Chloride Permeabilities of Rigid Concrete Bridge Deck Overlays

D. WHITING AND W. DZIEDZIC

A study of the chloride permeability of rigid concrete bridge deck overlays was conducted during the 1987 construction season. A total of thirteen latex-modified concrete (LMC) overlays, ten superplasticized dense concrete (SDC) overlays, and two condensed silica fume concrete (CSFC) overlays, were investigated. Concretes were tested both by the rapid chloride permeability test and by 90-day chloride ponding. Results of this study indicate that, of the three materials tested, CSFC is the most impermeable to chloride ions. Following CSFC, in order of increasing permeability, are LMC and SDC. Although all materials show a decrease in permeability with age, chloride ions slowly penetrate these materials and can build up to substantial levels over long periods of time. For newly constructed overlays, there was a good correlation between results of the rapid chloride permeability and 90-day ponding tests.

One of the most serious problems facing the highway engineering community today is the state of highway bridges across the country. It is estimated that at least 160,000 bridges on the interstate system alone are exhibiting such deterioration (*1*).

Of all solutions proposed, rigid overlays have certain advantages, including familiarity of technology, restoration of riding quality, and relatively low cost. The two most popular forms of rigid overlay are latex-modified concrete (LMC) and low-slump dense concrete (LSDC), the "Iowa" method. Superplasticizers may be used with the latter to increase workability, resulting in superplasticized dense concrete (SDC). The use of condensed silica fume concrete (CSFC) in bridge deck overlay applications is relatively new, although use is expected to increase. A comparison of these various overlay systems is needed with respect to their ability to reduce further ingress of chloride ions, so that the most effective methods of protecting this large number of bridge decks may be chosen.

OBJECTIVES AND SCOPE

The primary objective of this research program was to obtain information on the chloride permeabilities of LMC, SDC, and CSFC overlay concretes, both for in-place and new construction, for the purpose of ascertaining which system affords a more impermeable barrier to deicing salts. A secondary objective was to assess the utility of the rapid chloride permeability test (RCPT) (*2, 3*) as a means of measuring permeability of in-place structures and of monitoring permeability of concrete placed on new construction.

The objectives were carried out within the following scope:

1. Cores were obtained from existing LMC, SDC, and CSFC overlays and tested for chloride ion content and rapid chloride permeability. Overlays ranged in age from 1 month to 14 years.
2. Test specimens were cast during construction of LMC and SDC overlays and a CSFC bridge deck during the 1987 construction season. Specimens were subjected to 90-day chloride ponding and RCPT.
3. Results were analyzed to determine relative permeabilities of LMC, SDC, and CSFC overlay materials. Relationships between RCPT and 90-day ponding results were developed.

Construction Technology Laboratories, Inc., 5420 Old Orchard Road, Skokie, Ill. 60077.

BACKGROUND

The performance of rigid overlays, in general, has been favorable. The precursor to SDC, LSDC, incorporates a cement factor of approximately 820 lb/yd^3. A low water-cement ratio (w/c) of 0.30 to 0.32 by weight is most commonly used. Consolidation to a level of 98 percent of rodded unit weight must be achieved, and air contents are specified at 6.5 ± 1.0 percent. LSDC overlays generally are placed at thicknesses ranging from 1.75 to 2 in. Vigorous vibration is needed to achieve the required degree of consolidation of the concrete. A study by the Iowa Department of Transportation (DOT) on 15 overlays, ranging from 5 to 13 years of age, indicated that none of the installations showed evidence of riding surface distress (*4*). Although the top 1-in. of most of these overlays exhibited significant chloride penetration after 11 years of service, chloride contents at depths below 1.5 in. were less than 1 lb/yd^3 and did not appear to increase progressively with time, at least within the 11-year period of study. Likewise, LSDC overlays installed by the Minnesota DOT from 1975 through 1977 have shown good performance (*5*), although in these overlays the measured concrete chloride contents were somewhat higher at equivalent ages and depths than in the Iowa study. Most of these data, however, relate to the low-slump version of the system. Less work has been done and hence fewer performance data are available for SDC. A short-term laboratory study (*6*) indicates that SDC and LSDC should be equally resistant to chloride ion penetration. Results reported by Whiting and Kuhlmann (*7*), on the other hand, indicate significantly higher permeabilities (as measured by AASHTO T277) for SDC than for LMC.

