cycling and De-Icing Salts. Presented at International Workshop on Condensed Silica Fume in Concrete, CANMET, Energy, Mines and Resources Canada, Ottawa, Ontario, Canada, May 4, 1987.
13. B. B. Hope, A. K. Ip, and D. A. Manning. Corrosion and Electrical Impedance in Concrete. *Cement and Concrete Research*, Vol. 15, 1985, p. 523.

Publication of this paper sponsored by Committee on Chemical Additives and Admixtures for Concrete.

ODOT Experience with Silica-Fume Concrete

Dennis Bunke

Two bridge-deck-overlay projects placed in 1984 and 1987 are the basis for Ohio's specifications on the use of silica fume; they are reviewed along with a full-depth silica-fume structure placed in 1987. Data on mixing, placing, curing, compressive and flexural strengths, resistance to freezing and thawing, and permeability are presented. An assessment of these results shows that Ohio's 15 percent by mass of cement silica-fume requirement could be reduced, retaining high compressive and flexural strengths, good resistance to freezing and thawing, and favorable permeability characteristics. At present silica-fume-modified concrete appears to be a satisfactory and cost-competitive method of extending the life of bridge decks.

The Ohio Department of Transportation (ODOT) has a problem with deteriorating structures due mainly to the damage caused by deicers. In its search for a solution, ODOT has tried various remedies over the years. Epoxy-coated steel has been used in the upper layer of reinforcement for more than 10 yr; and in the summer of 1987, ODOT started using coated bars in all layers of reinforcing steel for additional corrosion protection. Another approach is the use of bridge-deck overlays with and without sealers. The sealers studied included silanes and epoxies. Dense concrete using high-range water-reducing admixtures; polymer-modified concrete; latex-modified concrete; and most recently, silica-fume-modified concrete have been evaluated.

OBJECTIVE AND SCOPE

Three cases are discussed: structure 1 (ODOT bridge ASD 511-1621), structure 2 (ODOT bridge FRA 33-0131), and structure 3 (ODOT bridge MAD 161-0151).

Structure 1—Background Information

ODOT's first silica-fume project was an overlay, 120 ft long and 32 ft wide, placed on October 18, 1984, on a slab bridge on State Route 511 near Ashland, Ohio. The department had previously used latex-modified concrete overlays, and a latex-modified concrete overlay was proposed for this structure. The contractor approached ODOT proposing the substitution of silica fume for latex, and it was decided to use silica fume on only one lane. A grout was spread ahead of placement and not allowed to dry before placement of the overlay. The grout consisted of the paste remaining after the coarse aggregate was removed from the silica-fume concrete mixture. An air-detraining admixture was used to remove any incidental air found in the mixture. (This information is from Mark Luther Elkem Chemicals, Inc., unpublished data.)

The concrete was mixed in a volumetric batching mobile mixer. The silica fume was added by pumping directly into the mobile mixing chamber from the transport truck (*1*). The silica-fume concrete was stable with no clumping during batching and mixing.

Petrographic examination of the silica-fume concrete was conducted for the silica-fume supplier, and the ODOT laboratory ran an examination in accordance with ASTM C 457 using the modified point-count method.

	Private Consultant Results	*ODOT Results*
Air content, hardened concrete, %	4.7	5.5
Specific surface of the air void system, in.^{2} per in.^{3}	162	168
Spacing factor, $\bar{L}$, in.	0.032	0.030

This structure has been under observation since placement. Two cracks were discovered in the July 1987 visit. Upon coring, it was discovered that both were in a variable depth placement area with an overlay depth of 3–3.5 in. The cracks measured 0.03 in. wide, about 16 in. long, and 1–1.5 in. deep. The deck was checked for delaminations, and none were discovered.

The other lane of the deck, which is latex-modified concrete, was also checked for delaminations; none were discovered, but several cracks were found. As with the silica-fume overlay, these cracks, in variable depth overlay areas, did not extend through the entire depth of the overlay and measured 0.03 in. wide, about 16 in. long, and 1–1.5 in. deep.

The silica-fume concrete was slightly darker in color than the latex-modified concrete. Two different curing methods were used. The color of the concrete is uniform within each lane.

Structure 2—Background Information

ODOT's second silica-fume overlay was placed on April 22 and May 5, 1987, on a bridge 27 ft long and 32 ft wide on Avery Road over U. S. Route 33 in Dublin, Ohio. In preparation for the project, a test slab was placed on April 16, 1987. On the test slab the finishers experienced problems where the surface became sticky and the tining tool tended to drag aggregate with it.

Cement and Concrete Section, Ohio Department of Transportation, Bureau of Testing, 1600 W. Broad Street, Columbus, Ohio 43223-1298.

At the time of project placement, a bonding grout consisting of equal parts of portland cement and sand was broomed onto the cleaned scarified surface just before the overlay placement and was not allowed to dry before overlay placement.

On this structure, the concrete was central-mixed and delivered to the project in truck mixers. Because of the finishing problem with the test slab, ODOT was prepared to allow a finishing aid, but it was not used on the April 22 placement since finishing on that day went smoothly. On May 5, a finishing aid was used. To date there is no difference in the appearance of the two surfaces.

Structure 3—Background Information

ODOT's third placement was a full-depth deck placed at night, started at 3:30 a.m. and finished at 7:00 a.m. on August 14, 1987. The structure, on Route 161 near Plain City, Ohio, is 123 ft long × 34 ft wide.

The concrete was central-mixed and delivered to the project in truck mixers. A concrete pump was used. Test results given in Table 1 indicate little variance in the concrete temperature, air content, slump, and yield.

The finishers on this project complained of finishing problems, and a finishing aid was used on the first few feet of the surface.

TABLE 1 ODOT'S THIRD SILICA-FUME PROJECT, FULL-DEPTH AIR CONTENT AND SLUMP FOR THE 21 LOADS DELIVERED

TRUCK NUMBER	TIME A.M.	ASTM C 231 AIR CONTENT, %	ASTM C 143 SLUMP, IN.
1	3:30	8.3	6
2	3:40	8.3	6 3/4
3	4:00	7.6	7 1/4
4	4:15	7.8	7
5	4:20	7.5	6
6	4:30	8.1	5 3/4
7	4:37	9.4	7 1/2
8	4:47	7.7	5 1/4
9	5:05	8.2	6 1/4
10	5:10	8.4	7 1/2
11	5:15	8.3	6 1/4
12	5:25	8.8	7 1/4
13	5:30	7.9	8
14	5:40	9.4	7 1/4
15	5:43	9.0	6 3/4
16	5:52	8.2	6 3/4
17	6:04	7.8	8 1/4
18	6:10	8.8	7 1/4
19	6:14	9.3	8
20	6:20	7.7	7 1/4
21	6:30	8.7	7 1/4

DATA COLLECTION

ODOT testing personnel were present at each of the three silica-fume deck placements and test-slab placements to perform concrete control tests such as slump and air content on the freshly mixed concrete. Cylinders and beams were also made on which compressive strengths, flexural strengths, examination by ASTM C 457, and tests for resistance to freezing and thawing were later made.

Test Slabs

In an attempt to familiarize the participants with silica-fume concrete and to give ODOT a chance to collect pertinent data, a test slab was specified as a separate pay item on each of the three silica-fume placement projects (*2*). On each project, the slab was placed a few days before the structure placement to allow a chance to correct any discovered deficiencies.

Deck Preparation

Structures 1 and 2

Both overlay decks were prepared in the same manner. Sound surface was removed to a depth of 0.25 in. by scarifying. Deeper areas of loose and unsound concrete were removed as needed to reach a solid concrete surface. The surface was then cleaned by abrasive blasting, followed by an air blast immediately before the overlay placement (*2*). A grout was applied to the clean and scarified surface just ahead of the overlay placement (*2*).

Structure 3

The full-depth deck was placed according to standard construction practices.

Finishing

All three structures were screeded in the same manner. The concrete was distributed using a finishing machine with a screw-type auger distribution system and a foller followed by a vibrating pan. The surface was finished by hand as needed and textured transversely with a tining tool (*1*, *2*).

Curing

Structure 1 (Silica-Fume Lane)

The northern half of the overlay was covered by a single layer of wet burlap with a layer of polyethylene film placed over the burlap. This covering remained for 2 days before it was removed and the deck was allowed to air-dry cure 2 more days before being opened to traffic. The southern half of the overlay was sprayed with white chlorinated rubber-membrane-forming curing compound.

TABLE 2 BATCH WEIGHTS FOR ODOT'S FIRST THREE SILICA FUME PROJECTS

	COARSE AGGREGATE NO.8 LIMESTONE, LB.	FINE AGGREGATE NATURAL SAND, LB.	PORTLAND CEMENT TYPE 1, LB.	SILICA FUME SLURRY, LB.	WATER, LB.
STRUCTURE #1	1361	1537	658	227 [A]	147
STRUCTURE #2	1417	1308	698	210 [B]	81
	27 OZS. OF AIR ENTRAINER 275 OZS. OF HRWR				
STRUCTURE #3	1475	1392	700	210 [B]	40
	24.5 OZS. OF AIR ENTRAINER 290 OZS. OF HRWR				

[A] 45% SILICA-FUME & 51% WATER - THE OTHER 4% IS MADE UP OF VARIOUS ADMIXTURES SUCH AS WATER REDUCERS AND HRWR. (INFORMATION FROM ELKEM CORPORATION INC.)

[B] 48% SILICA-FUME & 50% WATER - THE OTHER 2% IS MADE UP OF VARIOUS ADMIXTURES SUCH AS WATER REDUCERS AND HRWR. (INFORMATION FROM SIKA CORPORATION INC.)

Structures 2 and 3

As soon as the tining operation was completed, the finished overlay surfaces were covered with a single layer of wet burlap. The fresh overlay surface received a wet burlap cure for 3 days, during which the burlap was kept wet by continuous application of water through soaker hoses under a polyethylene sheet.

Mixture Proportions

The first overlay contained 658 lb of cement/yd^3 as had been specified for the latex-modified concrete. Then 227 lb of silica-fume slurry was added to approximate 15 percent by mass of the cement. Mixtures for the three structures are given in Table 2.

LABORATORY INVESTIGATION VARYING SILICA-FUME CONTENT

Shortly after the first overlay placement, ODOT's laboratory ran permeability tests on cylinders made from concrete mixtures of varying silica-fume content (*3*). The testing was performed according to the procedure found in FHWA report RD 81/119 (AASHTO T 227), and these results (Table 3) are then depicted graphically (Figure 1).

From this graph it can be seen that permeability decreases as silica-fume content increases. Based on these test results, ODOT chose to retain a 15 percent by mass silica-fume content requirement and require 700 lb of cement (*2*).

This concrete functioned well and was retained for ODOT's third placement.

The possibility of reducing ODOT's silica-fume content to 10 percent is discussed later in this paper (Analysis of Data—Rapid Permeability).

PLACEMENT CONDITIONS

Table 4 shows that the silica-fume projects were placed at various temperatures and humidities ranging from 62°F to 86°F. The temperature differentials between concrete and deck caused no significant adverse effects. Complaints of finishing problems existed on both high- and low-humidity days. There was virtually no wind on any of the placement days. In spite of the temperature differentials and finishing complaints, no cracking during curing was observed.

ANALYSIS OF DATA

Slump

Average slump test results performed in accordance with ASTM C 143 were the following:

	Test Slab	*Bridge Deck*	
Structure 1	6.9 in.	8.3 in.	
		4/22	5/5
Structure 2	6.0 in.	7.5 in.	7.4 in.
Structure 3	7.0 in.	6.5 in.	

TABLE 3 RAPID PERMEABILITY TEST RESULTS VARYING SILICA FUME CONTENT AND CEMENT CONTENT WITH AND WITHOUT FLY ASH AND HRWR

SAMPLE SERIES	SILICA-FUME CONTENT, %	FLY ASH	HRWR	CHARGE, COULOMBS	TIME, MIN.	CEMENT, LB.
275	2.5	NO	NO	12137	360	700
270	2.5	YES	NO	9711	360	560
265	2.5	YES	NO	9294	360	450
260	2.5	YES	NO	10582	360	380
280	5	NO	YES	3827	360	700
281	5	YES	YES	3201	360	560
283	5	YES	YES	4059	360	450
283	5	YES	YES	3631	360	380
285	6.75	YES	YES	851	360	560
286	6.75	YES	YES	2987	360	450
287	6.75	YES	YES	3080	360	380
284	6.75	NO	YES	392	360	700
289	10	YES	YES	328	360	560
290	10	YES	YES	941	360	450
291	10	YES	YES	1796	360	380
288	10	NO	YES	136	360	700
293	15	NO	YES	187	360	560
294	15	YES	YES	256	360	450
295	15	YES	YES	362	360	380
292	15	NO	YES	78	360	700

NOTE: Permeability tests performed according to procedure found in FHWA Report RD 81/119.

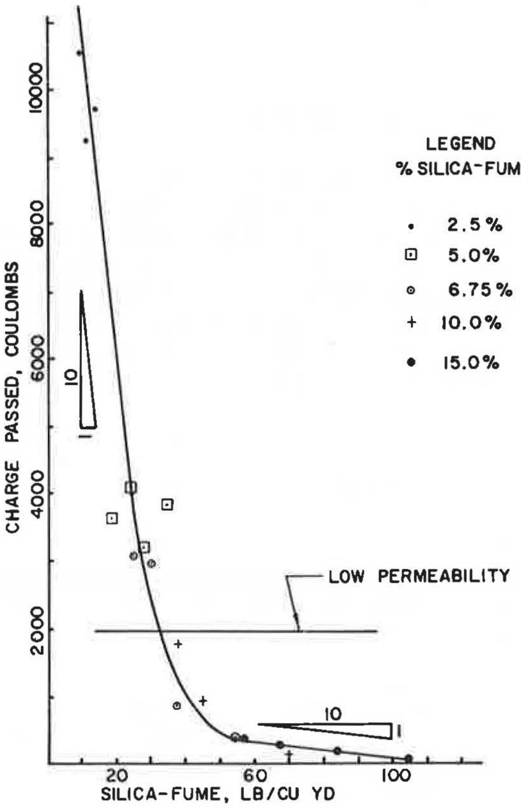


FIGURE 1 Chloride permeability vs. silica-fume content using an HRWR.

The slump was fairly constant on all three structures, although it varied more with the mobile mixer than with the truck mixer.

Compressive and Flexural Strengths

Tables 5 and 6 give compressive and flexural strengths. These results are higher than would be expected with plain structural concrete. Strength was gained rapidly. The 1-day compressive strengths for structures 1 and 2 averaged 3,390 psi and 3,620 psi respectively and rose to 6,880 psi and 6,220 psi at 28 days. The flexural strengths ranged from 490 psi and 560 psi average at 1 day to 940 psi and 1,035 psi average at 28 days. The compressive strengths for structure 3 were considerably higher at 6,240 psi at 1 day and 8,020 psi at 28 days. The flexural strengths started at 750 psi for 1 day and rose to 1,170 psi at 28 days. The test slab 28-day strengths were even higher at 8,810 psi compressive and 1,320 psi flexural.

Compressive strength increased with the increase in silica-fume content. Figure 2 compares compressive strengths attained varying silica-fume content.

The test-slab strengths were higher than those from the actual deck placements. This is to be expected as placement conditions were easier to control on a small test slab.

The higher strength of structure 3 was most likely achieved because of its low water-cement ratio (0.33). Table 2 shows that a large amount of a high-range water reducer (HRWR) was used, significantly reducing the amount of mixing water. However, there appeared to be a sufficient amount of water

TABLE 4 CONDITIONS FOR ODOT'S FIRST THREE SILICA-FUME PLACEMENTS

	AIR TEMP	DECK TEMP	CONCRETE TEMP	HUMIDITY	WIND	TIME PLACED
STRUCTURE #1 TEST SLAB	66°F	73°F	70°F	55%	0	9:30 AM
STRUCTURE #1 OVERLAY PLACEMENT OCTOBER 18, 1984	45°F TO 71.5°F	40°F TO 61°F	61.9°F TO 67.9°F	94% TO 75%	0	9:00 AM TO 11:00 AM
STRUCTURE #2 OVERLAY PLACEMENT APRIL 22, 1987	70°F	--- A	77.2°F	67%	0 TO 15 MPH GUST	9:00 AM TO 12:00 PM
STRUCTURE #2 OVERLAY PLACEMENT MAY 5, 1987	47°F TO 59°F	42°F TO 51°F	70.7°F TO 74.9°F	---	2 TO 10 MPH	8:00 AM TO 11:00 PM
STRUCTURE #3 PLACEMENT (FULL DEPTH) AUGUST 14, 1987	71°F	70°F	84°F TO 86°F	82% TO 85%	0	3:30 AM TO 7:00 AM

A DATA NOT AVAILABLE.

available for hydration. The HRWR worked well in conjunction with the silica fume.

Figure 3 also shows the effects of HRWR on silica-fume concrete (*3*). Addition of the HRWR, as expected, increased compressive strengths even more.

Fifteen percent was the highest silica-fume content investigated. It was felt that more than 15 percent silica fume would cause workability problems.

Resistance to Freezing and Thawing and Air Content

The air content of 5.2 percent (Table 7) on structure 1 appeared adequate, but the durability factor was very low at 5.5 (Table 8) and not much better for the test slab at 11.5. ODOT considers a durability factor of 80 and above as good.

The other air-void-system values (Table 7) indicate that the air-void system was not as good as the 5.2-percent air content suggested. The specific surface of the air-void system (α) of frost-resistant concrete should be at least 500–800 in.^{2}/in.^{3}. Structure 1 had an α of 168 in.^{2}/in.^{3}. The spacing factor (L) should be 0.008 in. or less. Structure 1 had an L of 0.03 in. It was not realized that air would be a problem, and no attempt had been made to control the air on structure 1. No air-entraining admixture was used, therefore a poor air-void system should have been expected.

The rapid permeability results (see silica-fume projects in Table 9) were very good. An average of only 670 coulombs

TABLE 5 COMPRESSIVE STRENGTH TEST RESULTS FOR ODOT'S FIRST THREE SILICA-FUME PROJECTS

	AGE	TEST SLAB, PSI	BRIDGE DECK, PSI	
STRUCTURE #1	1 DAY	4790	3390	
	3 DAY	5830	4650	
	7 DAY	6620	6060	
	28 DAY	8750	6880	
			4/22*	5/5*
STRUCTURE #2	1 DAY	3970	3550	3690
	3 DAY	5360	4870	4680
	7 DAY	5710	5940	5450
	28 DAY	6370	6060	6380
STRUCTURE #3	1 DAY	7700	6240	
	3 DAY	8370	7000	
	7 DAY	7900	7440	
	28 DAY	8810	8020	

*Lane 1 was placed on 4/22 and lane 2 on 5/5

NOTE: Performed in accordance with ASTM Method C 39.

TABLE 6 FLEXURAL STRENGTH TEST RESULTS FOR ODOT'S FIRST THREE SILICA-FUME PROJECTS

	AGE	TEST SLAB, PSI	BRIDGE DECK, PSI	
STRUCTURE #1	1 DAY	700	490	
	3 DAY	960	660	
	7 DAY	1060	800	
	28 DAY	1230	940	
			4/22	5/5
STRUCTURE #2	1 DAY	490	600	515
	3 DAY	730	740	730
	7 DAY	930	900	860
	28 DAY	1020	990	1080
STRUCTURE #3	1 DAY	795	750	
	3 DAY	1000	930	
	7 DAY	1055	955	
	28 DAY	1320	1170	

NOTE: Performed in accordance with ASTM Method C 78.

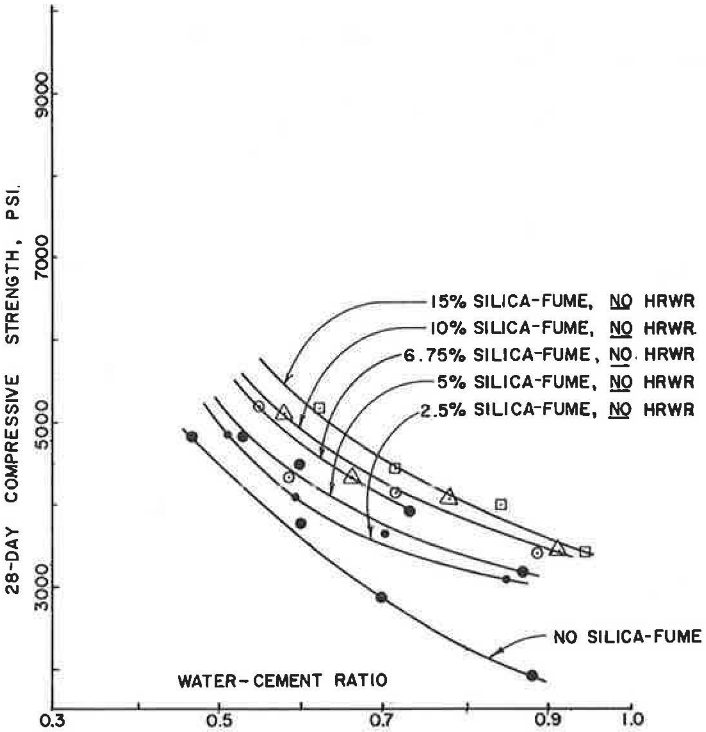


FIGURE 2 Compressive strength vs. water-cement ratio without using an HRWR.

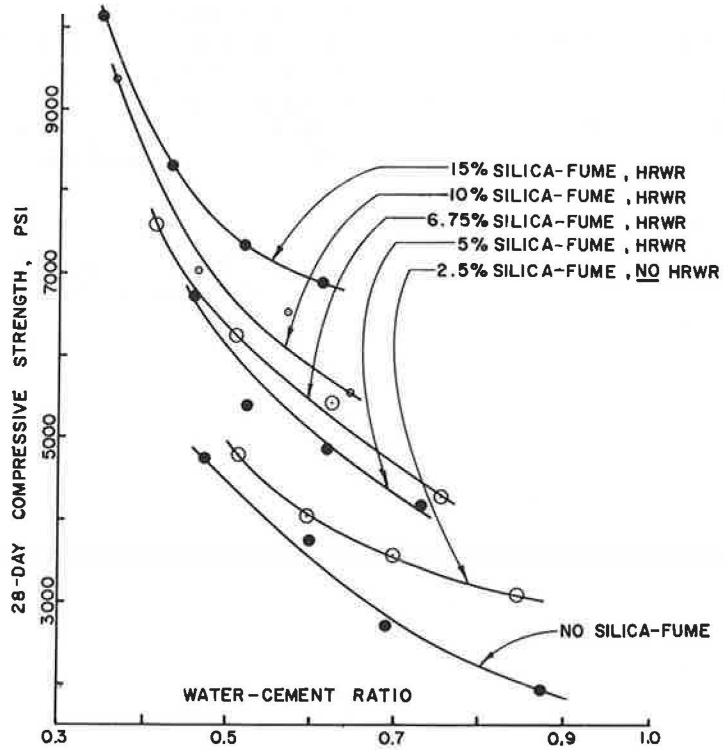


FIGURE 3 Compressive strength vs. water-cement ratio using an HRWR.

TABLE 7 PLASTIC AND HARDENED AIR-TEST RESULTS FOR ODOT'S FIRST THREE SILICA-FUME PROJECTS

		TEST SLAB	BRIDGE DECK	
STRUCTURE #1	AIR CONTENT OF UNHARDENED CONCRETE, %	4.2	5.2	
	AIR CONTENT OF HARDENED CONCRETE, %	7.1	5.5	
	SPECIFIC SURFACE, SQ.IN. PER CU.IN.	200	168	
	SPACING FACTOR, IN.	0.01	0.03	
			4/22	5/5
STRUCTUE #2	AIR CONTENT OF UNHARDENED CONCRETE, %	9.2	9.1	9.8
	AIR CONTENT OF HARDENED CONCRETE, %	10.8	10.7	--- A
	SPECIFIC SURFACE, SQ.IN. PER CU.IN.	533	620	---
	SPACING FACTOR, IN.	0.013	.004	---
STRUCTURE #3	AIR CONTENT OF UNHARDENED CONCRETE, %	6.7	8.1	
	AIR CONTENT OF HARDENED CONCRETE, %	---	5.8	
	SPECIFIC SURFACE, SQ.IN. PER CU.IN.	---	550	
	SPACING FACTOR, IN.	---	.008	

A DATA NOT AVAILABLE.

NOTE: Performed in accordance with ASTM Methods, C 231 and C 457, modified point-count method, respectively.

was recorded. ODOT has found normal concretes to exhibit 9,000–12,000 coulombs. ODOT considers any values under 2,000 as low.

Because the rapid permeability results were favorable on structure 1, the poor durability factors were attributed to a poor air-void system and not considered characteristic of silica-fume concrete.

Despite poor durability factors, structure 1 is sound. No delaminations have been discovered, and only two cracks were found, neither of which penetrated the full depth.

Structures 2 and 3 both have very good durability factors at 99.5, 97.5, and 101.1.

The air-void characteristics also were much better than those of structure 1. Structure 2 exhibited a specific surface of 620

TABLE 8 RESISTANCE TO FREEZING AND THAWING FOR ODOT'S FIRST THREE SILICA-FUME PROJECTS

	TEST RESULT	TEST SLAB	BRIDGE DECK	
STRUCTURE #1	LOSS IN MASS, %	-1.678	-1.054	
	EXPANSION, %	0.779	1.123	
	DURABILITY FACTOR	11.5	5.5	
			4/22	5/5
STRUCTURE #2	LOSS IN MASS, %	-.030	-0.050	-.045
	EXPANSION, %	.028	.019	.013
	DURABILITY FACTOR	103.1	99.5	97.5
STRUCTURE #3	LOSS IN MASS, %	-.031	-.022	
	EXPANSION, %	.022	.020	
	DURABILITY FACTOR	95.5	101.1	

NOTE: Performed in accordance with ASTM C 666 Method B.

TABLE 9 RAPID PERMEABILITY TEST RESULTS ON VARIOUS BRIDGE OVERLAYS IN OHIO AT 28 DAYS

LOCALE	OVERLAY TYPE	AVG. CHARGE PASSED, COULOMBS
FRA-270	POLYMER (X) 3/4"	33
MRW-229	EPOXY 1/4"	56
FRA-16	EPOXY 1/4"	77
FRA-270	POLYMER (X) 3/4"	270
ROS-207	EPOXY 1/4"	292
DEL-23	L.M.C. & H.M.W.M.	388
FRA-33	*SILICA FUME	522
MAD-161	*SILICA FUME (FULL DEPTH)	608
ASD-511	*SILICA FUME HALF DECK	670
FRA-270	POLYMER (Y) 3/4"	798
TUS-77	H.M.W.M.	837
ERI-250	L.M.C. 1 1/4"	869
ALL-30C	EPOXY 1/4"	934
ASD-511	L.M.C. HALF DECK	1267
WAS-73	S.D.C. 2 3/4"	1389
MAR-529	SILANE SEALER	1525
SUM-271	L.M.C. 1 1/4"	2072
WAY-30	SUPERPLASTICIZED CLASS 'S'	2264
BRO-221	SHRINK COMP. HALF DECK N.B.	2268
PIC-104	SILANE-SEALER N. 1/2	2751
RIC-97	SUPERPLASTICIZED CLASS 'S'	2806
PIC-104	SILANE SEALER S. 1/2	2849
FAI-22	S.D.C. 1 3/4"	2986
MUS-208	SILANE SEALER	3344
LIC-37	S.D.C. 1 3/4"	3438
MRW-314	CLASS 'S' DECK 9"	3969
CLI-68	SILANE SEALER	4223
MAR-746	SILANE SEALER	6116
BRO-221	CLASS 'S' HALF DECK S.B.	9015
DEL-229	SILANE SEALER	9039

L.M.C.=LATEX-MODIFIED CONCRETE

H.M.W.M.=HIGH MOLECULAR WEIGHT METHACRYLATE

S.D.C=DENSE CONCRETE WITH HRWR

CLASS'S'=ODOT'S STANDARD SUPERSTRUCTURE CONCRETE

in.^{2}/in.^{3} and spacing factor of 0.004 in., both characteristic of a good air-void system. Structure 3 exhibited a specific surface of 550 in.^{2}/in.^{3} and a spacing factor of 0.008 in. These results are not as good as those of structure 2, but they are still values characteristic of a good air-void system. Such results indicate that an air-entraining admixture is necessary.

Rapid Permeability Tests

Rapid permeability tests were performed on the concrete used in the structures using the whiting procedure (*4*). Specimens are rated according to the number of coulombs passed.

Concrete Permeability	*Charge Passed (coulombs)*
High	Greater than 4,000
Moderate	2,000–4,000
Low	1,000–2,000
Very Low	100–1,000
Negligible	Less than 100

As shown in Table 9, ASD 511 (structure 1) passed 670 coulombs, FRA 33 (structure 2) passed 522 coulombs, and MAD 161 (structure 3) passed 608 coulombs.

The test results were similar for the three structures. The concrete used in structure 3 contained a large amount of HRWR and therefore a low water-cement ratio, but this did not affect the rapid permeability values, all of which were very low.

In Table 9, a relationship between the various overlays and sealers used on Ohio bridge decks is given. As can be seen, ODOT's silica-fume concrete rates favorably on this comparison chart.

It is also of interest to note Figure 1, which is a plot of rapid permeability results, taken from Table 3. Placing a horizontal line at 2,000 coulombs (considered low permeability), it can be seen that the required percentage of silica fume could be lowered and still produce favorable results. Even at 7–10 percent silica-fume content, a rating of low permeability is achieved.

Cost

The life expectancy of overlay projects exceeds 10 yr. The cost per square yard for any type of overlay varies, depending on the quantity to be furnished and the amount of variable depth involved. Listed below are some prices bid on projects to be placed in spring 1988. These projects are of similar characteristics. (These prices were obtained from Keith Keeran, ODOT's construction bureau, unpublished data.) The prices are per square yard placed.

County	*1.25 in.-Thick Silica-Fume-Modified Concrete*	*1.25 in.-Thick Latex-Modified Concrete*	*1.75 in.-Thick Dense Concrete with HRWR*
CUY	$26	$30	$23
FRA	$28	$29	$35

CONCLUSIONS

On the basis of field observations and data analysis, the following conclusions can be drawn:

- The addition of silica-fume to concrete makes it less permeable and therefore more resistant to chloride penetration. Permeability decreases as silica-fume content increases, and very low permeabilities are achievable.
- Compressive and flexural strengths increase with the addition of silica-fume to concrete.
- An experienced concrete supplier can produce a consistent and homogeneous mixture using silica fume.
- If proper curing is achieved, a crackfree overlay or deck can be obtained; a 72-hr. continuous water cure is advisable.
- A high silica-fume content can cause finishing problems; 15 percent silica fume by mass appears to be the maximum amount that should be used.
- The addition of silica fume had no detrimental effects on the air-void system.
- A possible tendency to cracking in variable thickness overlays was detected.
- A reliable bond can be achieved when overlaying a bridge deck if the old wearing surface is removed to sound concrete and a bonding grout is scrubbed into the surface. No delaminations have been discovered to date.
- Silica-fume-modified concrete can be mixed successfully in a mobile mixer or in a central mixer. Latex-modified concrete should be mixed in a mobile mixer.
- The cost of silica-fume-modified concrete placed as an overlay is similar to that of a latex-modified overlay.

