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Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion

Volume 5: Methods for Evaluating the Effectiveness of Penetrating Sealers

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Abstract

An electrical resistance method and a surface absorption method for the evaluation of penetrating sealers for portland cement concrete for bridge structures were tested in the laboratory and in the field. Both methods are nondestructive, rapid, and can be used on horizontal and vertical surfaces. Laboratory results are comparable to the AASHTO T259 or NCHRP 244 Series II tests. Field results were generally successful, but hot or cold temperatures make it difficult to perform the tests. Further information about evaluating the field performance of penetrating sealants was obtained by surveying highway agencies in the United States and Canada.

Executive Summary

Highway agencies in the United States and Canada were surveyed about their use of penetrating sealers for portland cement concrete. The survey revealed that highway agencies are very interested in sealers, but use remains limited. Linseed oil is used although a number of agencies no longer use it because of its poor long-term performance. Highway agencies are using more materials such as silanes and siloxanes. Test procedures to evaluate the effectiveness of sealers vary among agencies, and need further standardization. Agencies reported problems with the application and performance of sealers that affect the long-term performance of these materials.

Preliminary experimental work carried out under this research program indicated that penetrating sealers could have a substantial effect on the surface electrical properties of concrete. Specifically, electrical resistance in the near-surface layers of concrete treated with effective penetrating sealers stayed higher after wetting than in untreated concretes. Additionally, regain of insulative characteristics after removal of surface water was more rapid for sealed than for unsealed specimens. These preliminary results suggested the basis for one of the methods developed under this project. In this method, which the researchers refer to as "surface resistance testing," two strip electrodes are created on a concrete surface by masking off an area 1/8 in. (3 mm) wide by 4 in. (100 mm) long, and creating two strips 1/4 in. (6 mm) wide of conductive paint (spray applied) on either side of this strip. The paint is applied in three layers, drying for 3 to 5 minutes between each layer using a hand-held infrared dryer. The surface is then wetted and blotted dry. Contact is made to each strip with standard needle probe test leads, and resistance across the 1/8-in. (3-mm) wide concrete test area is measured over time using a soil resistance meter with a maximum range of 1 megohm. A criterion of 200 k-ohms after 4 minutes of testing was selected for differentiating between effective and ineffective sealers. Under controlled laboratory conditions, the method is capable of resolving differences between sealers in this "effective" range (thereby ranking the sealers as to their effectiveness). However, field variables and differences in concrete substrates allow for only the single classification (pass or fail) to be made under actual field conditions. The test is therefore viewed as a rapid, qualitative check

test that will allow the user to determine whether a sealer has been uniformly applied (or applied at all).

A second rapid test method developed under this program consists of a modification of a European procedure used primarily for testing of masonry units (RILEM II.4). The modified device consists of a 3-in. (75-mm) diameter surface-mounted water reservoir that is affixed to the concrete with a clay/grease seal. A calibrated 1/8-in. (3-mm) I.D. plastic tube is used to monitor absorption of the water into the concrete with time. Testing has indicated that column drops of less than .4 in. (1 cm) in 4 minutes are generally associated with effective sealers, while drops over .8 in. (2 cm) in 4 minutes are associated with ineffective sealers or unsealed surfaces. Again, the test is an indicator of sealer effectiveness that can be used to rapidly assess sealer performance on a qualitative basis. A version of this method applicable to vertical surfaces, such as bridge piers, columns, and girders, has also been developed and tested.

Field trials of the methods were carried out in the states of Vermont, California, and Minnesota. Bridge elements tested included decks, columns, piers, and girders. Applications included a test project where sealers had recently been applied, an actual full-scale application on a number of bridge substructures, and a test project where sealers had been in place for a number of years. Agreement between the test methods and the expected performance of the sealers was generally good. Some problems were encountered under extremes of temperatures, especially for the surface absorption method. The surface resistance test, while somewhat slower to prepare, appears to be more adaptable to temperature fluctuations.

1

Introduction

Needs

Sealers have been used on concrete bridge component surfaces to retard or prevent the ingress of chlorides for some time. The practice of sealing has increased appreciably in recent years, and a variety of proprietary sealants is now available. Most sealants are not permanent, and periodic reapplications are necessary to maintain protective properties. At present, no test method exists to measure the effectiveness of concrete sealers quickly, accurately, and with minimal intrusion.

Although manufacturers claim that sealers can penetrate deeply into concrete, experience indicates that sealers can penetrate at most a few millimeters into concrete of reasonable quality. An appropriate field test for the effectiveness of a sealer need only evaluate the permeability and absorption of the concrete in the near-surface zone.

Objectives

The objective was to develop a rapid, nondestructive field test for assessing the effectiveness of penetrating sealers. A sealer is considered effective if it:

- Reduces ingress of chlorides into the concrete;

- Penetrates the concrete to a depth sufficient to avoid abrasion by traffic; and
- Lasts long enough so that repeat applications can be held to a minimum.

The emphasis here was on the first of these three items. Time-dependent properties, such as abrasion and durability, must be assessed either by accelerated laboratory testing or by repeated in situ measurements over time (with some extrapolation of results necessary for prediction of long-term performance).

This research focused on the development of sensitive, simple, rugged, and low-cost tests, in keeping with the philosophy of a minimum-cost solution to the problem.

Scope

The project was carried out within the following scope of activities:

1. Demonstration of the principles of the devices on available laboratory specimens;
2. Preparation and testing of companion specimens using standardized laboratory techniques for purposes of comparison;
3. Development and fabrication of portable field devices;
4. Testing of devices on laboratory specimens of known composition under controlled conditions; and
5. Verification of performance on actual field structures.

2

Background

Previous Research

One of the first, and most complete, independent comparative studies on penetrating sealers for concrete was reported in 1981 (1). In this study, funded by the National Cooperative Highway Research Program (NCHRP), a large number of sealers of various generic types were subjected to a battery of test procedures developed by the researchers. That study has become a benchmark for the evaluation of penetrating sealers, at least in a laboratory situation. The procedures used in that report primarily use the ingress of chloride solutions into the concrete (and subsequent chloride ion analyses) as a measure of sealer effectiveness. In this respect, the procedures are similar in principle to AASHTO T259 procedures (2) although sample geometry, conditioning, and exposure are significantly different, so that substantially different findings may occur when the two methods are applied to the same materials.

The Alberta Department of Transportation has also carried out extensive studies (3,4,5) on development of laboratory test procedures for the evaluation of penetrating sealers. While concrete mixtures used for evaluation are similar to those in NCHRP 244, curing is different, and specimens are conditioned prior to testing so as to obtain a pre-selected rate of water absorption for the unsealed control specimens. Plain tap water is used in the Alberta methods, as opposed to a sodium chloride solution, which is used in the NCHRP 244 procedures. Additionally, the Alberta procedures allow for sandblasting the surfaces *after* applying the sealer, in an attempt to simulate inservice surface abrasion.

State highway agencies (SHAs) provided laboratory evaluations of penetrating sealers. Petty (6) evaluated more than 20 products using both continuous immersion and cyclic soaking in 15-percent sodium chloride solutions. Less than 50 percent of the products tested met specification. Fernandez (7) applied sealers to oven-dried specimens, then performed water absorption tests and measured depth of penetration. The Ontario Ministry of Transportation utilized a variety of test procedures in their evaluations of penetrating sealers (8), including depth of penetration, water absorption, water-vapor transmission, chloride absorption, salt scaling, and rapid chloride permeability. Finally, Rutkowski (9) evaluated absorption, resistance to chloride ion penetration, vapor permeability, and impressed current as test procedures for evaluating effectiveness of sealers.

A number of field studies on the effectiveness of penetrating sealers also have been reported. Some of the earliest applications were carried out by the Oklahoma Department of Transportation. Smith (10) reports that by the end of 1985, 245 bridge decks had received a silane treatment. The bridges ranged in age from newly constructed to 15 years when sealers were first applied. Nine bridges were selected for periodic chloride sampling. At the time the report was issued, the data were insufficient to allow conclusions to be drawn as to the effectiveness of the sealers in reducing the rate of chloride accumulation in these decks. Rasoulia et al. (11) periodically obtained cores from five structures treated with silanes in 1981 and allowed to weather in northern and marine environments for 4 years. Results indicate that the absorption of cores gradually increased with time and was not much less than that of control (unsealed) samples in some cases. Depth of penetration of silanes was found to be 0.1 in. (2 mm) at most. Studies in Vermont (12,13,14) were similarly disappointing, with silane sealers failing to perform much better than conventional tar-emulsion or linseed oil tested products, though chloride penetration was reduced as compared with untreated concretes in wingwalls and median barriers.

In a somewhat more extensive study, the Minnesota Department of Transportation (15) evaluated nine products on a bridge deck overlaid in 1983 with low-slump dense concrete. After 3 years of sampling, the most effective products included an oligomeric alkoxy-silane and a penetrating epoxy. Other products, including silanes, fluorosilicates, silanoate, and methyl methacrylate, lost effectiveness within the 3-year test period, as measured by the percentage increase in chloride content compared to untreated sections. A similar study was carried out by the Pennsylvania Department of Transportation (17), in which seven sealants were applied to the deck, sidewalks, and parapets of a bridge constructed in 1984. Sampling for chloride content spanned a 4-year period. Only one penetrating sealer (a resin in mineral spirit formulation) was found to be as effective as conventional linseed oil treatment in reducing chloride ion penetration when compared to untreated sections.

In view of these somewhat conflicting results, it is apparent that a rapid means to determine sealer effectiveness via an in situ nondestructive test is sorely needed. Before proceeding, however, SHAs were surveyed in order to develop data on individual experiences and test methods currently in use.

Survey of SHA Experiences with Penetrating Sealers

The objectives of the survey were as follows:

1. Update information on extent of use of penetrating sealers;
2. Delineate the major applications areas for sealers;
3. Obtain information on testing procedures used by highway agencies in qualifying penetrating sealers; and
4. Note problems commonly occurring in application and performance of sealers.

A questionnaire constituted the primary means of obtaining this information. Responses were received from all 50 U.S. SHAs and 11 Canadian provincial highway agencies (PHAs). Details of the questionnaire and individual SHA responses are given in a publication by Whiting (17); only a summary is included in this report.

Extent of Use

Of the agencies surveyed, 46 U.S. and 9 Canadian agencies make use of sealers. Included among these sealers was linseed oil, which has a relatively long history of use for highway applications.

The current (1989) use of penetrating sealers and linseed oil is summarized in Table 2-1. The categories listed (i.e., extensive, moderate, limited, and experimental) represent the respondent's perception of the use of such materials by the agency. The number of agencies claiming extensive use of linseed oil outnumbers those claiming extensive use of penetrating sealers. The majority of agencies are using penetrating sealers on a limited or experimental basis.

Table 2-1. Extent of use of penetrating sealers.

Extent of Use	Number of Agencies	
	Penetrating Sealers	Linseed Oil
Extensive	7	9
Moderate	7	4
Limited	23	3
Experimental	9	0

Application Areas

By far, the most widely used application of penetrating sealers is on concrete bridge decks. Only about 30 percent of the respondents are utilizing penetrating sealers in substructural elements such as piers, pier caps, and support beams. This is likely due to the fact that deck deterioration is still the primary problem in most areas, although the incidence of salt-induced damage to support substructures has been increasing in recent years. About the same percentage is being applied to median barriers. Finally, 28 agencies reported use of penetrating sealers on appurtenance elements, which, for purposes of this discussion, include parapets, abutments, railings, and sidewalk.

Test Procedures

Many agencies use more than one test procedure for their evaluations. Additionally, a number of agencies rely on data submitted by vendors, and do not carry out their own tests. A tabulation of test procedures, in decreasing order of usage, is given in Table 2-2.