LMC concretes have exhibited generally good performance in terms of their ability to reduce chloride penetration. Mix designs used for LMC overlays usually call for 658 lb/yd^3 of cement, relatively low water content (w/c = 0.39 or less) and 15 percent (by cement weight) of a 46 percent emulsion of styrene-butadiene latex. Air entrainment normally is not used with LMC. Bishara (*8*), in a study of 132 bridge decks, reported much lower chloride contents in decks overlaid with LMC than in nonprotected decks. In the Minnesota study previously

cited (*5*), chloride contents below 1.5 in. in decks overlaid with LMC were at the same low levels (< 1 lb/yd³) as similar decks overlaid with LSDC. Studies in Indiana, Kentucky, and Michigan summarized in a recent publication (*9*), show equally good performance for LMC.

A new type of overlay system currently undergoing experimental trials in a number of states incorporates condensed silica fume and may be termed CSFC. These concretes generally use a relatively high cement content (600 to 700 lb/yd³), low w/c ratio (in many cases <0.30), and sufficient high-range water reducer to obtain a workable concrete mixture. Additions of silica fume have ranged from 5 to 15 percent, based on cement weight. Laboratory data (*10*, *11*) indicate that reduction in permeability to chloride ions is a function of silica fume addition, with the greatest reductions occurring at additions above 10 percent by weight of cement. Bunke (*12*) notes that permeability of silica fume concretes taken from CSFC placements in Ohio compares favorably with that of other systems including LMC, SDC, high-molecular-weight methacrylates, silane sealers, and epoxy overlays.

In spite of this generally favorable background, questions relating to the performance of both LMC and SDC remain unanswered. The relative effectiveness of each of the bridge overlay systems in forming impermeable barriers to chloride ions needs to be quantified. Although laboratory data may indicate favorable improvements in impermeability through the use of these protective overlay systems, the possibly deleterious effects that field construction variables may have on permeability are not known. Therefore, study of field-produced concretes is vital to answering these questions. Recent reports of high permeabilities exhibited by LSDC overlays (FHWA, unpublished data) and lack of field data on chloride permeability of SDC and CSFC creates a need for more information on these systems. Further work is needed before rigid overlays can be accepted as a long-term solution to the bridge deck deterioration problem.

SAMPLING PLAN AND PROCEDURES

The sampling plan is depicted in Figure 1. A total of 25 field sites were selected; these consisted of 13 in-place sites, 10 placements, and 2 additional sites. Sites selected for study of overlays are located in Figure 2. The majority of the sites lie in a band running roughly from the southwest to northeast corners of the state of Ohio. Two other sites were located in the southeast area of the state near the city of Marietta. In-place overlays ranged in age (at time of sampling) from 1 to 14 years for LMC, from 3 to 5 years for SDC, and less than 1 year for CSFC. All sampling from new construction was carried out during August and September 1987.

The 13 in-place sites were chosen to include 8 in-place LMC overlays and 5 in-place SDC overlays. At each of these sites five cores were taken. Four cores from each deck were tested for rapid chloride permeability by using AASHTO T277-83 (Standard Method of Test for Rapid Determination of the Chloride Permeability of Concrete).

For test preparation, each core was cut at the overlay bond line (or at 2.0 in. in those cases in which overlay depth exceeded 2 in.) so as to include only overlay material in the test.

The remaining core from each site was sectioned at 0.5-in. intervals up to the overlay bond line, and each slice was analyzed for total (acid-soluble) chloride ion by procedures described in AASHTO T260-82 (Standard Method of Sampling and Testing for Total Chloride Ion in Concrete and Concrete Raw Materials).

The ten placements were evenly divided between five LMC and five SDC sites. (Note: at one of the LMC sites shown in