RECOMMENDATIONS

On the basis of these conclusions, the following recommendations are made:

- Decrease ODOT's specified silica-fume content to 10 percent by mass of cement. This maintains favorable permeability characteristics, produces a more economical mix, and reduces the possibility of finishing problems.
- Use an air-entraining admixture. A proper air-void system can be achieved when the proper quantity of air-entraining admixture is used.
- Use an HRWR. Used in the proper quantity, it can help alleviate some finishing problems and increase compressive and flexural strength.
- Maintain the presently specified continuous water cure.
- Monitor the variable depth situations. Determine if stresses are created which promote cracking in these areas.
- Continue to monitor silica-fume overlays and other types of overlay systems, but the indication so far is that silica-fume-modified concrete forms a durable, highly impermeable surface using standard concrete mixing and finishing practices and readily available materials at moderate cost.

ACKNOWLEDGMENTS

The author thanks all of the ODOT personnel who aided in collecting the data referenced in this study. Thanks also to Mark Luther of Elkem Chemicals, Jeff Young of Sika Company, and John Mc Fadden of the Anderson Concrete Corporation for their assistance in data collection.

REFERENCES

1. *Bridge Deck Repair and Overlay with Latex Modified Concrete.* ODOT Specification. Ohio Department of Transportation, Columbus, Feb. 1986.
2. *Bridge Deck Repair and Overlay with Micro Silica Modified Concrete.* ODOT Proposal Note. Ohio Department of Transportation, Columbus, Aug. 1987.
3. J. E. McFadden. *Study to Determine Optimum Micro Silica Content.* Anderson Concrete, Columbus, Ohio, June 1986.
4. D. Whiting. *Rapid Determination of the Chloride Permeability of Concrete: Final Report.* FHWA Report RD 81/119. Construction Technology Laboratories, Skokie, Ill.; FHWA, U.S. Department of Transportation, 1981.

Publication of this paper sponsored by Committee on Chemical Addition and Admixtures for Concrete.

Experimental Installation of a Concrete Bridge-Deck Overlay Containing Silica Fume

CELIK OZYILDIRIM

This paper summarizes the experimental installation of a concrete bridge deck overlay containing silica fume (SF). The minimum thickness of the overlay was specified as 1.25 in. The objective was to determine whether concretes containing silica fume can be successfully used in thin overlays as a cost-effective alternative to the widely used latex-modified concrete (LMC). A two-lane, four-span bridge deck was overlaid with concrete containing silica fume at 7 percent or 10 percent by weight of the portland cement as an additional cementitious material. The concrete was mixed in a truck mixer rather than a continuous mixer (which is used for LMC), but otherwise the placement procedures established for LMC were applied to concretes with SF. Concretes with 7 percent or 10 percent SF exhibited satisfactory strengths and would be rated as having very low chloride permeability as determined by AASHTO Method T 277. The resistance of these concretes to cycles of freezing and thawing were satisfactory when air content was within specification. Performance of the SF concrete will be monitored for a period of at least 5 yr to evaluate the durability of the overlay.

Laboratory investigation at the Virginia Transportation Research Council and studies by others indicate that concretes containing silica fume (SF) exhibit low permeabilities and are resistant to the intrusion of chlorides or other corrosive solutions (*1–3*). Such liquids can cause corrosion of the reinforcing bars and consequent deterioration of the concrete in bridge decks. Currently, one of the protective systems against corrosion widely used in the repair of bridge decks is latex-modified concrete. This concrete, generally used in thin overlays with a minimum thickness of 1.25 in. is effective but costly. A possible alternative to LMC is concrete containing SF (*1*). In addition to the cost savings, other benefits such as improved strength and resistance to alkali-aggregate reaction are expected from the use of concrete with SF. Savings result from a reduction in actual material costs and from the use of widely available truck mixers for concretes with SF instead of mobile mixers, which are required for LMC.

The experimental installation described in this report was initiated to investigate SF concretes under field conditions as a possible alternative to LMC.

OBJECTIVE

The objective of the project was to determine whether concretes containing SF can be successfully used in thin overlays with a minimum thickness of 1.25 in. as a cost-effective alternative to the widely used LMC system.

PROJECT DESCRIPTION

The bridge overlaid with SF concrete was built in 1941 and is located on Route 50 over Opequon Creek near Winchester, Virginia. The deck carries westbound traffic and has two lanes and four spans; each span is 42.5 ft long and 24 ft wide. The deck is on a 5° grade and is lower at the west end. The minimum thickness of the overlay containing silica fume was specified as 1.25 in. Silica fume was added at 7 percent or 10 percent by weight of portland cement.

The degree of resistance of concretes to the penetration of chloride ion, was determined by the rapid chloride permeability test given in AASHTO T 277 and explained in detail in an FHWA report (*4*). This test measures the amount of electricity in coulombs passed through the specimen in 6 hr. The relative resistance to penetration of chloride ions is judged by the total charge passed through the specimen (Table 1). LMC produced from locally available materials is expected to yield low or sometimes moderate chloride permeability at 28 days and low or very low permeability at later ages (90 and 365 days) as indicated by this test. Such concretes have performed satisfactorily over the years (*5*). Concretes with silica fume will be considered satisfactory if low or very low permeability can be obtained at 28 and 90 days. In earlier laboratory work, concretes with 5 percent silica-fume replacement of the portland cement have yielded satisfactory results (*1*). However, because of the variabilities expected in the field and the recommendations of the marketers of the silica fume products, higher amounts (7 or 10 percent) were used in this study.

During construction, the placement procedure was observed and recorded. Samples were obtained from four of the seven truckloads of concrete and tested for air content, slump, and temperature at the fresh stage. Specimens were then prepared for tests on strength, permeability to chloride ions, and resistance to cycles of freezing and thawing. Also, a petrographic analysis of the air-void system in the hardened concrete was made (Table 2). The condition of the overlay will be monitored periodically for 5 yr.

Virginia Transportation Research Council, Box 3817 University Station, Charlottesville, Va. 22903–0817.

TABLE 1 RAPID CHLORIDE PERMEABILITY TEST

Charged Passed, coulombs	Chloride Permeability
>4000	High
2000 to 4000	Moderate
1000 to 2000	Low
100 to 1000	Very low
<100	Negligible

Materials and Mixture Proportions

A type 2 cement and a commercially available silica-fume slurry were used. The materials, including silica fume, were required to meet the special provisions attached in Appendix A. The silica fume used has a specific gravity of 2.25. The cement factor was 658 lb/yd^3. The maximum water-to-cementitious (cement plus SF) ratio (w/c) was 0.40. The fine aggregate was a siliceous sand with a fineness modulus of 2.90 and a specific gravity of 2.61. The coarse aggregate was gravel with a specific gravity of 2.66 and a unit weight of 104.0 lb/ft^3, and the nominal maximum size was 0.5 in. The concrete mixture proportions are summarized in Table 3.

All of the batches contained a commercially available neutralized vinsol resin for air entrainment and a sulfonated napthalene formaldehyde condensate as a high-range water reducer (HRWR), both of which were added at the plant. However, to achieve the desired workability while maintaining the w/c, more HRWR was added at the job site in two of the seven batches.

Placement Procedure

The traffic lane and the passing lane were overlaid on May 13, 1987, and June 5, 1987, respectively, with concrete containing 7 percent or 10 percent silica fume by weight of portland cement (Figure 1). A total of 29.5 yd^3 of concrete was placed: 17 yd^3 with 10 percent silica fume and 12.5 yd^3 with 7 percent silica fume. The actual w/c was 0.39 rather than 0.40 because a gallon of water per cubic yard was withheld at the plant and not added in the field. To minimize the time between batching and placement, the concrete was furnished in four trucks, each carrying about 4 yd^3 for the traffic lane, and three additional trucks, each with 4.5 yd^3 for the passing lane. The travel time for the truck mixers was about 20 min, and the average time from batching to discharge was about 35 min. The decks had previously been overlaid with an asphalt mixture that was completely removed by scarifying and milling.

TABLE 2 NUMBER OF SPECIMENS AND TESTS FROM EACH BATCH

	Specimens			Age (days)
Tests	No.	Size	Test Method	Tested
Comp. strength	12	4" x 8"	AASHTO T23	1,7,28
Flexural strength	3	3" x 3" x 11¼"	ASTM C78	28
Bond	3	4" in dia.	a	28
Chloride perm.	4	4" x 2"	AASHTO T277	28
Freeze-thaw	3	3" x 4" x 16"	ASTM C666[b]	21
Petrography	1	4" x 8"	ASTM C457	28

[a] 2-in thick overlays on base concrete were sheared at the interface.

[b] Cured 2 weeks moist, 1 week dry and tested in 2% NaCl.

TABLE 3 MIXTURE PROPORTIONS

	Silica Fume, 7%	Silica Fume, 10%
Portland cement	658 lb/yd^3	658 lb/yd^3
Silica fume	46 lb/yd^3	66 lb/yd^3
Maximum w/c	0.40	0.40
Fine aggregate	1,269	1,225
Coarse aggregate	1,516	1,516
Air content	7 ± 2%	7 ± 2%

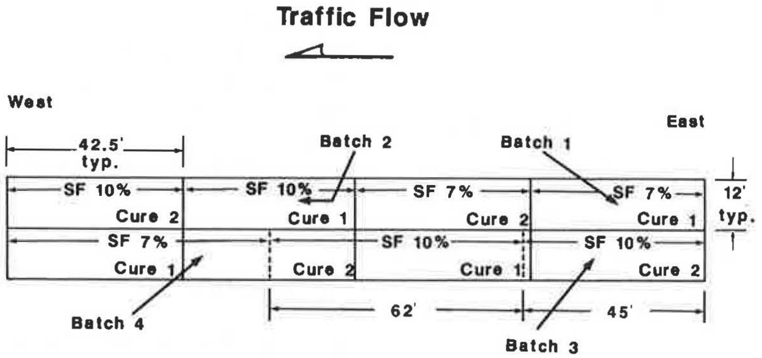


FIGURE 1 Westbound lanes. Cure 1: wet burlap and polyethylene sheet followed by a curing compound; cure 2: curing compound.

On the day before the placement of the overlay, the concrete surface was sandblasted, wetted, and covered with a plastic sheet to achieve a saturated surface dry condition. The placement of the overlay started from the higher east end. The plastic cover on the deck was removed, and the concrete surface was wetted if it was dry. To ensure a good bond between the base concrete and the overlay, the mortar fraction of the mixture from the truck mixer was scrubbed on the surface with coarse bristle brooms. All coarse aggregate from the concrete was brushed aside and discarded. As soon as possible after the scrubbing, the concrete from the trucks was placed on the deck surface. It was consolidated using a vibratory roller screed. The concrete along the joints and the edge of parapets was vibrated using immersion-type vibrators. Behind the screed, the surface levelness was checked and hand floats were used to eliminate the surface defects. Along the edge of the parapet and at the longitudinal joint, the surface was screeded with hand floats. The deck surface was textured using metal tines and subsequently subjected to curing.

Two curing procedures were used: (a) The concrete was covered with wet burlap and a polyethylene sheet. These were removed the next day and the concrete was then sprayed with a curing compound, and (b) a curing compound was applied only after finishing and texturing. Water curing by the use of wet burlap is a very effective curing method and is commonly used the first day for LMC. In SF concretes, additional curing may be necessary and is accomplished by using curing compound. The second procedure was used to determine whether it provides adequate curing in concretes containing silica fume, which would provide additional savings and convenience.

At each span, different amounts of silica fume in the concrete and different curing method were alternated to minimize differences in external factors, such as traffic, geometry, and weather. When burlap was used, care was taken not to disturb the grooves. Special attention was given to prompt curing to eliminate plastic shrinkage cracks.

Placement of the overlay was completed with no major problems.

Test Data

Concrete samples for testing were obtained from the middle third of the truck load. Four batches were tested individually for slump, air content, and temperature at the freshly mixed stage; and from the same batches, specimens were prepared for tests on the hardened concrete (Table 2). In the first batch of concrete, slump was intentionally held low because of concerns about placement of high-slump concretes on a grade. At the job site, two additional doses of HRWR were added to this concrete for workability. In the other three batches, higher initial slump than in the first batch was attained, and no additional HRWR was used at the job site, even though some slump loss occurred.

When the first two batches were placed, the weather was cloudy with high temperatures in the 70s (F); when the next two batches were placed, it was a sunny day with high temperatures in the 80s (F). Test specimens were covered by wet burlap and plastic and left at the job site for a day before they were transferred to the laboratory.

Freshly Mixed Concrete

The results of tests on slump (ASTM C 143) and air content (ASTM C 231) and the measurements of temperature of the air and concrete from the sample obtained in the middle third of the truck load are summarized in Table 4. One of the four batches had a lower slump than the specified 6 ± 2 in. However, slumps were within specification when tested for acceptance as the loads arrived at the job site. As time passed, slump loss occurred. If the addition of the HRWR at the job site is not desired, slumps at the plant should be adjusted for the upper limit. The air content was low, and two of the four batches did not meet the specified 7 ± 2 percent. Air content should be adjusted to yield values near the center of the acceptable range.

Hardened Concrete

The tests conducted on the hardened concretes are listed in Table 2 and are explained in detail in the following sections.

Compressive Strength The compressive strengths were determined in accordance with AASHTO T 22 using 4-in. × 8-in. cylinders; neoprene pads in steel end caps were used for capping. The results of tests at 1, 7, and 28 are summarized in Table 5. The 1-day compressive strengths exceeded 3,000

TABLE 4 CHARACTERISTICS OF FRESHLY MIXED CONCRETE

Batch	Lane	Silica Fume, %	Slump, in	Air, %	Temp., °F Air	Temp., °F Concrete
1	Traffic	7	7.5	3.7	62	80
2	Traffic	10	2.5	4.5	62	78
3	Passing	10	7.5	5.2	68	80
4	Passing	7	7.0	6.0	79	82

psi in concretes with either 7 or 10 percent silica fume. This strength is accepted as sufficient for opening to traffic. All concretes had strengths at 7 days that were significantly above the specified strength of 4,500 psi. The minimum value was 6,090 psi.

Flexural Strength The flexural strengths were determined at 28 days in accordance with ASTM C 78 using a simple beam measuring 3 in. × 3 in. × 11.25 in. The test results ranged from 763 psi to 957 psi (Table 5) indicating that either addition rate of silica fume provides satisfactory values.

Bond Strength To determine bond strengths, specimens were prepared by overlaying slabs cut from 4-in. diameter cylinders and subjecting the interface to shear after 28-day moist-curing of the overlay. The slabs used as the base concrete were made from a typical bridge-deck concrete prepared in the laboratory where they were moist cured for at least a month. Prior to placing overlays, the base concrete surface was allowed to dry for at least 1 day. This condition differs from that at the bridge deck where a mortar layer was scrubbed on the saturated-surface dry-base concrete. As shown in Table 5, the minimum bond strength was 383 psi. This is well above the 200 psi reported as being satisfactory by the Portland Cement Association (*6*). The lowest and the highest values were obtained in concretes with 10 percent silica fume. The satisfactory bond strengths obtained by the laboratory procedures indicate that a mortar layer is not necessary for proper bonding. In fact, wetting prior to scrubbing is a questionable practice. If puddles of water are left, they could significantly weaken the bond. Specifications for the placement procedure did not require the application of the mortar layer for bonding, but the contractor chose to apply this layer, which is a routine procedure with the LMC overlays.

Chloride Permeability The resistance to intrusion of chloride ions was determined using AASHTO T 277. The specimens were 2-in.-thick slabs cut from the top of 4-in. × 8-in. cylinders. The specimens were moist cured for 2 weeks and then air dried until the time of the test. In the test, 60 v are applied across the specimen, and the current passing through the specimen in 6 hr is determined in coulombs. The results show that concretes containing 10 percent silica fume exhibited lower coulomb values than did those with 7 percent silica fume, however, all the concretes exhibit values below 1,000 coulombs, which indicates very low chloride permeability (Table 6).

Resistance to Freezing and Thawing The resistance of concretes to damage from cycles of freezing and thawing was

TABLE 5 STRENGTH DATA

Batch	Lane	Silica Fume, %	Compressive Str. 1 day	Compressive Str. 7 days	Compressive Str. 28 days	Flexural Str. 28 day	Bond Str. 28 days
1	Traffic	7	4340[a]	6850	9180	957	387
2	Traffic	10	3730[a]	6090	7890	903	383
3	Passing	10	5880[b]	6770	7800	860	697
4	Passing	7	5370[b]	6100	6950	763	603

NOTE: Values are psi for the average of three specimens.

[a] 28 hours

[b] 29 hours

TABLE 6 CHLORIDE PERMEABILITY DATA

Batch	Lane	Silica Fume, %	28-Day
1	Traffic	7	648
2	Traffic	10	354
3	Passing	10	437
4	Passing	7	716

NOTE: Average of two specimens.

determined using Procedure A of ASTM C 666 except that (a) the specimens were air-dried for a week following the 2 weeks of moist-curing and (b) the test water contained 2 percent NaCl. The acceptance criteria required that for satisfactory performance at 300 cycles the average weight loss (WL) be 7 percent or less, the durability factor (DF) be 60 or more, and the surface rating (SR) be 3 or less. The SR was determined in accordance with ASTM C 672. The top and molded surfaces were rated separately and averaged. The WL, DF, and SR values are summarized in Table 7. The results indicate that the resistance to cycles of freezing and thawing is low or marginal when the air content was below the specified limit. Concretes with air content within the specification exhibited satisfactory resistance to cycles of freezing and thawing.

Petrographic Examination The petrographic examination involved the determination of the characteristics of the air-void system in the hardened concrete using the linear traverse method of ASTM C 457. The specimens were moist-cured for at least a month and cut vertically; then one side was lapped for the linear traverse analysis. Voids were separated into two groups: small (<1 mm) and large (>1 mm). Small voids are considered to result from air entrainment; large ones, from a lack of consolidation or from extra water in the mixture. The amount of coarse voids is generally 2 percent or less in properly prepared concretes. For adequate protection of critically saturated concrete from extreme exposures, specific surface values of 600 in.$^{-1}$ or more and spacing factors of 0.008 in. or less have been recommended by Mielenz et al., and these values are generally accepted for satisfactory performance (7).

The data on small, large, and total voids, specific surface and the spacing factor are summarized in Table 8. The total air-void content was in the lower half of the specified range. One of the specimens exhibited a high amount of large voids. The slump for that batch was low, and the large voids could have resulted from difficulties in consolidation.

TABLE 7 FREEZE-THAW DATA AT 300 CYCLES

Batch	Lane	Silica Fume	Wt. Loss, %	D.F.	S.R.
1	Traffic	7	5.8%[a]	33	2.5
2	Traffic	10	7.8%	60	1.9
3	Passing	10	0.5	80[b]	1.1
4	Passing	7	0.4	79	0.8

NOTE: Average of three specimens.

[a] Test terminated at 200 cycles when relative dynamic modulus values fell below 60%.

[b] One beam exhibited a DF of 63.

TABLE 8 AIR-VOID SYSTEM OF HARDENED CONCRETE

Batch	Lane	Silica Fume, %	Void Content <1mm	Void Content >1mm	Void Content Total	Specific Surface in^{-1}	Spacing Factor in.
1	Traffic	7	4.2	1.0	5.2	539	0.0088
2	Traffic	10	3.5	3.0	6.5	489	0.0085
3	Passing	10	4.5	1.3	5.8	582	0.0077
4	Passing	7	5.1	2.1	7.2	455	0.0082

The specific surface values were low, indicating a coarse air-void system, which is expected in concretes containing HRWR (*8*). Spacing factors in three of the four concretes were above the maximum 0.008 in. recommended for satisfactory performance. However, one of the three had a value of 0.0082 in., which is very close to the limit. The concretes that had the two highest spacing factors had the smallest amount of small voids and exhibited low or marginal performance in the freezing and thawing tests.

It should be recognized that concretes used on bridge decks are not normally critically saturated and those with low w/c and low permeabilities, such as the SF concretes are expected to resist cycles of freezing and thawing in service better than the specimens subjected to ASTM C 666 Procedure A. Similarly, specimens of LMC sometimes exhibit poor performance when tested with ASTM C 666 (*5*), but their field performance has been satisfactory. Thus, these borderline characteristics will not necessarily lead to poor field performance of the experimental overlays.

INITIAL DECK SURVEY

To observe the condition of the decks and to obtain initial background data, the bridge was inspected on June 9, 1987. At that time, the passing lane was still closed, and the traffic lane had been opened to traffic for only 2 weeks. The only visible crack in the deck was about a foot long at the east end of the passing lane; it extended through the thickness of the overlay slab. The lack of cracks suggests that curing without wet burlap would be acceptable. Chain drag soundings revealed some delaminated areas along the longitudinal joint in the first three spans, mainly in the passing lane. The delaminations are attributed to poor consolidation, which occurred in areas that could not be consolidated by the roller screed and were supposed to be consolidated by an immersion-type vibrator. The contractor has made repairs to eliminate the delaminated areas to the extent possible.

SUMMARY AND CONCLUSIONS

- Concretes containing SF can be a cost-effective alternative to LMC for use as thin overlays on bridge decks. Similar placement procedures can be followed for the two materials. However, truck mixers can be used for the SF concrete, and a curing compound can be used instead of the wet burlap and the plastic sheeting. Thus it appears that cost savings in addition to those realized from the lower cost of materials could be achieved.
- Concretes containing 7 or 10 percent SF exhibited satisfactory strengths and very low chloride permeabilities.
- The resistance of concretes to cycles of freezing and thawing was satisfactory when air content was within the specification.
- Addition of more HRWR at the job site does not appear to affect the strength and chloride permeability of the concretes.

ACKNOWLEDGMENT

The study reported here was conducted at the Virginia Transportation Research Council under funds administered through the Federal Highway Administration.

REFERENCES

1. O. Celik. Laboratory Investigation of Concrete Containing Silica Fume for Use in Overlays. *ACI Materials Journal*, Vol. 84, No. 1, Jan.-Feb. 1987, pp. 3–7.
2. P. K. Mehta and O. E. Gjorv. Properties of Portland Cement Concrete Containing Fly Ash and Condensed Silica Fume. *Cement and Concrete Research*, Vol. 12, No. 5, Sept. 1982, pp. 587–595.
3. ACI Committee 226. Silica Fume in Concrete. *ACI Materials Journal*, Vol. 84, No. 2, March-April 1987, pp. 158–166.
4. D. Whiting. *Rapid Determination of the Chloride Permeability of Concrete*. Report FHWA/RD-81/119. FHWA, U.S. Department of Transportation, 1981.
5. M. M. Sprinkel. *Overview of Latex Modified Concrete Overlays*. VHTRC Report No. 85-RI, Virginia Transportation Research Council, Charlottesville, 1984, 43 pp.
6. E. J. Felt. Resurfacing and Patching Concrete Pavements with Bonded Concrete. *HRB Proc.*, Vol. 35, 1956.
7. R. C. Mielenz, V. E. Wolkodoff, J. E. Backstrom, and R. W. Burrows. Origin, Evolution, and Effects of the Air Void System in Concrete, Part 4: The Air Void System in Job Concrete. *ACI Journal*, Vol. 55, No. 4, October 1958, pp. 507–517.
8. M. M. Sprinkel. Super-Water Reduced Concrete Pavements and Bridge Deck Overlays. In *Transportation Research Record 720*, TRB, National Research Council, Washington, D.C., 1979, pp. 19–28.

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

Publication of this paper sponsored by Committee on Chemical Additives and Admixtures for Concrete.

High Early Strength Latex-Modified Concrete Overlay

MICHAEL M. SPRINKEL

This paper describes the condition of the first high early strength latex-modified concrete (LMC-HE) overlay to be constructed for the Virginia Department of Transportation. The overlay was prepared with type III cement and with more cement and less water than is used in the conventional latex-modified concrete (LMC) overlay. Tests of the bond and compressive strength of the LMC-HE overlay performed during the first 24 hr after installation indicated that traffic could be placed on the overlay within 24 hr rather than the 4–7 days required for the conventional LMC overlay. Tests of the bond strength and permeability to chloride ion conducted after 1 yr in service indicate that the overlay is performing satisfactorily. Pending continuing favorable test results, it is anticipated that LMC-HE overlays can be used in situations in which it is desirable to accelerate construction, to reduce inconvenience to motorists, to allow for installation during off-peak traffic periods such as weekends, to provide a more rapid cure in cold weather, to provide low permeability (compared to concrete without latex), and to provide high strength, particularly, high early strength.

Latex-modified concrete is a portland cement concrete in which an admixture of latex emulsion is used to replace a portion of the mixing water. This type of concrete, which has been used on highway bridges over the past 25 yr (*1*), was first used on a bridge deck in Virginia in 1969 (*2*).

The Virginia Department of Transportation's special provision for LMC overlays requires 3.5 gal of styrene butadiene latex emulsion (46.5–49.0 percent solids) per bag of cement (*3*). Other Department requirements are a minimum cement content of 658 lb/yd^3; a maximum water content of 2.5 gal per bag of cement; a water-cement ratio (w/c) of 0.35–0.40; an air content of 3–7 percent; a slump of 4–6 in. when measured 4.5 min after discharge from the mixer; and a cement, sand, coarse aggregate ratio by weight of 1.0/2.5/2.0. By comparison, the requirements for class A4 concrete used in bridge decks include a minimum cement content of 635 lb/yd^3, a maximum w/c of 0.45 (0.47 from 1966 to 1983), an air content of 5–8 percent, and a slump of 2–4 in. (*4*). Thus, it can be seen that by design the LMC is batched with more cement, less water, less air, and at a higher slump.

Compared with A4 bridge-deck concrete, the LMC is reported to be more resistant to the intrusion of chlorides; to have higher tensile, compressive, and flexural strengths; and to provide better freeze-thaw performance (*1*). The greater resistance to chloride intrusion is said to be attributable to the lower w/c and a plastic film which the latex emulsion produces within the concrete and which inhibits the movement of chlorides. The concrete reportedly has a higher strength because the w/c is lower and because the plastic film produces a higher bond strength between the paste and aggregate. Its freeze-thaw performance is said to be superior because the lower permeability helps keep water out of the concrete and because the concrete is more flexible and therefore able to withstand the expansion and contraction associated with frost action (*1*).

The installation of LMC overlays is one of the most popular ways to extend the service life of bridge decks constructed without epoxy-coated reinforcement. The life of the deck is extended because the LMC overlay inhibits the movement of chlorides to the reinforcement and this delays the onset of corrosion.

On occasion, a bridge in need of an overlay cannot be closed to traffic without subjecting the public to significant inconvenience unless the overlay can be installed during off-peak traffic periods. Because of the slow strength development of currently used LMC mixtures, other systems such as polymer or epoxy overlays or penetrating sealers are often applied to these bridges, but current studies are revealing the shortcomings of some of these systems (*5*).

OBJECTIVE

The objective of the research described by this paper was to refine currently used LMC mixtures to allow the installation of a high early strength LMC (LMC-HE) overlay that can be subjected to traffic in less than 24 hr. Once installed, the objective was to monitor the compressive strength, bond strength, and permeability to chloride ion of the LMC-HE overlay.

COOPERATIVE AGREEMENT

A contract for the installation of an LMC overlay was modified to allow the installation of the LMC-HE mixture on a bridge on Rte. 340 over Hawksbill Creek in Rockingham County. The bridge was selected for the experimental installation because of the small surface area (269 yd^3), low traffic volume (ADT = 1,190), and the willingness of the Staunton district bridge engineer (Larry Misenheimer), the contractor (Lanford Brothers Company, Inc.), and the polymer supplier (Dow Chemical U.S.A.) to participate in the installation. Based on two meetings among the contractor, the polymer supplier, the bridge engineer, and the principal investigator, the following responsibilities for conducting the project were agreed upon.

Virginia Transportation Research Council, Box 3817, University Station, Charlottesville, Va. 22903–0817.

Contractor

- Construct LMC-HE overlay that equals or exceeds the requirements for LMC overlays, except as otherwise specified.
- Modify installation equipment (ASTM C 685) and techniques as necessary (no modifications were required).
- Provide necessary materials.
- Calibrate mobile mixer to provide acceptable LMC-HE concrete mixture.

Polymer Supplier

- Assist with the proportioning of the concrete mixture and provide latex.
- Assist with calibration of mobile mixer.
- Recommend necessary modifications to mobile mixer and installation equipment (none were required).
- Provide technical assistance.

Virginia Department of Transportation

- Approve mixture proportions and installation technique.
- Measure compressive strength (ASTM C 39) at early ages (≦24 hr) and at 28 days.
- Measure bond strength at ≦24 hr, 28 days, and 1 yr using guillotine smear apparatus.
- Measure permeability to chloride ions at approximately 1 mo and 1 yr using AASHTO T 277 procedure.
- Measure freeze-thaw performance of specimens of the mixture using ASTM C 666 Procedure A.
- Write report describing the installation (including materials and equipment) and the condition of the overlay initially and at 1 yr.

MIXTURE PROPORTIONS

The LMC-HE mixture used in the overlay was selected after three trial batches (lab mixes 1, 2, and 3) were prepared in the laboratory using the ingredients that would be used in the overlay. Lab mix 1 was prepared after consideration was given to the mixtures that contained type III cement (ASTM C 150) and that were successfully used for patching decks and pavements and in the production of precast prestressed bridge members (*6–8*). Particular consideration was given to the LMC-HE mixture used for deck patching by the Richmond/Petersburg Turnpike Authority and the Michigan Department of Transportation (*6*). Lab mix 1 had a water-to-cement ratio of 0.34, a cement content of 815 lb/yd^3, and a fine-aggregate-to-total-aggregate ratio of 0.47. For lab mix 2, the ratio of fine aggregate to total aggregate was increased to 0.55. For lab mix 3, the water-to-cement ratio was reduced to 0.27, and the cement content was reduced to 681 lb/yd^3. Lab mix 2 was selected for use in the overlays because the mixture exhibited the best properties in the plastic state and produced the desired properties in the hardened concrete.

A comparison of the mixture proportions for typical A4 concrete, typical LMC, and the LMC-HE lab mix 2 is shown in Table 1. The basic differences between the LMC and the LMC-HE mixture are (a) the LMC-HE mixture contains type III cement, whereas the LMC mixture contains type II cement (ASTM C 150); (b) more cement is used in the LMC-HE mixture; and (c) the LMC-HE mixture has a lower w/c. The physical and chemical properties of the cement used in the LMC-HE are shown in Table 2.