The most widely used procedure is AASHTO T259, "Resistance of Concrete to Chloride Ion Penetration," which is commonly referred to as "90-day ponding" (2). The second most widely used test is Series II of NCHRP 244 (1). It must be recognized that this is not a standardized test method but rather the report of a laboratory investigation. As such,

Table 2-2. Test procedures used in evaluation of penetrating sealers.

Test Procedure	Number of Agencies
AASHTO T259	13
NCHRP 244 ^a	9
ASTM C642	6
Absorption (Not ASTM C642)	6
Rely on Vendor Data	6
Penetration Depth ^b	5
Vapor Permeability ^b	5
Other Tests	5
ASTM C672	3
AASHTO T277	2
Freeze-Thaw Testing	2
Skid Resistance Testing	1

^aMost agencies utilize the Series II testing procedure described in NCHRP Report 244 (1).

^bTest procedures developed by Oklahoma DOT.

considerable latitude in testing and interpretation of test results is possible. ASTM C642, "Standard Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete," (18) is the next most widely used method, along with other nonstandard absorption methods. A number of techniques have been developed by the Oklahoma Department of Transportation, and are used by a number of other agencies. These include tests for average penetration depth of sealers and vapor permeability. Finally, tests for deicer scaling resistance (ASTM C672), freeze-thaw resistance (ASTM C666), rapid chloride permeability (AASHTO T277), and skid number (AASHTO T278) are used by a relatively small number of agencies (19-22).

Problem Areas

Respondents noted a variety of problems with the application of penetrating sealers. These included the following: drifting and evaporation in hot and windy conditions, difficulty in obtaining specified coverage on newly placed concrete, slippery surfaces when linseed oil or other more viscous sealers are used, runoff during application, discoloration of concrete, flammability, non-uniform application, and little or no apparent penetration.

Respondents also said that the performance of penetrating sealers was less than desired. A number of responses indicated that many penetrating sealers were ineffective (or at least not as effective as claimed) in reducing infiltration of chloride ions into concrete. In many cases, this was manifested as a loss of effectiveness with time, and was especially bothersome on wearing surfaces, where effectiveness was stated to be about 3 years at most. Other performance problems included: reduction of skid resistance (for sealers that left a surface residue), failure to improve freeze-thaw and scaling resistance in non-air-entrained concretes, and failure to halt corrosion of reinforcing steel (as measured by half-cell potential surveys).

Field Test Procedures

Field tests of penetrating sealers have used core or drill samples to determine the extent and severity of chloride ion penetration. While this provides information on long-term effectiveness, the tests are destructive, time-consuming, and costly, and the number of samples from a structure is limited. A second technique, used by at least two agencies, is to flood the treated sections with water. If the water remains on the surface or "beads up," the sealer is judged to be effective; if it is rapidly absorbed into the concrete, the sealer is judged to be ineffective. Obviously, this test is qualitative and has significant subjective aspects. The California Department of Transportation (Caltrans) uses a concrete moisture meter (R. Maggenti, personal communication). No published information is as yet available.

3

Specimen Preparation and Comparison Tests

Preparation of Test Specimens

Test specimens were prepared for two purposes. First, the specimens were used to serve as concrete substrates onto which sealers could be applied and subsequently tested using laboratory procedures in common practice, such as NCHRP 244 Series II (1) and AASHTO T259 (2). Second, the sealed concrete specimens were also used for development and trial of the new field test procedures described in Chapter 4.

The mix proportions for the test concrete are shown in Table 3-1. Aggregates used were a chloride-free siliceous gravel from Eau Claire, Wisconsin, having a maximum size of 3/4 in. (19 mm), and a chloride-free siliceous sand from the same locality with a fineness modulus of 3.0. A Type I (low alkali) cement was used in the mixtures. A 2-percent aqueous solution of neutralized Vinsol resin was used as an air-entraining agent.

All mixtures fell within the selected slump range of 3 ± 1 in. (75 ± 25 mm) and 6 ± 1.5 -percent air content.

Table 3-1. Mixture proportions for concrete test mixtures.

Quantities (lb/yd ³)					
<u>Cement</u>	<u>Sand</u>	<u>Gravel</u>	<u>Water</u>	Water : Cement <u>Ratio</u>	<u>Admixture</u>
456	1479	1764	230	0.50	NVR-5 fl oz/cwt

Note: 1 lb/yd³ = 0.59 kg/m³; 1 fl oz/cwt = 0.00065 L/kg.

Two types of concrete test specimens were cast. The first type, produced primarily for NCHRP 244 Series II testing, consisted of 4-in. (100-mm) cubes (1). The second type, produced for AASHTO T259 ponding and for evaluation of prototype field methods, consisted of 12- x 12- x 3-in. (305- x 305- x 75-mm) slabs (2). A total of six batches of concrete was prepared, with six cubes and two slabs being produced from each batch. All specimens were covered with wet burlap and polyethylene sheeting immediately after casting and finishing was completed. After 24 hours, all specimens were demolded and placed into separate heavy-duty polyethylene bags for a period of 28 days. After 28 days of storage, one-half of the specimens (i.e., the specimens produced from the first three batches of concrete) were placed into an environment maintained at 73°F ± 3° (23°C ± 1.7°) and 50-percent relative humidity (± 5 percent). This was denoted as "Set A," or the "dry" set of specimens. The remaining specimens were removed from the storage bags and subjected to one of the following moist cycles, depending on whether cubes or slabs were used. Cubes were placed in a moist room of the type used to cure concrete specimens for an 8-hour period at weekly intervals. When not in the moist room, they were stored in the same environment as the dry specimens. Slabs were placed on masonry blocks in a horizontal position, and the top surfaces covered with wet burlap and soaked twice during 1 day at weekly intervals. The burlap covering was removed the day following each soaking day in the cycle. All specimens were given a light sandblast (just enough to remove surface paste) 14 days after removal from the polyethylene bags. Cubes were sandblasted on all faces; slabs were sandblasted on the finished face only.

Selection and Application of Penetrating Sealers

Five penetrating sealers were chosen for use in the development program. These were coded from 1 through 5. Generic descriptions of the sealer compositions were provided by manufacturers. The sealers were chosen so as to represent the most commonly used types of penetrating sealers. Materials that function primarily as surface coatings or materials whose primary application is for sealing cracks were not included in the program. Sealer codes, generic descriptions, and coverage rates are given in Table 3-2.

Table 3-2. Penetrating sealers used in development program.

Code	Generic Description	Coverage Rate (ft ² /gal)
1	40-percent isobutyltrimethoxy silane in isopropanol	125
2	20-percent oligomeric alkyl-alkoxysiloxane in mixture of mineral spirits, naphtha, and diacetone alcohol	125
3	40-percent alkylalkoxy silane in water	125
4	Water-based solium silicate solution	150
5	Two-component solvent-based epoxy penetrant	150
6	Control	no sealer applied

Note: 1 ft²/gal = 0.0246 m²/L

All sealers were applied with a brush. The brush was pre-saturated with sealer prior to application to reduce errors due to retention of sealer on the brush. Sealers 1, 2, 3, and 5 were applied in single coats at the rate indicated in Table 3-2. Sealer 4 was applied in two coats, the surface being allowed to dry between coats. The surface was misted with tap water following the final coat. Additionally, the specimens treated with this sealer were also misted within 1 to 12 hours following application of sealer.

For Set A (dry) specimens, sealers were applied 21 days after removal from the polyethylene bags. For Set B (cycled) specimens, sealers were applied 15 weeks after commencement of

the moist cycling routine. Sealers were applied 2 days after removal of the soaked burlap in the last cycle.

Comparison Testing

Two procedures were chosen for comparison of test methods developed in this program (see Chapter 4) with standard laboratory results. These are included in the NCHRP 244 Series II procedures (1) and AASHTO T259 (2). Descriptions of the test procedures as applied to the specimens produced in this study and results of this testing follow.

NCHRP 244 Series II Testing

Series II testing was applied to cubes prepared from Set A and Set B concretes. Testing was started on Set A specimens 10 days after the application of sealers. Testing was started on Set B specimens after an additional five moist cycles had been accrued after the application of sealers. All cubes were exposed to a 15-percent aqueous solution of sodium chloride for a period of 21 days at $73^{\circ}\text{F} \pm 3^{\circ}$ ($23^{\circ}\text{C} \pm 1.7^{\circ}$) and 50-percent relative humidity, ± 5 percent, for an additional 21 days. Each cube was then split in half. One-half of each cube was crushed to a 50-mesh (300- μm) sieve. A 10-g sample was then taken from each lot of powder and analyzed for total (i.e., acid soluble) chloride ion as described in AASHTO T260 (23). Results are given in Tables 3-3 (Set A) and 3-4 (Set B).

The Set A sealers performed as follows:

Sealer 2 > Sealer 1 > Sealer 3 > Sealer 5 > Sealer 4 > Control

The Set B sealers performed as follows:

Sealer 1 \approx Sealer 3 > Sealer 2 > Sealer 5 > Sealer 4 > Control

In both cases, the most effective sealers were of the alkyl-alkoxy silane and siloxane categories. Epoxy was generally less effective by a factor of 2 or more, and silicate was essentially ineffective, differing only marginally from the behavior of unsealed specimens.

Table 3-3. Results of NCHRP 244 Series II testing on Set A cubes.

Cube Number	Sealer	Percent Chloride by Mass of Concrete	
		Individual	Average
1	None	0.305	0.253
7	None	0.223	
13	None	0.230	
2	1	0.038	0.035
8	1	0.031	
14	1	0.035	
3	2	0.030	0.028
9	2	0.026	
15	2	0.027	
4	3	0.069	0.055
10	3	0.037	
16	3	0.059	
5	4	0.180	0.209
11	4	0.225	
17	4	0.222	
6	5	0.099	0.133
12	5	0.177	
18	5	0.123	

AASHTO T259 Testing

AASHTO T259 testing (2), commonly referred to as "90-day ponding," was applied to slabs prepared from Set A concretes. Due to time limitations, Set B concretes were not subjected to this procedure. Foamed polystyrene dikes 1/2 x 1/2 in. (12 x 12 mm) in cross section were affixed to the finished surface of each slab with silicone caulk. Ten days after the application of sealers, a 3-percent solution of sodium chloride was applied to each slab to a

Table 3-4. Results of NCHRP 244 Series II testing on Set B cubes.

Cube Number	Sealer	Percent Chloride by Mass of Concrete	
		Individual	Average
19	None	0.198	0.172
25	None	0.160	
31	None	0.157	
20	1	0.017	0.021
26	1	0.032	
32	1	0.015	
21	2	0.025	0.031
27	2	0.035	
33	2	0.033	
22	3	0.027	0.023
28	3	0.020	
34	3	0.022	
23	4	0.161	0.153
29	4	0.155	
35	4	0.142	
24	5	0.089	0.071
30	5	0.065	
36	5	0.060	

depth of 1/2 in. (12 mm). Each slab was then covered with a rigid acrylic sheet to prevent evaporation of the solution. The solution was replenished at frequent intervals. After 90 days of ponding, the solution was removed, the slab surfaces allowed to air dry, and the surfaces brushed to remove loose crystals. Three holes were then drilled into the surface of each slab using a 1.125-in. (28-mm) impact hammer drill. Drill powder was removed at depths of 1/16 to 1/2 in. (2 to 12 mm) and 1/2 to 1 in. (12 to 25 mm). The powder was processed through a 50-mesh (300- μ m) sieve, and analyzed for total chloride ion using AASHTO T260 procedures (23). Results are shown in Table 3-5. The following ranking, in order of sealer effectiveness, can be assigned:

Sealer 1 > Sealer 3 > Sealer 2 > Sealer 5 > Sealer 4 > Control

While the positions of individual sealers within the rankings differ between the T259 and Series II results, the relative performance of the broad classes of sealers remains the same. That is, silanes and siloxanes reduce chloride penetration more than the epoxy and silicate tested. These results, then, were used as a base of comparison for results obtained from the more rapid field techniques under development in this research program and described in the following chapter.