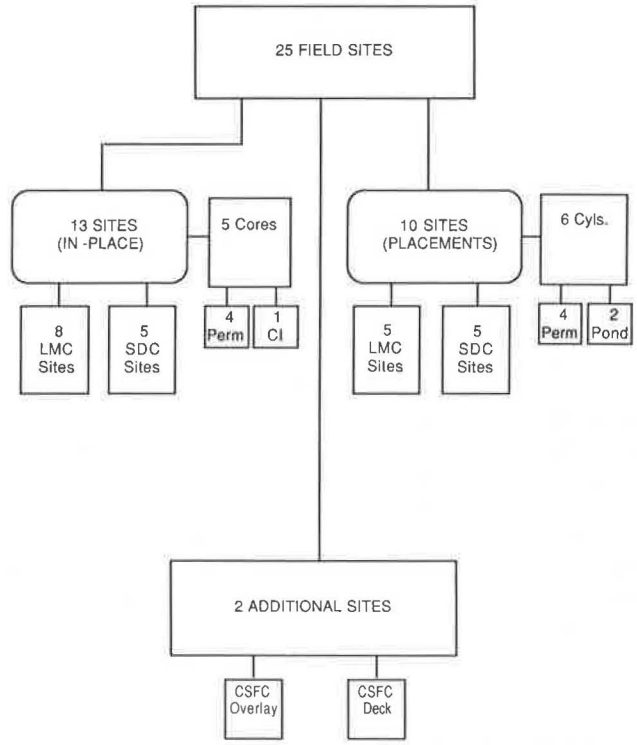

FIGURE 1 Sampling plan.

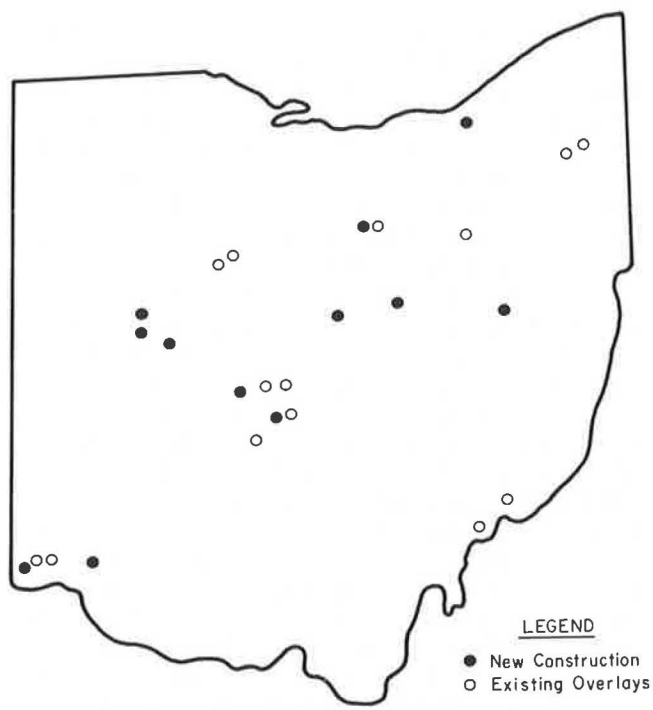

FIGURE 2 Location of sites selected for sampling.

Figure 2, samples were obtained from two separate pours. These are denoted as J and K in subsequent discussions of results.) At each site a total of six 4-in.-diameter by 8-in.-long cylinders were cast by using rigid plastic molds. In most cases, this represented three cylinders cast from each of two trucks (or concrete mobiles) selected for sampling. Cylinders were initially cured on site under a covering of wet burlap and polyethylene sheeting. After completion of initial moist curing (72 hours for SDC and CSFC; 48 hours for LMC) cylinders were transported to laboratory facilities and curing was continued (moist cure for SDC and CSFC; air cure for LMC) until the specimens had reached an age of 5 weeks, at which time testing was initiated. From each set of three cylinders, two were tested by AASHTO T277 and one was subjected to a saline ponding procedure similar to that described in AASHTO T259-80 (Standard Method of Test for Resistance of Concrete to Chloride Ion Penetration).

The two additional sites shown in Figure 2 represent an in-place condensed silica fume overlay and condensed silica fume placement of a full-depth bridge deck. Procedures used for these sites were identical to those used for the other in-place sites and placements.

RESULTS AND DISCUSSION

In-Place Sites

Chloride contents of cores obtained from LMC and SDC overlays are shown in Figure 3. There is a wide range of values in each set of data. Values in the near-surface (0 to 0.5-in.) layer for LMC range from 0.05 percent (core 6-2) to 0.40 percent (core 12-2). In some cores, such as 12-2 and 14-3, there is a sharp decrease in chloride content with depth. In other cores, such as 11-2 and 7-2, the decrease is much more gradual. For the most part, high chloride contents are associated with those LMC overlays that have been in service for the longest period of time: e.g., overlays at site numbers 2 and 12 have been in service for 12 and 14 years, respectively.