INSTALLATION OF LMC-HE OVERLAY

The installation procedure for the LMC-HE overlay was the same as for an LMC overlay. The deck was scarified to remove the top 0.5 in. of the old concrete. In areas that required partial- and full-depth repairs, the concrete was removed with hammers. Twenty-four hours prior to the placement of the overlay, the exposed surfaces of the concrete were sandblasted, sprayed with water, and covered with a sheet of polyethylene. The overlay placements for both the southbound lane (SBL) and the northbound lane (NBL) were scheduled to begin at daybreak.

The concrete for the SBL was placed on May 21, 1986, beginning at 7:00 a.m.; the air temperature was 60°F. The high air temperature for the 24-hr period following the placement was 78°F, and the low was 55°F. The concrete for the NBL was placed on June 19, 1986, beginning at 6:10 a.m.; the air temperature was 48°F. The high air temperature for the 24-hr period following the placement was 85°F and the low was 50°F.

TABLE 1 MIXTURE PROPORTIONS

	A4	LMC	LMC-HE
Cement, lb/yd^3	635	658	815
W/C	0.45	0.37	0.34
Latex, gal/bag	0	3.5	3.0
Air, percent	5-8	3-7	3-7
Fine aggregate, (S.G. = 2.61, F.M. = 3.0), lb/yd^3	1178	1571	1402
Coarse aggregate, (S.G. = 2.51), lb/yd^3	1809	1234	1142

TABLE 2 PHYSICAL AND CHEMICAL PROPERTIES OF CEMENT USED IN LMC-HE (cement type MT-III)

Chemical Analysis		Physical Analysis	
S102	20.82%	Fineness:	
AL203	4.44%	Blaine	5040
(CM2/GM)			
FE203	2.12	Passing #325	99.1%
CAO	62.23%		
MGO	3.24%	Compressive Strength	
S03	4.40%		
Ignition Loss	0.90%	1 Day	3,010 (psi)
Free CAO	0.45	3 Days	4,860 (psi)
NA20 Equiv.	0.69%	7 Days	5,930 (psi)
		28 Days	---

Meets Latest Requirements of ASTM C 150 and AASHTO M 85

The concrete for both lanes was batched and mixed with a concrete mobile (ASTM C 685). The concrete was discharged onto the deck at a slump of about 5–7 in. The mortar fraction of the mixture was brushed onto the surface with coarse-bristle brooms just ahead of the overlay placement. A rotating drum screed was used to consolidate and strike off the concrete except along the parapet, center line, and joints, where immersion-type vibrators and hand floats were required. A tined texture was applied for skid resistance, and wet burlap was applied immediately after the surface was textured. The wet burlap was covered with polyethylene to retain the moisture and to prevent plastic shrinkage cracks.

The overlays were moist-cured for 24 hr, except the last 10 ft of each lane, which were moist-cured for only 12 hr because it was anticipated that the 3,000 psi compressive strength necessary to open the overlay to traffic might be obtained at 12 hr. Rather than waiting the 4–7 days typical for LMC overlays, the NBL was opened to traffic after 24 hr. No cracks were found in either overlay at 24 hr and 28 days. After 1 yr in service, several short longitudinal cracks were observed in the NBL adjacent to the transverse joint between two spans.

RESULTS

Compressive Strength

Cylinders of concrete, 4 in. in diameter by 8 in high, were fabricated and tested in compression using steel end caps and neoprene pads (AASHTO T 22). During the first 24 hr, the specimens were cured in plastic molds with wet burlap on the surface. The specimens from the NBL LMC-HE were cured and tested at the job site for the first 16 hr and those from the SBL LMC-HE for the first 10 hr prior to being transported to the laboratory located approximately 1 hr from the job site. The specimens were removed from the molds at 24 hr and air-cured in the laboratory. The results shown in Table 3 are based on the average of tests on three cylinders for ages of 12 hr, 24 hr, and 28 days and the average of tests on two cylinders for other ages.

A comparison of the compressive strength with age for a standard LMC overlay and the NBL LMC-HE is shown in Figure 1. Four to 7 days are required to obtain the 3,000 psi compressive strength necessary to place traffic on a standard LMC overlay, whereas 3,000 psi was obtained in approximately 21 hr with the NBL LMC-HE mixture.

A comparison of the compressive strength with age for the NBL LMC-HE and lab mix 2 is shown in Figure 2. The strength of the NBL LMC-HE is somewhat lower than the strength of the mixture prepared in the laboratory. A strength of 3,000 psi was obtained in approximately 16 hr with lab mix 2 as compared to 21 hr for the NBL LMC-HE mixture.

A comparison of the compressive strength with age for lab mix 2 and the SBL LMC-HE is shown in Figure 3. A strength of 3,000 psi was obtained in 12 hr with the SBL LMC-HE. The 28-day strengths were about the same for the two mixtures. It is believed that the SBL LMC-HE mixture duplicated lab mix 2 but obtained 3,000 psi sooner because the curing temperature was higher. The cylinders were cured next to the bridge deck, in the sun, under wet burlap and polyethylene, and at a maximum air temperature of 78°F as compared to 73°F in the laboratory.

Shear Bond Strength

Figure 4 shows the guillotine shear apparatus used to collect the shear bond strength data reported in Table 4. A test value was determined by placing a 4-in.-diameter core or specimen into the base, placing the top part of the apparatus over the overlay, and subjecting the apparatus to a compressive force that sheared the overlay from the base concrete. Tests were conducted on cores from the bridge deck and specimens of A4 bridge deck concrete that were overlaid at the job site.

TABLE 3 COMPRESSIVE STRENGTHS

Age	LMC	Lab Mix 2	SBL LMC-HE	NBL LMC-HE
6 hr.	---	---	---	130
7 hr.	120	---	---	320
8 hr.	---	---	---	930
9 hr.	---	---	---	1,520
10 hr.	---	---	---	1,990
11 hr.	---	---	---	2,190
12 hr.	580	2,330	3,000	2,360
14 hr.	---	---	---	2,570
18 hr.	1,150	3,290	---	---
24 hr.	1,570	3,740	4,010	3,190
2 day	2,360	4,330	---	---
7 day	3,360	5,100	5,230	4,650
28 day	4,630	6,210	6,140	5,260

NOTE: Units are lb/in.^{2}.

The results shown in Table 4 are based on the average of tests on three specimens or cores for ages of 12 hr, 24 hrs, 28 days, and 1 yr and the average of tests on two specimens for other ages.

A comparison of the bond strengths with age for specimens prepared with the SBL and the NBL LMC-HE mixtures is shown in Figure 5. As with compressive strength, the bond strength was somewhat higher for the mixture used on the SBL as compared to that used on the NBL.

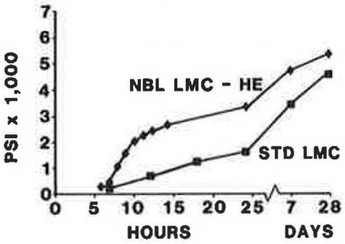


FIGURE 1 Compressive strength vs. age (NBL LMC-HE and STD LMC).

A comparison of the average shear bond strength for both lanes with age for specimens prepared at the job site and cores taken from the deck is shown in Figure 6. The shear bond strengths of the specimens and cores are similar at 24 hr and 28 days. At 12 hr, the average bond strength of the specimens was 350 psi; at 24 hr, 500 psi; and at 28 days, 580 psi. The average shear bond strength of the cores removed and tested at 28 days was 580 psi; and after approximately 1 yr in service, it was 620 psi. The average shear strength of the base concrete was 640 psi.

Figure 7 shows the shear strength data taken from a study done in 1983 in which cores were taken from 12 bridges that had been overlaid with standard LMC over a 13-yr period (*9*). At the time of the evaluation, the overlays ranged in age from 1 yr to 13 yr. Three cores were taken from each overlay and sheared twice. The two curves show the average shear bond strengths and the average shear strengths of the base concretes at various ages. The data show that good bond strengths have been obtained with LMC overlays in Virginia, and the strengths have been maintained over a 13-yr period. Typically the bond strengths were slightly higher than the strengths of the base concretes.

Figure 8 shows the shear strengths versus age for the bond

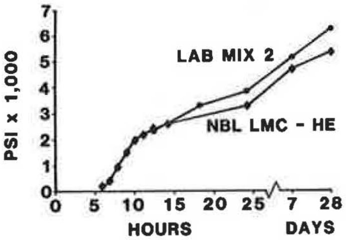


FIGURE 2 Compressive strength vs. age (NBL LMC HE and lab mix 2).

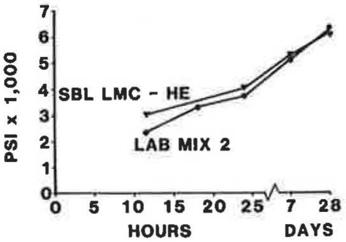


FIGURE 3 Compressive strength vs. age (lab mix 2 and SBL LMC-HE).

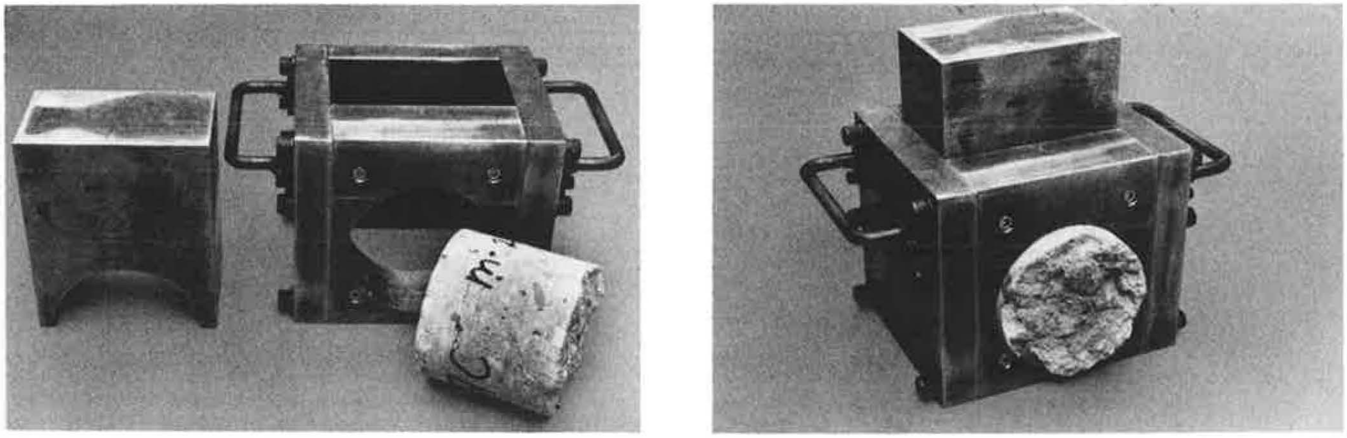


FIGURE 4 Apparatus used to subject cores to shear.

interface and the standard LMC overlay mixture. The LMC has a higher shear strength than the bond interface.

A comparison of the 28-day and 1-yr shear bond strengths for the LMC-HE overlay and the 1–13-year bond strengths for the standard LMC overlays is shown in Figure 9. It is obvious that on the average, the LMC-HE overlay is bonded as well as the standard LMC overlays.

According to Felt, shear bond strengths 200 psi are adequate for good performance (*10*). Based on the data in Table 4 and Figures 5–9, both LMC and LMC-HE have more than adequate bond strength, and LMC-HE can develop adequate bond strength within 12 hours.

A rapid permeability test (AASHTO T 277) was used to measure the permeability to chloride ions of 2-in.-thick slices cut from 4-in.-diameter cores taken from the bridge decks and 4-in. diameter cylinders prepared with the concrete mixtures. The results reported in Table 5 are based on the average of tests on three slices.

Figure 10 shows the relationship between permeability to chloride ion and age for cylinders prepared with a standard

TABLE 4 SHEAR BOND STRENGTHS

	Specimens		Cores	
Age	SBL LMC-HE	NBL LMC-HE	LMC-HE	LMC
6 hr.	---	40	---	---
7 hr.	---	130	---	---
8 hr.	---	150	---	---
9 hr.	---	160	---	---
10 hr.	---	160	---	---
11 hr.	---	290	---	---
12 hr.	360	340	---	---
14 hr.	---	240	---	---
24 hr.	600	400	460	---
7 day	---	650	---	---
28 day	620	550	580	---
1 yr.	---	---	620	740
3 yr.	---	---	---	810
4 yr.	---	---	---	560
8 yr.	---	---	---	780
9 yr.	---	---	---	530
13 yr.	---	---	---	690

NOTE: Units are lb/in.^{2}.

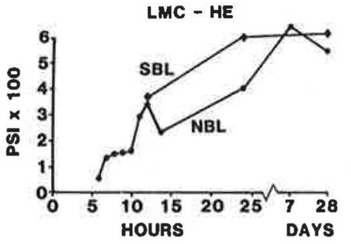


FIGURE 5 Shear bond strength vs. age, LMC-HE (SBL and NBL).

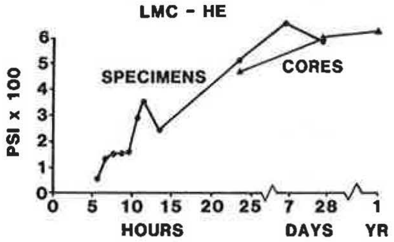


FIGURE 6 Shear bond strength vs. age, LMC-HE (specimens and cores).

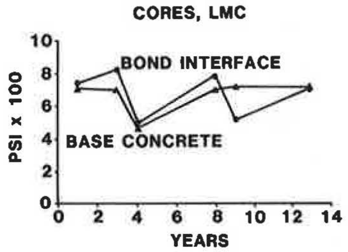


FIGURE 7 Shear strength vs. age, cores, LMC (bond interface and base concrete).

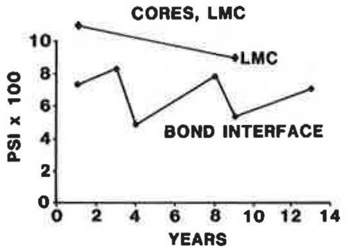


FIGURE 8 Shear strength vs. age, cores, LMC (LMC and bond interface).

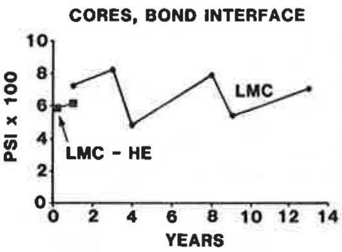


FIGURE 9 Shear strength vs. age, cores, bond interface.

LMC mixture and cores removed from the 12 bridges with standard LMC overlays. It is obvious that the permeability of the standard LMC decreased with age through 4 yr for the cylinders and 9 yr for the cores. The increase reported at 13 yr is likely not typical of LMC but rather an indication of the permeability of an LMC overlay of less than average quality. The reduction in permeability with age agrees with data reported by Whiting (*11*). Based on the test of cores removed from the 12 bridges, the average permeability of a 1.25-in. LMC overlay is 773 coulombs (very low) and that of the A4 concrete below the overlay is 4,590 coulombs (high) (*9*).

A comparison of the relationship between permeability and age for cylinders prepared with the LMC-HE and the standard LMC is shown in Figure 11. The LMC-HE lab mix 2 has a higher permeability at an early age than the standard LMC. However, some standard LMC mixtures have permeabilities of 2,000–3,000 coulombs at an age of 3 weeks. Also, since the permeability of lab mix 2 at an age of 26 weeks was 917 coulombs and at 1 year was 324 coulombs, it is obvious that at later ages, the permeabilities of the LMC-HE is about the same as that of the standard LMC.

A comparison of the permeability of the LMC-HE used on the SBL and lab mix 2 is shown in Figure 12. The cores tested at 4 weeks of age had a permeability of 2,457 coulombs, which falls on the curve for lab mix 2. The cores tested at 1 yr of age had a permeability of 1,464 coulombs. Cylinders tested at 6 and 12 weeks and 1 yr had permeabilities of 1,819, 1,745, and 371 coulombs, respectively. Clearly the LMC-HE used on the SBL has a permeability similar to that of lab mix 2, and it is very low after 1 yr.

A comparison of the permeability of the LMC-HE used on the NBL and lab mix 2 is shown in Figure 13. At an early age both the cores and the cylinders had permeabilities that were higher than for lab mix 2. However, at 1 yr, the average permeability of the NBL cylinders was 347 coulombs, which is about the same as the cylinders for lab mix 2. Also, the permeability of the cores removed after 1 yr in service was 2,018 coulombs, a significant improvement over the 3,269 coulombs obtained at 6 weeks of age. It should be noted that the permeability of the cores is higher than the permeability of the cylinders because the overlay has a minimum thickness of 1.25 in. and therefore as much as 0.75 in. of the 2-in test slice from the cores is A4 concrete rather than LMC-HE. The base concrete exhibited an average permeability of 3,704 coulombs.

Freeze-Thaw Performance

The excellent condition of the 12 bridges with the standard LMC overlays provides evidence that scaling due to freezing and thawing has not been a problem. Nevertheless, six to eight 3-in. × 4-in. × 16-in. beams were prepared during the construction of A4, LMC, and LMC-HE overlays and subjected to the council's freezing and thawing test, a modified version of ASTM C 666 Procedure A, which includes freezing and thawing in a 2-percent NaCl solution (*9*, *12*). The results of the tests are shown in Table 6. Prior to testing, the specimens were moist-cured for 24 hr and air-cured for approximately 6 mo. The standard procedure is to start the test when the specimens are 3 weeks old, but because of problems with

TABLE 5 PERMEABILITY TO CHLORIDE ION

Concrete Age	Type Specimen	Permeability, Coulombs LMC	Lab Mix 2	SBL LMC-HE	NBL LMC-HE
3 wk.	Cylinder	1,462	2,744	---	---
4 wk.	Cores	---	---	2,457	---
6 wk.	Cylinders	---	1,932	1,819	2,783
6 wk.	Cores	---	---	---	3,269
12 wk.	Cylinders	---	---	1,745	3,437
6 mo.	Cylinders	---	917	---	---
6 mo.	Cores	928	---	---	---
1 yr.	Cylinders	---	324	371	347
1 yr.	Cores	712	---	1,464	2,018
3 yr.	Cores	708	---	---	---
4 yr.	Cylinders	80	---	---	---
4 yr.	Cores	545	---	---	---
8 yr.	Cores	367	---	---	---
9 yr.	Cores	464	---	---	---
13 yr.	Cores	1,298	---	---	---

Relationship between Coulombs and Permeability

Coulombs		Permeability
>4000	-	High
2000-4000	-	Moderate
1000-2000	-	Low
100-1000	-	Very Low
<100	-	Negligible

the freeze-thaw machine, the testing of specimens was delayed. All the concrete mixtures passed the test.

Drying Shrinkage

The shrinkage of the LMC-HE at 28 da was 0.042 percent, somewhat greater than the 0.024 percent typical of A4 concrete but slightly less than the 0.049 percent typical for standard LMC concrete (*9*, *12*). The lower shrinkage of the LMC-HE relative to the LMC may be due to the lower water-to-cement ratio of the LMC-HE. Shrinkage values are based on tests of six to eight specimens 3 in. × 3 in. × 11.25 in. subjected to 2 weeks of moist-curing (ASTM C 511) followed by 2 weeks of air-drying in the laboratory.

Skid Resistance

A bald-tire skid number (ASTM E 524) of 41 and a treaded-tire number (ASTM E 501) of 44 were measured at 40 mph several months after the LMC-HE overlay was opened to

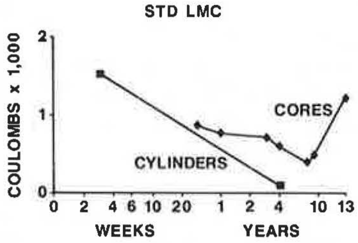


FIGURE 10 Permeability to chloride ions vs. age, STD LMC.

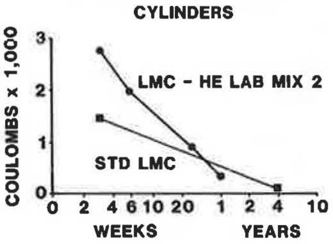


FIGURE 11 Permeability to chloride ions vs. age, cylinders.

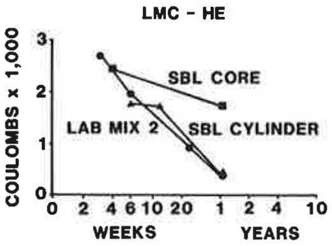


FIGURE 12 Permeability to chloride ions vs. age, LMC-HE (SBL core, lab mix 2, and SBL cylinder).

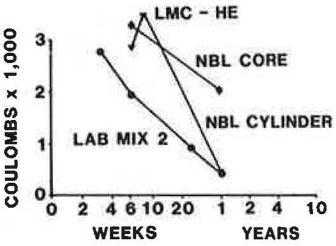


FIGURE 13 Permeability to chloride ions vs. age, LMC-HE (NBL core, lab mix 2, and NBL cylinder).

traffic. Numbers of 46 and 51 respectively, were measured approximately 1 yr later. All four numbers indicate that the tined texture is providing very good skid resistance.

WHY USE AN LMC-HE OVERLAY?

The use of type III cement in pavement and bridge-deck construction has been avoided because of concerns about slump loss, flash set, thermal cracking, sulfate resistance, and durability (*13*). However, these concerns do not apply to a 1.25 in.-thick LMC-HE overlay. The concrete is continuously batched, minimizing the problems associated with slump loss and preventing flash set in the mixer. Also, because the overlay is typically 1.25–2-in. thick, there is insufficient mass to cause major thermal cracks. In addition, the concrete is modified with a polymer and therefore should have sulfate resistance, even though sulfate resistance is not generally needed in a bridge-deck overlay. Finally, concretes prepared with type III cement are durable when used in precast and prestressed concrete members. Freezing and thawing tests conducted in accordance with ASTM C 666 Procedure A indicate that these concretes are durable; therefore, type III cement should be suitable for use in an LMC-HE overlay (*7–9*).

In fact, type III cement may be better suited for use in LMC overlays than are types I and II. In LMC mixtures, the cement gel is gradually formed by cement hydration. As the capillary water is reduced, the polymer particles flocculate to form a continuous close-packed layer on the surfaces of the cement gel and unhydrated cement particles (*14*). Because the hydration process proceeds more rapidly in mixtures with type III cement, the latex film can form more rapidly. Because most LMC overlays are constructed while traffic uses the adjacent lane, a mixture that can be placed and cured in a short time during off-peak traffic periods is less likely to be damaged by traffic and thermal loads than a mixture that cures more slowly.

The results of this study indicate that it is practical to use an LMC-HE overlay to accelerate construction, to reduce inconvenience to motorists, to allow for installation during off-peak traffic periods such as weekends, to provide a more rapid cure in cold weather, to provide low permeability (compared to concrete without latex), and to provide high strength, particularly high early strength.

With the successful installation of the LMC-HE overlay in Virginia, Dow Chemical U.S.A. has continued the use of LMC-HE for overlays where high early strength is necessary. Table 7 shows data reported for the successful installation of an LMC-HE overlay on a one-lane span of the Delaware Memorial Bridge (*15*). The compressive strengths of 4-in. x 8-in. cylinders prepared at the job site are similar to those obtained in Virginia. The permeabilities of slices from cylinders are lower than those obtained in Virginia, and cores removed from the overlay showed that "the bond was excellent" (*15*).

Because it is desirable to use the minimum amount of cement necessary to get the desired strength in the overlay, an effort is under way at Dow Chemical U.S.A. to design LMC-HE mixtures with a lower cement content (*15*). Also modifications to the latex emulsion that would accelerate the hydration of the cement and the formation of the latex film should improve the LMC-HE mixture. Although the concept of an LMC-HE overlay has been implemented, it is likely that with additional trial batching and testing the LMC-HE mixture used in Virginia can be improved.

TABLE 6 FREEZING AND THAWING TEST RESULTS, ASTM C 666-A

Concrete	Weight Loss, %	Durability Factor, %	Surface Rating
A4	1.1	90	1.9
LMC	4.2	92	1.1
LMC-HE	6.9	77	2.2
(Failing values)	>7.0	<60	>3.0

TABLE 7 LMC-HE OVERLAY ON DELAWARE MEMORIAL BRIDGE

Location:	Second Eastbound lane from right curb
Size of Placement:	150 ft by 12 ft-6 in by 1.25 in
Date Installed:	6/18/87
Date Opened to Traffic:	6/19/87
Contractor:	Wagman
Mixture Proportions:	
Cement, Hercules Type III, lb/yd^3	800
W/C	0.36
Sand, York, lb/yd^3	1,416
Stone, lb/yd^3	1,069
Compressive Strength @ 14 days, lb/in^2	5,690
Compressive Strength @ 28 days, lb/in^2	7,490
Permeability @ 14 days, coulombs	1,442
Permeability @ 28 days, coulombs	1,088

SOURCE: L. Kuhlmann and A. Merolla, Dow Chemical U.S.A., personal communications.

CONCLUSIONS

- An evaluation of 12 bridges with LMC overlays ranging in age from 1 to 13 yr indicates that the overlays are soundly bonded to the base concrete and provide good protection against the infiltration of chloride ion.
- The shear strength of the bond between the LMC overlays and the base concretes was about the same or greater than that of the base concrete, indicating that good bonds were achieved and maintained.
- The permeability to chloride ions based on the rapid permeability test was an average of 773 coulombs for a 1.25-in. thick LMC overlay and 4,590 coulombs for the base concretes.
- The bond strengths were about the same for LMC overlays of all ages, but the permeability to chloride ion typically decreased with age.
- Based on the data collected after 1 yr in service, the LMC-HE overlay provides a bond strength and permeability that is equal to that provided by an LMC overlay.
- Based on the early age bond and compressive strength data and 1-year performance data, an LMC-HE overlay can be opened to traffic within 24 hr.

ACKNOWLEDGMENTS

This research was sponsored by the Virginia Transportation Research Council. The research was the result of a cooperative effort by Lanford Brothers Construction Company, Inc.; Dow Chemical U.S.A.; the Virginia Department of Transportation; and the Virginia Transportation Research Council.

REFERENCES

1. *Lower Lifetime Costs for Parking Structures with Latex Concrete Modifier*. Form 173-1089-80. Dow Chemical U.S.A., Midland, Mich.
2. M. H. Hilton, H. N. Walker, and W. T. McKeel, Jr. *Latex Modified Portland Cement Overlays: An Analysis of Samples Removed from Bridge Decks*. VHTRC 76-R25. Virginia Highway & Transportation Research Council, Charlottesville, Nov. 1975.
3. *Special Provision for Latex Portland Cement Concrete Bridge Deck Repairs and Widening Work*. Virginia Department of Highways & Transportation, April 28, 1982.
4. *Road and Bridge Specifications*. Virginia Department of Highways & Transportation, July 1, 1982, p. 180.
5. M. M. Sprinkel. *Comparative Evaluation of Concrete Sealers and Multiple Layer Polymer Concrete Overlays*. VTRC 88-R2. Virginia Transportation Research Council, Charlottesville, July 1987.
6. M.G. Brown. *Memorandum—Compressive Strength Results of Special 9 Sack LMC*. Michigan Department of Transportation, Jan. 15, 1985.
7. M. M. Sprinkel. *Working Plan—Evaluation of Concrete Pavement Patching Techniques*. VHTRC 84-WP23. Virginia Highway & Transportation Research Council, Charlottesville, April 1984.
8. M. M. Sprinkel. *Radiant Heat Curing of Concrete*. VHTRC 85-R34. Virginia Highway & Transportation Research Council, Charlottesville, May 1985.
9. M. M. Sprinkel. *Overview of Latex Modified Concrete Overlay*. VHTRC-5-Rl. Virginia Highway & Transportation Research Council, Charlottesville, July 1984.

10. E. J. Felt. Resurfacing and Patching Concrete Pavements with Bonded Concrete. *HRB Proc.*, Vol. 35, 1956, pp. 444–469.
11. D. Whiting and L. Kuhlmann. Curing and Chloride Permeability. *Concrete International*, April 1987, pp. 18–21.
12. M. M. Sprinkel. *Effective Field Use of High-Range Water Reduced Concrete*. VHTRC 82-R24. Virginia Highway & Transportation Research Council, Charlottesville, Nov. 1981, p. B-23.
13. T. E. Shelburne. *Progress Report No. 3 on High Early Strength Concrete*. Virginia Department of Highways, Division of Tests, Research Section, Sept. 1948.
14. D. G. Walters. *Latex Hydraulic Cement Additives*. Emulsion Polymers Division, Reichhold Chemicals, Inc., Dover, Del., July 31, 1987.

Publication of this paper sponsored by Committee on Mechanical Properties of Concrete.

Using Styrene-Butadiene Latex in Concrete Overlays

L. A. KUHLMANN

This paper will review the material and end-use properties of concrete containing styrene/butadiene latex. Information on mix design is included, with special emphasis on construction techniques. Field performance data are cited, particularly on resistance to chloride penetration. Reports from several states that have many years of experience with LMC are referenced for their performance history.

Thirty years ago, the world's first latex-modified portland cement bridge-deck overlay was installed on a small bridge in northern Michigan by a crew using simple hand tools and directed by research personnel. An experimental system then, concrete modified with styrene-butadiene latex has now grown to be accepted as a standard material of construction covering millions of square yards of bridge and parking decks, installed at an estimated rate of 80,000 yd^3/yr. Latex for this use is supplied by three manufacturers: Dow Chemical Co., Polysar Inc., and Reichhold Chemical Company (*1*). Latex-modified concrete (LMC) has proven to be a reliable method for not only the repair of existing deteriorated bridges and parking structures, but also for protection of new concrete decks.

MIX DESIGN

The inclusion of latex in concrete reduces water demand of the mix, achieving a workable slump (4–6 in.) at a water-cement ratio of 0.40 or less. This includes the water in the latex, typically 52 percent by weight.

The primary criteria for LMC overlays are workability in the plastic state, bond and low permeability in the hardened state. The higher sand content typical in workable LMC mixes is not a concern because compressive strength is not a significant design factor.

Although the sand-stone ratio will vary with the particular aggregate used, a typical mix design for LMC would be:

Component	*Amount*
Cement, type I	658 lb
Sand	1,710 lb
Stone	1,140 lb
Latex	24.5 gal
Water	19 gal, maximum

In LMC, unlike conventional concrete, air entrainment is not required for freeze-thaw durability. The latex itself apparently provides this protection. However, some air is entrained by the latex during the mixing process so it is common for a specification to include a maximum air content, typically 6.5 percent, but not a minimum.

Normally, type I or type I/II cement is used in LMC. For special needs, however, type III cement has been successfully utilized. On the Marquam Street Bridge in Portland, Oregon, it was used to decrease setting time to minimize movement on the superelevations (*2*). In Virginia (*3*) and Delaware, type III cement was incorporated in the LMC mix to shorten curing time and to allow traffic on the overlay in 24 hr.