Table 3-5. Results of AASHTO T259 testing on Set A slabs.

Slab	Sealer	Hole 1 Depth (in.)		Hole 2 Depth (in.)		Hole 3 Depth (in.)		Average Depth (in.)	
		1/16-1/2	1/2-1	1/16-1/2	1/2-1	1/16-1/2	1/2-1	1/16-1/2	1/2-1
1	None	0.180	0.050	0.158	0.042	0.173	0.046	0.170	0.046
2	1	0.032	0.004	0.032	0.007	0.037	0.007	0.034	0.006
3	2	0.043	0.011	0.067	0.023	0.055	0.005	0.055	0.013
4	3	0.042	0.013	0.047	0.009	0.026	0.007	0.038	0.010
5	4	0.157	0.018	0.129	0.028	0.133	0.018	0.140	0.021
6	5	0.098	0.005	0.082	0.007	0.082	0.010	0.087	0.007

Note: 1 in. = 2.54 cm

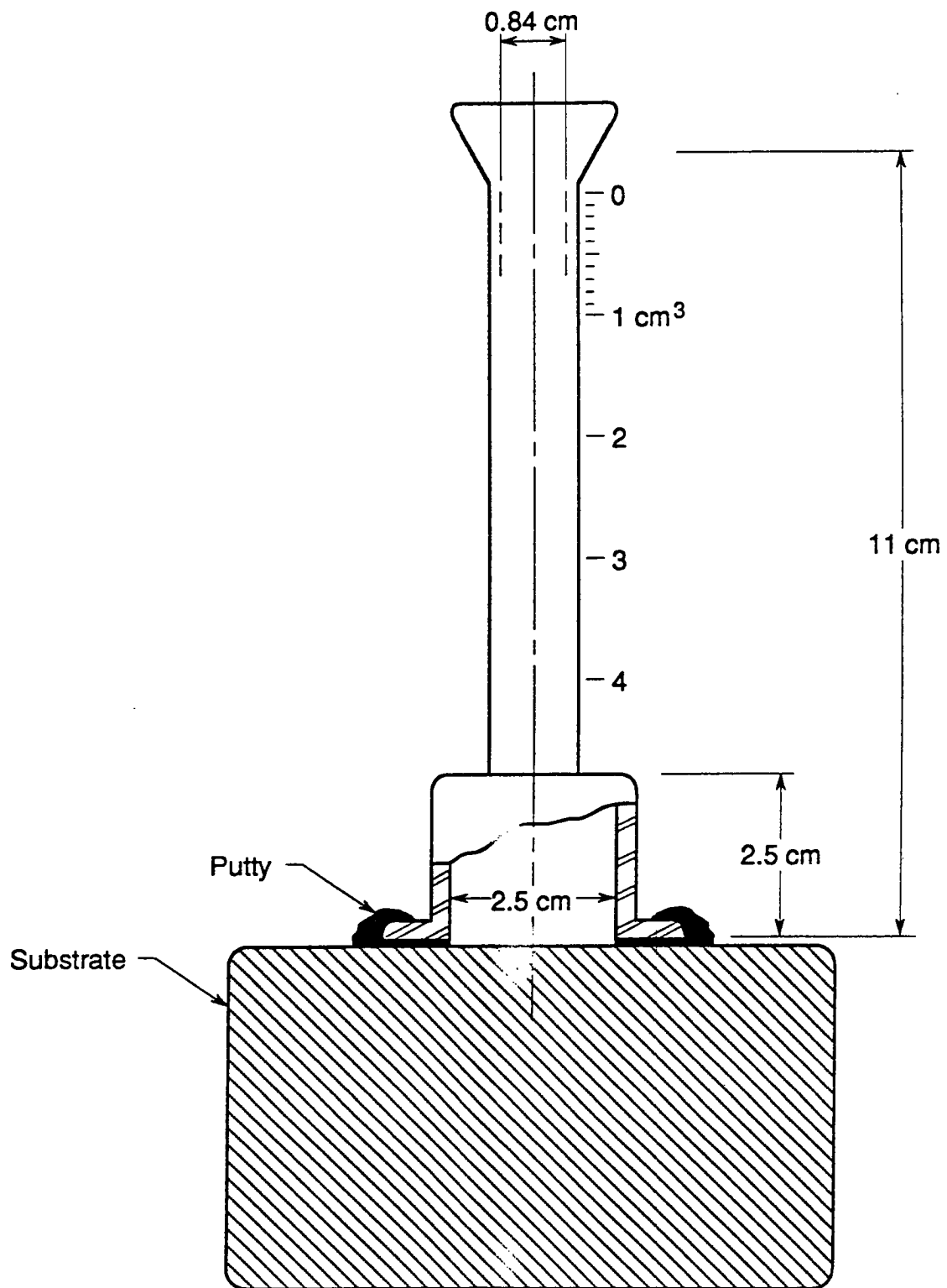
4

Development of Test Methods

Two potential test methods were investigated. The first approach was to develop a method based on the electrical response of the surface layer of concrete. Penetrating sealers are able to prevent moisture from entering the concrete, so they have a significant effect on the electrical properties of concrete, which are known to be a strong function of the moisture content (24). The second approach was somewhat more direct, relying on determination of moisture-barrier properties by measuring the surface absorptivity. Test procedures for surface absorptivity of natural building stones (25) and concrete (26) have been published, but modifications were deemed necessary for the desired application. Development of these two procedures, "surface resistance" and "surface absorption," respectively, is described in this chapter.

Surface Absorption Test

The equipment follows RILEM procedure II.4 (25) for testing the water resistance of natural building stones and is similar in principle to the British ISAT concrete permeability method (26). The RILEM equipment was donated to the project by the manufacturer. A diagram of the equipment is shown in Figure 4-1. The standpipe is graduated in units of cm^3 , with a total capacity of 4 cm^3 . The tube is readable to $\pm 0.1 \text{ cm}^3$.



Note: 1 in. = 2.54 cm

Figure 4-1. RILEM II.4 surface absorption device.

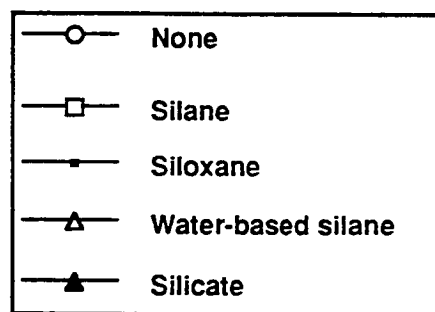
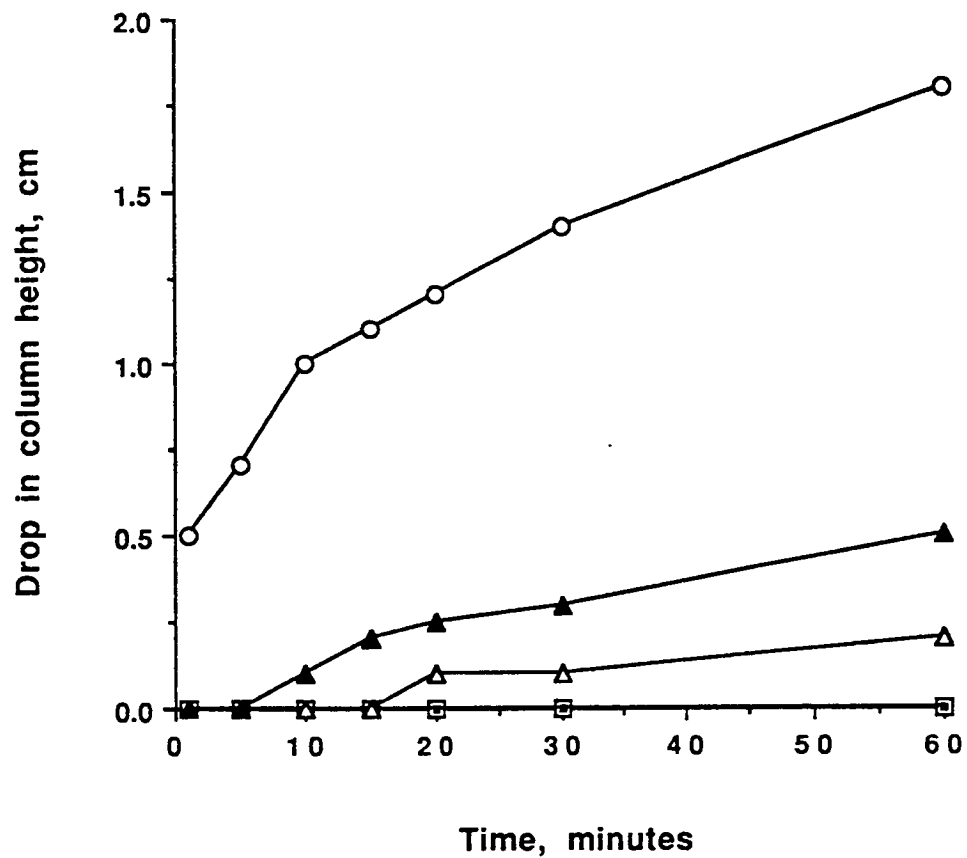
Preliminary tests using this device were performed on 4-in. (100-mm) cube specimens prior to preparation of the main specimen set described in Chapter 3. The concrete used was similar in proportions to that shown in Table 3-1, but coarse aggregate was sieved from the concrete mixture so that only the mortar phase was used for casting. This was done primarily to allow for development of the electrical test method (see below), but since the cubes were available they were used for partial tests of the RILEM II.4 method also. Four sealers were applied, these being identical to Sealers 1, 2, 3, and 4 described in Chapter 3, but from different lots.

In carrying out the test, the device is affixed to the test surface by means of an elastic putty. The tube is then filled with water to just above the zero mark. When the meniscus reaches the zero mark, timing is initiated. Results are shown in Figure 4-2. The test exhibited a good potential for distinguishing between sealed and unsealed concrete. It was also noted that the silicate-sealed concretes in this instance performed less favorably than the silanes and siloxanes, which reflected their relative performance in the comparison testing using the laboratory techniques. Sensitivity, however, was limited early in the test, with differences not becoming apparent until after 15 to 20 minutes. Improvement in sensitivity and reduction in test time were needed.

A modified version of the RILEM II.4 device was designed and fabricated. This consisted of a larger water reservoir having a 3-in. (75-mm) diameter contact area with the concrete surface (see Figure 4-3). A capillary tube having a 0.125-in. (3-mm) inner diameter is threaded into the top end of the reservoir. The cell is affixed to the concrete surface by using a blend of modeling clay and axle grease (5 g grease to 50 g clay) that is rolled into a cylindrical shape and cut and fit to the circumference of the bottom of the cell.