Chloride profiles for cores taken from SDC overlays are similar in many respects to those from LMC overlays. Near-surface values range from 0.14 percent (core 5-3) to 0.32 percent (core 9-2). There is a relatively sharp decrease of chloride content with depth, except for core 9-2.

A comparison of chloride contents at the 1.0-in. level for LMC and SDC cores is shown in Figure 4. For these data the effect of age of overlay is readily apparent. With increasing age, chloride contents at 1.0 in.-depth increase for both LMC and SDC overlays. Unfortunately, there are no SDC overlays in Ohio of sufficient age that can be compared to the 12- and 14-year-old latex sites; consequently the question of long-term penetration of chlorides into SDC remains unanswered at this time.

Results of RCPT on in-place core slices are presented in Figure 5. For each site, individual results on each of the four core slices tested are shown. There is a strong effect of overlay age on test results. For the most part, LMC permeability tends to decrease with age. If the high values within site numbers 10 and 11 are excluded, there is a gradual reduction of charge passed from an average of about 900 coulombs at 1 year to about 400 coulombs at 14 years. Most of the results after 1 year of age lie below 600 coulombs. This age effect has been previously reported in laboratory studies (*7*, *13*).

For SDC, on the other hand, within the ages from 3 to 5 years, there is little effect on permeability. The range of ages of structures for which cores could be obtained was more limited than for LMC. Values range from approximately 600 coulombs for site 8 to an average of 1,200 coulombs for site 9, placing these SDC overlays within the low to very low categories, as defined in AASHTO T277. Within any given

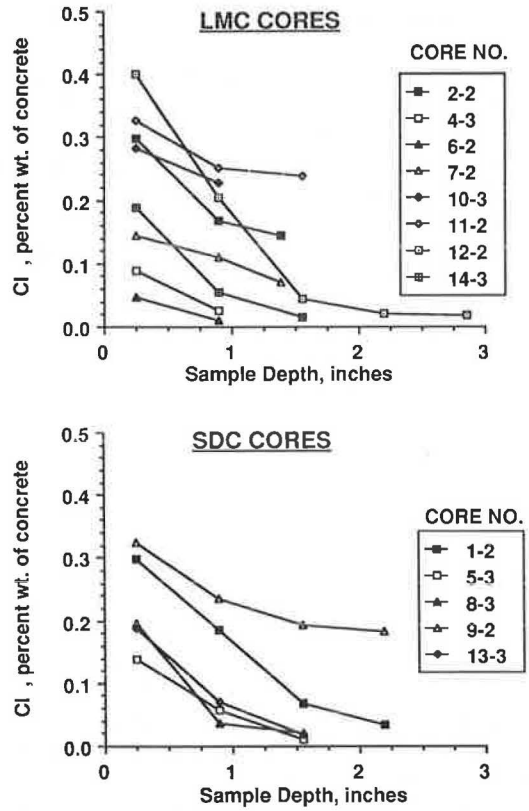

FIGURE 3 Chloride contents of cores obtained from in-place overlays.

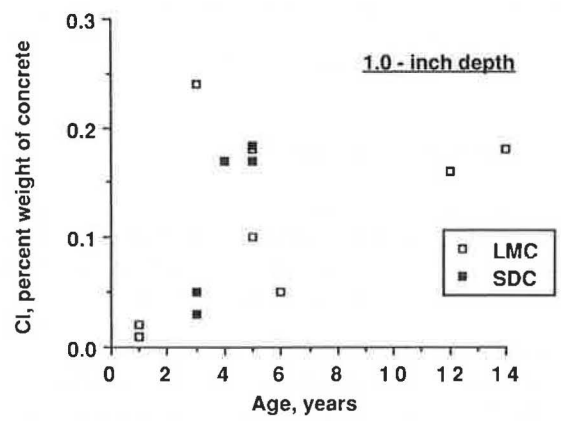

FIGURE 4 Effect of age on chloride content of overlays.