PROPERTIES

The properties of concrete containing latex are changed in several ways. In the plastic state, the latex functions as a water reducer, providing a workable mixture at low water-cement ratios. However, at high temperatures, rapid slump loss will occur along with increased placing difficulties. In the hardened state, this low water-cement ratio, combined with the film characteristics of the latex, improves bond, freeze-thaw resistance, flexural strength, and permeability (*1*). The effect of the cured latex on the concrete can be seen with a microscope. In Figure 1, cured LMC and conventional concrete are compared at 12,000 magnification. The microvoids of the unmodified concrete are filled by the latex film in the LMC. This is also evident in Figure 2 where photos (*4*) of latex-modified and conventional mortars, as seen through the fluorescent microscope, are compared. Here the micropores in the unmodified are filled with the fluorescent agent, indicating penetration of the agent, whereas the latex modified shows very little penetration.

Figures 3–7 contain some of the typical properties of LMC. It should be noted that most of these data are ranges of values, typical of those reported by various state highway departments and in published research reports. Little has been reported on the effect of latex on modulus of elasticity, but current data indicate that LMC will yield a modulus that is approximately 85 percent of conventional concrete made of the same materials. All of these results are based on a cure cycle of 1 day at 100 percent relative humidity (RH) and subsequent time in dry air, typically 50 percent RH.

Several years ago, an electrical test was developed to determine the chloride permeability of hardened concrete (*5*). This Rapid Permeability Test (AASHTO T 277) requires only 2 days to complete, rather than the 90 days for the AASHTO ponding test, T 259-78 (*6*). Table 1 lists the ranking of the concretes in terms of their permeability as determined by this Rapid Permeability Test. Research studies (*7–9*) using this test procedure have also shown the improved permeability

---

Dow Chemical Co., Midland, Mich. 48640.

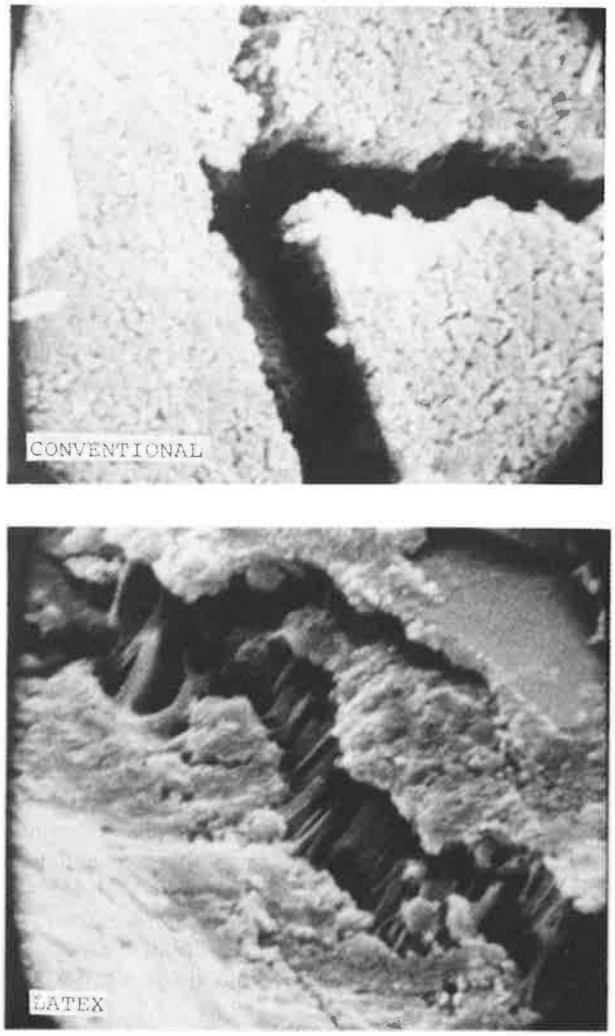


FIGURE 1 Microscopic photographs of latex-modified and conventional concretes (magnification = 8,880×).

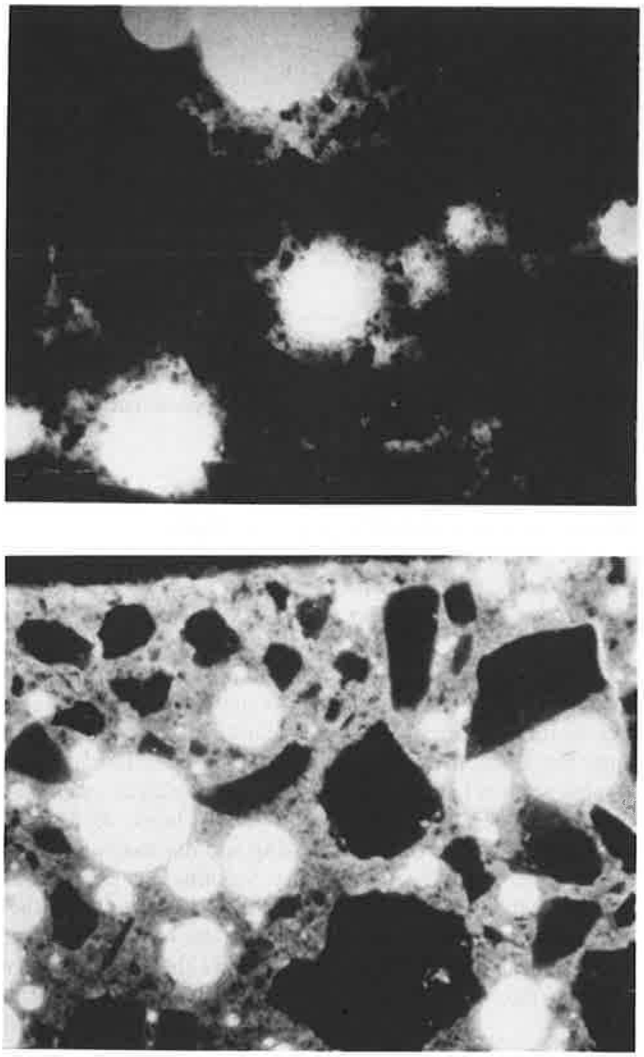


FIGURE 2 Photos of latex-modified and conventional mortars through the fluorescent microscope.

performance of LMC and the effect of variables such as air content and cure time.

APPLICATION TECHNIQUES

Surface Preparation

A clean, sound surface is the key to any material being prepared for adhesion. First, all unsound concrete must be removed from the surface whether the deck is new concrete receiving a protective overlay or deteriorated concrete being repaired. Scarifiers, shotblasters, or scabblers are typically used for this process. Hydrodemolition is a recent development that holds promise for efficient concrete removal with little or no damage to the remaining concrete. Hand clipping follows if there are deep pockets of deteriorated concrete or if concrete below reinforcing steel needs to be removed. The entire area is then blasted to clean surface laitance from the concrete and rust from the rebar. Sandblasting has been the most common and efficient method, although waterblasting has merit in areas

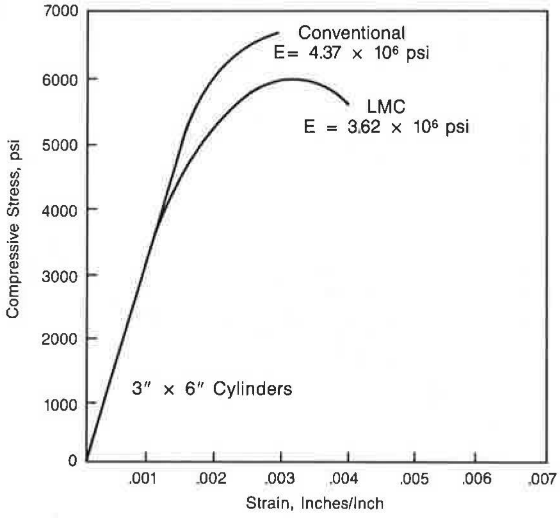


FIGURE 3 Modulus of elasticity of styrene-butadiene latex-modified concrete.

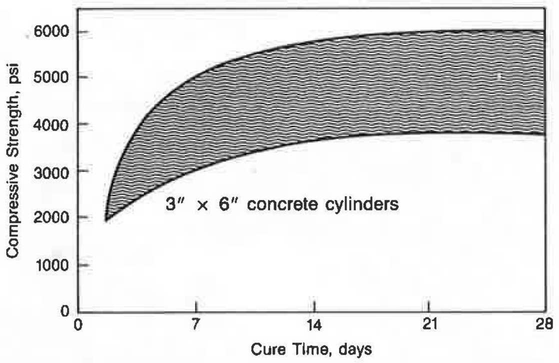


FIGURE 4 Compressive strength of styrene-butadiene latex-modified concrete.

concerned with dust. In either case, the dust and debris must be removed, so that a clean surface is provided.

Mixing

Accurate proportioning and thorough mixing are key requirements for LMC. For LMC and particularly for projects where significant quantities of quality concrete are distributed over large flat areas, the self-contained, mobile, continuous mixer is most appropriate. These machines (Figure 8) carry enough unmixed materials (sand, stone, cement, latex, and water) for at least 6 yd^3 of concrete, mixing and discharging only as much concrete as needed by the finishing operation. The machines should be calibrated regularly to assure the owner of an accurate mix design. In addition, they minimize waste and clean-up time because the auger is the only part that contains mixed concrete.

Placement

The normal construction practice is to drive the mixer to the area of placement and to discharge directly onto the work area. However, where load or space restrictions limit the access of the mixer, alternate means have been used. These include buggies, buckets, and pumps (Figure 9).

If the project contains deep repair areas, these can be handled in one of two ways: (a) LMC can be placed into the deep repair areas simultaneous with the overlay or (b) conventional concrete can be placed first to fill deep holes; the areas are then brought to grade, cured, and overlaid with LMC. If the latter is selected, the conventional concrete should be sandblasted prior to placement of the LMC.

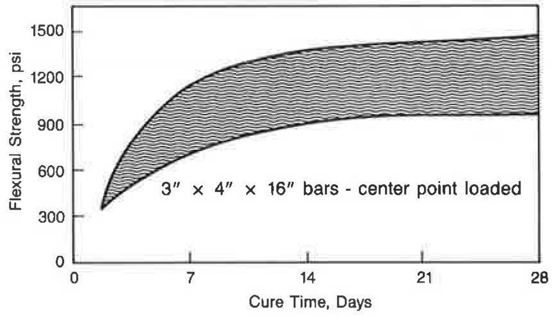
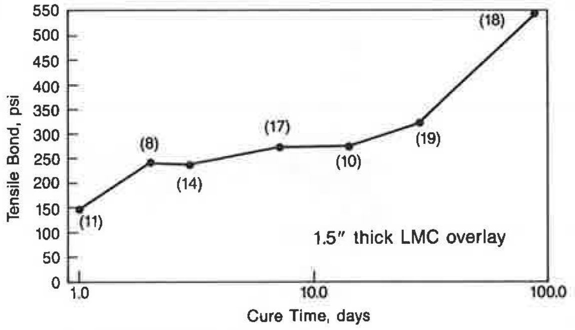


FIGURE 5 Flexural strength of styrene-butadiene latex-modified concrete.



1. Tensile stength of bases >600 psi
2. % coefficient of variation in ( )
3. Failures were predominantly cohesive

FIGURE 6 Tensile bond strength of styrene-butadiene latex-modified concrete.

In either case, the placement of LMC is preceded by wetting the substrate concrete, normally within 24 hr. It is desirable to cool the deck in hot weather. Standing water and puddles are removed by oil-free compressed air.

To ensure bond, the LMC is normally broomed into the surface of the deck to enhance contact between the mortar phase and the substrate. (In this process, overlooked dirt and debris may be included in the mix, rather than remain a bond-breaker under it.) Any excess stones that accumulate are discarded.

An alternative to the above is the use of a latex mortar grout prepared in a separate mixer and applied just ahead of the concrete overlay. This method has also worked well.

Finishing

Self-propelled roller finishers (Figure 10) have proven to be the most popular method of screeding and finishing LMC. The auger, rollers, and vibrating pan combine to provide the proper thickness of overlay. Prior to the placement, the finisher is "calibrated" with shims to assure the contractor and

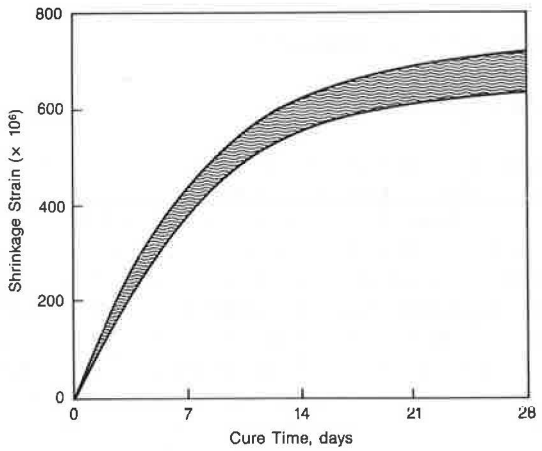


FIGURE 7 Shrinkage of styrene-butadiene latex-modified concrete.

TABLE 1 INTERPRETATION OF RESULTS OF RAPID CHLORIDE PERMEABILITY TEST

Chloride permeability	Charge passed, coulombs	Type of Concrete
High	4000	High water-cement ratios 0.6
Moderate	2000-4000	Moderate water-cement ratios (0.4 to 0.5)
Low	1000-2000	Low water-cement ratios, Iowa dense concrete
Very low	100-1000	Latex modified concrete

FIGURE 8 Continuous mixer.

owner that the proper thickness will be applied to the deck. In locations where a drag or broom finish is desired, this is accomplished by an attachment on the machine. If a grooved finish is required, a workman with a rake is positioned on a workbridge directly behind the finishing machine. In either case, the finishing operation should be completed before the surface of the LMC overlay begins to dry.

Curing

As soon as the finishing operation is complete, wet burlap is applied, followed by white or clear polyethylene film. The intent is to keep the surface damp for approximately 24 hr. The burlap is not to be dripping wet, and the polyethylene film should be held down at the edges with lumber or suitable weights to prevent it from being blown off. After this initial damp cure, the film and burlap are removed to allow air-drying. It is during the air-cure period that LMC gains its physical properties.

WEATHER LIMITATIONS

Latex-modified concrete sets and gains strength at about the same rate as conventional concrete. Indiana studied the setting time of LMC (*10*) and compared it to a conventional concrete, using ASTM C 403, Time of Setting of Concrete Mixtures by Penetration Resistance. The results, shown in Figure 11, demonstrate that LMC does not set any faster than concrete without latex. It will, however, form a "crust" or relatively dry layer on the surface if exposed to dry air for prolonged periods, even though the concrete underneath is

FIGURE 9 Placement by pump.

FIGURE 10 Double-roller finisher.

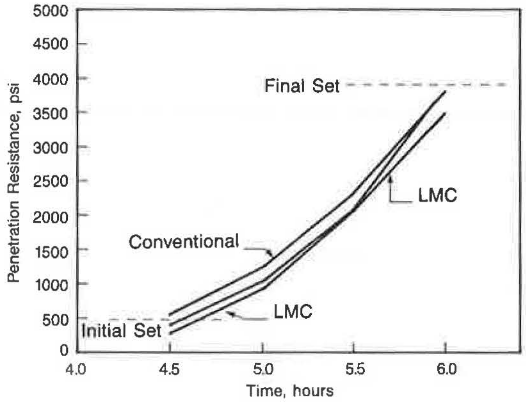


FIGURE 11 Time of set (ASTM C-403) of LMC and conventional concrete.

still quite plastic. This is caused by drying of the latex itself and, if not controlled, can result in tearing during the finishing operation. This condition is aggravated by hot, dry, windy conditions and can be minimized by following ACI's Recommended Practice for Hot Weather Concreting, 305-72. A maximum evaporation rate of 0.15 to 0.20 lb/ft²/hr is recommended.

For cold weather construction, most specifications have either adopted a 45°F minimum for placing LMC or follow ACI 306-66, Recommended Practice for Cold Weather Concreting.

FIELD PERFORMANCE

Although the construction practices for LMC have remained fairly constant over the years, research into one of LMC's

TABLE 2 PERMEABILITY OF FIELD-PLACED LMC

Type of Project	Location	Date of Placement	Overlay		Permeability Coulombs	Tested By
			Thickness Inches	Age		
Bridge	Indiana	11/83	1 3/8	5 months	524	FHWA
			1 3/4	5 months	302	FHWA
			1 7/8	5 months	346	FHWA
			1 3/8	5 months	257	FHWA
			1 1/2	5 months	214	FHWA
			1 1/4	5 months	323	FHWA
			1 1/2	5 months	285	FHWA
			1 3/4	5 months	274	FHWA
			1 1/2	5 months	419	FHWA
			1 1/2	5 months	310	FHWA
Bridge	Pennsylvania	1978	1 7/8	6 years	243	Dow
			1 7/8	6 years	215	Dow
			1 3/4	6 years	366	Dow
			1 5/8	6 years	160	Dow
			1 7/8	6 years	249	Dow
			2	6 years	104	Dow
			1 7/8	6 years	269	Dow
Parking Garage	Pennsylvania	Summer 85	2	4 months	619	Dow
			2	4 months	538	Dow
Bridge	Washington	unknown	2	5 months	260	Dow
			2	5 months	260	Dow
Bridge	Illinois	1982	2	4 years	287	Dow
			2	4 years	277	Dow
Bridge	Illinois	1982	2	4 years	433	Dow
			2	4 years	441	Dow
Stadium	Illinois	1981	2	3 years	48	Dow
			2	3 years	65	Dow
			2	3 years	43	Dow
			2	3 years	65	Dow
			2	3 years	26	Dow
Parking Garage	North Dakota	unknown	2	2 years	397	Dow
			2	2 years	379	Dow

NOTE: All samples were 2" thick when tested; therefore some samples contained conventional deck concrete.

TABLE 3 WEAR RESISTANCE OF LMC OVERLAY ON THE MARQUAM STREET BRIDGE, OREGON, AFTER 3 YRS OF SERVICE

	average of all wheelpaths for 2 lanes	average of all wheelpaths for 2 lanes	average of all wheelpaths for 3 lanes
	Upper level		
Total ADT[1]	26,600	21,200	47,800
Avg. Wear Rate[2]	0.013	0.019	0.034
Projected Life[3], yrs	40-100	40-59	13-43
	Lower level		
Total ADT[1]	20,200	15,400	35,600
Avg. Wear Rate[2]	0.028	0.038	0.042
Projected Life[3], yrs	23-45	24-40	13-36

[1] Average daily traffic

[2] in/yr/10,000ADT

[3] Based on 1" wear; varies with each wheelpath

most important properties has been stimulated by the advent of the Rapid Permeability Test (*5*). Concrete prepared and cured in the field has been evaluated by this test. The results are given in Table 2.

From these data, it can be seen that the permeability of LMC in the field is well within the criteria established in the initial evaluations of the test method (Table 1).

Other properties of field-cured LMC have been reported recently by the Virginia Transportation Research Council (*3*, *7*). In 1986, the Oregon Department of Transportation measured the wear characteristics (*2*) of the LMC overlay on the Marquam Street Bridge in downtown Portland. Using a straight edge, the department measured the wear in each lane at several locations and then projected a lifetime of the overlay based on time to achieve 1-in. wear. The results (Table 3) indicate a life expectancy of 13–100 yr, depending on the traffic exposure.

The state of Ohio has installed more than 1,500 LMC overlays during the past 14 yr. Recently the state has been conducting condition surveys of these overlays, assigning four ratings: good, fair, poor, and critical. In 1987, the state reported that 74 percent of these LMC overlays were in good condition; 14 percent, fair; and only 2 percent, poor. None were critical.

Another state that has a long history of LMC overlays is Indiana. This history, combined with an intensive effort to inspect and evaluate its bridges, has led the state to the following conclusion: ". . . these overlays have given good service and, with maintenance, the overlays should have a service of life of about 20 years."

ACKNOWLEDGMENT

The author would like to acknowledge the assistance of D. Moldovan whose continuing help in the laboratory has been instrumental in developing the data base reported here.

REFERENCES

1. K. C. Clear and B. H. Chollar. *Styrene Butadiene Latex Modifiers for Bridge Deck Overlay Concrete.* FHWA, U.S. Department of Transportation, April 1978.
2. J. Howard. Case History of the Marquam St. Bridge. Presented at TRB Session 90, Washington, D.C., Jan. 1988.
3. M. Sprinkel. High Early Stength Latex Modified Concrete Overlay. Presented at TRB Session 90, Washington, D.C., Jan. 1988.
4. P. A. Hauenstein and M. Taylor. *Polymers Used to Upgrade the Quality of Concrete Repair Materials.* Dow Chemical Europe; Horgen, Switzerland; and Rheinmuenster, Germany, Oct. 1987.
5. D. Whiting. *Rapid Determination of the Chloride Permeability of Concrete.* Technical Report FHWA-RD-81/19. FHWA, U.S. Department of Transportation, August 1981.
6. *AASHTO T 259-78, Resistance of Concrete to Chloride Ion Penetration.*

7. M. Sprinkel. *Overview of Latex Modified Concrete Overlays*. Report 85-R1. Virginia Transportation Research Council, Charlottesville, July 1984.
8. L. A. Kuhlmann and N. C. Foor. Chloride Permeability Versus Air Content of Latex Modified Concrete. *Cement, Concrete, and Aggregates*, CCAGDP, Vol. 6, No. 1, Summer 1984, pp. 11–16.
9. D. Whiting and L. Kuhlmann. Curing and Chloride Permeability. *Concrete International*, Vol. 9, No. 4, April 1987, pp. 19–21.
10. R. K. Smutzer and R. B. Hockett. *Latex Modified Portland Cement Concrete: A Laboratory Investigation of Plastic and Hardened Properties of Concrete Mixtures Containing Three Formulations Used in Bridge Deck Overlays*. Indiana State Highway Commission, February 1981.

Publication of this paper sponsored by Committee on Mechanical Properties of Concrete.

Marquam Bridge Repair: Latex-Modified-Concrete Overlay and Joint Replacement

JOHN D. HOWARD

The Marguam Bridge in Portland, Oregon, provides a crossing of the Willamette River for the north-south I-5 freeway. After 17 yr of service, the bridge, which was opened to traffic in 1966, had a badly worn deck and numerous deck expansion joints in need of repair. The bridge has a daily traffic count of approximately 86,000 vehicles. Because of lack of capacity of detour routes, complete closure to traffic could be permitted only during night hours. To correct the deck and joint problems, a contract was awarded in May 1983 for a latex-modified-concrete overlay and joint repair. On a previous job with a 3-percent grade, the tendency of the finished surface to shift downhill during the early cure stages was noted, and it was thought that this tendency could be a major problem on this structure with ramps on 6-percent grades and 0.10 ft/ft supers. Type III cement was suggested; it was tried and was found to be a workable solution. Narrow pour widths required by traffic staging were as significant a factor to surface irregularities as were the steep slopes. The pour widths also restricted the pour rate. Three years after completion of the overlay, a check on the wear was made. This found wide variation in the projected life due to traffic patterns and irregular wear in the individual wheel tracks. From the survey, a general conclusion can be made that the latex-modified-concrete has equivalent or possibly better wear resistance than the original concrete surface had. Also from this information and a similar survey on the I-205 Columbia River Bridge, a normal wheel track wear rate of 0.0313 in./yr per 10,000 average daily traffic (ADT) can be anticipated.

The Marquam Bridge and ramps in Portland, Oregon, provide a crossing of the Willamette River for the I-5 north-south freeway. They are also a segment of I-5 and of the I-405 inner city loop (Figure 1). The bridge was opened to traffic in 1966. The photographs shown in Figures 2 and 3 are general views of the structure. The main spans are a double-deck cantilevered truss with 301-ft side spans, 90-ft cantilevers, and a 260-ft center suspended span. The approach ramps begin with a single or multiple poured-in-place span followed by several 60–80-ft precast prestressed spans. The remainder and majority of the ramps' length are simple composite welded girder spans 85–178 ft long. The ramps have varying horizontal curvature up to a maximum of 8°, superelevation varying up to a maximum of 0.10 ft/ft, and grades up to a maximum of 6 percent. This difficult alignment plus the traffic made for an unusual and challenging overlay job.

CONDITION OF DECK AND JOINTS

Prior to and after award of the contract, surveys were made to determine the extent of work needed to be done. (Overlay contract was awarded May 10, 1983.) Both surveys found significant wear throughout the structure, with a number of spans that had the top mat of reinforcing exposed and a number of locations with loose angles at the joints (Figures 4 and 5). Based on the elevation of the armored corners at the joint, approximately 0.5–1 in. of rutting in the wheel tracks occurred during the 17-yr life of the deck. Bridge plans showed 1.5-in. cover on the top mat of reinforcing, which apparently was not available in some cases. Where the steel was exposed, it showed very little rusting and appeared to be well bonded. Checks on the chloride content found 1–2 lb/yd^3 in the top 1 in. These minimal amounts are the result of using very limited amounts of chlorides in the sanding materials during the winter months. The first survey showed some small areas with delaminations. These were checked with cores through the deck and no problems were found.

Figure 6 shows a detail of the double-angle armored corner joints. Poor consolidation of concrete under the horizontal leg plus traffic created a void which was found at all locations. Where it was severe, flexing of the angle between the studs caused the stud welds to fracture. At these loose angle locations, the overlay plans specified removing all of the joint and replacing it with a strip seal. A recheck found only portions of the joints needed removal so it was decided to use the Figure 6 detail throughout.

Figure 7 shows the paving dam detail for the finger plate joints on the main span. The existing plates are part of the structural steel stringer system and were all found in good condition.

TRAFFIC

Traffic was a major consideration; the ADT for the bridge was in excess of 47,000 northbound and 39,000 southbound. On the west interchange, there is an approximately 60–40 split between I-5 and I-405, with 60 percent on I-5 (Figure 1).

The specifications permitted night closure of the bridge between 8:00 p.m. and 6:00 a.m. with traffic detoured via I-405. To avoid restricting the detouring, the E and F ramps linking I-405 with I-5 had to be overlaid first. During daylight hours, the bridge had to remain open; this meant on the sections between pier 1 and D13 – C13 (Figures 4 and 5), with

Oregon Department of Transportation, 2206 N. W. Thurman St., Portland, Oreg. 97210.

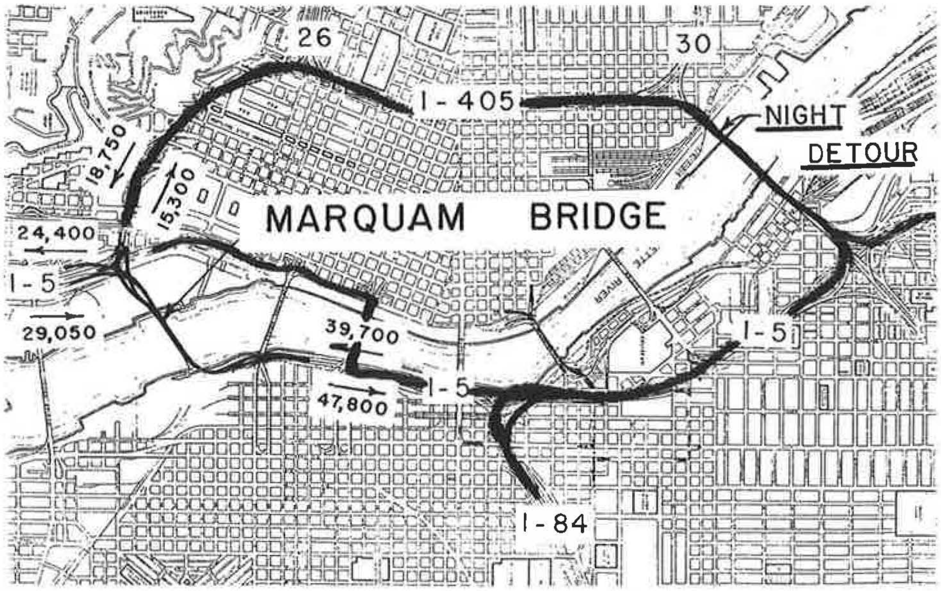


FIGURE 1 Portland inner freeway loop—ADTs and night detour.

a ramp width of 32 ft, the pour width would be limited to approximately 10.5 ft. This pour width was tried on the first stage of the lower deck, and it was found difficult to maintain the cones and barricades separating the traffic from the work area. It was decided to revise the staging, widening the first pour to the center and restricting traffic to one lane. Because this caused some backup of traffic, the contractor agreed to expedite the work in this section.

MIX DESIGN—LATEX-MODIFIED CONCRETE

On a previous bridge that had a 3-percent grade, it was noted that latex-modified concrete had a tendency to shift downhill during the wet cure period, leaving an undulating, unacceptable surface. This presented a significant problem for the Marguam Bridge with its 10-percent super and 6-percent grade. The Dow representative knew of a successful overlay placed on a steep grade, using type III cement. Based on this information, trial mixes were made using both type II and type III cements from Kaiser Permanette, Oregon Portland Cement, and Ideal Cement. Slump was measured immediately after it came from the mixer and at 5-, 10-, and 15-min intervals. Also, small 1.5-in.-thick slabs were formed and poured on the maximum grade that was anticipated. These gave a check on workability, and after 30 min they were jarred to see if there was a tendency for movement down the slope. From this it appeared that a mix with a 3-in. or less slump after 5 min would maintain an acceptable surface. The Kaiser type III gave a 5–6-in. initial slump followed by a 3.-in and 2-in. slump at 5 and 10 min plus good workability; therefore Kaiser type III was recommended. All of the others showed little difference in the initial and other slumps, and it was felt a 3-in. initial slump could have placing and finishing problems. Table 1 gives the mix data that resulted from these tests. It might be noted the coarse aggregate is a ¾ minus crushed basalt, which was desired for wear resistance.