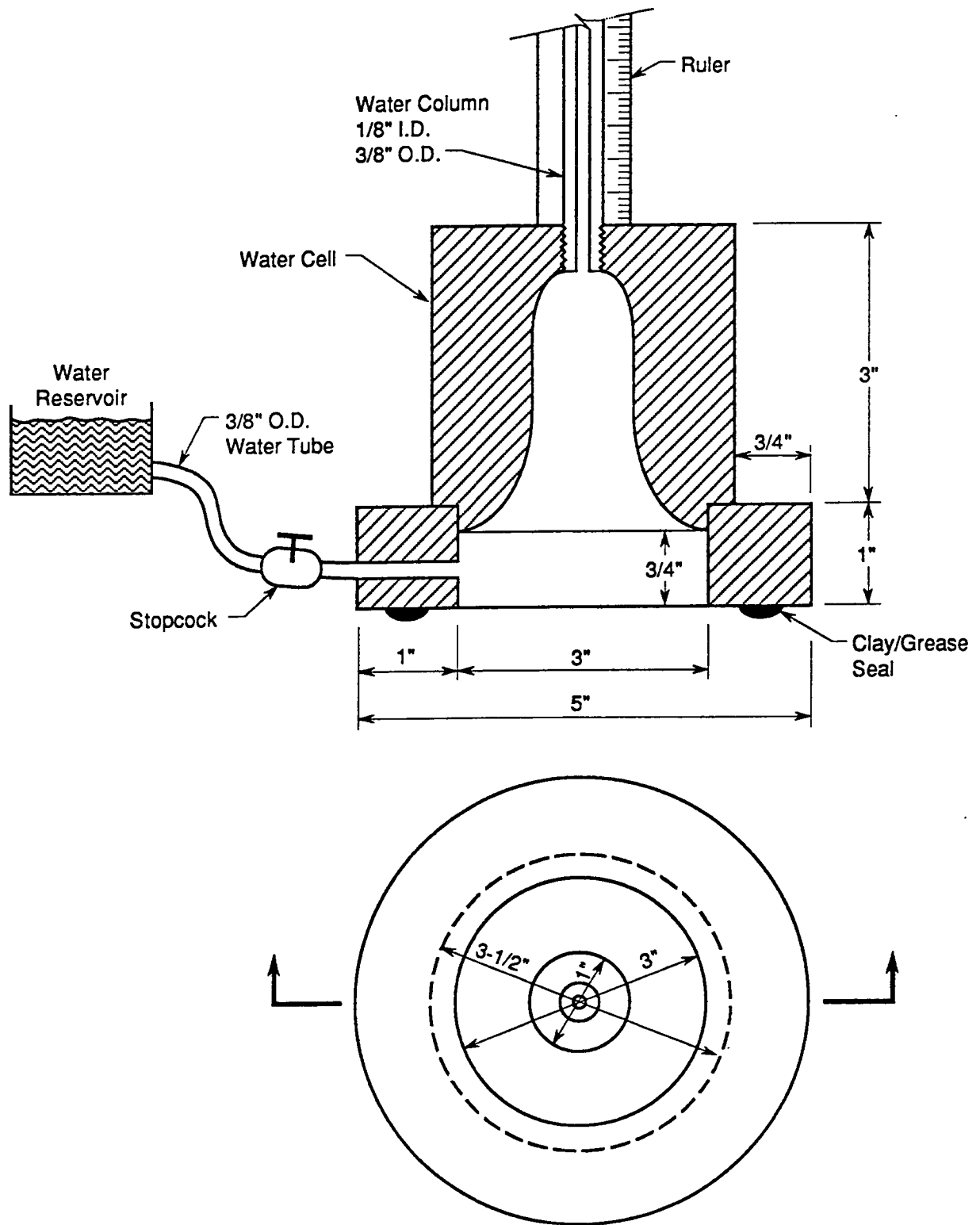
The test is conducted by allowing water to flow from an external reservoir into the base unit until the water column is filled to a height of approximately 16 in. (40 cm). The intake tube is then closed and the column drop monitored as a function of time over a 10-minute period. Some results obtained at 4 and 10 minutes are shown in Table 4-1. These tests were carried out with Set A slabs after approximately 16 weeks of storage in laboratory air.

The results follow the general trends seen in the comparison testing, with the exception that the epoxy sealant (No. 5) is somewhat more effective in this test than in the tests carried out on cube specimens. However, the distinctions between the unsealed concrete, concrete sealed with an ineffective product (Sealer 4), and concrete treated with penetrating sealer are readily discernable.



Note: 1 in. = 2.54 cm

Figure 4-2. Results of RILEM II.4 testing using various penetrating sealers.



Note: 1 in. = 2.54 cm

Figure 4-3. Modified RILEM II.4 device for use on horizontal surfaces.

Table 4-1. Results of modified RILEM II.4
(surface absorption) testing.

Sealer	Drop in Capillary Column (cm) at Time Indicated	
	<u>4 Minutes</u>	<u>10 Minutes</u>
None	4.5	8.0
1	0.7	1.0
2	0.6	0.7
3	1.3	1.7
4	3.0	5.0
5	0.7	1.3

The technique was then applied to Set B slabs given the "moist cycle" previously described. Even for unsealed slabs, in contrast to previous results, drop in column height was less than 2 cm at 4 minutes and less than 4 cm at 10 minutes. Obviously, moisture in the slab was impeding inflow of water during testing. By subjecting the slab surface to drying for a period of 10 minutes at 120°F (48°C), more reasonable values were obtained. In the field, however, this would reduce significantly the number of areas that could be tested in a given time period, and it would be more practical simply to schedule tests during dry periods. In order to evaluate the effects of temperature, a series of Set A slabs was conditioned at pre-selected temperatures and subjected to the surface absorption testing. Results are given in Table 4-2.

Although there are some differences caused by temperature, the general pattern of the data remains fairly consistent. Examination of the results leads to the following suggested preliminary criteria for interpretation of test results:

Column Drop in 4 Minutes

< 1 cm (.39 in.): Good Sealer
> 2 cm (.78 in.): Poor or No Sealer

Column Drop in 10 Minutes

< 2 cm (.78 in.): Good Sealer
> 4 cm (1.56 in.): Poor or No Sealer

Table 4-2. Results of surface absorption testing at various temperatures.

Sealer	Column Drop (cm) in 4 Minutes at Indicated Temperature			Column Drop (cm) in 10 Minutes at Indicated Temperature		
	38°F	73°F	104°F	38°F	73°F	104°F
None	4.9	4.5	3.0	9.2	8.0	5.5
1	0.1	0.7	0.1	0.3	1.0	0.2
2	0.1	0.6	0.2	0.3	0.7	0.4
3	0.3	1.3	0.2	0.5	1.7	0.2
5	0.5	0.7	0.6	1.1	1.3	1.2
4	3.5	3.0	2.2	7.0	5.0	4.3

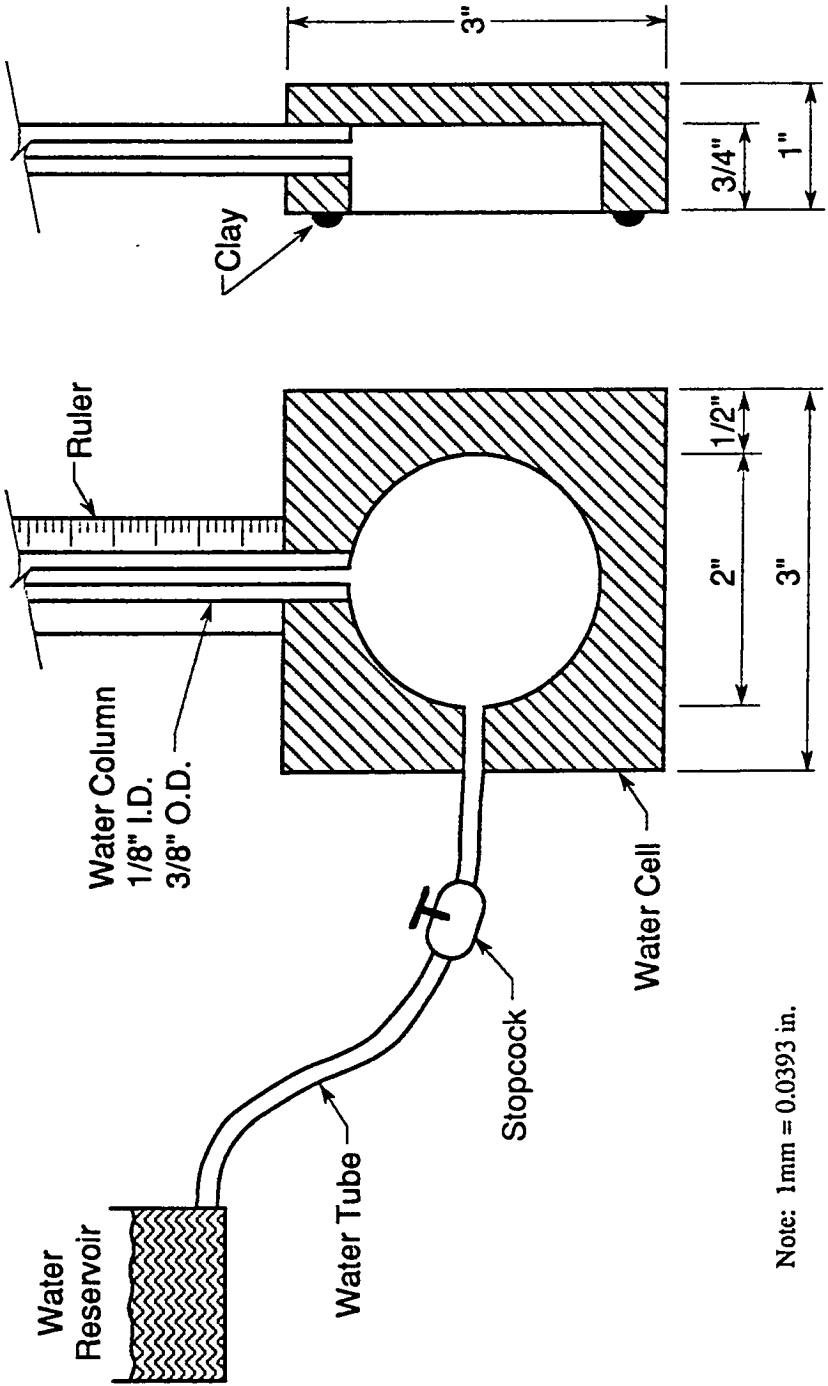
Note: °F = 1.8 x °C + 32; 1 in. = 2.54 cm.

It was recognized that the modified test pieces would be applicable only to horizontal surfaces as presently configured. In order to be able to test vertical surfaces, a new cell was constructed. This utilized one-half of an "osmotic cell" developed by Stark for use in studies of alkali-silica reactivity (27).

A diagram is shown in Figure 4-4. This cell is used in much the same manner as the horizontal unit, with the cell being affixed to the surface with a clay/grease seal, water let in to fill the cell, and the water in the column brought to the desired starting level. The preliminary results were very similar to those obtained for the horizontal unit, and it appeared that the same acceptance criteria could be used.

Electrical Resistance Test

Electrical resistance testing has been used to assess the integrity of membranes applied to bridge deck surfaces. In this test procedure, covered by ASTM Designation D3633 (28), a copper plate is placed onto a wetted sponge placed on the surface of the deck. An electrical connection is made to the reinforcing steel in the top mat of the deck. The electrical resistance between the top mat and the copper plate is then measured by an ohmmeter. A high value (typically greater than 500 k-ohm) indicates that the membrane is functioning essentially as a dielectric material. Attempts to apply this technique to surfaces treated with



Note: 1 in. = 2.54 cm

Figure 4-4. Modified RILEM II.4 test piece for use on vertical surfaces.

penetrating sealers has not been successful, primarily because only a very small thickness of concrete is actually affected by the sealer, and the total resistance measured mainly reflects the resistance of the body of unsealed concrete. A technique more sensitive to the sealed surface zone of the concrete was needed.

It was decided to pursue a technique based on the measurement of resistance in the surface zone. In order to examine the validity of such an approach, it was necessary to develop information on the effects of sealers on resistance of thin layers of concrete. A set of 4-in. (100-mm) mortar cubes was cast for initial evaluation of the electrical response of sealers. The cubes contained copper mesh electrodes embedded at 1/8-in. (3-mm) and 1/4-in. (6-mm) depths from one of their faces. Cubes were cured 21 days in plastic bags, then exposed to lab air for an additional 21 days. Sealers similar to 1, 2, and 3 in Table 3-2 were then applied to the cube faces at manufacturer's recommended rates of application.