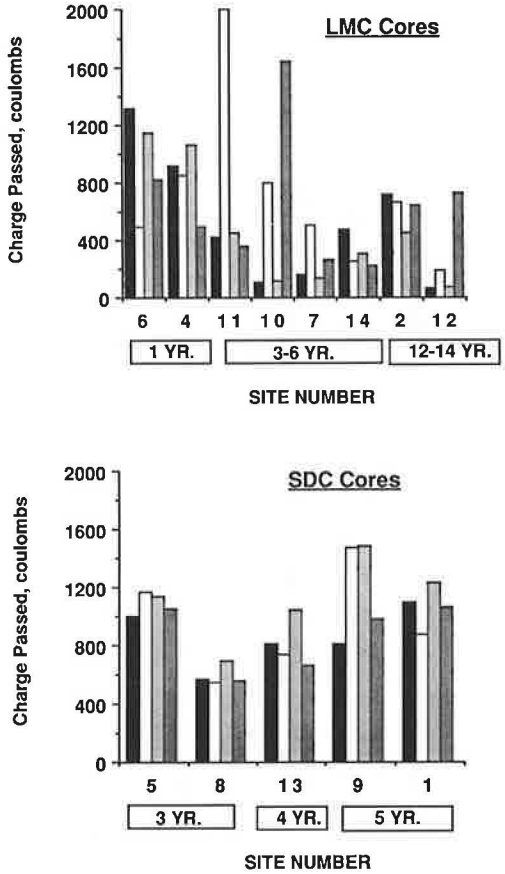

FIGURE 5 Results of rapid chloride permeability testing on samples taken from in-place overlays.

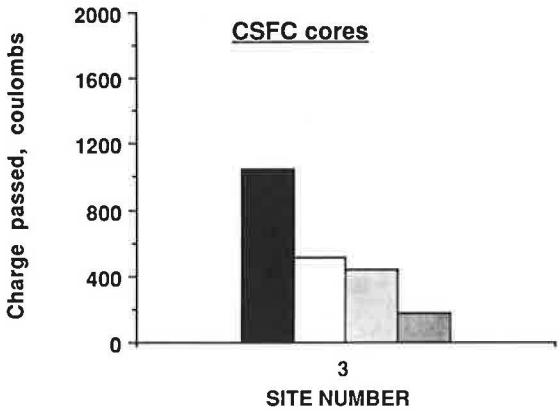

FIGURE 6 Rapid chloride permeability test results on CSFC overlay samples.

set of four SDC cores, results appear to be more uniform than for the LMC cores. For instance, the widest range of results for SDC was exhibited by site 9, where the lowest value was 810 coulombs and the highest was 1,490, representing a difference of 60 percent of the mean value. In comparison, for LMC site 10, highest and lowest values were 1,640 and 110, a difference of 175 percent of the mean value. Likewise, LMC sites 11 and 12 show large differences in charge passed between specimens in the same sets. Results on CSFC specimens, all obtained from site 3, are presented in Figure 6. Even though this overlay had been in place for only 2 months before sampling, rapid chloride permeability values were already lower than all of those for the SDC overlays and were roughly equivalent to most of those for the LMC overlays that had been in place for a number of years. These very low values for chloride permeability are in agreement with data recently presented by Luther (*14*) and Ozyildirim (*15*) on CSFC overlays.

Placements

RCPT results on cylinders cast from overlay placements are presented in Figure 7. Each bar represents the average of two test cylinders. Most of the LMC results (with the exception of site D) lie between 1,000 and about 2,000 coulombs, which is somewhat higher than has been reported in previous laboratory (*7*, *16*, *17*) and field (*18*, *19*) studies, where LMC concretes typically exhibited values lower than 1,000 coulombs. However, it is reasonable to expect that field concretes will exhibit somewhat higher permeabilities than concretes prepared under more controlled laboratory conditions. It is also worth noting that most of the RCPT values reported for field concretes pertain to cores taken at ages considerably greater than the 6-week test period used in the current study.