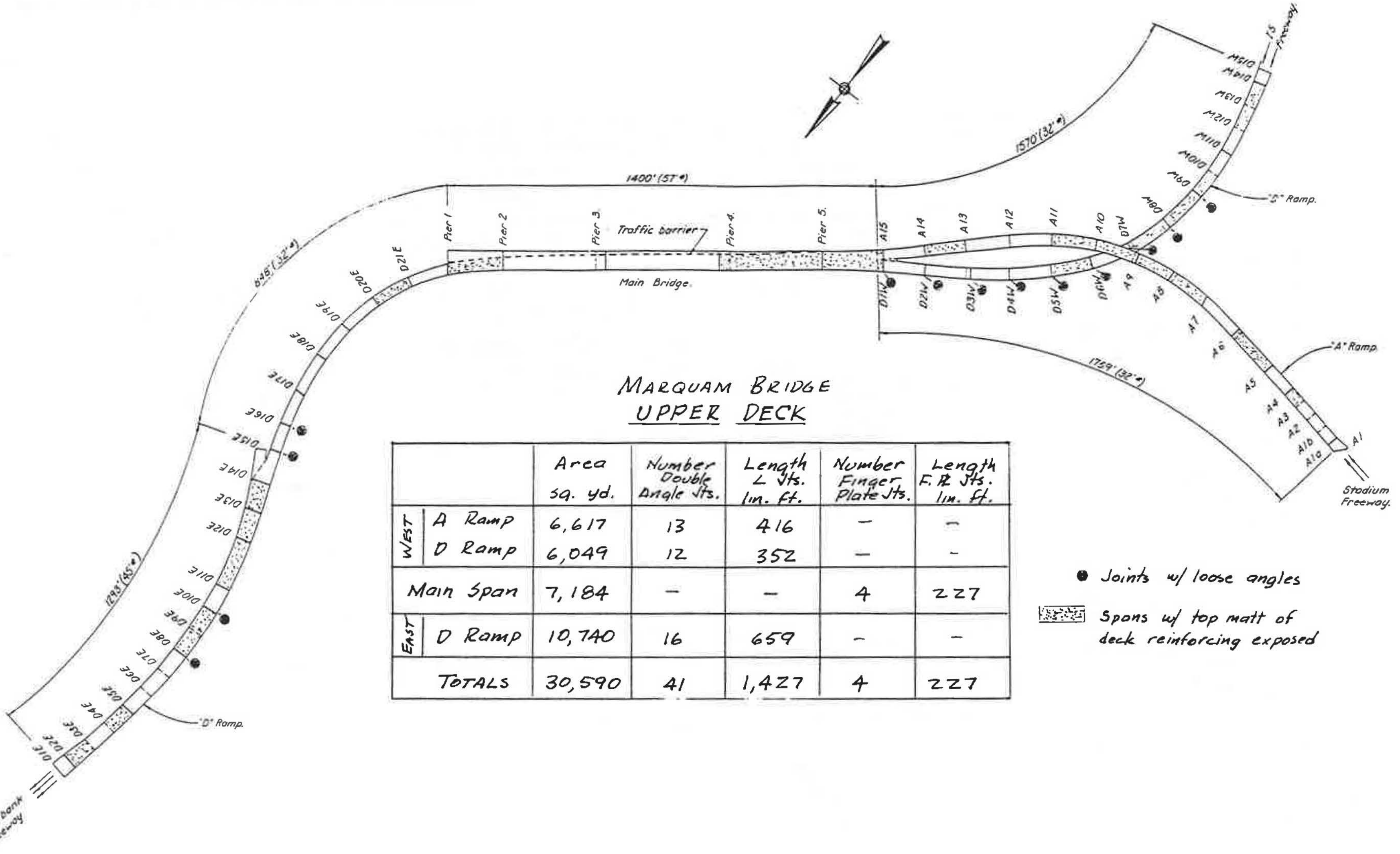
CONSTRUCTION

Deck Joints

From Figures 4 and 5, one of the first things that become apparent is the number of deck joints that require repair and addition of the 1-in. plate paving dam. On the approach ramps,

FIGURE 2 Marquam Bridge west approach ramps and main spans.

FIGURE 3 Marquam Bridge east approach ramps.



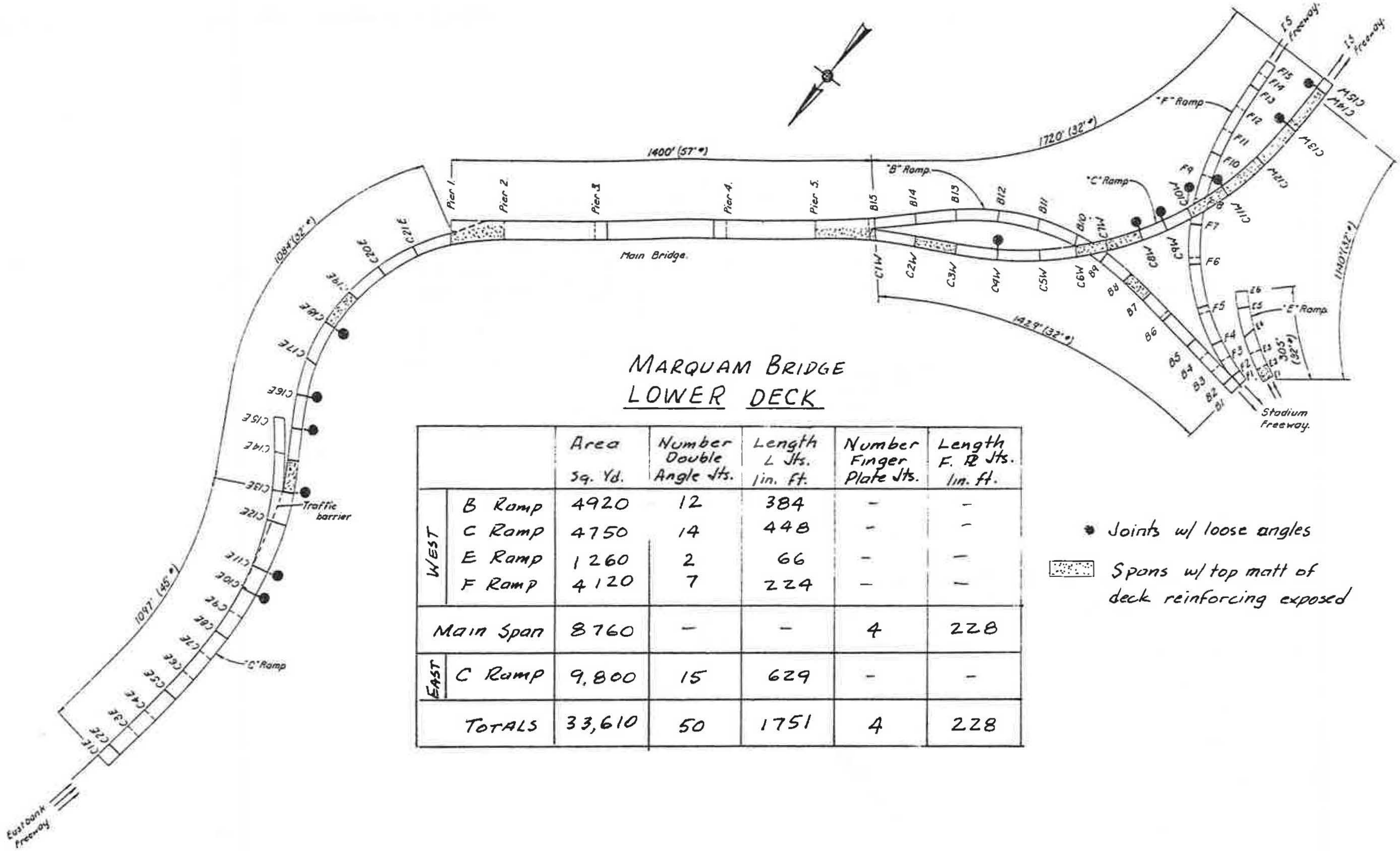
MARQUAM BRIDGE
UPPER DECK

		Area sq. yd.	Number Double Angle Jts.	Length ∠ Jts. lin. ft.	Number Finger Plate Jts.	Length F. Pl. Jts. lin. ft.
WEST	A Ramp	6,617	13	416	–	–
	D Ramp	6,049	12	352	–	–
Main Span		7,184	–	–	4	227
EAST	D Ramp	10,740	16	659	–	–
TOTALS		30,590	41	1,427	4	227

● Joints w/ loose angles

▨ Spans w/ top matt of deck reinforcing exposed

FIGURE 4 Upper deck—loose angles and exposed reinforcing.



MARQUAM BRIDGE
LOWER DECK

		Area Sq. Yd.	Number Double Angle Jts.	Length ∠ Jts. lin. ft.	Number Finger Plate Jts.	Length F. PL Jts. lin. ft.
WEST	B Ramp	4920	12	384	–	–
	C Ramp	4750	14	448	–	–
	E Ramp	1260	2	66	–	–
	F Ramp	4120	7	224	–	–
Main Span		8760	–	–	4	228
EAST	C Ramp	9,800	15	629	–	–
TOTALS		33,610	50	1751	4	228

● Joints w/ loose angles

▨ Spans w/ top matt of deck reinforcing exposed

FIGURE 5 Lower deck—loose angles and exposed reinforcing.

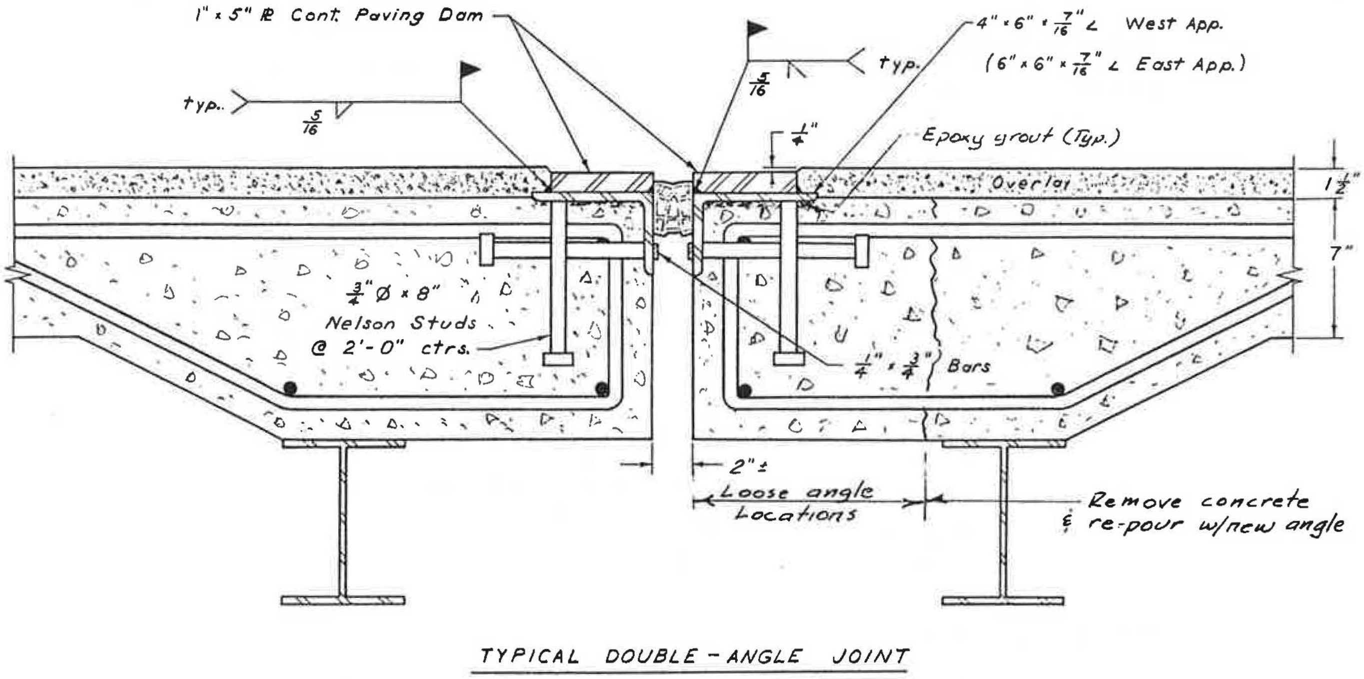


FIGURE 6 Typical double-angle joint.

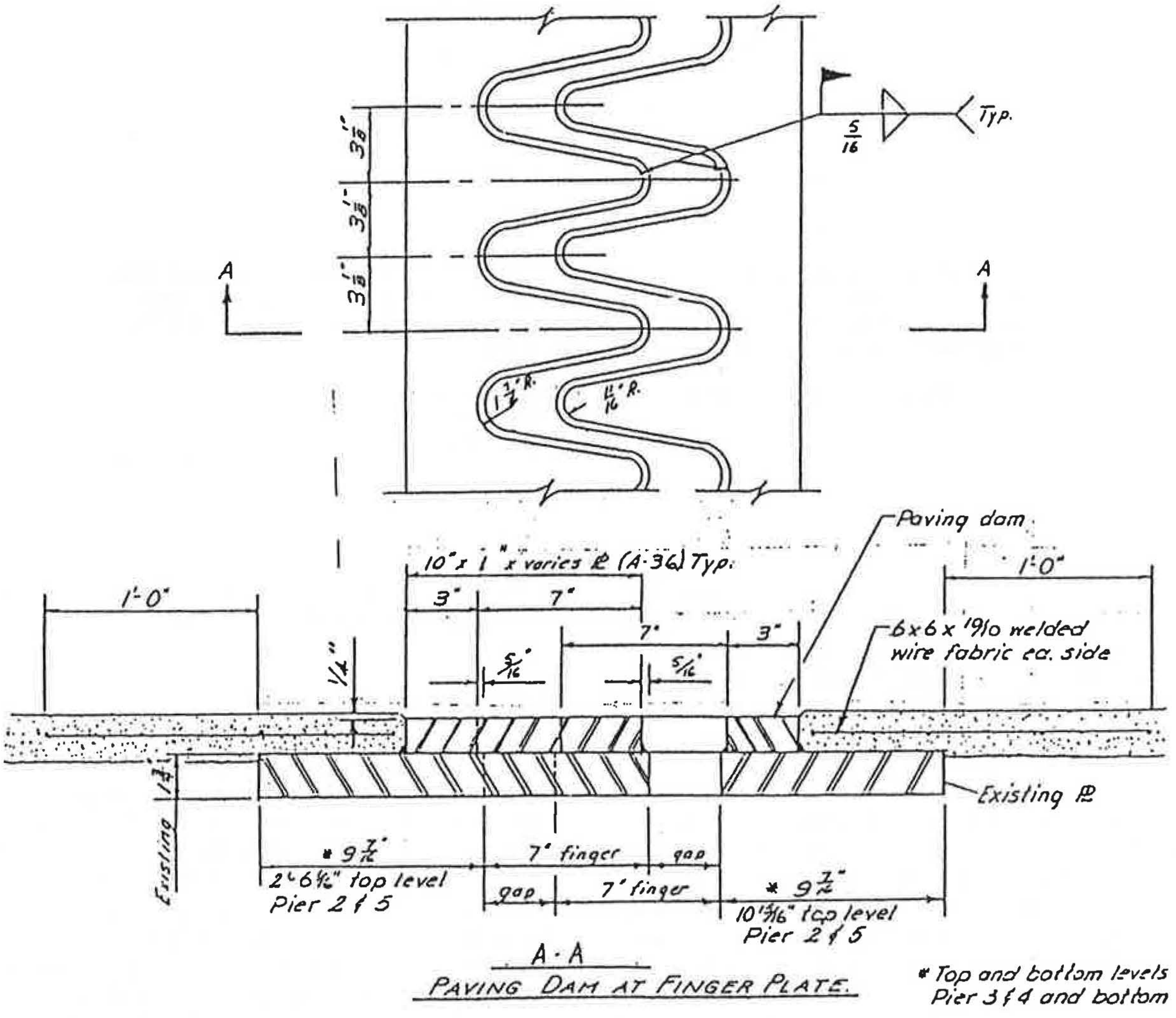


FIGURE 7 Paving dam at finger plate.

TABLE 1 MIX DESIGN AND TEST DATA

Aggregate Gradation:

Coarse	% Passing	Fine	%Passing
1"	100	3/8"	100
3/4	90 - 100	#4	90 - 100
3/8	20 - 50	#16	45 - 75
#4	0 - 10	#30	25 - 55
#200	0 - 1.5	#50	5 - 30
		#100	0 - 8

Concrete Mix Designs:

Cement	7 sacks/cy Type III	
Latex	3.5 gal/sack	
Water	maximum = 2 gals/sk	w/c = 0.33
Slump	3 - 5 inches	
Coarse Agg.	50%	
Fine Agg.	50%	

Concrete Cylinder Strengths:

No minimum strength specified

29 Tests taken

7 day breaks -	minimum	2120 psi
	maximum	4970 psi
	average	3688 psi
28 day breaks -	minimum	3610 psi
	maximum	6555 psi
	average	5296 psi

Pullout Bond Tests:

100 psi minimum specified

This test was made using a 3-inch diameter core taken through the overlay into the deck approximately 1/4 inch. A pulling cap was bonded to the core with epoxy. From the 25 tests taken, 18 failed in the epoxy bond of the cap to the core.

Results of 25 tests -	minimum	191 psi
	maximum	478 psi
	average	300 psi

the average span length works out to be approximately 130 ft, which means with a normal night's run the overlay would cross four or five joints. To avoid transverse construction joints, it was decided to do the joint work first. This started with sounding the angles with a hammer to determine the sections requiring removal and replacement. A typical joint that required the removal of one angle is shown in the pictures of Figure 8. The pour back was made using latex-modified concrete. Because of its flow characteristics, good bond and easy cure, this is in our opinion an excellent material for such repairs. This was followed with the welding of the 1-in. × 5-in. paving dam and pressure-grouting the angles with epoxy grout. Welding the paving dam tended to lift the horizontal leg of the angle so grouting could not be done before this welding. A total of 210 gal of epoxy were used for the 3,178 linear ft of angle joint, about 8.5 oz/ft of joint. Where removal of the angles was necessary, approximately 6 weeks lead time before placing the overlay was needed.

Deck Preparation

Because of the significant number of spans with exposed deck reinforcing, shot blasting was specified for the deck preparation. Two "Blastrac" units were used for the cleaning plus a bag unit to retrieve the dust. This method removed 0.125–0.25 in. of the fine aggregate-cement mortar, but did not remove or fracture the large aggregate. This left a smoother surface than the grooves from a rotary milling machine, which raised the question of the bonding surface. Based on the pullout tests (Table 1), this proved to be more than adequate to meet the required 100 psi. Fifty-eight shifts were needed to do the 64,200 yd^2, giving an average of 1,107 yd^2/shift. Areas that could not be reached with the shot blaster were done with single or multiple-headed scabblers. This work as well as setting screeds and work on the joints was done during the day on the half of the ramp closed to traffic. Just before the overlay was placed, the deck was cleaned with high pressure water to remove any remaining dust and steel shot.

Latex-Modified Overlay

All concrete pours were made during the night, when the bridge could be closed to traffic. Concrete was delivered by three Daffin high-production mobile mixers adapted for latex concrete with a 6 yd^3 capacity. The stockpiles for recharging were located approximately 5 mi from the job site. The haul presented no problem, but the stockpile site was limited in size, requiring frequent deliveries by the aggregate producer. With the water in the latex considered, the free moisture in the sand could not exceed 10 percent to maintain the desired water-cement ratio. Some of the sand was delivered directly after washing and exceeded this limit. The problem was solved by the aggregate producer making multiple stockpiles as the material was produced and by making deliveries from the oldest, giving the excess water time to drain.

Finishing was accomplished with two Bidwell dual-drum deck finishers. Because many of the ramps were 32 ft wide, most of the pours were 16 ft wide. Pours were made going both up and down the grade. Pouring down the grade seemed to produce the best surface, and it was preferable for wetting down ahead of the pour. The deck finisher was supported on 2-in. steel pipe screeds. It was general practice to check adjustment of the machine by running the length of the pour and checking the match to the paving dams at the deck joints. One crew made all the pours. The second finishing machine was used where there was a second pour location or a change in width.

The concrete mix with the type II cement worked as anticipated except that control of the water was difficult. Even with the multiple stockpiles, there were variations in the free moisture in the aggregates, and a 6-in. slump as it comes directly from the mixer is difficult to judge. A second problem was the coarse aggregate, which in the beginning had a gradation on the coarse side of the specified limits. The Bidwell finisher in our opinion is as good as any that are available, but with close to 10 percent of the coarse aggregate retained on the ¾ sieve and the overlay thickness near the plan 1.5 in., the finisher would not seal the surface, so hand-finishing was required. The aggregate was adjusted to the finer side of the limits, and there was no further problem.

An inherent problem was the 16-ft pour width, which allowed the dumping of only one truck. Hand-finishing was required on the edges, a relatively large area. If the staging had permitted closing the ramp during the cure period, a better riding surface could have been obtained by pouring full width. Pour no. 56 in Figure 9 shows a maximum production for a single shift of 2,000 yd^2. This pour, located on the east upper-deck

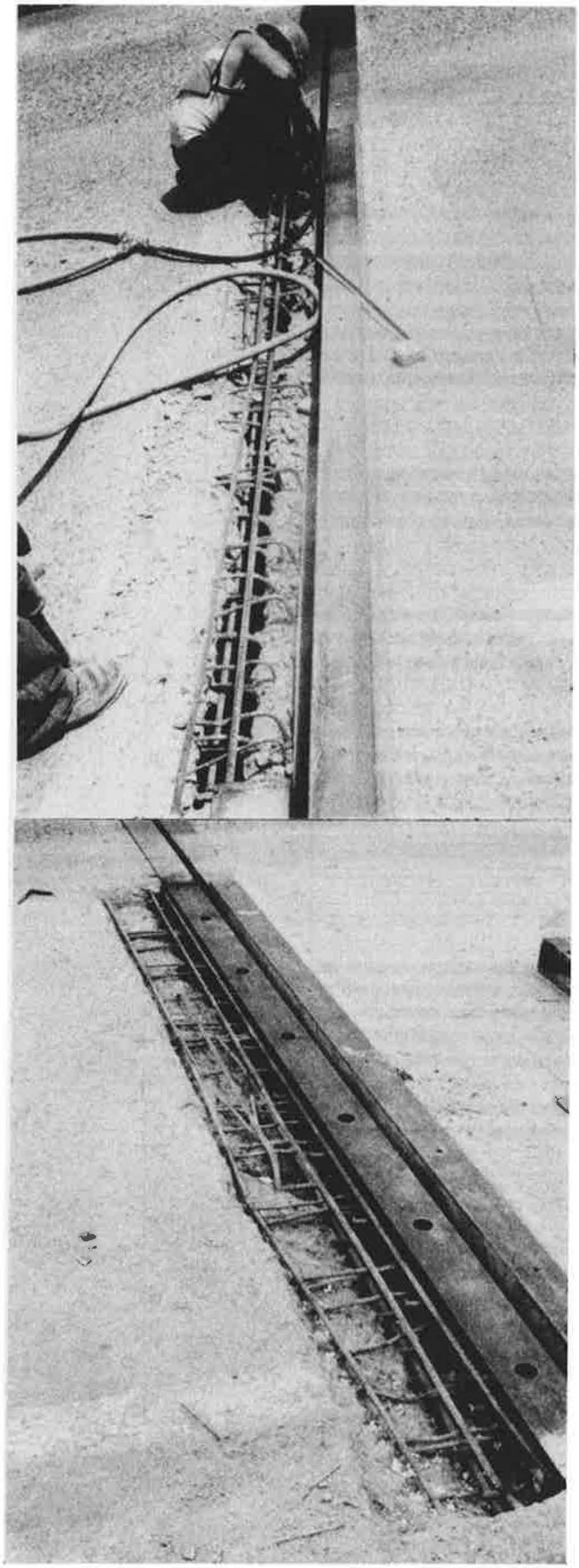


FIGURE 8 Typical joint replacement: loose angle removed (*top*) and new angle installed and deck ready to be poured back (*bottom*).

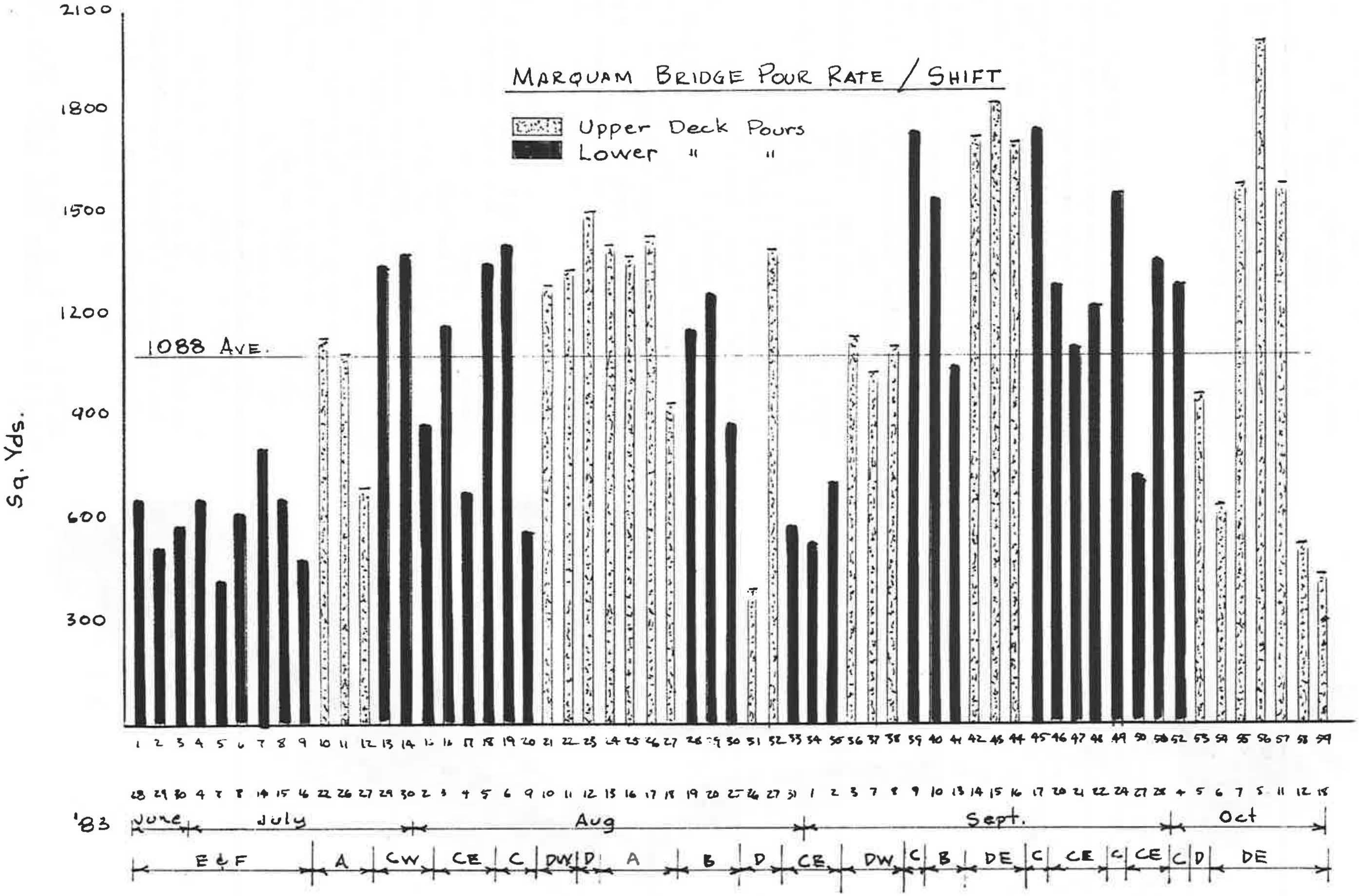
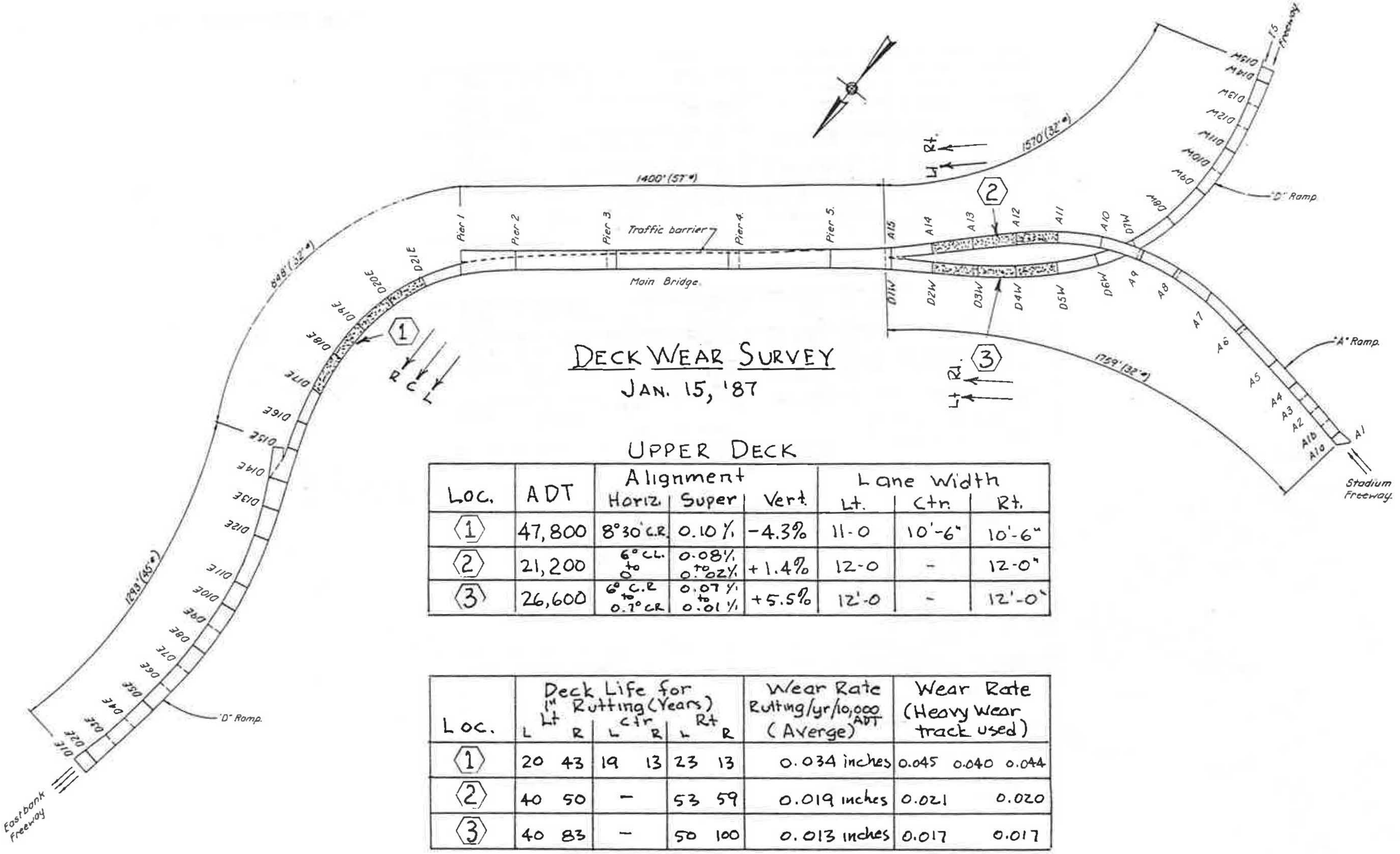


FIGURE 9 Pour record.