One week after sealer application, the face nearest to the embedded copper mesh was coated with conductive silver spray paint, masking out a grid of 1/16-in. (1.5-mm) wide lines spaced 1/2 in. (12 mm) apart to allow for subsequent wetting of the surface. An electrical connection was made using a thicker conductive paint formulation.

After the paint was dried, connections were made between the embedded electrode mesh and the surface electrode (paint). An AC soil resistance meter (maximum range = 1.1 megohm) in 2-pin mode was used to measure electrical resistance through the concrete. Initial electrical resistance was taken, and each specimen was then wetted with tap water. The drop in resistance with time over a 2-minute period was measured. The surface was re-wetted 90 seconds into the test.

Results are shown in Figure 4-5. Initial resistance readings (unwetted) are very similar. A difference is seen, however, when surfaces are wetted; the unsealed concrete exhibits a dramatic drop in resistance with time. Solvent-based silane and siloxane (Sealers 1 and 2) performed similarly. The water-based silane showed a somewhat greater drop in resistance with time. As these results agreed favorably in ranking with laboratory tests carried out on the same sealer formulations, the basis for the method was considered valid, and further development warranted.

It was recognized that a field technique that could be applied to in-place concrete could not exactly reflect the conditions used in the demonstration series described earlier. Obviously, copper mesh could not be embedded in existing concrete. However, it was felt that by placing relatively thin electrodes a small distance apart on the surface of the concrete, the

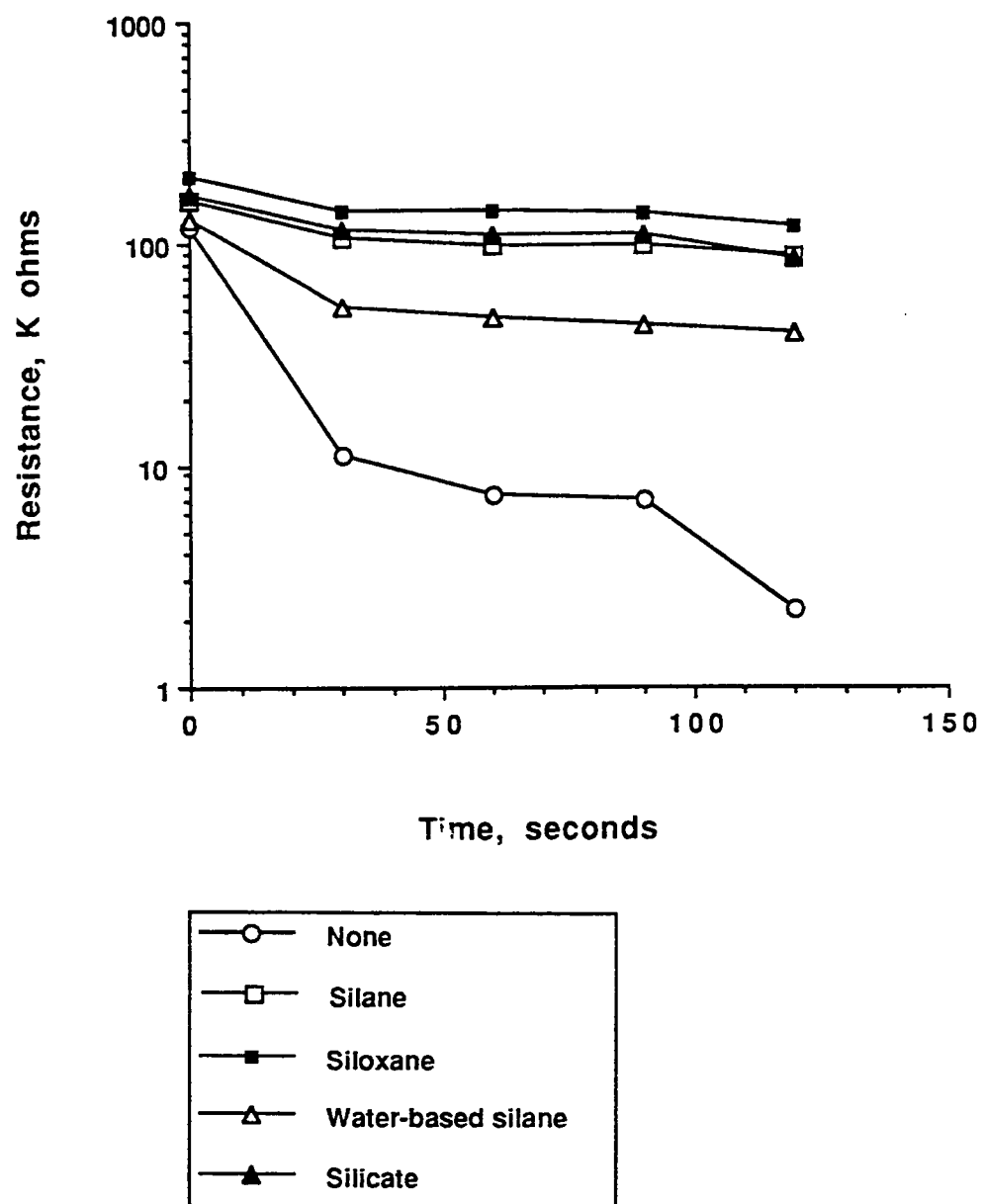


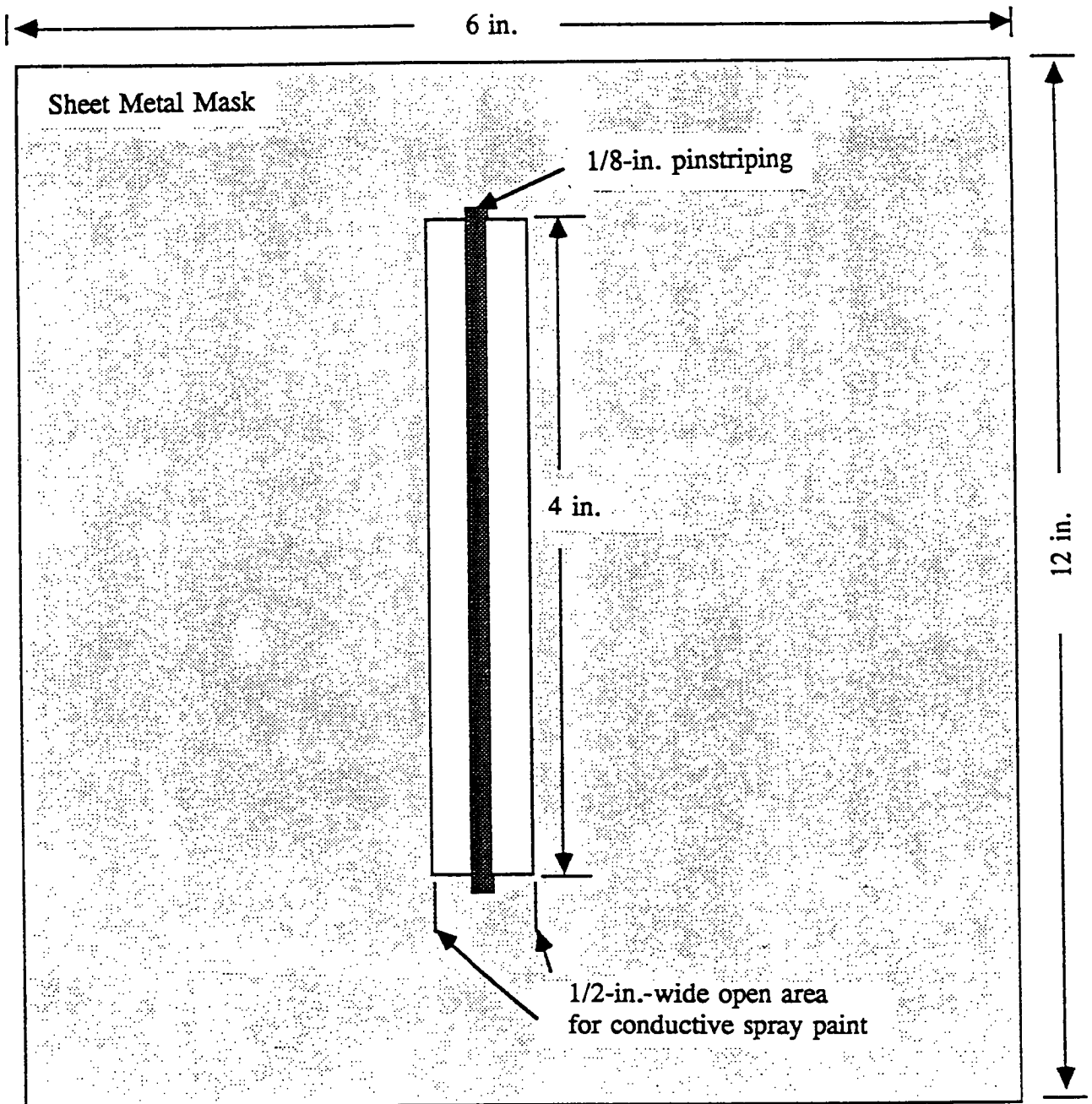
Figure 4-5. Electrical resistance versus time for various sealers after wetting surface.

effective volume of measurement could be confined to the near-surface zone. To evaluate this configuration, two strip electrodes were created on the concrete surface by masking off an area 1/8 in. (3 mm) wide by 4 in. (100 mm) long, and creating two strips of conductive paint (spray applied) on either side of this strip 1/4 in. (6 mm) wide (see Figure 4-6). The spray paint is silver-based and quite expensive (approximately \$40 per can). Less expensive, nickel-based paint was also tried; however, reproducible low resistance strips were more difficult to achieve, and the application appeared to be more operator-dependent.

The paint was applied in three layers, drying for 3 to 5 minutes between each layer using a 1500W hand-held blow dryer. Optimum coatings appeared to be achieved when the surface temperature reached 120°F (49°C). This can be monitored using either a surface thermocouple or a liquid-crystal temperature strip indicator. As soon as the paint had dried, contact was made to each strip with standard needle probe test leads, and the resistance of each separate strip measured using a hand-held multimeter. This resistance should be less than 50 ohms if it has been applied properly. Resistance across the 1/8-in. (3-mm) wide concrete test area was then measured using the soil resistance meter. Because of the high readings obtained (normally in excess of 1 megohm), lead resistance was negligible. The first area was then wetted with a hand-held sponge for a period of 5 minutes and excess water removed from across the 1/8-in. (3-mm) strip with a towel to prevent shorting of the electrodes. Five minutes after initial contact of the surface with water, the first readings were taken.

The technique was applied to Set A slabs that had been stored for 12 weeks at approximately 50-percent relative humidity (RH) since the first application of sealers. Results are shown in Figure 4-7. For control and Sealer 4 slabs, resistance remained fairly constant at low values for a few minutes. For slabs treated with the more effective sealers, resistance rose quickly to a high value. The researchers have interpreted this behavior as representing evaporation of the small amount of water that does penetrate (or initially forms a very thin film) on the concrete surface. Examination of these plots of resistance versus time indicated that the parameter "time to 1.1 megohm" appeared to offer the most meaningful comparison between sealers. This value is the upper limit of the soil resistance device being used. Resistance of the concrete between the gages prior to wetting varies between 5 and > 18 megohms (using a laboratory impedance meter).

Data are presented in Table 4-3 (average of four positions on each slab), and they compare very favorably with rankings developed using standard laboratory methods. That is, solvent-based silane and siloxane (Sealers 1 and 2) appear most effective, water-based silanes (Sealer 3) somewhat less so, followed by epoxy (Sealer 5). Silicates (Sealer 4) appear no more effective than uncoated concretes.