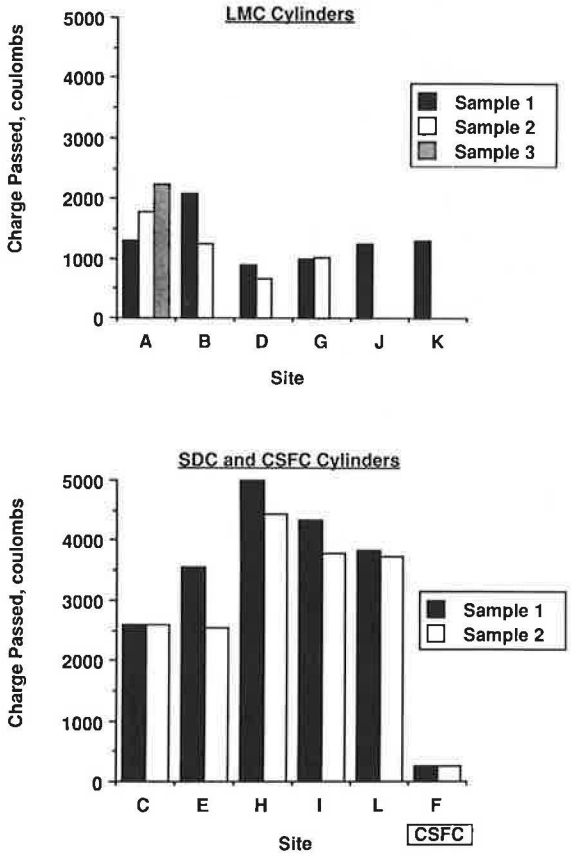

FIGURE 7 Results of rapid chloride permeability tests on cylinders cast at overlay placements.

All SDC test results are considerably greater than results obtained on LMC cylinders. The highest LMC results (obtained on sample 3 from site A and sample 1 from site B) were slightly lower than the lowest SDC results (site C and sample 2 from site E). The average of all LMC RCPT results, 1,290 coulombs, is 60 percent lower than the average of all SDC results, 3,640 coulombs. The SDC results are far above the range of 1,000 to 2,000 coulombs suggested as being typical of RCPT results on low w/c ratio concretes in the original permeability method development study (*2*). However, the current results are in close agreement with values reported by Whiting and Kuhlmann (*7*) for LSDC and SDC mixtures tested at ages of 1 and 2 months. It appears that the low permeability values said to typify LSDC and SDC-type concretes based on the initial RCPT development studies may have been overly optimistic and may be possible only under controlled laboratory conditions.

Results on the CSFC specimens, on the other hand, further demonstrate the low permeability inherent in this material. The very low values of charge passed, in the range of 250 coulombs, are typical of mixtures with the high silica fume loadings (15 percent solids basis) used in the site F deck placement. The CSFC specimens exhibited the lowest values of charge passed among all of the specimens sampled from placements included in this study.

After exposure to 3.0 percent sodium chloride solution for 90 days, companion cylinders obtained from overlay placements were sectioned at 0.5-in. intervals and analyzed for total (acid-soluble) chloride ion. These values were then graphically integrated over the sampling depths to obtain the "integral" chloride values (*2*) previously used in development of the RCPT. Results are presented in Figure 8. In general, 90-day ponding results for the SDC set lie somewhat above those for LMC. Mean value for total integral chloride for all SDC samples was 0.124, compared with 0.097 for the LMC. This represents a difference of a factor of 1.3. Statistical treatment of the two data sets indicates a significant difference (i.e., lower LMC values) at the 99 percent confidence level. As was the case for the RCPT results, CSFC overlay concretes show much lower values for total integral chloride than values obtained for either SDC or LMC.

In previous laboratory studies (*2*, *20*) fairly good relationships between results of RCPT and 90-day chloride ponding tests were established. There is little published information, however, on these relationships with respect to field concrete samples. To obtain such information on LMC, SDC, and CSFC samples, linear regression analyses were carried out on the RCPT and 90-day ponding data, by using RCPT as the independent and 90-day ponding as the dependent variable. The resultant relationship is shown in Figure 9. Considering the variability that can exist in field concrete samples, the results are encouraging. There is a gradual increase of total integral chloride values (90-day results) with an increase in charge passed (RCPT). For the most part, SDC samples, as a group, exhibit higher values of charge passed and correspondingly higher total integral chloride values than do LMC or CSFC samples. The relationship is expressed in the following form:

$$Y = 0.0704 + 1.53 \times 10^{-5}X$$

where Y equals total integral chloride and X equals charge passed in coulombs.