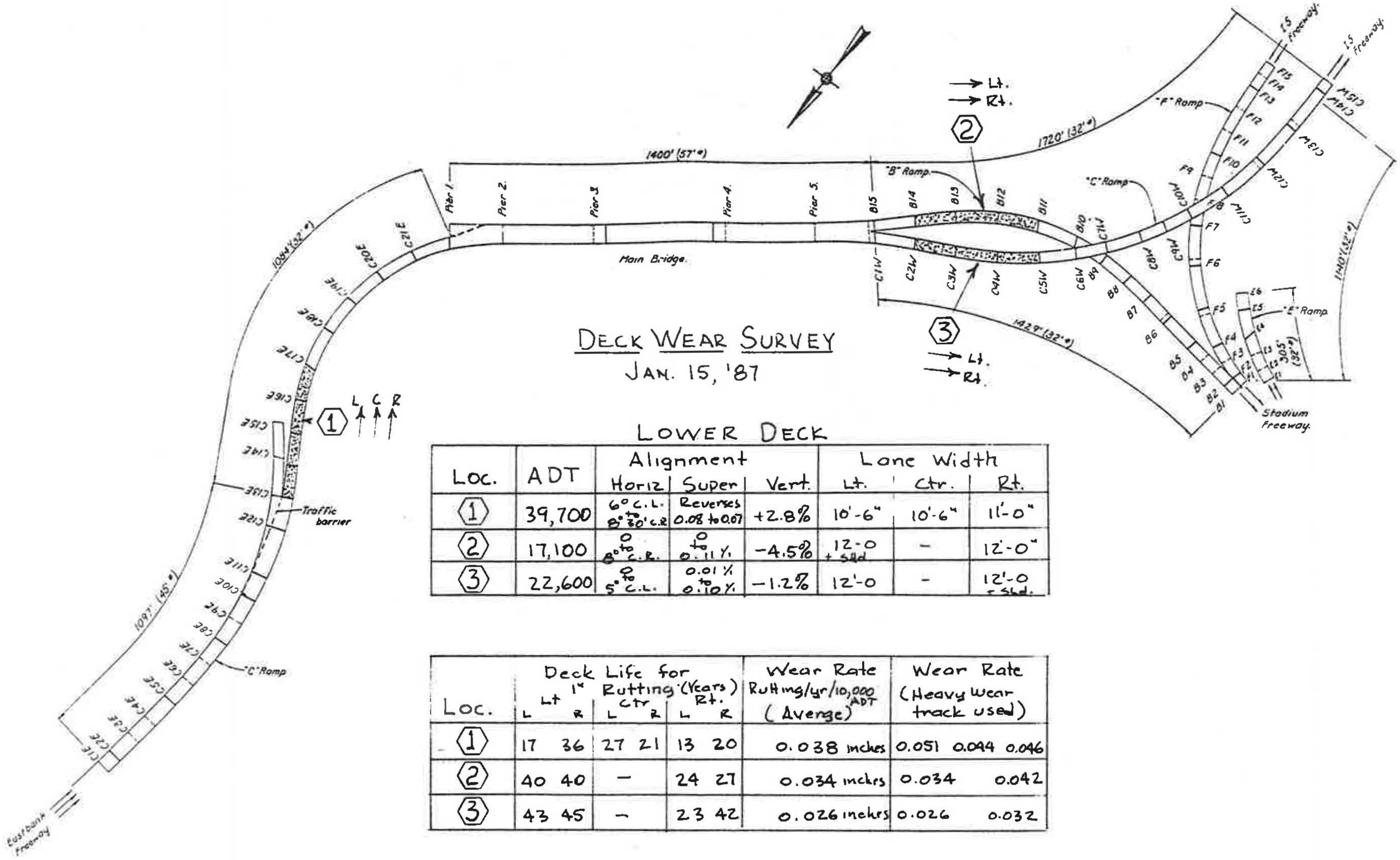
DECK WEAR SURVEY
JAN. 15, '87

UPPER DECK

Loc.	ADT	Alignment			Lane Width		
		Horiz.	Super	Vert.	Lt.	Ctr.	Rt.
⟨1⟩	47,800	8°30' C.R.	0.10 %	−4.3%	11-0	10'-6"	10'-6"
⟨2⟩	21,200	6° C.L. to 0°	0.08% to 0.02%	+1.4%	12-0	-	12-0"
⟨3⟩	26,600	6° C.R to 0.7° CR	0.07 % to 0.01 %	+5.5%	12'-0	-	12'-0"

Loc.	Deck Life for 1" Rutting (Years)						Wear Rate Rutting/yr/10,000 ADT (Averge)	Wear Rate (Heavy Wear track used)		
	Lt		Ctr		Rt					
	L	R	L	R	L	R				
⟨1⟩	20	43	19	13	23	13	0.034 inches	0.045	0.040	0.044
⟨2⟩	40	50	–		53	59	0.019 inches	0.021		0.020
⟨3⟩	40	83	–		50	100	0.013 inches	0.017		0.017

FIGURE 10 Deck wear survey—upper deck.



DECK WEAR SURVEY
JAN. 15, '87

LOWER DECK

Loc.	ADT	Alignment			Lane Width		
		Horiz	Super	Vert.	Lt.	Ctr.	Rt.
⟨1⟩	39,700	6° C.L. to 8° 30' C.R	Reverses 0.08 to 0.07	+2.8%	10'-6"	10'-6"	11'-0"
⟨2⟩	17,100	0° to 8° C.R.	0 to 0.11%	−4.5%	12-0 + Shld	–	12'-0"
⟨3⟩	22,600	0° to 5° C.L.	0.01% to 0.10%	−1.2%	12'-0	–	12'-0 + Shd.

Loc.	Deck Life for 1st Rutting (Years)						Wear Rate Rutting/yr/10,000 ADT (Average)	Wear Rate (Heavy Wear track used)
	Lt L	Lt R	Ctr L	Ctr R	Rt. L	Rt. R		
⟨1⟩	17	36	27	21	13	20	0.038 inches	0.051 0.044 0.046
⟨2⟩	40	40	–		24	27	0.034 inches	0.034 0.042
⟨3⟩	43	45	–		23	42	0.026 inches	0.026 0.032

FIGURE 11 Deck wear survey—lower deck.

ramp, varied in width from 28 ft to 32 ft. It is one of the better riding segments of concrete deck.

Some bond failures occurred at the center line bulkhead after the first half was poured. The cause was not determined, but the failures could have been due to deflections in the deck caused by traffic running next to the pour. To find the bad areas, the edge was sounded with a hammer. The hollow sounding areas were marked, then saw cut, removed, and repoured with the adjoining pour. Seldom did they extend more than 1 ft from the bulkhead into the first pour.

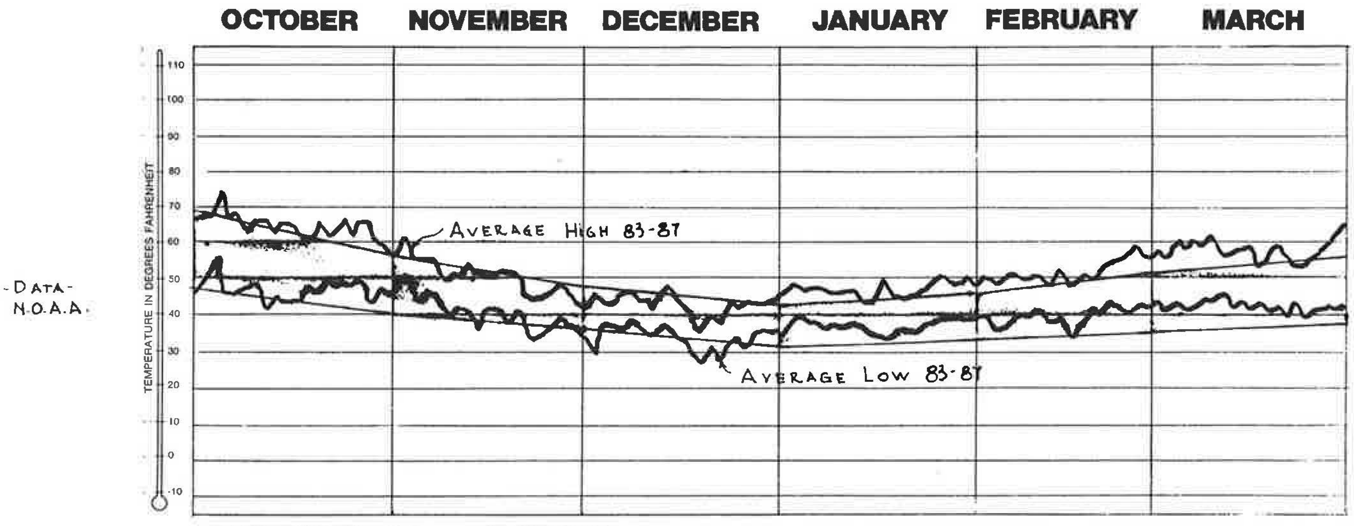
The riding quality of the completed overlay is acceptable but not good. Some shifting in the steep grade areas occurred, and hand-finishing of the deck and construction joints contributed to the surface irregularities. Eleven days with a large deck grinder were needed to bring the surface into the 0.125-in. in 10-ft tolerance.

Figure 9 shows the pour rate per shift for the 59 pours required to do the job. The 1,088 yd² average translated to 612 linear feet, 16 ft wide. It might be noted that of 20 workdays in July, pours were made 11 nights; of 23 workdays in August, pours were made 19 nights, and of 21 workdays in September, pours were made 18 nights. Continuous production requires close coordination of all phases. Shot blasting cannot be done in wet weather, and weather caused some delay in July. The method of deck preparation was never far in advance of the pouring and, in some instances, limited the pour size. The average production rate is the direct result of being able to pour from only one truck on most pours. Pour 56 with the 2,000-yd² rate used two trucks. The year before the Marquam job, this office worked on the overlay of the I-205 Columbia River Bridge. This project was almost twice the area, two trucks placed at the same time on all pours, and the average pour rate was 2,400 yd²/shift.

Costs

There were five bidders on this project. The low bid was approximately $5,000 less than the second and $831,000 less than the high bid. The following are the major items, some of which are combined. These are the final costs and 1983 prices.

	Unit Cost	*Quantity*	*Total Cost*
1 Mobilization			$ 221,000
2 Traffic items			321,943
3 Deck preparation	$ 4.00/yd²	63,389	253,556
4 Latex mod. Overlay	15.09/yd²	63,389	956,712
5 Finger-plate joints	60.00/lin ft	403.5	24,210
6 Paving dam w/comp. seal	85.17/lin ft	3,178	270,658
7 Epoxy grout joint	56.01/lin ft	3,178	178,179
8 Replace joint angles	180.42/lin ft	406	73,250
TOTAL			$2,299,508



DAYS HIGHS BELOW FREEZING

83-84	0	0	7	0	0	0
84-85	0	0	3	0	0	0
85-86	0	7	1	0	0	0
86-87	0	0	0	0	0	0

DAYS LOWS BELOW FREEZING

83-84	0	0	13	9	1	0
84-85	0	1	8	19	11	1
85-86	2	16	25	0	6	0
86-87	0	0	4	9	0	0

FIGURE 12 Climatological data—deck wear period.

PERFORMANCE

In January of 1987, after about 3 yr of service, the areas shown in Figures 10 and 11 were straightedged and the depth of the wheel ruts measured. Of interest was the expected life of the overlay and a comparison of the wear rate on the narrow three lane section of the east ramps to the west ramps. At the same time, after about 4 yr of service, a similar survey was made on the I-205 Columbia River Bridge.

Figure 12 shows the average high and low air temperatures for the winter months during the survey period. Also given are the number of days the temperature was below freezing for the full day and for part of a day. It is general practice to sand icy surfaces, and the abrasive effect of this material plus the use of studded tires or tire chains can significantly affect the amount of wear. It can be noted that, with the exception of portions of November and December, the average highs and lows are above the mean temperature range, and there were a total of only 18 days when temperatures remained below freezing. From this we would have to assume the wear measured is somewhat less than might normally be expected.

The traffic count, alignment, and lane width, which could be possible factors in the wear, are shown in Figures 10 and 11. At about 20-ft intervals, the depth of the wheel tracks was measured, averaged, and prorated to give the years for a 1-in. rut shown in the lower block. Of significance is the much heavier wear found at several locations in the outside wheel track. As expected, the narrow lanes on the east ramps show the shortest life. By comparison, the original deck after 17 yr had an estimated 1-in. wear in this area. During the 17 yr, the layout was changed from the two-lane design to the narrow three lanes, which shifted the wear pattern and extended the life of the deck. With this in mind, in our opinion the minimum 13 yr shown makes the latex overlay equal or possibly superior to the original deck.

To compare the east and west ramps, the wear rates given in Figures 10 and 11 need to be considered. Also, as a further reference the survey from the I-205 Columbia River Bridge is useful. This structure is on a 3-percent grade with light horizontal curvatures (1° maximum) and shows a relatively even wear pattern. The wear rate at this location is approximately 0.031 in. rutting per yr per 10,000 ADT, and in our opinion might be considered a normal rate. The west ramps of the upper deck (Figure 10, locations 2 and 3) give a rate of about half of this figure. Both of these areas are subject to lane changing, so have less well-defined wheel tracks and were probably a poor choice for the survey. The west ramps on the lower deck (Figure 11, locations 2 and 3) have rates close to the norm. The east ramps, when all the measurements are averaged, also give a rate close to 0.031 in. However, because of the uneven wear pattern, this would not be a valid rate on which to predict life expectancy. Using measurements from the heavy wear tracks, the second rate shown on the two figures was determined. This indicates the rate for the narrow east lanes is approximately 50 percent higher.

Publication of this paper sponsored by Committee on Mechanical Properties of Concrete.

Latex Hydraulic Cement Additives

D. GERRY WALTERS

This paper describes latexes used to modify hydraulic cement mixes. It includes definitions and brief descriptions of the history, chemistry, types, and production of latexes, together with an explanation of how latex modifies hydraulic cement, and discusses the problems and advantages associated with such systems.

What is a latex?

As reported in the literature (*1*), an accepted definition is a dispersion of organic polymer particles in water.

But this really doesn't tell you very much. What does it look like? What is an organic polymer? Most latexes or latices are milky fluids that are generally white to off-white in color. Their consistency can vary from very fluid to very viscous.

What is meant by an organic polymer?

This can be defined as a substance that is composed of giant molecules and that has been formed by the union of a considerable number of simple molecules, usually many tens of thousands.

The simple molecules are known as monomers and the reaction that combines them is called polymerization. The polymer may be a homopolymer if it is made by the polymerization of one monomer, or a copolymer when two or more monomers are polymerized.

The first reference to latex was in the early 16th century when the Spanish explorers reported that the South American Indians were making rubber footwear by standing in latex that was obtained from trees. That tree, known as *Hevea brasilienis*, produces latex naturally, which, of course, is known as natural rubber latex (NRL).

Seedlings of those trees were transferred from South America to Europe; and from Europe, a few were taken to Malaya in the Far East. From those few seedlings, huge plantations and a large industry have grown. The latex, obtained from the tree by a process known as tapping, may be concentrated to be sold as latex or coagulated and dried to be sold as rubber. Production of natural rubber latex in Malaya for 1984 exceeded 200,000 metric tons.

Natural rubber latex is a dispersion of polyisoprene (a homopolymer) that is polymerized and formed into a latex by the tree. Incidentally, NRL has been, and in some places continues to be, used in conjunction with hydraulic cements. In 1924, a patent was granted to Lefebure for the combined use of NRL and cement (*2*).

Until early in the 20th century, the only available latex was natural rubber latex; then synthetic latexes started to appear on the scene.

Since World War II, there has been a tremendous increase in the number and type of synthetic polymer latexes that have been made and are commercially available.

The following is a list of the majority of latex types used with hydraulic cements today:

- Styrene-butadiene copolymers (S-B)
- Polyacrylic esters (PAE)
- Styrene-acrylic copolymers (S-A)
- Vinyl acetate homopolymers (PVA)
- Vinyl acetate–ethylene copolymers (VAE)
- Vinyl acetate–acrylic copolymers (VAC)
- Vinyl acetate–vinyl ester of versatic acid copolymers (VA-VEOVA)

This list is not all inclusive. Many other types of latexes are made, probably have been tested, and possibly are being used with hydraulic cements. Some of the latexes listed above are used with hydraulic cements other than portland; and in some cases, the mixes do not contain any aggregate. For this reason, they are referred to as additives rather than the more usual term, admixtures.

All of the latexes listed above are manufactured by a process known as emulsion polymerization and therefore are sometimes referred to as emulsions.

The basic process involves mixing the monomer(s) with water, a stabilizer, and an initiator. The initiator generates a free radical that causes the monomer(s) to polymerize by chain addition.

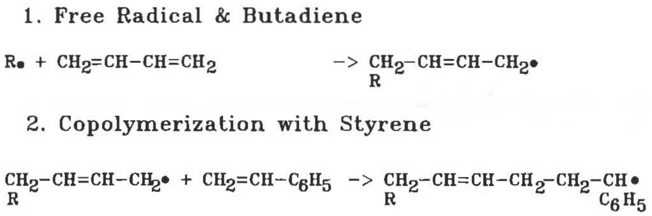
An example of chain addition polymerization is given in Figure 1. The free radical reacts with a molecule of butadiene (or styrene), and the resultant molecule further reacts with a molecule of styrene (or butadiene). This chain of molecules continues to grow until the free radical either no longer contacts a suitable molecule or contacts a chemical that "absorbs" it.

A typical recipe for emulsion polymerization is given in Figure 2. The usual method of polymerization is to charge the water, the stabilizers, the other ingredients, and part of the monomer(s) to the reactor under agitation. The temperature is increased to a desired point, then the initiator system is fed to the reactor followed by the remainder of the monomer(s). By temperature control and possibly other chemical additions, the reaction is normally taken to a 90 to 99 percent conversion. Excess monomer(s) are reduced to acceptable levels by a process known as stripping.

The resultant latex may be concentrated or diluted, and small levels of materials such as preservatives and stabilizers may be added. Many other ingredients are used in polymerization; they are incorporated for a myriad of reasons, such as controlling pH, particle size, and molecular weight.

Many, many latexes are on the market, but about 95 percent of them are not suitable for use with hydraulic cements.

Emulsion Polymers Division, Reichhold Chemicals, Inc., Dover, Del. 19901.



1. Free Radical & Butadiene

$$\mathrm{R\cdot + CH_2{=}CH{-}CH{=}CH_2 \rightarrow \underset{R}{CH_2}{-}CH{=}CH{-}CH_2\cdot}$$

2. Copolymerization with Styrene

$$\mathrm{\underset{R}{CH_2}{-}CH{=}CH{-}CH_2\cdot + CH_2{=}CH{-}C_6H_5 \rightarrow \underset{R}{CH_2}{-}CH{=}CH{-}CH_2{-}CH_2{-}\underset{C_6H_5}{CH\cdot}}$$

FIGURE 1 Free radical polymerization of butadiene and styrene (*1*).

Latexes can be divided into three classes according to the type of electrical charge on the particle, which is determined by the type of stabilizers: cationic (positively charged), anionic (negatively charged), and nonionic (no charge). In general, cationic or anionic latexes are not suitable for use with hydraulic cements because they lack the necessary stability. Most latexes used with portland cement are stabilized primarily with nonionic stabilizers. Typical recipes for some of the latexes used with portland cement are given in Figures 3, 4, and 5.

The preservatives added to the latex after polymerization usually provide protection against bacteria contamination and give improved aging resistance. Sometimes additional stabilizers are added to provide more stability. Also, defoam or antifoam agents may be added to reduce air entrainment when the latex is mixed with the cement and aggregates.

PRINCIPLE OF LATEX MODIFICATION

Classical theories on the principle of latex modification of hydraulic cement concrete and mortars have appeared in the literature (*3*, *4*). Latex modification is governed by two processes: cement hydration and latex film formation. Generally the cement hydration process precedes the film formation (*5*), except at surfaces where loss of water by evaporation causes the latex film to form faster than the cement hydrates. It is believed that a co-matrix phase, which consists of the cement gel and latex polymer, is formed as the binder for the mix.

The process of forming the polymer film from the latex is usually referred to as coalescence.

When latex is mixed with fresh cement mortar or concrete, the organic polymer particles are uniformly dispersed in the cement paste. In such latex-cement paste, the cement gel is gradually formed by cement hydration. With water loss due to the development of the cement gel structure and to evaporation, the polymer particles of the latex are gradually confined in the capillary pores.

As cement hydration and evaporation loss continue, the capillary water is reduced and the polymer particles flocculate to form a continuous close-packed layer on the surfaces of the cement gel–unhydrated cement particle mixtures. These layers simultaneously adhere to the mixtures and the silicate layer of the aggregate surfaces. One should bear in mind that the size of the pores in the cement paste ranges from a few angstroms to several thousand angstroms; whereas the particle size of latexes typically used with cement ranges from 500 to 5,000 angstroms (*6*). Ultimately, with water loss by cement hydration and evaporation, the close-packed polymer particles on the cement hydrates coalesce into continuous films or membranes.

	Parts by Weight
Monomers	100.0
Stabilizer	1.0 – 10.0
Initiator	0.1 – 2.0
Water	80.0 –150.0
Other Ingredients	0.0 – 10.0

FIGURE 2 Typical recipe for emulsion polymerization (*1*).

	Parts by Weight
Vinyl acetate	100.0
Partially hydrolyzed polyvinyl alcohol	6.0
Sodium bicarbonate	0.3
Hydrogen peroxide 35%	0.7
Sodium formaldehyde sulfoxylate	0.5
Water	80.0

FIGURE 3 Vinyl acetate homopolymer latex (*1*).

These films or membranes bind the cement hydrates together, resulting in a monolithic network in which polymer films interpenetrate the cement-hydrate phase. Such a structure acts as the co-matrix phase for latex-modified mortar and concrete, with the aggregates being bound by such a matrix.

It is generally considered that unmodified hardened cement paste is predominantly an agglomerated structure of calcium silicate hydrates and calcium hydroxide bound together by relatively weak van der Waal's forces. Consequently, microcracks occur easily in such a paste under stress, leading to the low tensile strength and fracture toughness of ordinary cement mortar and concrete.

By contrast,in latex-modified mortar and concrete, it appears that the microcracks are bridged by the polymer films or membranes which greatly reduce crack propagation and simultaneously give a strong cement hydrate-aggregate bond. This effect increases with increasing latex content and leads to increased tensile strength and fracture toughness.

The sealing effect due to the films or membranes formed in the structure also provide a considerable increase in water-

	Parts by Weight
Ethyl acrylate	98.0
A vinyl carboxylic acid	2.0
Nonionic surfactant	6.0*
Anionic surfactant	0.3**
Sodium formaldehyde sulfoxylate	0.1
Caustic soda	0.2
Peroxide	0.1
Water	100.0

*The nonionic surfactants may be nonyl phenols reacted with 20–40 molecules of ethylene oxide.

**The low levels of anionic surfactant are used to control the rate of polymerization.

FIGURE 4 Polyacrylic latex (*1*).

	Parts by Weight
Styrene	64.0
Butadiene	35.0
A vinyl carboxylic acid	1.0
Nonionic surfactant	7.0*
Anionic surfactant	0.1**
Ammonium persulfate	0.2
Water	105.0

*The nonionic surfactants may be nonyl phenols reacted with 20–40 molecules of ethylene oxide.

**The low levels of anionic surfactant are used to control the rate of polymerization.

FIGURE 5 **Styrene-butadiene copolymer latex (*1*).**

proofness or watertightness, resistance to moisture transmission, resistance to vapor penetration, chemical resistance, and freeze-thaw resistance. Such effects are promoted with increasing latex content. Excess latex and/or air entrainment causes discontinuities in the formed monolithic network structure, resulting in a reduction of such characteristics. In most latex-modified portland cement aggregate mixtures, the optimum level is between 10 and 20 percent of dry polymer on the cement (*7*).

Some latexes used with hydraulic cement mixes contain reactive groups. It is probable that some chemical reactions may take place between these groups and metallic ions and salts in the surfaces of the cement gel and the aggregates. Such reactions are expected to improve the bond between the cement hydrates and aggregates with subsequent improvements in the properties of the hardened latex-modified mortars and concretes.

Wagner studied the influence of latex modification on the rate of specific area development of latex-modified pastes (*5*). According to his results, the initial rate of cement hydration can be accelerated or retarded by the addition of the latexes, depending on their chemical nature. However, the specific surface area of all the pastes after a 28-day cure is comparable, indicating that while latex modification may have some effect on the initial hydration process, it has little effect on the final hydration of the cement.

According to Ohama and Shiroishida (*8*) or Kasia et al. (*9*), the porosity or pore volume of the latex-modified mortars differs from unmodified mortar in that the former has a lower number of pores in the larger radius of 0.2 microns or more, but significantly more in the smaller radius of 750 angstroms or less. Also the total porosity or pore volume tends to decrease with increasing polymer-cement ratios. This can be found to contribute to improvements in the impermeability to liquids, resistance to carbonation, and freeze-thaw durability.

PROBLEMS WITH LATEX-MODIFIED CONCRETES AND MORTARS

Which Latex?

One of the major problems associated with latex-modified concretes and mortars is that most users do not have an adequate understanding of latex. A latex is a latex, right? WRONG!

Each type of polymer latex can and usually does impart different properties to hydraulic cement mixtures. Also, it must be realized that within each type of latex, particularly copolymers, there can be many variations which can and do give different properties. If there is a doubt, the latex supplier should be contacted. There have been jobs where the wrong latex was used, resulting in disastrous consequences. For example, a vinyl acetate homopolymer was used in mortar to hold air conditioning units in the walls of a high-rise apartment. The moisture condensation caused by the air conditioners was sufficient, with the high pH of the portland cement mortar, to hydrolize the homopolymer, causing the air conditioners to fall out.

Cost

Using latex in hydraulic cement mixes generally increases the cost of raw materials by at least a factor of two. A comparsion of an unmodified and an S-B latex-modified portland cement concretes is given in Figure 6.

Mud-Cracking

If a latex-modified mix is being placed when the ambient conditions are such that the surface of the mix is exposed to

UNMODIFIED CONCRETE

Ingredient	Weight lb/yd^3	cost $/lb	Extension $/yd^3
Portland Cement, Type I	658	0.0580	38.16
Concrete Sand	1645	0.0048	90
Pea Gravel	1315	0.0078	10.27

Cost per cubic yard = $ 56.33

LATEX–MODIFIED CONCRETE

Ingredient	Weight lb/yd^3	cost $/lb	Extension $/yd^3
Portland Cememt, Type I	658	0.0580	38.16
Concrete Sand	1645	0.0048	7.90
Pea Gravel	1315	0.0078	10.27
Styrene–butadiene latex	207	0.4850	100.40

Cost per cubic yard = $ 156.73

FIGURE 6 **Cost comparison of UMC and LMC.**

good drying conditions, i.e., windy and low humidity, the polymer particles of the latex may coalesce to form a latex skin on the surface of the mix prior to noticeable cement hydration.

When this occurs, the skin or crust may exhibit mud-cracking due to shrinkage of the latex skin before the cement hydration has proceeded enough so that the mix has sufficient strength to withstand the shrinkage forces. Consequently steps must be taken to avoid such an occurrence. With S-B latex-modified concretes used for bridge-deck overlays, these steps usually involve covering the concrete as soon as possible with wet burlap and and plastic sheeting. This process usually costs time and money and, if performed incorrectly, can give the job a very poor appearance.

Mixing Times

All latexes used with hydraulic cements contain relatively high levels of stabilizers or "soaps." As in a washing machine, these soaps, if mixed sufficiently, will incorporate air and form a froth. In hydraulic cement mixes, this process can result in unacceptably high air contents, which, as illustrated in Figure 7 with a PAE-latex-modified mortar, reduces strength properties. Consequently, when latex-modified hydraulic cement concrete or mortar is being prepared, it is essential that the mixing time is kept to a minimum, usually less than 3 min. This requirement eliminates the use of normal ready-mix trucks; and for large jobs, demands the use of the more expensive mobile-mixer.

SO WHY USE LATEX?

As mentioned when explaining how latex modifies hydraulic cement concretes or mortars, the latex and the cement form a co-matrix to bind the aggregates. This co-matrix is superior to unmodified mixes in bridging the microcracks, resulting in increased resistance to movement of fluids within the concrete and in increased strength properties. As the latex-cement co-matrix improves adhesion to the aggregates in the mix, it also improves adhesion of the mix to most substrates. In fact, when placing latex-modified concrete or mortar (LMC), one should always clean the tools before the mix hardens or they become very difficult to clean.

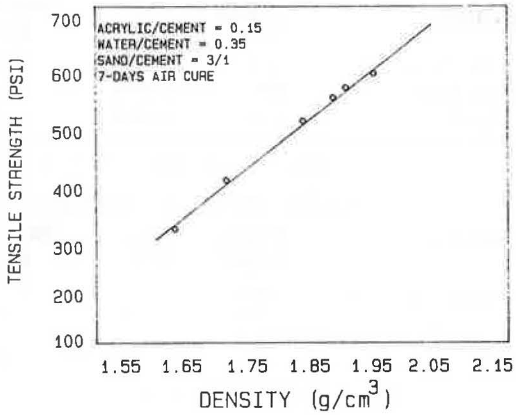


FIGURE 7 Tensile strength vs. density (*16*).

	UMC	SB-LMC	
FHWA 90 ponding test (10)			
0.75 inch depth, lb chloride	10.53	1.37	(10)
0.75 inch depth, lb chloride	7.70	1.08	(11)
AASTHO T277-831, Rapid Determination (12)			
Coulombs	2560	876	

FIGURE 8 Resistance to penetration of chlorides

The only two economical reasons for using latex modification are to increase adhesion or to improve resistance to movement of fluids through the hardened cement mix. Improvements in some strength properties are also obtained, but there are usually cheaper ways to obtain similar improvements if this is all that is required. Incorporation of latex does not improve compressive strength; in fact, usually a decrease is observed.

Resistance to Penetration of Fluids

Resistance to movement of fluids through the concrete provides protection to the concrete. Work by the Federal Highway Adminstration (*10*), the Department of Transportation of Louisiana (*11*), and the Portland Cement Association (*12*) showed improvements in freeze-thaw and scaling resistance and improvements in resistance to penetration of water-soluble salts of S-B latex-modified concretes in comparison with similar unmodified mixes (Figures 8 and 9).

Figure 10 illustrates improvement in resistance to penetration of gases, such as carbon dioxide, with both S-B and VAE latex-modfied mortars, confirming work by Ohama (*13*). In this work, concrete or mortar cylinders are exposed to a vacuum and then to carbon dioxide gas under pressure for specific time periods. The cylinders are then split using a splitting tensile device. Immediately, the split surface is painted with a colorless aqueous solution of phenolphthalein. The latter, a pH indicator, indicates where the carbon dioxide gas has not penetrated by changing to a red-purple color.

Improvement in Adhesion

Improvements in adhesion of latex-modified cement mixes over similar unmodified mixes have been shown with different

	UMC	SB-LMC
1. FREEZE-THAW – ASTM C-666 (B)		
Durability factor	14	78
2. SCALING RESISTANCE – ASTM 672		
Cycles	14	52
Durability factor	5	1

FIGURE 9 Resistance to freeze-thaw and scaling (*11*).