Note: 1 in. = 2.54 cm

Figure 4-6. Mask for production of surface electrodes (not to scale).

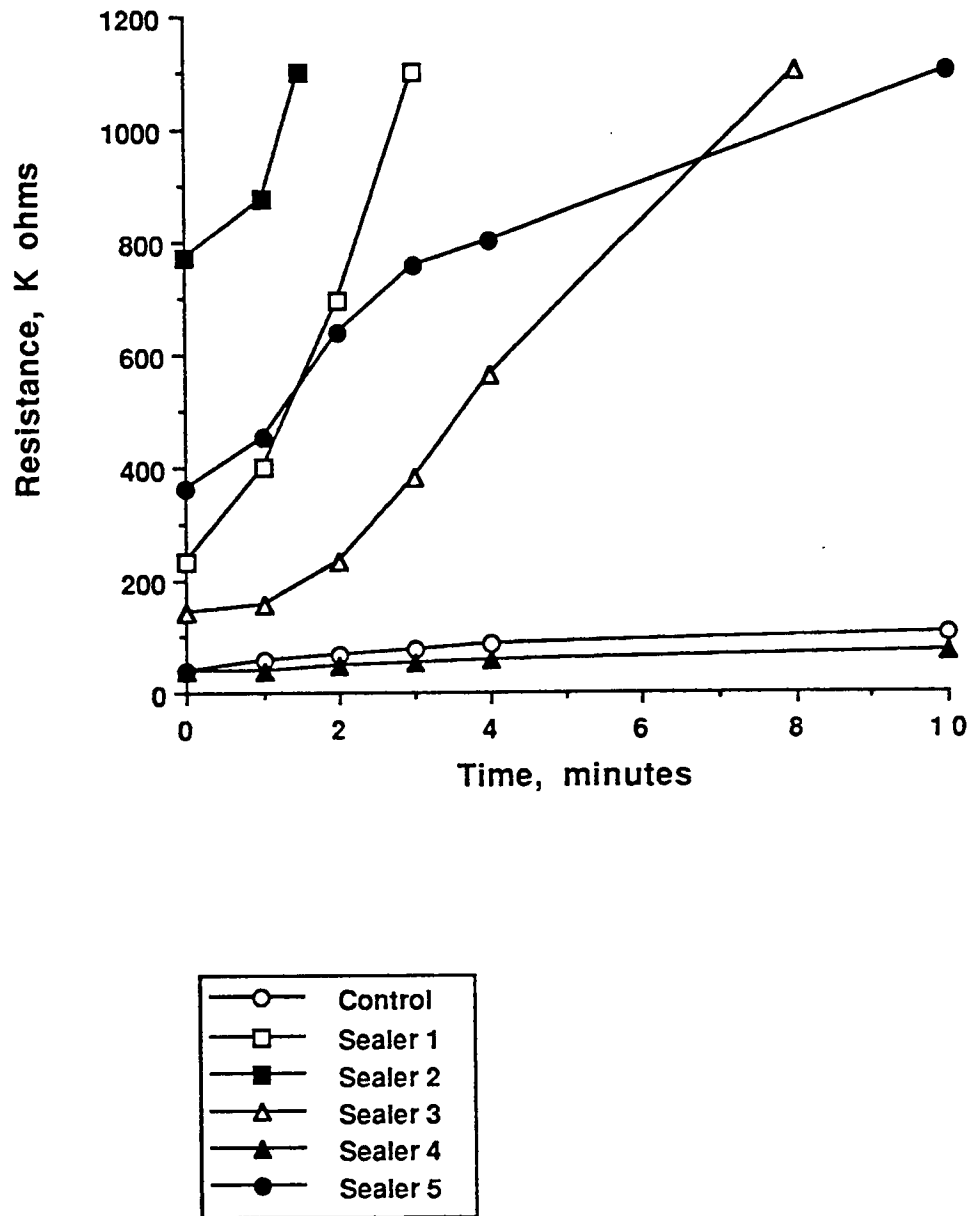


Figure 4-7. Resistance testing on air-dried (Set A) slabs.

Table 4-3. Results of surface resistance testing on air-dried (Set A) slabs.

Slab	Sealer	Time to Reach 1.1 Megohm (Minutes)
7	None	> > 10
15	4	> > 10
16	5	10
10	3	8
9	1	3
8	2	1.5

Reproducibility of the readings was fairly good, considering that this is meant to be a rapid field technique. Standard deviations were in the vicinity of ± 2 minutes, certainly adequate to separate high performance sealers (with times to 1.1 megohms less than 3 minutes) from ineffective sealers (times over 10 minutes).

The method was also applied to slabs that had been surface wetted for 1 day each week since initial curing (Set B). Sealers had been applied after approximately 12 weekly cycles. Cycling was then continued for an additional 6 weeks until 1 week prior to testing. Results (shown in Table 4-4) present a somewhat different ranking than for the air-dried slabs and indicate epoxy to be more effective than in the previous series.

In order to evaluate the effects of ambient temperature, the surface resistance test was applied to Set A slabs conditioned at 38°F (3°C) and 104°F (40°C) prior to testing. Results are presented in Table 4-5.

Results at 104°F (40°C) are in reasonable accord with previous results at ambient temperature. Results at 38°F (3°C), however, fall into a somewhat different pattern. It was also noted that there was more variability to the results at lower temperatures, and that in certain cases, decreases, rather than increases, in resistance over time were noted. Field trials in cold conditions (described in Chapter 5) corroborated these observations, and point to a need for fairly temperate test conditions in order to obtain meaningful results.

Table 4-4. Results of surface resistance testing on moist-cycled (Set B) slabs.

Slab	Sealer	Time to Reach 1.1 Megohm (Minutes)
37	None	> > 10
45	4	> > 10
40	3	9
39	1	2.5
46	5	2
38	2	1.5

Table 4-5. Effects of temperature on surface resistance testing.

Slab	Sealer	Time to Reach 1.1 Megohm (Minutes)		
		38°F	73°F	104°F
7	None	> > 10	> > 10	10
8	2	0.5	1.5	1.5
9	1	6	3	1
10	3	9	8	12
15	4	> > 10	> > 10	> > 10
16	5	3	10	10

Note: °F = 1.8 x °C + 32.

Further tests were carried out on an outdoor test slab placed in 1965 by the Portland Cement Association (PCA) (29). The slab had been produced with the same aggregates and approximately the same mix design as used in the concrete test specimens prepared for the present research program. Sealers were applied to six equal areas on the surface of this

4- x 5-ft (1.2- x 1.5-m) elevated slab. Because of the very rough surface (caused by accelerated deicing applications during early PCA studies), the gage application technique had to be modified. The following technique was employed:

1. Heat area to 120°F (49°C) surface temperature using a propane-fired, hand-held, infrared heater;
2. Apply three coats of silver spray paint, dry 5 minutes;
3. Apply three coats of silver spray paint, dry 5 minutes;
4. Apply three coats of silver spray paint, dry 5 minutes;
5. Spray surface with water, blot, and wipe dry; and
6. Read resistance between electrodes at 1, 2, 4, and 10 minutes.

Since this modified technique gave more consistent results, it was decided that this application sequence would be used for all future testing. After sealing, slabs were allowed to cure for approximately 1 week, during which time there were some rainy periods. On the first available dry day, gages were applied and resistance tests were carried out. Results are given in Table 4-6.

Table 4-6. Surface resistance test results: outdoor slabs.

Sealer	Time to Reach 1.1 Megohm (Minutes)
None	> > 10
4	> > 10
5	2
3	7
1	3
2	2

Results indicated approximately the same rankings as for the indoor tests, with the exception that epoxy (Sealer 5) ranked closer to silanes (Sealers 1 and 2) in this case. This variable performance of epoxy had been noted previously and might be due to the fact that it is not a true penetrating sealer, as significant amounts of material remain on the surface. This may form a variable surface, depending on application technique and inhomogeneities in the surface.

It was recognized that since the surface resistance method is based on the electrical properties of the surface layers, the presence of salts will alter the electrical continuity and may pose interference with the method. To examine these effects, resistance gages were applied to a series of test slabs previously ponded with 3-percent sodium chloride solution. The procedures employed in the outdoor tests were used. The behavior of resistance versus time for these slabs is shown in Figure 4-8. In all cases, values are considerably lower than in previous test series, with most slabs failing to meet the previously established criterion for acceptability based on time to reach 1.1 megohm.

Based on these results, the criterion was reconsidered. The entire data set (i.e., dry slabs, cycled slabs, slabs tested at different temperatures, outdoor slabs, and slabs ponded with sodium chloride solution) was examined. From analysis of these data, it was found that if a criterion of 200 k-ohm at 4 minutes was selected, acceptable sealers would exhibit values exceeding this criterion in 97 percent of the cases included. Therefore, the previous criterion of "time to reach 1.1 megohm" was discarded, and the new criterion of at least 200 k-ohm after 4 minutes of drying was substituted as the value to use when interpreting test results.

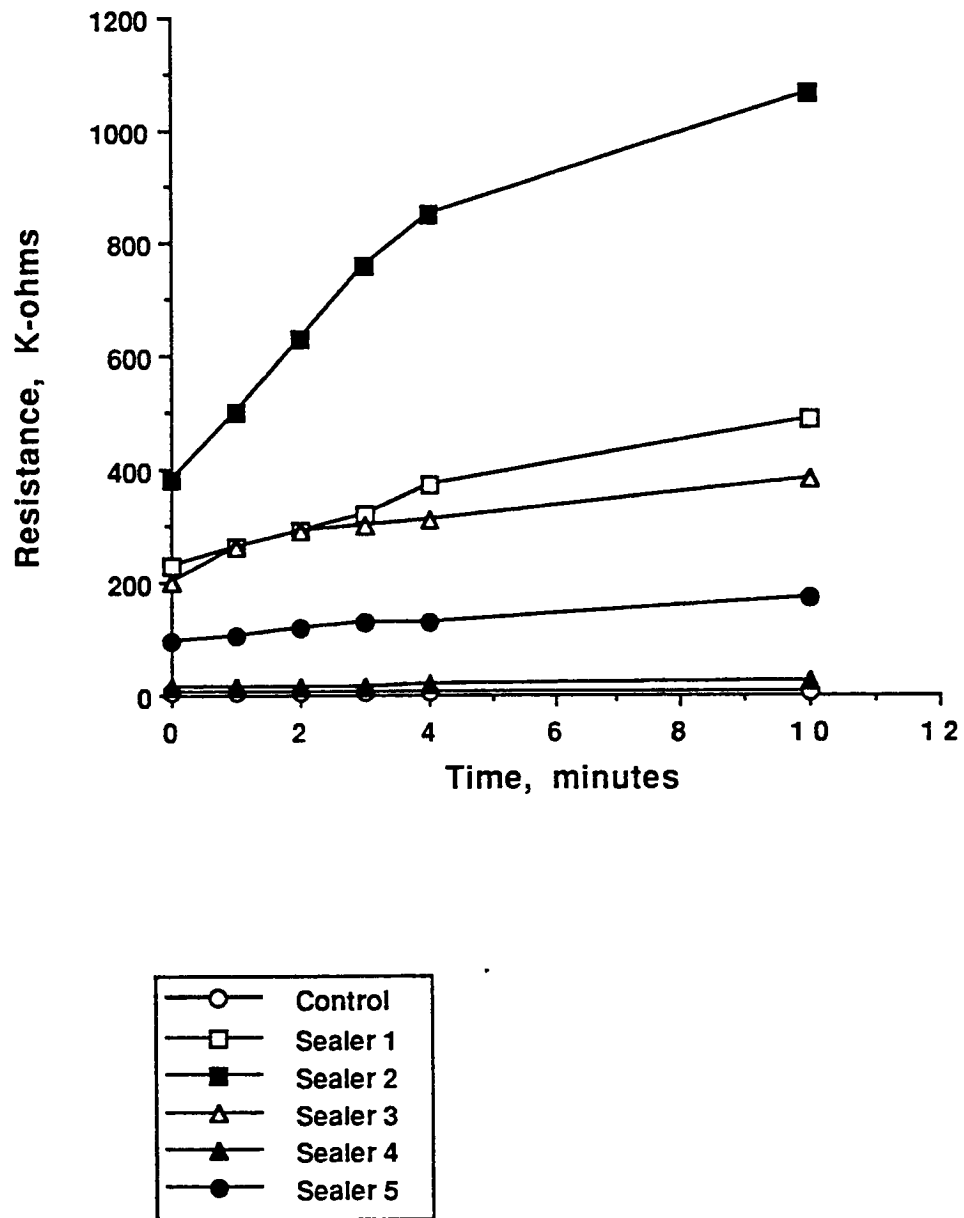


Figure 4-8. Resistance testing on slabs previously ponded with 3-percent sodium chloride solution.