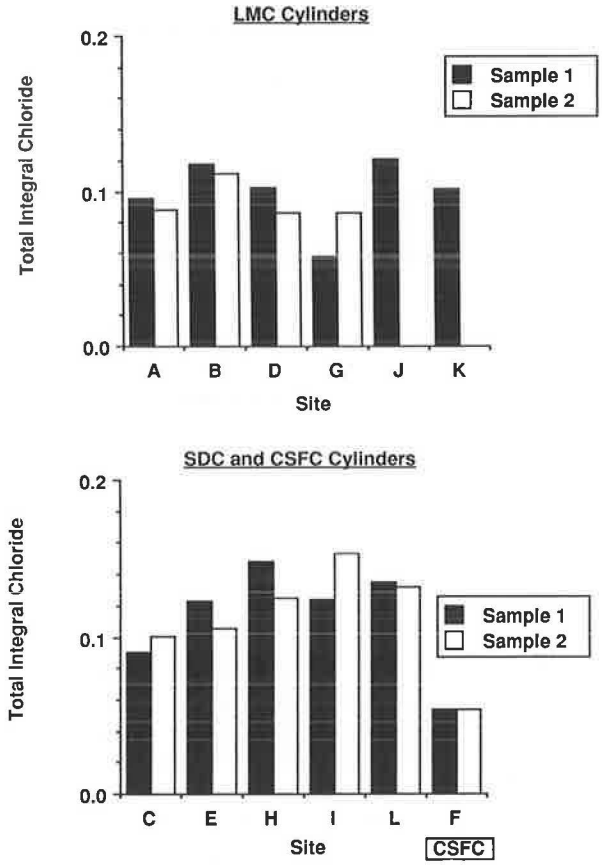

FIGURE 8 Total integral chloride contents of cylinders cast at overlay placements and subjected to 90-day ponding.

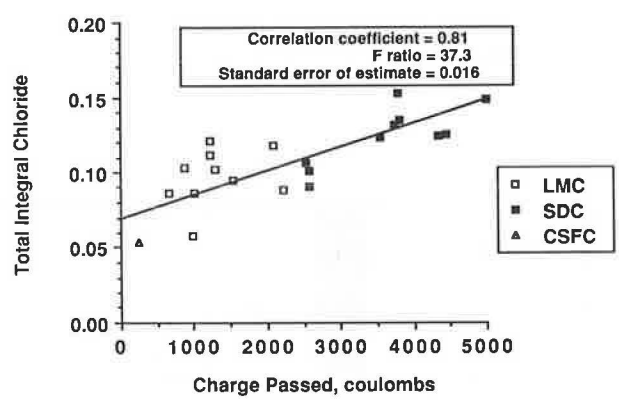

FIGURE 9 Relationship between rapid chloride permeability test results and total integral chloride contents for cylinders taken from placements.

The association between the variables is highly significant (F statistic = 37.3), the correlation coefficient is relatively high (0.81), and the standard error of estimate (0.016), amounts to approximately 16 percent of the mean value of integral chloride. The correlation coefficient for the current study is essentially equivalent to that developed in the initial laboratory study (*2*), and the standard error is less. These data demonstrate that the RCPT can be used as a fairly reliable

indicator of the long-term permeability of concrete to chloride ions and that it, therefore, has considerable merit as a rapid quality control tool for this purpose.

CONCLUSIONS

Based on the results of this study the following conclusions may be drawn:

- Rigid concrete overlay systems, such as LMC, SDC, and CSFC can be used to reduce infiltration of chloride ions into reinforced concrete bridge decks with varying degrees of effectiveness. The most impermeable overlays appear to be those incorporating condensed silica fume concrete, although long-term data with which to substantiate this conclusion are, as yet, not developed.
- Latex-modified concrete represents the next level of relative permeability. Initial permeabilities typically are in the low to very low category and decrease substantially over a period of years. Variability across a structure, however, can be high, and substantial amounts of chloride can migrate into LMC given sufficient time and exposure to severe conditions.
- Superplasticized dense concrete overlays appear to be somewhat more permeable than their LMC or CSFC counterparts. Initial permeabilities are generally in the moderate range, and high permeability values have been encountered. Over a period of years, it appears that permeability of SDC will decrease to low values.
- The rapid chloride permeability test (AASHTO T277) shows good potential for use as a means of establishing relative effectiveness of rigid overlay materials. The test may be carried out on test cylinders prepared at the jobsite and agrees well with more time-consuming procedures, such as 90-day salt ponding.