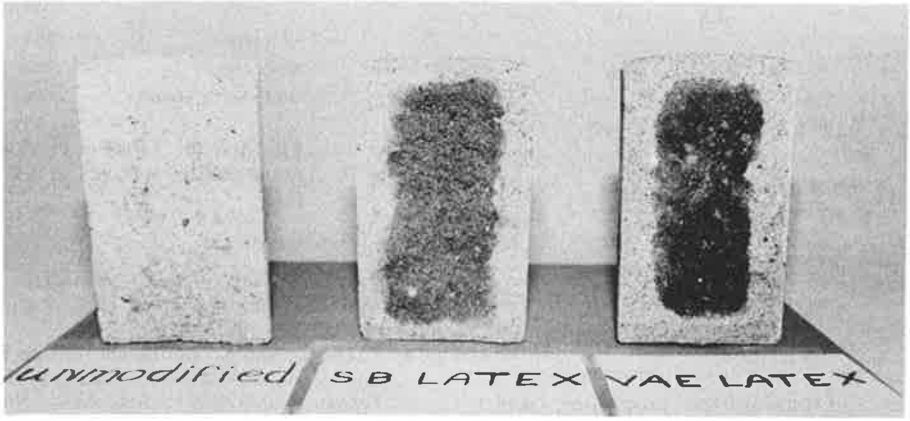


FIGURE 10 Comparison of UMC and LMC for carbonation resistance.

latexes (*14–16*) and are illustrated in Figures 11 and 12 with S-B and PAE latex-modified mixes.

Improvements in Strength

Figure 13 shows that flexural strengths and splitting tensile values of S-B latex-modified concrete are significantly higher than for similar unmodified mixes (*11*). Improvements in abrasion resistance caused by latex modification of cement mixes has been shown by both Ohama (*17*) and Alexanderson (*18*). The latter's work, with styrene-butadiene latex-modified mixes, is shown in Figure 14. It should be noted that measurably lower values of these strength properties are obtained if the latex-modified concrete or mortar is tested in the wet state.

A Forgiving System

Although latex-modified mixes have some unique characteristics that require special handling when being placed, basically the same techniques and practices are used as with unmodified cement mixes. Also, LMC is a very forgiving system. Because the latex-cement co-matrix significantly reduces the movement of fluids through the concrete, a latex-modified mix does not require curing compounds, fog sprays, or water soaking to ensure adequate water for hydration and strength development of the cement. Once it is strong enough to withstand early shrinkage forces, usually 24 hr or less, the concrete will retain sufficient water to ensure adequate hydration of the cement. Comparsion of strength attributes of unmodified and PAE latex-modified mortars, cured wet and dry respectively, confirms this postulation (*16*).

Although latex-modified concretes and mortars can have high air contents, work by Kuhlmann and Foor (*19*) has shown that high air contents have little effect on permeability of S-B latex-modified mixes, as measured by the rapid method AASHTO T277-83l. Figure 15, which gives confirmation, shows data obtained from an S-B LMC overlay in a parking garage in Madison, Wisconsin, placed in June 1986. The permeabilities were determined on cores taken in May 1987.

Figure 16, which shows data obtained by Kuhlmann (*15*), illustrates that the mud-cracking tendencies of S-B LMC have no apparent effect on permeability resistance.

CURE days	UMC psi	SB–LMC psi
3	161	262
7	181	278
14	215	327
28	243	334
90	256	365

FIGURE 11 Tension bond (*15*).

PAE–CEMENT Ratio	Cure	Shear Bond psi	Adhesion Mode
0.00	dry	45	Adhesive
0.00	wet	185	Adhesive
0.10	dry	500	Cohesive
0.15	dry	650	Cohesive
0.20	dry	550	Cohesive

FIGURE 12 Shear bond adhesion (*16*).

	UMC	SB –LMC
Flexural Strength, ASTM C 78,psi	441	538
Splitting Tensile, ASTM C 496,psi	639	1061

FIGURE 13 Strength properties (*11*).

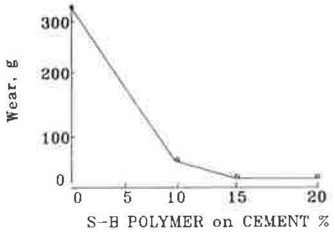


FIGURE 14 Abrasion resistance (*18*).

	A	B
Air content, %	7.3	>10.0
Compressive strength 28 days, psi	5360	3520
Permeability resistance, 11 months, coulombs	515	415

FIGURE 15 Effect of air content on permeability resistance of S-B LMC.

	Permeability Resistance coulombs
No cracks	260
Mud-cracks	260
Half-depth cracks	700

FIGURE 16 Effect of cracking on permeability resistance of S-B LMC (*15*).

SUMMARY

In summary, the use of latex with hydraulic cements results in a co-matrix that gives improvements in adhesion, resistance to transmission of fluids, and some strength properties. Generally this use is justified economically only to improve adhesion and/or water resistance of the system. The type of latex must be carefully selected to ensure its suitability for use with hydraulic cements and for the intended application. Although latex-modified mixes require short mixing times and often require steps to avoid mud-cracking, the system uses normal hydraulic cement techniques except that normal curing is not required.

ACKNOWLEDGMENTS

Acknowledgement is given to all at Reichhold Chemicals, Inc., who willingly supplied material, information, and advice, particularly Peter Callaway, Ed Jusko, Linda Riley, Patricia Ruszkay, and Emil Sammak.

REFERENCES

1. D. G. Walters. What are Latexes? *Concrete International*, Vol. 9, No. 97, Dec. 1987, pp. 44–47.
2. V. Lefebure. *Improvement in or Relating to Concrete, Cements, Plaster, and the Like*. British Patent 217, 279, June 5, 1924.
3. J. E. Isenburg and J. W. Vanderhoff. Hypothesis for Reinforcement of Portland Cement by Polymer Latex. *Journal of the American Ceramic Society*, Vol. 57, No.6, June 1974, pp. 242–245.
4. Y. Ohama. Principle of Latex Modification & Some Typical Properties of Latex-Modified Mortars and Concrete. Presented at ACI Fall Convention, Baltimore, Md., Nov. 1986.
5. H. B. Wagner. Polymer-Modified Hydraulic Cement. *Industrial and Engineering Chemistry, Product Research and Development*, Vol. 4, No. 3, 1965, pp. 191–196.
6. V. R. Riley and I. Razl. Polymer Additives for Cement Composites: A Review. *Composites*, Vol. 5, No. 1, 1974, pp. 27–33.
7. Y. Ohama. Polymer-Modified Mortars and Concretes. In *Concrete Admixture Handbook* (V.S. Ramachandran, ed.), Noyes Publications, 1984.
8. Y. Ohama and K. Shiroishida. Freeze-Thaw Durability of Polymer-Modified Mortars (in Japanese). *Nihon-Kenchiku-Gakkai Tohoku-shibu Kenkoyo-Hoko-kusku*, No. 41, 1983, pp. 163–168.
9. Y. Kasai, I. Matsui, and Y. Fukushima, Physical Properties of Polymer-Modified Mortars. *Proc., Third International Congress on Polymers in Concrete*, Vol. 1, Japan, 1982, pp. 172–192.
10. K. C. Clear and B. H. Chollar. *Styrene-Butadiene Latex Modifiers for Bridge Deck Overlay Concrete*. Report FHWA–RD–78–35, PB 82140724. FHWA, U.S. Department of Transportation, April 1978.
11. S. M. Law and M. Rasoulian. *Polymer Modified Concrete Study*. Report FHWA/LA–80/139, PB 81102212. FHWA, U.S. Department of Transportation, April 1980.
12. D. Whiting. *Rapid Determination of the Chloride Permeability of Concrete*. Report FHWA/RD–81/119, PB 82140724. FHWA, U.S. Department of Transportation, August 1981.
13. Y. Ohama, T. Moriwaki, and K. Notoya. Accelerated Carbonation of Polymer-Modified Mortars by Carbon Dioxide Pressurizing Method. *CAJ Review*, 1984, pp. 288–291.
14. *A Handbook on Portland Cement Concrete & Mortar Containing Styrene-Butadiene Latex*. Dow Chemical U.S.A., 1985.
15. L. A. Kuhlmann. Performance of the Latex Modified Concrete Overlay. The Institute for Bridge Integrity and Safety, Seminar on Bridge Rehab and Modern Materials, New York, May 28 1987.
16. J. A. Lavelle. Acrylic Latex Modified Portland Cement. ACI Fall Convention, Baltimore, Md., Nov. 11 1986.
17. Y. Ohama, K. Shiroishida, and T. Moriwaki. Abrasion Resistance of Polymer-Modified Mortars. *Journal of the College of Engineering*, Nihon University, Series A, Vol. 25, Japan, 1984.
18. J. Alexanderson. Polymer Cement Concrete for Industrial Floors. *Proc., Third International Congress on Polymers in Concrete*, Vol. 1, Japan, May 1981.
19. L. A. Kuhlmann and N. C. Foor. Chloride Permeability Versus Air Content of Latex Modified Concrete. *Cement, Concrete, and Aggregates*, Vol. 6, No. 1, summer 1984, pp. 11–16.

Publication of this paper sponsored by Committee on Mechanical Properties of Concrete.

Efficient Test Setup for Determining the Water-Permeability of Concrete

PRASIT SOONGSWANG, MANG TIA, DAVID G. BLOOMQUIST, CONSTANTINOS MELETIOU, AND LARRY M. SESSIONS

The permeability of concrete is one of the most important factors influencing the durability of a concrete structure, and is a property of great interest to designers of concrete structures. However, very little data on this property of concrete exist, and there is not any widely used standard procedure for determining the permeability of concrete. The major problems generally encountered in performing a water-permeability test on concrete include (a) the great amount of time required for each test; (b) the possible leakage of water through the sides of the test specimens; and (c) the extremely low water flow rate, which makes an accurate measurement difficult to obtain. This paper presents a test setup and procedure that have been developed through experimentation and that have proven effective in dealing with the above-listed problems. The developed test setup can test 20 concrete specimens simultaneously by using 20 permeability apparatuses, which are connected to the same regulated compressed air source. The concrete specimens can be placed into and removed from the permeability apparatuses with a minimal loss of time and with no disturbance to the other test specimens. The problem of the effects of water evaporation on the measured flow rate has also been effectively dealt with. Another major advantage of this test setup is that it can be duplicated easily and economically. This paper also presents the results of permeability tests on three different Florida concretes subjected to four different curing conditions. The test setup has been demonstrated to be both reliable and efficient for determining permeability on a large number of concrete specimens.

The permeability of concrete plays a very important role in influencing the durability of a concrete structure. First, it controls the rate of flow of water, which can cause disruption to the concrete upon freezing. Second, it controls the rate of flow of chemicals, such as chloride ions, which can reduce the pH of the concrete and increase the rate of corrosion of the steel rebars in the concrete structure. The work presented in this paper deals with the development of an efficient laboratory test setup for measuring the permeability of concrete and is part of an ongoing research project on the study of factors affecting the durability of concrete.

The permeability of concrete to water is a property of interest to nearly all designers of concrete structures (*1*). Very little test data are available on the permeability of concrete at present, especially for Florida concrete. Although a widely used standard procedure for determining the permeability of concrete does not exist (*2*), quite a few different methods for measuring permeability have been used in the past. Researchers who have studied the permeability of concrete include McMillan and Lyse (*3*), Norton and Pletta of Wisconsin (*4*), Ruettgers, Vidal, and Wing (*5*), Tyler and Erlin (*1*), and Meulen and Dijk (*6*). The various apparatuses used by these researchers to measure permeability of concrete were similar in that all of them measured the flow rate of water under pressure through the concrete specimens after a steady flow condition had been reached. The sides of the concrete specimens were sealed so that water could flow through the specimens without leakage through the sides. The sealants used included asphalt (*4*, *5*), epoxy (*6*), and paraffin and resin (*3*).

The major problems generally encountered in performing a permeability test on concrete include (a) the great amount of time required for each test, (b) the possible leakage of water through the sides of the specimens, and (c) the extremely low water flow rate that makes an accurate measurement difficult to obtain. This paper presents a test setup and procedure that have been developed through experimentation and that have proven to be effective in dealing with the above-listed problems.

PERMEABILITY APPARATUS

In the development of a suitable permeability apparatus, the following requirements and concerns were considered:

- The apparatus should be easily duplicated.
- The concrete specimens could be inserted and removed with a minimal loss of time.
- Concrete specimens cut from larger-size concrete specimens should be used.
- The small quantity of water flowing through the concrete specimen should be measured accurately.

Through months of experimentation, the permeability apparatus as shown in Figure 1 was developed. It consists of a 1-in.-thick acrylic top plate, a 1-in.-thick acrylic base plate, an acrylic tube (with an inside diameter of 4.5 in., a wall thickness of 0.5 in., and a height of 1 in.), four steel bolts (6.5 in. long and 0.375 in. in diameter) and four matching nuts. The top and bottom of the acrylic tube are provided with neoprene gaskets. One gasket is placed between the bottom of the acrylic tube and the top of the specimen; the other gasket is placed between the top of the acrylic tube and the acrylic top plate. A steel connection tube is inserted through

---

P. Soongswang, M. Tia, D. G. Bloomquist, and C. Meletiou, Department of Civil Engineering, University of Florida, Gainesville, 32611. L. M. Sessions, Bridge Inspection and Evaluation Engineer, Florida Department of Transportation, 605 Suwannee St., Tallahassee, 32301.

the center of the acrylic top plate to provide a connection between the water in the acrylic tube to the pressure source and the manometer tube, which measures the amount of water going into the specimen. A quick connection is installed on the top acrylic plate at 2 in. from the center. It is used for refilling water into the manometer tube.

The 20 permeability apparatuses described above were built and connected to 20 manometer tubes, which were held in a vertical position against two boards. All the manometer tubes were connected to a main pressure line, which runs along the top of the vertical boards. The pressure is held constant by a regulator and is indicated on a pressure gauge, which is attached to one side of the vertical board for ease of reading. Any line can be disconnected from the main pressure line at any time without interfering with the operation of the other lines by turning off the individual valves. A picture of the test setup is shown in Figure 2.

Another regulator and pressure gauge are used to regulate the pressure in the water reservoir. The water reservoir, which is used for refilling water into the manometer tube, consists of an acrylic tube 8 in. in diameter and 14 in. long, top and bottom steel plates, two quick connections (one on each end), eight 0.375-in. × 18-in. threaded rods, and eight matching nuts. The water reservoir used is shown in Figure 3.

PREPARATION OF TEST SPECIMENS

The test specimens, cylindrical specimens 4 in. in diameter and 2 in. high, are made by cutting 8-in.-thick cast cylinders into 2-in.-thick cylinders. A 0.0625–0.125-in.-thick layer is removed by sawing from the bottom surface of the cast specimens. The circumference of the test specimens are wire-brushed until all loose particles have been removed. Care is taken to ensure that the surfaces of the test specimens are dry.

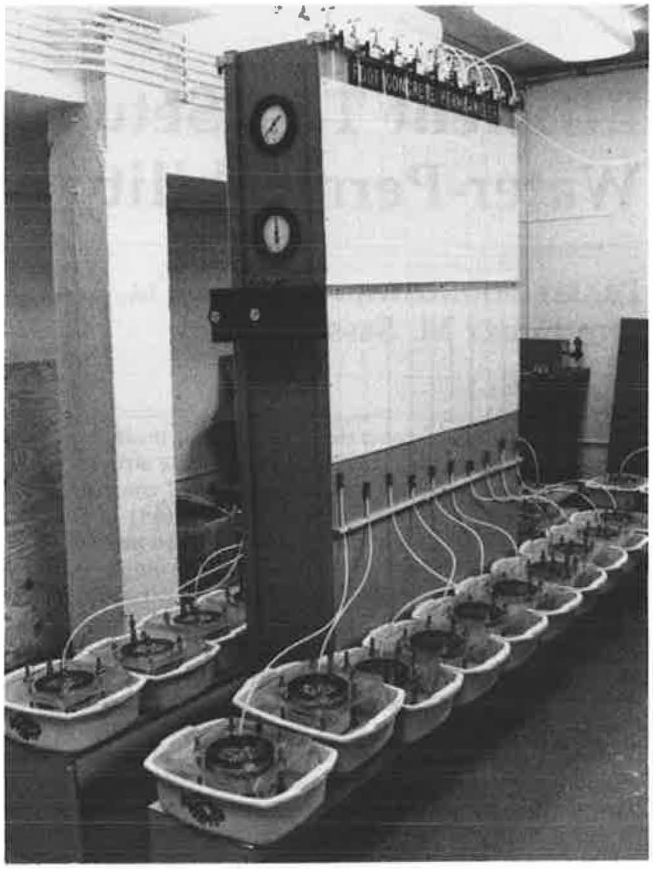


FIGURE 2 Permeability test setup.

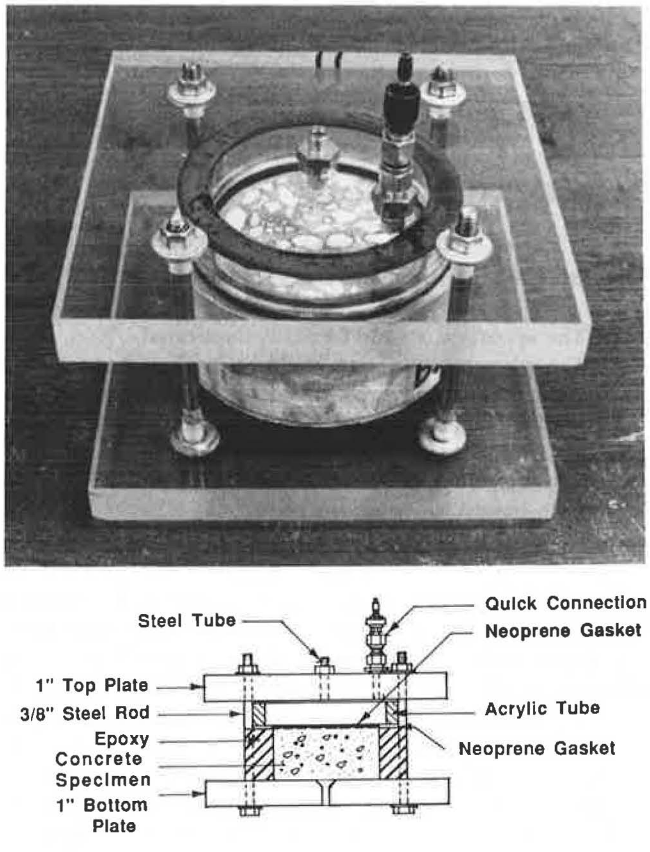


FIGURE 1 Permeability test apparatus.

A 1-in.-thick layer of epoxy (Sikadur 32, Hi-Mod) is cast around the side of the test specimen by means of a casting mold. The casting mold is 6 in. in diameter and 2.25 in. high and is bolted down to a steel plate. The inner surface of the casting mold and the top surface of the steel plate are coated with a very thin layer of release agent. The side of the specimen is first coated with a thin layer of epoxy. The specimen is then placed in the center of the casting mold, and the remaining gap between the casting mold and the test specimen is filled with epoxy. The air bubbles are eliminated from the epoxy by using a small hand vibrator. When the epoxy has hardened, the test specimen is taken out of the casting mold. The small amount of epoxy that may adhere to the top surface of the test specimen is removed. Figure 4 shows a casting mold; a picture of the prepared concrete specimens coated with epoxy on the side is shown in Figure 5.

TESTING PROCEDURE

The prepared test specimen is placed into the permeability apparatus in the following steps:

1. The test specimen is placed on the center of the base plate.
2. A neoprene gasket is placed on the specimen.
3. The acrylic tube is placed on the neoprene gasket.
4. Another neoprene gasket is placed on the acrylic tube.
5. The top plate is placed on the neoprene gasket and bolted to the base plate with four 0.375-in.-diameter rods (Figure 1).

The permeability apparatus is then connected to the manometer tube in the following procedure:

1. The valve for the manometer tube is turned off.
2. The manometer tube is connected to the connection tube at the center of the top plate of the permeability apparatus.
3. Pressure is applied to the main pressure line and maintained at 100 psi by the regulating valve, which controls the pressure from the air compressor.
4. The water reservoir is connected to the other pressure regulator through one of the two quick connections of the water reservoir, and a pressure of 102 psi is maintained.
5. The other quick connection of the water reservoir is connected to the quick connection at the top plate of the permeability apparatus, and water is injected into the permeability apparatus and the manometer tube by opening the manometer valve slowly until the water in manometer tube reaches the top level. The valve is then turned off, and the permeability apparatus is disconnected from the water reservoir.
6. The air bubbles trapped inside the permeability apparatus are released through the quick connection at the top plate.

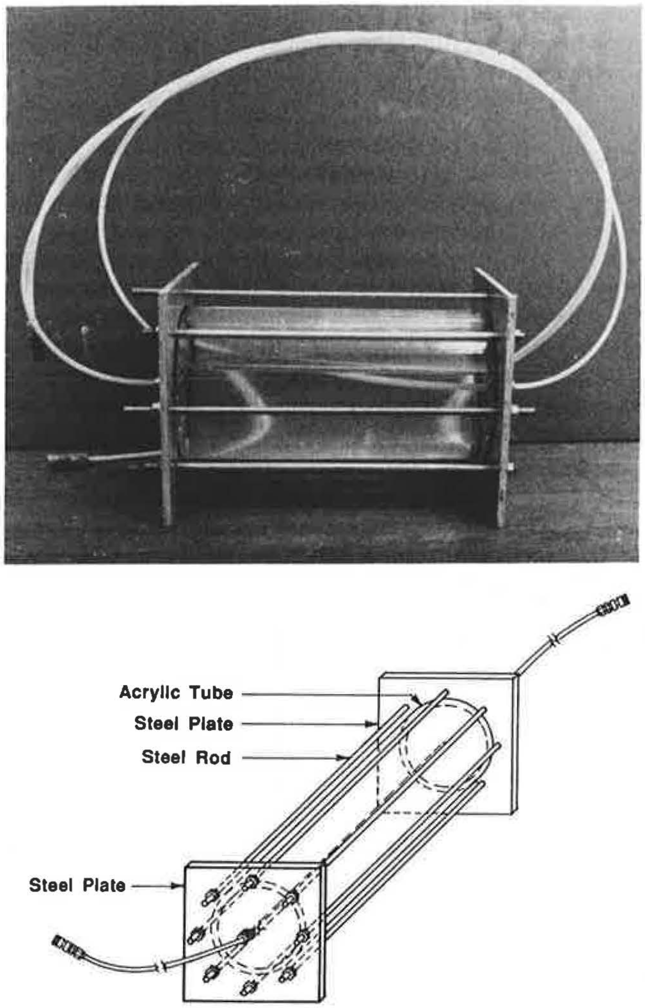


FIGURE 3 Water reservoir.

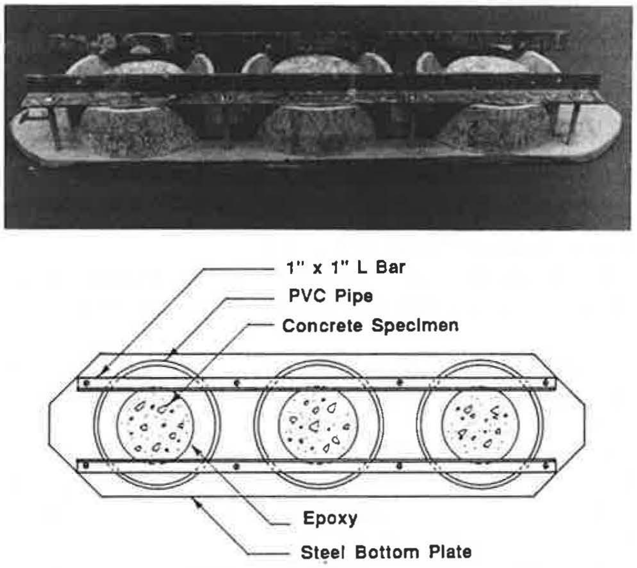


FIGURE 4 Casting molds.

At this stage, the permeability test can be started by simply opening the manometer valve to connect the 100-psi air pressure line to the manometer. The water level in the manometer tube and the time at the start of the test are recorded. Possible leakage of water between the epoxy and the side of the test specimen is to be checked. If leakage occurs, the specimen must be discarded. However, leakage has occurred very infrequently. The test is continued if no leakage is found. When the water level in the manometer tube reaches a low level, additional water can be added to the manometer tube from the water reservoir. The process of refilling the manometer tube is the same as the initial filling as described earlier.

METHOD OF MEASURING RATE OF FLOW

The amount of water flowing into a test specimen is measured by reading the water level of the 0.125-in. manometer tube

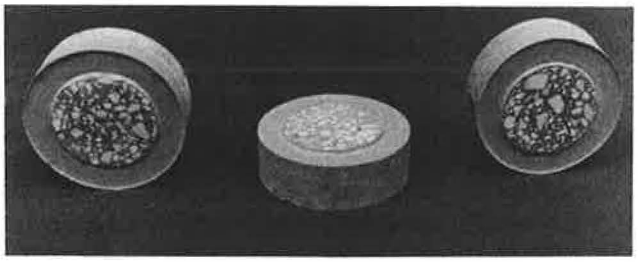


FIGURE 5 Prepared concrete specimens.

at least once a day. A plot of the cumulative amount of water flowing into the test specimen vs. time is drawn for each test specimen to determine when a steady-state flow condition has been reached. The steady-state condition is usually reached within 10–14 days. The test is continued for about 5–7 days beyond the steady-flow condition. The average rate of inflow in the last 5–7 days is used as the rate of inflow for the test specimen. Two typical plots of cumulative amount of water flow vs. time are shown in Figure 6.

The evaporation of water introduces complications to the measurement of water inflow in the following two ways:

- The water in the manometer may evaporate into the compressed air line, resulting in a drop in the manometer water level.
- After water has flowed through the test specimen, the water at the bottom surface of the specimen may evaporate and produce a slight suction which can increase the rate of flow.

The amount of water evaporating into the air line is estimated by using a reference permeameter, which is connected to a manometer tube of the same size and the same main pressure line. The reference permeameter contains no test specimen and has a base plate with no hole, creating a condition of zero flow. The reference permeameter is filled with water and connected to a manometer tube and the main pressure line in a manner similar to that for the other permeameters. The water level in the reference manometer tube is read periodically to estimate the amount of water evaporating into the air line, which is then used to adjust the measured rate of inflow for the other permeameters.

The problem of the effects of evaporation of water from the bottom surface of the test specimen is dealt with by soaking the lower portion of the permeameter in water about 4–5 days after the test is started. The permeameter is not soaked in water immediately after the start of test to allow examination for leakage.

CALCULATION OF COEFFICIENT OF PERMEABILITY

The coefficient of permeability of a test specimen is computed from the net rate of inflow by using the following equation which is based on Darcy's Law:

$$K = \rho \frac{H}{P} \frac{Q}{A} \tag{1}$$

where K = coefficient of permeability in in./sec or cm/sec.
ρ = density of water in lb/in.^{3} or kg/cm^3.
H = length of test specimen in in. or cm.
P = water pressure in psi or kg/cm^2.
Q = net rate of inflow in in.^{3}/sec or cm^3/sec.
A = cross-sectional area of test specimen in in.^{2} or cm^2.

RESULTS OF PERMEABILITY TESTS ON FLORIDA CONCRETES

This section presents the results of permeability tests on three different Florida concretes using the developed test setup and procedure. The three concretes tested were Florida type II, type III, and type IV concretes made with a type II portland cement and Florida aggregates. Table 1 displays the physical properties of the coarse and fine aggregates used. All the concrete mixes had a target slump of 3 in., which was achieved by adding the appropriate amount of a sup[illegible] proportions of ingredients for these three [illegible] the properties of the fresh concrete a[illegible] in Table 2.

Four different curing conditions were used on each of the three concrete mixes: (a) 16-hr steam curing at 160°F, (b) 28-day moist-room curing, (c) 3-day moist-room curing followed by 25-day air curing, and (d) 1-day curing in form followed by stripping and applying curing compound and 27-day curing. Two replicate specimens were tested for each of the combinations of concrete type and curing condition.

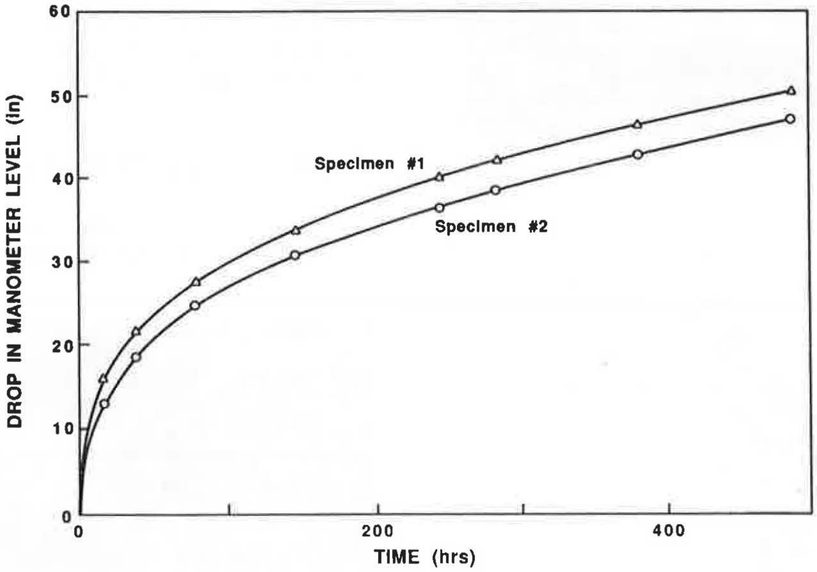


FIGURE 6 Typical plots of manometer readings in permeability tests.

TABLE 1 PHYSICAL PROPERTIES OF AGGREGATE

	Coarse Agg. (Brooksville Limestone)	Fine Agg. (Goldhead Sand)
Dry Bulk Specific Gravity	2.39	2.54
Saturated-Surface-Dry Specific Gravity	2.47	2.55
Absorption	3.16%	0.75%
Unit Weight (lb/ft^3)	92	-
Fineness Modulus	-	2.15

TABLE 2 MIX PROPORTIONS AND PROPERTIES OF FRESH CONCRETE

Concrete Type	II	III	IV
w/c	0.45	0.38	0.33
cement (lb/yd^3)	564	658	752
water (lb/yd^3)	253	250	248
Coarse Aggregate (lb/yd^3)	1702	1702	1702
Fine Aggregate (lb/yd^3)	1302	1238	1169
Superplasticizer (lb)	4.0	3.88	4.26
Unit Weight (lb/ft^3)	145.1	146.1	147.9
Slump (inches)	2 3/4	2 3/4	3 1/4
Air Content	3%	2 1/4%	2 1/4%

TABLE 3 RESULTS OF TESTS ON FLORIDA CONCRETE

Concrete Type	II w/c = 0.45				III w/c = 0.38				IV w/c = 0.33			
Curing Condition*	A	B	C	D	A	B	C	D	A	B	C	D
Coefficient of Permeability (X10^{-12} in/sec)	21	6.7	7.5	7.7	8.3	4.4	4.8	5.9	3.6	2.8	3.8	3.9
	18	7.1	8.5	7.5	8.9	4.6	5.0	5.0	3.4	3.2	4.0	3.4
Mean Compressive Strength (psi)	4661	7114	6574	5982	5209	7761	7209	7225	6734	8582	7800	8196
Mean Splitting Tensile Strength (psi)	252	438	483	528	385	618	477	586	507	637	562	612
Mean Modulus of Rupture (psi)	599	543	590	602	681	666	496	613	638	709	637	643

Note: * Curing Conditions:

A = 16-hour steam curing

B = 28-day moist curing

C = 3-day moist & 25-day air curing

D = 1-day in form & 27-day with curing compound.