5

Field Trials

In order to evaluate the techniques under actual field conditions and to obtain some indication of their ability to discriminate between effective and noneffective sealers on actual structures, a series of field trials was carried out. The primary purpose of these field trials was to try the methods under a variety of conditions, make modifications (if necessary), and thereby refine the methods, making them more practical and reliable. Due to the absence of standard field techniques for assessing the on-site effectiveness of field-applied sealers, it was not possible to make an absolute assessment of the accuracy of the methods in the field. However, from records supplied by SHAs and from the investigators' own experience with a large variety of sealers, it was possible to draw some tentative relative assessments of the potential ability of the sealers used in each case studied. Field trials carried out under winter, spring, and summer conditions are described in the following sections.

Field Trial No. 1--Georgia Center, Vermont

The Vermont Agency of Transportation (VTAT) expressed an interest in participating in the research since VTAT was planning its own test programs on penetrating sealers. VTAT selected six sealers corresponding to the following general types:

- Sealer 1--solvent-based alkyl alkoxysilane;
- Sealer 2--water-based silane;

- Sealer 3--solvent-based siloxane;
- Sealer 4--solvent-based polymeric alkyl silane;
- Sealer 5--penetrating epoxy;
- Sealer 6--a second penetrating epoxy; and
- A control (unsealed) section

Sealers were applied to a patch area approximately 12 ft (3.6 m) high on four faces of a bridge pier. Approximately 1 week elapsed between sealer application and testing.

The bridge selected for testing was Bridge 86S on Interstate Route 89 in Vermont. This bridge is located approximately 19 mi north of Burlington near the town of Georgia Center, at mile marker 107.6. Sealers were applied to pier 25 as described above.

The preparation of gages started at approximately 11 a.m. on October 29, 1990. The air temperature was approximately 35°F (2°C). Wind velocity near the pier was estimated to be 12 to 15 mph (19 to 24 kmph) with gusts to 20 mph (32 kmph). Silver conductive paint was used to spray the gages using the standard gage mask. The concrete was preheated using a propane infrared portable heater for 5 minutes. The temperature was controlled at about 120°F (48°C) as indicated by a thermocouple attached to the metal mask. Nine coats of the paint were applied with 5 minutes of heating to 120°F (48°C) after each set of three coats. Due to the heavy wind, it was necessary for an assistant to hold a plywood wind shield next to the gage being sprayed. Two gages each were prepared on areas coated with Sealers 1, 2, and 3, and one gage was applied on the area treated with Sealer 4. The temperature the next day reached 45°F (7°C) in the shade, and the wind velocity was much reduced. Gage application was completed by noon for Sealers 4 and 5 and the uncoated control patch. Considerable time was spent in attempting to produce a usable gage on the area treated with Sealer 6 (epoxy). Even after an added heating period of 15 minutes at 135°F (57°C) followed by the spraying of another nine coats, the gage still showed infinite resistance. The epoxy coating had been applied on October 26, 1990, and, due to the low temperature, had presumably not cured adequately to prevent an interaction between the residual solvents of the coating and the silver gage. No further tests were done on the area containing Sealer 6.

Gages were tested using the procedures previously described. The resistance readings are shown in Table 5-1. Two of the gages (right-hand Sealer 1 and left-hand Sealer 2) were close to an area where overhead drilling had been done on the morning of October 30. A

considerable amount of cooling water spray was being blown by the wind, and some of this spray reached the test area. It is conceivable that the water may have contained chloride dissolved in the drilling operation and may account for the low resistance readings for the two gages. The readings for these two gages might therefore reasonably be disregarded. Overall, it appears that Sealer 5 was slightly more effective, at least in terms of the magnitude of resistance at 4 minutes. All other sealers met the 200 k-ohm criterion, with the exception of the left gage on the Sealer 4 area. However, the reading was still more than three times the control reading, indicating that the sealer did exhibit some degree of advantage over an untreated surface.

Table 5-1. Results of surface resistance testing at Vermont field test site.

Sealer	Resistance at 4 Minutes (Megohms)	
	Left Gage	Right Gage
1	470	50
2	150	460
3	440	190
4	370	575
5	850	720
Control	70	60

Attempts were made to field test the vertical modified RILEM II.4 device on the same structure in Vermont. It was difficult to work with the clay/grease seals under such cold conditions. It was necessary to preheat the clay in a vehicle and quickly transfer the seal to the wall. Also, preheating the test surfaces just prior to the test improved the seal. Some results of the testing are given in Table 5-2. The unsealed section appeared to exhibit lower column drops than normally would be associated with unsealed concrete; however, in all cases except for Sealer 3, the unsealed readings were greater than readings on sealed surfaces. The high readings on the Sealer 3 section were attributed to surface voids in the test sections.

Table 5-2. Results of surface absorption testing at Vermont field site.

Sealer	Drop in Capillary Column (cm) at Time Indicated	
	4 Minutes	10 Minutes
1	0.7	1.0
2	0.8	0.9
3	3.0	4.5
4	0.9	1.2
5	0.6	0.9
Control	1.4	2.5

Note: 1 in. = 2.54 cm

Problems encountered in these initial field trials indicated that while consistent readings could be obtained under controlled and uniform lab conditions as low as 40°F (4°C), difficulties in operating under actual cold field conditions resulted in reduced confidence in readings taken under those conditions. The cold concrete surfaces require preheating, much more conductive paint needs to be applied (and wasted if wind velocities are high), and the clay seals for the absorption device do not form as good a seal as under more temperate conditions. For these reasons, the researchers recommend that this type of testing be carried out only when air temperatures (and corresponding concrete surface temperatures) exceed 50°F (10°C).

Field Trial No. 2 - Santa Barbara County, California

Caltrans had applied penetrating sealers to a series of bridge structures in Santa Barbara County that had experienced distress due to alkali-silica reactivity (ASR). The intent was to reduce the interior relative humidity by allowing the sealer to transmit water vapor to the relatively dry ambient environment, while at the same time preventing liquid water from entering the concrete during exposure to direct rainfall. The sealers were applied to the bridge support and substructures in 1988 and 1989, 2 to 3 years prior to this testing. Three bridges on Route 101 were selected for testing. These included two bridges to which a 40-percent solution of silane had been applied, and one bridge that had not been treated and

was used as a "control." A steel arch bridge on Route 154 to which a 40-percent solution of silane had been applied to concrete elements was also included in the study.

Site 1--Hollister Avenue over Rt. 101

The first bridge selected carried Hollister Avenue over Rt. 101 and was designated as bridge No. 51-123 at post mile 26.91. Testing was carried out on April 16, 1991. Weather was clear, with an average daytime temperature of about 65°F (18°C) and light winds. Resistance gage tests were carried out in the same manner as for the previous trials. A total of eight locations was tested, which included tests on three of the piers, a concrete beam, and a wingwall. Results are presented in Table 5-3.

Table 5-3. Results of surface resistance testing at Hollister Avenue Bridge.

Location	Resistance at 4 Minutes (k-ohms)
1--Pier No. 1	340
2--Pier No. 2	330
3--Pier No. 2	950
4--Pier No. 1	330
5--Beam	58
6--Beam	23
7--Pier No. 3	240
8--Wingwall	20

All 4-minute readings obtained on the piers exceeded the criterion of 200 k-ohms, indicating that the sealer was applied in these locations and should have been effective. Readings obtained on the beam and wingwall indicated that the sealer had not been applied in these locations.

The modified RILEM II.4 surface absorption device was also tested at this site. Because water is used for both test methods, and because inadvertent wetting prior to the test may

interfere with each test, test locations for the absorption test were located a short distance away from those used for the resistance testing. Results are presented in Table 5-4.

Table 5-4. Results of surface absorption testing at Hollister Avenue Bridge.

Location	Drop in Capillary Column (cm) at Time Indicated	
	4 Minutes	10 Minutes
1--Pier No. 1	0.5	0.9
2--Pier No. 2	0.8	1.3
3--Pier No. 2	1.3	5.1
4--Pier No. 1	0.7	1.6
5--Beam	1.4	3.4
8--Wingwall	0.8	1.2

Note: 1 in. = 2.54 cm

Although there was good agreement between the methods in most cases, some discrepancies did occur. At location No. 3, while resistance readings were very high and indicated a particularly effective application, absorption results were indicative of a marginal or poor sealer. Close inspection of the test area after tests were completed indicated the presence of surface voids, which may have led to the high results. At location No. 8, the opposite was encountered. That is, the resistance test indicated that no sealer had been applied, while the absorption test indicated the presence of sealer. The absorption test was carried out at a location considerably removed from the resistance test, as it was necessary to carry out testing simultaneously in this area. It is possible that the applicators had simply not applied sealer to the location used for the resistance test.

Site No. 2--Cold Spring Canyon Bridge

The second bridge selected carried Rt. 154 over Cold Spring Canyon and was designated as bridge No. 51-37 at post mile 23.00. Testing was carried out on April 17, 1991. Weather was clear, with an average daytime temperature of about 65°F (18°C) and no wind. In all, seven locations were tested. These included one test on each of two wingwalls, one test on each of two parapet railings, one test on each of two support columns, and one test on the abutment wall underneath the deck. Results of resistance gage testing are given in Table 5-5.

Table 5-5. Results of surface resistance testing at Cold Spring Canyon Bridge.

Location	Resistance at 4 Minutes (k-ohms)
1--Wingwall No. 1	> 1,100
2--Parapet Railing No. 1	> 1,100
3--Column No. 1	> 1,100
4--Column No. 2	550
5--Wingwall No. 2	> 1,100
6--Parapet Railing No. 2	> 1,100
7--Abutment Wall	510

All 4-minute resistance readings exceeded the 200 k-ohm criterion by a significant amount. A number of the readings exceeded the scale of the instrument even within the first few minutes of the test, indicating that a very effective sealer was in place.

Surface absorption tests were carried out in six locations close to those used for the resistance testing at this structure. Results are presented in Table 5-6. They corroborate the resistance tests to show that the sealer appears to be very effective in reducing water penetration into the concrete.

Site No. 3--Glenn Annie Road at Storke Avenue over Rt. 101

The third bridge selected carried Glenn Annie Rd. at Storke Ave. over Rt. 101 and was designated as bridge No. 51-122 at post mile 24.41. Testing was carried out on April 18, 1991. Weather conditions were nearly identical to those for the previous 2 days of testing. Three locations were tested on the median piers. Results of resistance gage testing are given in Table 5-7, and companion surface absorption test results are given in Table 5-8.

Table 5-6. Results of surface absorption testing at Cold Spring Canyon Bridge.