ACKNOWLEDGMENTS

This research was sponsored by the Ohio Department of Transportation (ODOT) and the FHWA. The authors acknowledge the assistance of Keith Keeran, ODOT Construction Bureau, who served as project monitor for this research. They also thank Dennis Bunke and his staff at the ODOT Bureau of Testing, for their assistance in coordination of sampling and testing. Finally, the authors thank the many ODOT district engineers and inspection staff who assisted the investigators during the field studies.

REFERENCES

1. *Solving Corrosion Problems of Bridge Surfaces Could Save Billions*. Report PSAD-79-10. General Accounting Office, Jan. 19, 1979.
2. D. Whiting. *Rapid Determination of the Chloride Permeability of Concrete*. Report FHWA/RD-81/119. FHWA, U.S. Department of Transportation, Aug. 1981.
3. *AASHTO Designation: T277-83* (Standard Method of Test for Rapid Determination of the Chloride Permeability of Concrete).
4. B. C. Brown. *A Further Evaluation of Concrete Bridge Deck Surfacing in Iowa*. Special Report. Iowa Department of Transportation, Ames, Iowa, March, 1979.
5. M. G. Hagen. *Bridge Deck Deterioration and Restoration—Final Report*. Report FHWA/MN/RD-83/01. FHWA, U.S. Department of Transportation, Nov. 1982.
6. W. F. Perenchio and S. L. Marusin. Short-Term Chloride Penetration into Relatively Impermeable Concrete. *Concrete International*, Vol. 5, No. 4, April 1983, pp. 37–41.
7. D. Whiting and L. Kuhlmann. Curing and Chloride Permeability. *Concrete International—Design and Construction*, Vol. 9, No. 4, April 1987, pp. 18–21.
8. A. G. Bishara. Latex-Modified Concrete Bridge Deck Overlays: Field Performance Analysis. In *Transportation Research Record 785*, TRB, National Research Council, Washington, D.C., 1980, pp. 24–32.
9. *A Handbook on Portland Cement Concrete and Mortar Containing Styrene/Butadiene Latex*. Dow Chemical Co., Midland, Mich., 1985.
10. S. L. Marusin. Chloride Ion Penetration in Conventional Concrete and Concrete Containing Condensed Silica Fume. In Special Publication SP-91: *Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*, Vol. 2. American Concrete Institute, Detroit, Mich., 1986, pp. 1119–1133.
11. D. Perraton, P. C. Aitcin, and D. Vezina. Permeabilities of Silica Fume Concrete. In Special Publication SP-108: *Permeability of Concrete*. American Concrete Institute, Detroit, Mich., 1988, pp. 63–84.
12. D. Bunke. ODOT Experience with Silica-Fume Concrete. In *Transportation Research Record 1204*, TRB, National Research Council, Washington, D.C., 1988, pp. 27–35.
13. M. M. Sprinkel. High Early Strength Latex Modified Concrete Overlay. Report VHTRC 88-R12. Virginia Highway and Transportation Research Council, Charlottesville, Va., 1988.
14. M. D. Luther. Silica Fume (Microsilica) Concrete in Bridges in the United States. In *Transportation Research Record 1204*, TRB, National Research Council, Washington, D.C., 1988, pp. 11–20.
15. C. Ozyildirim. Experimental Installation of a Concrete Bridge-Deck Overlay Containing Silica Fume. In *Transportation Research Record 1204*, TRB, National Research Council, Washington, D.C., 1988, pp. 36–41.
16. S. M. Law and M. Rasoulian. *Polymer Modified Concrete Study*. Report FHWA/LA-80/139. FHWA, U.S. Department of Transportation, 1980.
17. L. A. Kuhlmann and N. C. Floor. Chloride Permeability Versus Air Content of Latex Modified Concrete. *Cement, Concrete, and Aggregates*, Vol. 6, No. 1, Summer 1984, pp. 11–16.
18. M. M. Sprinkel. *Overview of Latex Modified Concrete Overlays*. Report VHTRC85-R1. Virginia Highway and Transportation Research Council, Charlottesville, Va., 1984.
19. L. A. Kuhlmann. Using Styrene-Butadiene Latex in Concrete Overlays. In *Transportation Research Record 1204*, TRB, National Research Council, Washington, D.C., 1988, pp. 52–58.
20. D. Whiting. Permeability of Selected Concretes. In Special Publication SP-108: *Permeability of Concrete*. American Concrete Institute, Detroit, Mich., 1988, pp. 195–222.

Publication of this paper sponsored by Committee on Performance of Concrete.