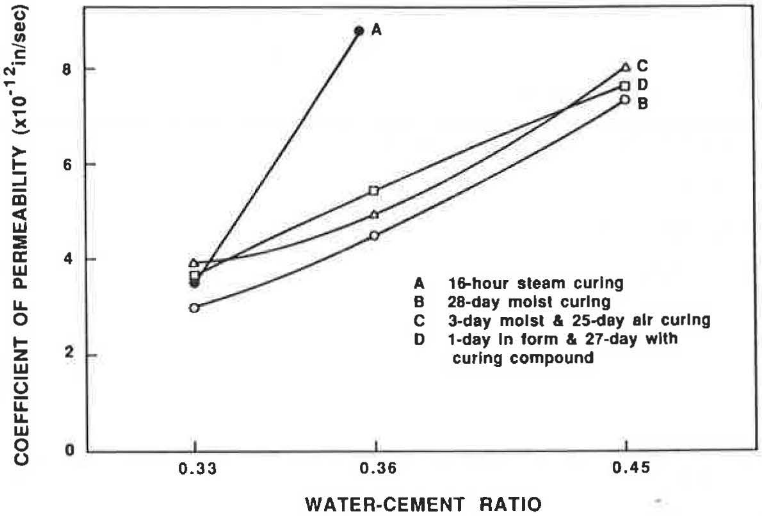


FIGURE 7 Effects of water-cement ratio on the coefficient of permeability of concrete.

The results of the permeability tests on these test specimens are displayed in Table 3. For references, the mean compressive, splitting tensile, and flexural strengths of these mixes are also displayed in Table 3. From the permeability test results, it can be noted that the coefficients of permeability of the replicate specimens (of the same mix and curing condition) are very close to one another, while the effects of concrete types (or w/c) and curing conditions on concrete permeability are fairly significant. This indicates that the test setup and procedure were able to produce precise and consistent results. Figure 7 shows plots of the mean coefficient of permeability as functions of water-cement ratio for three curing conditions. It can be seen clearly that the permeability of concrete decreases as the water-cement ratio decreases. Of the four curing conditions studied, the 28-day moist-room curing condition gave the best result.

CONCLUSION

The test setup and procedure as presented in this paper have been developed through experimentation and have been demonstrated to be both efficient and reliable for determining the permeability of concrete, especially when a large number of specimens have to be tested. One major advantage of this test setup is that it can be duplicated easily and economically.

Water-cement ratio had a significant effect on the water permeabilities of all the concretes in this study, regardless of the curing conditions. The lower water-cement ratio mixes yielded lower permeabilities.

ACKNOWLEDGMENTS

The work presented in this paper is part of a research project supported by the Florida Department of Transportation. The authors also wish to extend their appreciation to Ed Dobson and Danny Richardson for their technical support and to Pat Cribbs for typing and correcting the manuscript.

REFERENCES

1. I. L. Tyler and B. Erlin. A Proposed Simple Test Method for Determining the Permeability of Concrete. *Journal of the PCA Research and Development Laboratories*, Sept. 1961, pp. 2–7.
2. A. M. Neville and J. J. Brooks. *Concrete Technology*. Longman Scientific & Technical, 1987.
3. F. R. McMillan and I. Lyse. Some Permeability Studies of Concrete. *Journal of the American Concrete Institute*, Vol. 25, Dec. 1929, pp. 101–142.
4. P. T. Norton and D. H. Pletta. The Permeability of Gravel Concrete. *Journal of the American Concrete Institute*, Vol. 27, May 1931, pp. 1093–1131.
5. A. Ruettgers, E. N. Vidal, and S. P. Wing. An Investigation of the Permeability of Mass Concrete with Particular Reference to Boulder Dam. *Journal of the American Concrete Institute*, Vol. 31, March–April 1935, pp. 382–416.
6. G. J. R. Von der Meulen and J. van Dijk. A Permeability-Testing Apparatus for Concrete. *Magazine of Concrete Research*, Vol. 21, No. 67, June 1969, pp. 121–123.

Publication of this paper sponsored by Committee on Mechanical Properties of Concrete.

High Molecular Weight Methacrylate Sealing of a Bridge Deck

VERNON J. MARKS

The Iowa Department of Transportation used a high molecular weight methacrylate (HMWM) resin to seal a 3,340-ft × 64-ft bridge deck in October 1986. The sealing was necessary to prevent deicing salt brine from entering a substantial number of transverse cracks that coincided with the epoxy-coated top steel and unprotected bottom steel. HMWM resin is a three-component product composed of a monomer, a cumene hydroperoxide initiator, and a cobalt naphthenate promoter. The HMWM was applied with a dual spray-bar system and flat-fan nozzles. Initiated monomer delivered through one spray bar was mixed in the air with promoted monomer from the other spray bar. The application rate averaged 0.956 gal/100 ft^2 for the tined textured driving lanes. Dry sand was broadcast on the surface at an average coverage of 0.58 lb/yd^2 to maintain friction. Coring showed that the HMWM resin penetrated the cracks more than 2 in. deep. Testing of the treated deck yielded friction numbers averaging 33, with a treaded tire compared to 36 prior to treatment. An inspection soon after treatment found five leaky cracks in one of the 15 spans. One inspection during a steady rain showed no leakage, but leakage from numerous cracks occurred during a subsequent rain. A second HMWM application was made on two spans to determine if a double application would prevent leakage. This evaluation has not been completed.

The U.S. 136 bridge over the Mississippi River at Keokuk, Iowa, is a 15-span 3,340-ft × 4-ft continuous welded plate girder bridge. It was designed by Howard, Needles, Tammen and Bergendoff of Kansas City, Missouri, and constructed by Shappert Engineering Company of Belvidere, Illinois, in 1984 and 1985. Inspection of the construction was by Howard, Needles, Tammen and Bergendoff. The bridge was opened to traffic November 23, 1985.

The bridge-deck placement began November 6, 1984, and was completed August 15, 1985. The deck was placed in 16 sections, beginning on the Iowa side of the river. The concrete was placed east to west in each section using a telescoping belt conveyor and a full-width finishing machine. The completed portion of the deck was used as the work area for unloading concrete trucks when placing the next section and for storage of equipment.

Very fine, tight transverse cracks in the deck were observed before deck placement had been completed. Further observation revealed that the cracks were the full depth of the deck; and during periods of rain, water was observed dripping from the cracks. The combined effects of stresses from drying shrinkage and changes in moment from concrete placement are the apparent cause of the cracking. As the moisture dripped and evaporated from the bottom of the deck, an efflorescent deposit was left on the concrete. It was determined that at least 215 cracks allowed water to pass through the bridge deck.

It was also determined that the cracks coincided with the location of the transverse reinforcing steel and that they would allow corrosive deicing salts to reach the uncoated bottom layer of transverse reinforcing steel, which is directly below the epoxy-coated top layer. The deicing salts could also contaminate the supporting girders, causing them to corrode.

In an attempt to determine a method to prevent the intrusion of water into the cracks, three conventional sealants were applied on small areas of the bridge deck. Two of the sealants were very fluid and could be applied by spraying or brooming, while the third was quite viscous and was applied to each crack with a squeeze bottle. This method of application was impractical as the cracks were very difficult to follow due to the deep transverse tined texture of the deck. Although all three sealants penetrated into the cracks, none prevented the passage of water through the cracks.

PART I—INITIAL APPLICATION

In February 1986, it was decided to investigate the use of HMWM resin as a deck sealant (*1*). The California Department of Transportation had made successful experimental applications of HMWM resin (*2*) and had developed specifications.

HMWM resin was obtained from two suppliers for experimental purposes. The resins were mixed and applied by hand to three 50-ft-long sections in the inside lane of the eastbound roadway. Sand was sprinkled on the treated sections to maintain friction quality.

A steady rain fell early on the morning after application of the HMWM, and observation from a catwalk beneath the bridge revealed water along the cracks in the treated areas as well as the untreated area. The question then became, did the treated cracks leak or did the water come through untreated cracks and move laterally along the bottom of the treated crack? A ponding test revealed that the treated sections did leak, although not as quickly as the untreated section. The ponding test also showed that leakage would occur on both treated and untreated areas in the morning and the leakage would cease in the afternoon. One explanation of this unexpected development is a more rapid temperature rise (and corresponding expansion) of the concrete deck than of the steel girders.

Two HMWM formulations were then applied as a single application and as a double application. These applications were completed by 7:00 a.m., before the deck temperature had risen. All HMWM-treated areas were sprinkled with sand to maintain friction. Ponding tests early the next morning revealed slight leakage through the single-application areas and no leakage through the double-application areas of HMWM.

Friction of treated areas was tested with an ASTM E 274 friction test trailer and was deemed satisfactory.

With the information obtained from the field trials on the bridge deck and experiences of other Departments of Transportation, it was decided that a single application of HMWM resin applied when the deck temperature was relatively cool would suffice to prevent deicing salts from reaching the uncoated bottom layer of reinforcing steel.

The bridge contract with Shappert Engineering Company had not been closed, so it was decided to apply the HMWM resin by extra work order to the existing contract.

The California DOT specification for High Molecular Weight Methacrylate Bridge Deck Treatment was obtained and Iowa DOT Special Provision 668, Special Provision for High Molecular Weight Methacrylate, was developed.

Specifications

The special provision used for this project was Special Provision 668 (*3*):

The standard specifications, series of 1984, are amended by the following additions. These are special provisions, and they shall prevail over those published in the Standard Specifications.

668.01 DESCRIPTION. This work shall consist of preparing the portland cement concrete surface and furnishing and applying High Molecular Weight Methacrylate (HMWM) treatment materials.

668.02 MATERIALS. The material used for treating the concrete shall be a low viscosity, non-fuming, HMWM resin conforming to the following:

HIGH MOLECULAR WEIGHT METHACRYLATE RESIN

Viscosity:	Less than 25 cps (Brookfield RVT wUL adaptor 50 RPM @ 77°F) Calif. Test 434
Specific Gravity:	1.02 to 1.08 @ 77°F — ASTM D 2849.
Flash Point:	Greater than 200°F (Pinsky-Martens CC)
Vapor Pressure:	Less than 1.0 mm Hg @ 77°F — ASTM D 323
Transition Temperature:	Higher than 58°C — ASTM D 3418 Tg (DSC)

A compatible promoterinitiator system shall be capable of providing a resin gel time of not less than 40 minutes nor more than 1½ hours at the temperature of application. Gel time shall be adjusted to compensate for the change in temperature throughout treatment application.

The Contractor shall arrange to have a technical representative on-site to provide mixing proportions, equipment suitability, and safety advice to the Contractor and Engineer.

The promoter and the initiator, if supplied separate from the resin, shall not contact each other directly. Containers of promoters and initiators shall not be stored together in a manner that will allow leakage or spillage from one to contact the containers or material of the other.

Material Safety Data Sheet (MSDS) shall be furnished for the HMWM resin to be used on this project. A certification showing conformance to these specifications shall be provided with each batch of resin. The following materials are approved as HMWM treatment material:

Company	*Address*	*Brand*
Rohm and Haas Company	727 Norristown Road, Spring House, PA 19477	PCM-1100
Rohm and Haas Company	727 Norristown Road, Spring House, PA 19477	PCM-1500
Revolan	P. O. Box 18922, San Jose, CA 95158	RS-200W
Adhesive Engineering Co.	1411 Industrial Road, San Carlos, CA 94070	Concresive AEX 2075

The sand shall be an aggregate conforming to the quality requirements of Section 4110, "Fine Aggregate for Concrete", of the Standard Specifications and shall conform to the following limits for grading:

Sieve Size	*% Passing Max.*
No. 4	100
No. 8	90–100
No. 16	0–15
No. 50	0–5

It is the intention of this specification to allow the use of commercially available blast sands of No. #820.

668.03 SURFACE PREPARATION. Concrete surfaces shall be prepared by air cleaning the entire deck surface to be treated and blowing all loose material from visible cracks using high-pressure air. All accumulations of dirt and debris shall be removed from the surface. The surface to be treated shall be dry (visual inspection) and above 40°F prior to resin application.

668.04 APPLICATION OF HMWM. The rate of application of promoted initiated resin shall be approximately 100 square feet per gallon in a single application; the exact rate shall be determined by the Engineer.

The application may be made by machine, using a two-part resin system utilizing a promoted resin for one part and an initiated resin for the other part. The pressure at the spray nozzle shall not be great enough to cause appreciable atomization of the resin. Compressed air shall not be used to produce the spray.

The quantity of initiated, promoted resin shall be limited to 5 gallons of mixed resin at a time for manual application. A significant increase in viscosity prior to proper penetration shall be cause for rejection. The treatment shall be applied within 5 minutes after complete mixing.

The deck and sidewalk are to receive the HMWM resin treatment. The surfaces shall be flooded with resin, allowing penetration into the concrete and filling of all cracks. Excess material shall be redistributed by brooms within 5 minutes after application. Curbs and rails are not to receive this treatment; reasonable care shall be taken to keep these surfaces free from resin.

668.05 APPLICATION OF SAND. The entire treated area of the bridge deck shall have sand broadcast by mechanical means to effect a visually uniform coverage of 0.40 to 0.60 pound per square yard. The sand shall be applied by a common lawn broadcast-type seederspreader. If cure time allows, sand shall be placed 25–35 minutes after the resin has been applied and before any gelling of the resin occurs. The sand shall be dried and shall have a maximum total moisture content of less than 0.5 of the aggregate absorption determined in accordance with Iowa Laboratory Test Method 202.

668.06 LIMITATIONS. The Contractor shall use every reasonable means to protect persons and vehicles from injury or damage that might occur because of his operations. During the construction, the Contractor shall provide such traffic control as required by the contract documents. Iowa DOT Standard Specifications, Articles 1107.08 and 1107.09, shall also apply.

The road shall be kept open to traffic unless otherwise directed by the Engineer. Except when an accelerated work schedule is required, no work will be permitted on Sundays and holidays. The Contractor may restrict traffic but shall permit traffic to pass safely at all times, except for occasional, unavoidable interruptions.

Application of HMWM materials shall be made between the hours of 11:00 p.m. and 7:00 a.m. HMWM treatment of the entire bridge deck shall be completed between April 1 and October 31. The temperature of the surfaces to be treated shall range from 40°F to 100°F. Care shall be exercised to prevent spillage of HMWM material or solvents into waterways.

Solvent for cleaning and flushing of equipment, tools, etc., shall be used in such a manner to minimize personal and environmental hazards, as approved by the Engineer. A soap and water wash station shall be provided for the workers at the job site.

Traffic shall be permitted on the treated surface when the sand cover adheres sufficiently and there is no tracking of HMWM material. Particular care shall be exercised when there is a possibility of tracking material on asphaltic concrete at the end of the bridge.

668.07 METHOD OF MEASUREMENT. The area treated will be calculated by the Engineer, based on plan dimensions, and will be paid for as HMWM Bridge Deck Treatment.

Furnishing the high molecular weight methacrylate resin will be measured by the gallon of mixed material actually placed, by count. No payment will be made for material wasted or not used in the work.

668.08 BASIS OF PAYMENT. The contract price paid per square foot for HMWM Bridge Deck Treatment shall include full compensation for furnishing all labor, materials (except treatment resin) tools, equipment and incidentals, and for doing all the work involved in preparing concrete surfaces, applying treatment material and sand, providing a technical representative, and clean up, as specified herein and as directed by the engineer.

The contract price paid per gallon for Furnish HMWM Bridge Deck Treatment Material shall include full compensation for furnishing all resin treatment materials to the site of the work, ready for application, as specified herein and as directed by the Engineer.

Two changes to Special Provision 668 are proposed for future HMWM treatment projects. In section 668.03, the modification would read "The surface to be treated shall remain dry for 24 hours and above 40°F prior to resin application." The period when the treatment would be allowed in section 668.06 would change to "between April 1 and September 30."

Materials

The contractor opted to use RPM−2000W produced by Revolan Systems, an approved equal to one of four HMWM resins from three suppliers allowed by Special Provision 668. It is a three component system composed of a monomer, a cumene hydroperoxide initiator, and a cobalt naphthenate promoter. As recommended by the producer, 2 oz of promoter and 2 oz of initiator were added to 1 gal of monomer.

The dried sand required for maintenance of friction was a natural sand from Northern Gravel at Muscatine, Iowa. The gradation is shown in Table 1.

TABLE 1 MUSCATINE SAND GRADATION

Sieve No.	% Passing
8	100
16	7.9
30	0.6
200	0.4

Equipment

The system used for the application of the HMWM was developed originally by Leo Ferroni, formerly with the California DOT, now a technical consultant.

The system was transported on a four-wheel flatbed trailer pulled by a small farm tractor. Barrels of resin and two positive displacement pumps were placed on the bed of the trailer, and two spray bars were mounted horizontally parallel to each other across the rear of the trailer (Figure 1). Each bar had 12 nondrip, flat-fan nozzles spaced 12 in. apart. The nozzles of each bar were connected in series with flexible tubing and then connected to a pump. The positive displacement feature of the pumps was negated by a pressure-regulated recirculation system.

The parallel spray bar mixed the HMWM in the air by having the nozzles tilted so that the fan shape of the front and rear opposing nozzles intersected about 3 in. above the deck surface. One bar sprayed from a barrel that had monomer mixed with the initiator required for two barrels, and the other bar sprayed from a barrel of monomer mixed with the promoter required for two barrels.

Also mounted on the trailer were floodlights for night operation. A rotary power broom, hand brooms, and shovels were used to clean the deck. An air compressor furnished air for final cleaning. Two lawn-type broadcast fertilizer spreaders were used to spread the dry sand.

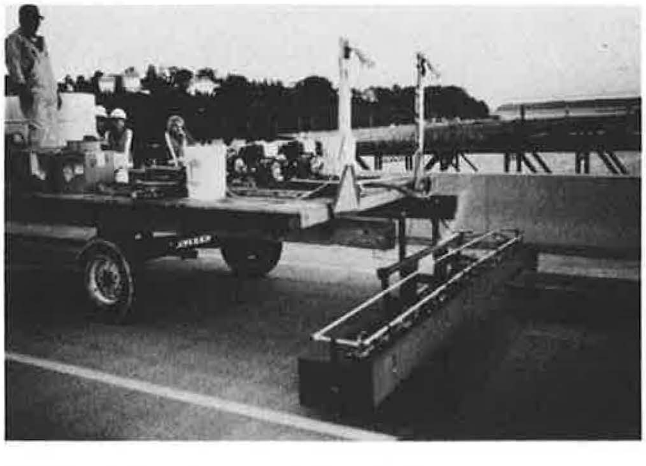


FIGURE 1 Spray bar mounted on the flatbed trailer.

Deck Preparation

A rotary power broom was used initially to remove sand and to loosen dirt from the bridge deck. Stiff-bristle hand brooms were used to loosen the dirt in the transverse grooves. After brooming, the deck was blown clean with compressed air. The deck was usually cleaned in the morning and sealed that night. When the sealing was done more than 24 hr after cleaning, recleaning with hand brooms and compressed air was required.

Styrofoam was cut to fit the drains and sealed with caulking compound to prevent the HMWM resin from leaking into the river.

HMWM Resin Application

Special Provision 668 limits application to the hours between 11:00 p.m. and 7:00 a.m. It was decided to allow application until 8:00 a.m. and also agreed that the bridge-deck surface would be dry for 24 hr prior to sealing.

In preparation for a September 17 application, the system was calibrated using water instead of HMWM resin for a fan width of 12 in. from each nozzle. Nozzle delivery tables showed this to require about 20 psi pressure with the resin at about 65°F. Two barrels of monomer were prepared for application, but the planned September 17 application was cancelled because of rain and there continued to be rains throughout September and into October.

The first application of HMWM was on October 7, 1986. The operation began by 4:00 a.m. with a calibration check in the contractor's staging area. It was observed that the system would not produce the required 12-in. fan pattern. This was attributed to the material being more viscous at the current temperature of 45°F than at the 65°F temperature at the time of the original calibration. The pressure was increased to 35 psi to obtain the 12-in. fan pattern, and application began on the outside westbound lane.

The HMWM was sprayed 12 ft wide and was broomed to make an application width of 17 ft (Figure 2). The intended application rate was 1 gal of HMWM per 100 ft^2. With constant pressure, the application rate was regulated by the forward speed of the tractor. The amount of HMWM resin in the 55-gal drums prior to and after treatment of a section was estimated after determining the depth remaining with a rod. Travel was intended to be 60 ft/min. This resulted in an application rate of 1.304 gallons per 100 ft^2.

FIGURE 2 Application of HMWM resin.

The speed of the farm tractor was increased for the application of the second 100 gal of HMWM resin to reduce the rate of application. The travel speed was too fast, resulting in areas with insufficient resin; and the equipment was moved back to touch up those places. For subsequent applications, the travel speed was adjusted to give sufficient resin as determined by observation.

Sand was applied about 90 min after resin application due to the very cool temperature delaying the gel time. The air and deck temperature during the application ranged between 48°F and 55°F. Higher temperatures would have reduced the gel time of the resin, allowing sand to be spread sooner after application.

The sand was spread with two broadcast-type lawn fertilizer spreaders. Various speeds and transverse spreader locations were tried until the desired coverage was obtained. Sand coverage varied between 0.51 lb and 0.61 lb/yd^2 with an average of 0.58 lb/yd^2 on the deck and 0.52 lb/yd^2 on the sidewalk. This sand was intended to provide temporary friction properties until the HMWM coating was worn away.

The eastbound inside lane was sealed on October 8, 1986. The areas that had been previously treated for ponding tests were not retreated. The outside eastbound and the inside westbound lanes were treated October 10, 1986.

The sidewalk was treated by applying the resin with garden sprinkler cans and spreading with squeegees and brooms. The application rate averaged 0.896 gal/100 ft^2, slightly less than the 0.956 gal/100 ft^2 on the driving portion of the deck, which has a tined texture.

It was at least 24 hr after treatment before vehicle traffic was allowed on the bridge. There was minor tracking, but no adverse effects were observed because of tracking.

Cost

The cost of sealing the bridge is broken down as follows:

236,050 ft^2 of treatment @ 0.35	$82,617.50
2,256 gal HMWM @ 35.45	79,975.20
Traffic control—lump sum	12,500.00
Total	$175,092.70

Evaluation

A total of six 2-in.-diameter cores were drilled from both inside lanes October 14, 1986. They were drilled, on a crack, 2 in. deep to avoid damaging the epoxy coating of the top reinforcing steel, which has only 2 in. of cover. The core holes were filled with portland cement concrete and were treated with HMWM resin the following day.

When the cores were split to determine penetration, the split did not always follow the crack. In some instances, the concrete fractured instead of the crack, indicative of the bonding capabilities of the HMWM resin.

The bottom edges of the cores were treated with a 50-percent concentrated sulfuric acid/50-percent water solution.

Heating to 140°F in an oven for 2 hr caused the organic resin to turn black. The test indicated that the HMWM had penetrated at least 2 in. deep at all core locations.

Friction of the treated deck was tested with an ASTM E 274 trailer November 3, 1986, in all lanes. The friction numbers ranged from 27 to 39, averaging 33 with the treaded test tire, and ranged from 20 to 33 with an average of 24 with the smooth tire.

The underside of the bridge was inspected October 25, 1986, during a 0.25-in. rain. There was leakage observed from five cracks between piers 7 and 8. Other inspections were made during light rains March 18 and March 25, 1987; and no leakage was observed. Two inspections were made April 13 and 14, 1987, from all catwalks during steady rains; no leaking cracks were found.

Another inspection to check for leakage was made on August 25, 1987, during a steady rain very much like that of April 13 and 14. There had been a substantial period with free water standing on the surface. Leakage was identified in all spans of the bridge deck. More then 300 cracks under the eastbound lanes and more than 400 cracks under the westbound lane showed some leakage. Water was not dripping from any cracks. From visual observation, it appeared that that the leakage rate was reduced compared to leakage prior to the treatment. Some leakage was noted from cracks that had no efflorescent deposit. It is possible that some new cracks developed.

PART II—SECOND APPLICATION

Consideration of Second Application

With evidence that one application of HMWM had failed to prevent leakage, it was necessary to consider additional protective measures. A second application of HMWM or of an Iowa method dense concrete overlay was the only further protection given serious consideration. The Iowa method overlay had been very successful on another long bridge that developed substantial transverse cracking immediately following construction.

The HMWM system had not been fully evaluated. In the laboratory, a double application of HMWM had been successful in preventing leakage through cracks believed to be wider than those in the bridge deck. One potential problem was that the first HMWM application had filled two-thirds of the depth of the transverse groove texturing. The second application of HMWM would certainly fill the balance of the transverse groove texture. A small trial on the Keokuk Bridge showed that the HMWM material was removed very quickly and effectively by sandblasting.

Materials

The HMWM material used for the second application was the same RPM – 2000W used for the initial application.

In an effort to obtain better frictional properties, a manufactured crushed quartzite sand was obtained from Del Rapids, South Dakota. The gradation of the dried sand is given in Table 2.

TABLE 2 DEL RAPIDS SAND GRADATION

Sieve No.	% Passing
4	100
8	85
16	13
30	1.2
50	0.4
100	0.2
200	0.1

Weather Conditions

The decision to use the second application of HMWM was made soon after the observation of leakage on August 25. Delivery of the HMWM material required almost 4 weeks. The manufacturer strongly recommended that the HMWM not be applied at temperatures below 50°F. Most of October was quite cold, and it appeared that application would be delayed until warm weather in 1988. Fortunately, in early November, the low temperatures for three nights were 58–60°F.

Deck Preparation

The city of Keokuk used its street sweeper to remove essentially all of the dirt and debris. The drains were again plugged with Styrofoam sheeting and caulked to prevent HMWM from running into the river. Compressed air was used to blow the deck clean immediately preceding the HMWM application.

HMWM Resin Application

The second application of HMWM was placed the full width of the deck on 421 ft from an expansion assembly 15 ft east of pier 6 to pier 8. Traffic was restricted to one lane in each direction, with the other two lanes closed for treatment. The second treatment was applied manually by Iowa DOT personnel. The Iowa DOT maintenance personnel had set up traffic control and blown the westbound inside lane clean on November 3, 1987, a comfortable 60°F night. The HMWM was hand-mixed in 5-gal buckets and poured onto the deck. Beginning at 5:15 a.m., soft nylon-bristled push brooms were used to spread the HMWM 15 ft wide for an average coverage of 0.82 gal/100 ft^2. Two push brooms were used behind the application to move the excess material ahead. HMWM application on the westbound lane was completed at 6:00. The crushed quartzite sand was applied. Sand application should have begun earlier, as the first portion of HMWM had begun to gel. The sand coverage was 1.17 lb/yd^2.

Application of HMWM to the eastbound inside lane began at 7:00 a.m. and was completed at 7:40. The operation was the same as for the westbound lane except that sand spreading

TABLE 3 FRICTION TESTING (ASTM E-274 at 40 mph)

	Friction Number	
	Treaded Tire	Smooth Tire
Prior to treatment	36	23
After Single Application		
6-15-87	33	20
10-12-87	40	21
After Double Application		
11-16-87 Driving Lane	50	34
Passing Lane	61	48

began at 7:25. Sand coverage for the westbound lane was 1.31 lb/yd². The temperature at 8:20 was 66°F with a daily high of 79°F. Traffic was allowed on both the eastbound and westbound applications at about 3:00 p.m.

The Iowa DOT maintenance personnel had blown the outside westbound lane clean and were ready for application of HMWM at 5:00 a.m. on November 4 (nighttime low of 58°F). Application procedures remained unchanged, and sand application began at about 5:15 a.m. HMWM application was finished at 5:40. Quartzite sand was used at 1.31 lb/yd².

The outside eastbound lane and sidewalk were treated from 6:30 to 7:10 a.m. The sand coverage on the outside eastbound lane was 1.46 lb/yd². No quartzite sand was used on the sidewalk. The temperature at 8:00 was 61°F.

Evaluation

The depth of penetration of the second application cannot be determined as there is no way to distinguish from the organic HMWM material of the initial application that penetrated the 2 in. to the top steel. Friction testing was conducted prior to treatment, twice after the initial application, and once since the double application (Table 3). The friction numbers of the surface with a single application are similar to those prior to treatment. The crushed quartzite sand has given improved friction numbers after the second application. Continued testing will be necessary to determine the longevity of the improved friction numbers.

There have been no rains of sufficient duration and intensity to determine if a double application will prevent leakage.

PRELIMINARY CONCLUSIONS

The HMWM resin penetrated the fine cracks to a depth of at least 2 in. A single application of HMWM reduced the leakage, but failed to prevent leakage. Further evaluation is necessary to determine if a double application will prevent leakage. There was an initial loss of frictional properties after HMWM treatment, but as traffic wore away the surface coating, the friction numbers returned to pretreatment levels. The crushed quartzite yielded improved friction numbers immediately following the second application of HMWM.

ACKNOWLEDGMENTS

The HMWM treatments and evaluation were partially funded by the Federal Highway Administration. The excellent work of all those involved with the HMWM treatments allowed both initial and second applications of a material new to Iowa with very few problems. Excellent technical advice was provided by Al Klail and Ersell Ingram of the Revolan Systems and by Leo Ferroni, a private consultant. Jeff Boldt and the other Shappert Engineering personnel and Iowa DOT personnel are to be commended on an outstanding job of applying the HMWM material. Ron Thompson and S. Thomas McKay of the Iowa DOT Mt. Pleasant Resident Construction Office provided excellent project inspection. Mr. Thompson compiled an excellent documentation of the coverage of both the resin and the sand and also the air and surface temperature during the initial application of the resin. The cooperation of the Illinois DOT personnel was appreciated.

REFERENCES

1. *A Study of the Transverse Cracks in the Keokuk Bridge Deck*. Iowa Department of Transportation, July 1986.
2. P. Krauss. *New Materials and Techniques for the Rehabilitation of Portland Cement Concrete*. Report FHWA/CATL-8516. California Department of Transportation; FHWA, U.S. Department of Transportation, 1985.
3. *Special Provision for High Molecular Weight Bridge Deck Treatment*. Iowa Department of Transportation, Ames, Aug. 5, 1986.

Publication of this paper sponsored by Committee on Construction of Bridges and Structures.