Location	Drop in Capillary Column (cm) at Time Indicated	
	4 Minutes	10 Minutes
1--Wingwall No. 1	0.6	1.0
2--Parapet Railing No. 1	0.7	1.1
3--Column No. 1	0.7	1.1
4--Column No. 2	0.2	0.5
5--Wingwall No. 2	0.5	1.0
6--Parapet Railing No. 2	0.6	1.1

Note: 1 in. = 2.54 cm

Table 5-7. Results of surface resistance testing at Glenn Annie Road/Storke Avenue Bridge.

Location	Resistance at 4 Minutes (k-ohms)
1--Pier No. 1	18
2--Pier No. 2	89
3--Pier No. 2	41

Table 5-8. Results of surface absorption testing at Glenn Annie Road/Storke Avenue Bridge.

Location	Drop in Capillary Column (cm) at Time Indicated	
	4 Minutes	10 Minute
1--Pier No. 1	2.5	3.7
2--Pier No. 2	2.9	4.2
3--Pier No. 3	2.0	3.0

Note: 1 in. = 2.54 cm

All test results are in the ranges to be expected from control (i.e., unsealed) concretes. The resistance gage results are especially telling in this respect. This corroborates information later received from Caltrans indicating that because of the advanced state of deterioration and the need for extensive reconstruction of an adjacent structure, this bridge was scheduled for replacement rather than for treatment with a penetrating sealer.

Site No. 4--Los Caneros Road over Rt. 101

The final bridge selected for testing in this series carried Los Caneros Road over Rt. 101 and was designated as bridge No. 51-241 at post mile 23.72. Testing was carried out immediately after completion of testing at site No. 3. Five locations were selected for testing. These consisted of two tests each on the two median piers and one test on a concrete support beam. Results of resistance gage testing are presented in Table 5-9.

All test locations are indicative of sealed concrete. Location No. 5 exhibits a lower resistance than the others, which may indicate less effective application on this member.

Results of surface absorption testing are given in Table 5-10. With the exception of location No. 2, results were within the general ranges expected to be exhibited by sealed concretes.

Results at location No. 2 were more typical of unsealed concrete, and again this may be attributable to the presence of small surface voids, which seemed to be widespread across the test face and therefore could not be avoided during testing of this member.

Table 5-9. Results of surface resistance testing at Los Caneros Road Bridge.

Location	Resistance at 4 Minutes (k-ohms)
1--Pier No. 1	> 1,100
2--Pier No. 2	> 1,100
3--Pier No. 2	> 1,100
4--Pier No. 1	> 1,100
5--Beam	300

Table 5-10. Results of surface absorption testing at Los Caneros Road Bridge.

Location	Drop in Capillary Column (cm) at Time Indicated	
	4 Minutes	10 Minutes
1--Pier No. 1	1.2	1.5
2--Pier No. 2	2.0	3.2
3--Pier No. 2	0.6	0.9
4--Pier No. 1	1.0	1.9
5--Beam	0.7	1.1

Note: 1 in. = 2.54 cm

Field Trial No. 3--St. Paul, Minnesota

As noted in the background section of this report, the Minnesota Department of Transportation (15) evaluated nine products on a bridge deck in St. Paul, Minnesota, overlaid in 1983 with low-slump dense concrete. The bridge is located on I35E over Jefferson Avenue in St. Paul and is designated as bridge No. 62865. The left (passing) lanes on both north- and southbound sections were treated with a variety of penetrating sealers. While the deck had been tyned for skid resistance, an 18-in. (460-mm) section near the median barrier had not been skid textured and was therefore available for testing the methods. A description of the products applied to the test sections is given in Table 5-11.

The preparation of gages started at 10:00 a.m. on June 11, 1991. Weather was clear, with high temperatures near 85°F (30°C). The temperature of the deck surfaces exposed to sun ranged from near 80°F (27°C) early in the day to over 100°F (38°C) in the early afternoon. Because of the hot deck surface, problems were encountered in application of the surface absorption method.

Apparently, the high deck temperatures caused expansion of the water in the measurement column during the course of the test, resulting in near-zero (and even positive) column measurements. While resistance gage tests could be carried out the first day of testing, work

Table 5-11. Description of products applied to test sections on St. Paul bridge deck.

Product Description	Test Section
40-percent Alkyl-alkoxy silane in ethanol	TS18
Modified fluorosilicate in water	TS16
Alkoxy-silane prime coat with methyl methacrylate polymer top coat	TS17
20-percent oligomeric alkoxy-silane in mineral spirits	TS13
20-percent methyl methacrylate-ethyl acrylate copolymer in toluene and xylene	TS21
50-percent solids epoxy (2-part)	TS12
40-percent alkyltrialkoxo silane in isopropanol	TS22
Alkyl-alkoxy silane	TS15
5-percent sodium methyl silanolate	TS20
Control (no sealer)	TS14, TS19

with the surface absorption device was suspended until the following day, when testing was carried out earlier in the day to avoid the peak temperatures of the afternoon. Additionally, during the second day of testing, the high deck temperatures on sections TS20 and TS21 resulted in unusually rapid heating of the gages immediately after drying with the infrared heater was initiated. This resulted in damage to the gages on these sections, and no readings were obtainable. Results of surface resistance testing on the 11 test sections selected are given in Table 5-12.

For the most part, all readings fall within the region characterized by untreated concretes (less than about 200 megohms). This would indicate either that sealers had deteriorated over time, or that they had been worn away under traffic over the 8-year exposure period. No distinction could be made between performance of the individual sealers, as all had apparently failed by this point in time.

Table 5-12. Results of surface resistance testing at St. Paul, Minnesota, bridge test site.

Test Section	Resistance at 4 Minutes (megohms)	
	Left Gage	Right Gage
TS12	160	16
TS13	172	150
TS14 (control)	160	140
TS15	470	160
TS16	240	200
TS17	145	182
TS18	120	210
TS19 (control)	155	120
TS20	---	---
TS21	---	---
TS22	190	105

*Problems encountered in heating of gages. No readings obtained.

As previously noted, work with the surface absorption device was suspended until the second day of testing due to problems caused by the high deck temperatures on the first day. On the second day, testing commenced early in the day to take advantage of cooler conditions and the shade of the median barrier. Tests were carried out on nine of the sections tested using the resistance device. Results are presented in Table 5-13.

Results for all sections tested were very similar. Sealed sections performed no better than the control, corroborating results obtained using the resistance gages and substantiating the conclusion that the sealers were no longer effective on these test sections. However, all results obtained using the absorption device were very low and indicative of properly sealed

Table 5-13. Results of surface absorption testing at St. Paul, Minnesota, bridge test site.

Test Section	Drop in Capillary Column (cm) at Time Indicated	
	4 Minutes	10 Minutes
TS13	0.4	0.5
TS14	0.5	0.7
TS15	0.6	0.7
TS16	0.5	0.8
TS17	0.3	0.4
TS18	0.6	0.8
TS19 (Control)	0.4	0.7
TS20	0.4	0.5

Note: 1 in. = 2.54 cm

concrete, even for the control section. This discrepancy can be explained by the fact that the concrete used to place this deck was a low-slump concrete with a w/c ratio near 0.35, designed to reduce infiltration of chlorides into the deck. All previous work with the absorption device had been on more conventional concretes with higher w/c ratios. Therefore, this is seen as a limitation of the absorption technique--the established test criteria are applicable only to conventional concrete mixtures.

6

Summary and Recommendations

Summary of Test Methods

Two test methods were developed under this research program for use in evaluating the effectiveness of penetrating sealers for concrete. The methods developed include a technique based on electrical resistance of the surface layers of concrete and a technique based on the rate of water absorption into concrete. In the surface resistance method, two thin electrodes are created on the surface of concrete by use of conductive silver-based aerosol paint. The paint is then forced-dried using a liquified propane heater. After drying, the thin area between the gages is wetted and initial resistance is measured. The rate of increase of resistance as the surface dries is an indication of sealer effectiveness. More effective sealers reduce the amount of water that penetrates into the surface during wetting; therefore, the surface dries much faster and resistance increases at a greater rate than on unsealed or poorly sealed surfaces. A criterion of a minimum resistance of at least 200 k-ohms after 4 minutes of drying has been shown to be a reasonable limit for separation of effective from ineffective sealers in both laboratory and field testing. A recommended test procedure, in ASTM format, has been prepared for the electrical resistance method. It is presented in Volume 8, "Procedure Manual," of this report series.

The second technique utilizes a capillary column, which is filled with water from a reservoir held in contact with the concrete surface. By monitoring the rate of decrease in the column height, the ingress of water into the concrete surface can be determined. The test is carried out over a period of 10 minutes, and readings taken after 4 and 10 minutes can be used to establish the effectiveness of the sealers. A recommended test procedure, in ASTM format,

has been prepared for the absorption method. It is presented in Volume 8, "Procedure Manual," of this report series.

Applicability of Test Methods

The methods have been shown to be applicable under both laboratory and field conditions. They have shown good correlation with long-term methods currently in use, including those based on NCHRP Report 244 (1) and the AASHTO 90-day ponding test procedure (2). While not as quantitative as these standard laboratory techniques, the new methods are able to rank sealers in approximately the same order of effectiveness in reducing chloride ion ingress as the long-term techniques. Therefore, the new methods could be used in conjunction with standard laboratory evaluations of a group of sealers to obtain a more rapid indication of the sealers' relative effectiveness. This should be verified, however, by completing the evaluations using standard techniques.

The major advantage of the new methods is that they can be used under field conditions on in-place concrete structures. The methods are relatively simple to conduct, equipment is fairly inexpensive, and the test procedures are rapid (especially when compared with standard lab techniques). While there are some limitations, the methods have been used on a variety of structures under differing climatic conditions with overall good success.

Limitations of Test Methods

In field testing, any method will be subject to a variety of largely uncontrollable variables. A number of factors must be taken into consideration when applying these techniques in the field. Both methods require an initially dry surface; therefore, the methods cannot be carried out under wet conditions. Additionally, the surface absorption technique will be influenced by internal concrete moisture content, even if the surface is dry. If testing is to be carried out on a surface that has recently been wetted, it may be necessary to pre-dry the test areas prior to initiation of testing. This is not as great a problem with the resistance method, since drying is included as a standard part of the method due to the necessity for force-drying the conductive paint used to produce the surface electrodes.

Laboratory testing has shown that temperature does not appear to have significant effects on test results. However, temperature and wind become significant factors in the field. Under extremely cold conditions, the clay/grease seals used to affix the absorption reservoir to the surface do not bond properly, and it is difficult to achieve a good seal. The conductive paint

used in the resistance method dries very slowly in cold conditions, and the drying regimen may need to be lengthened. Under hot conditions, especially in full sun, the clay seals may become very soft and fail to seal properly. Additionally, and more significantly, a hot surface may cause expansion of the water in the capillary column and lead to erroneous readings. While the resistance technique performs more reliably under hot conditions, it was noticed that forced-drying must be monitored carefully, or else the temperature of the gage may rise above the recommended surface drying temperature. Finally, windy conditions make it difficult to apply uniform coatings of paint and may require the use of more paint than under normal conditions.

Although the field testing in this research program was limited, indications were that the same criterion used in the laboratory testing of the resistance technique could be applied to field test results as well. In the case of the surface absorption technique, however, it appears that the absolute value of absorption may be related to the particular concrete under test. Therefore, the results of the surface absorption method must be interpreted with caution, and it is preferable that an unsealed section be available as a basis of comparison.

Recommendations

It is recommended that further evaluations of the methods be carried out under actual field conditions on structures treated with a variety of surface sealers. It would be quite useful for agencies to evaluate the methods in conjunction with long-term approaches such as chloride sampling. It would also be beneficial to integrate these evaluations into studies where a variety of sealers are being evaluated on the same structure or series of structures, so as to have available "control" sections and eliminate the effects of different types of concrete on the methods.

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