Field Tests of Resistance to Chloride Ion Penetration on Sealed Concrete Pavement

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The results and methodologies of a field study of portland cement concrete sealers on a traffic bearing surface in Indiana are presented. The study was to examine the resistance of chloride ion penetration on sealed concrete pavement. Various generic sealers were put on the surface of concrete pavement, then replicate samples were taken from the unsealed and sealed parts of the pavement. The content of chloride ions in the samples was analyzed and compared with the results of *NCHRP Report 244*. After 3 years of exposure, the test areas for some generic sealers continued to demonstrate better effectiveness than others in maintaining resistance to chloride ion penetration in concrete. Meanwhile, the field test results are significantly different from the laboratory test results in this study.

It has been well documented that deicing salts penetrate concrete and cause embedded reinforcing steel to corrode; moreover, the corrosion accumulates around the steel, causing cracks that allow the intrusion of even more damaging chloride ions. Thus, these cracks accelerate corrosion, induce spalling, and eventually shorten the service life of the concrete structure. Surface sealer has been applied to the concrete in attempts to minimize the damage caused by chloride ions from deiced salt (*1–3*). Although the use of sealers has met with varying degrees of success in the past, it is not uncommon for their use to result in premature failure of the highway concrete structure because of the corrosion caused by chloride ions.

The purpose of this paper is to present the results and methodologies of a field study on a traffic bearing surface. The study was to examine the resistance of chloride ion penetration on sealed concrete pavement. Various generic sealers were put on the surface of concrete pavement, and then replicate samples were taken from the sealed concrete pavement. The content of chloride ions in the samples was analyzed and compared with the reported laboratory tests.

After a detailed introduction of the field test methods and the presentation of their results, the differences between field and laboratory test results will be discussed. Finally, the conclusion and recommendation for future study will be made. The reader should be cautious: many methods have been developed to evaluate the performance of concrete sealers. Traditionally, most performance evaluations of concrete sealers are conducted in the laboratory. In a laboratory environment, not only can the variables be easily controlled, but the test processes can be accelerated. However, the laboratory test results do not always correlate with the results of the field tests or service tests; sometimes they are poor predicators of the long-term field performance (*4*). In this study the laboratory test procedure of *NCHRP Report 244* (*5*) is compared with the sealer's field performance on a traffic bearing surface.

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METHODOLOGY

Type of Sealers Evaluated

A field evaluation was authorized by the New Products Evaluation Committee of the Indiana Department of Transportation (INDOT) to appraise the field performance of seven portland cement concrete (PCC) sealers (*6*). These sealers are totally different types of brands of materials. On the basis of their generic content, they are named as the following (to facilitate the discussion, the abbreviations will be used to represent the individual type):

- Silane (Silane)
- Siloxane 1 (Silox 1)
- Siloxane 2 (Silox 2)
- Blend of siloxane and silane (Blend)
- Modified aluminum siloxane (Modified)
- Epoxy 1 (EPS 1)
- Epoxy 2 (EPS 2)

Location of Test Site

A concrete pavement contract was selected as the site for the field evaluation of these sealers. All seven of the PCC sealers are one-coat systems. A 5-gal sample of each PCC sealer was received from the product manufacturer for use in the evaluation. The test strip was in the southbound traffic lane from Station 274 + 60 to Station 277 + 00 along I-69, just north of the I-69 and SR-18 interchange, near Marion, Indiana. The average daily traffic along the test section is approximately 7,700.

Concrete Mix Design

The properties of the concrete and its materials are as follows:

- Cement: Louisville Type IA
- Cement content: 564 lb/yd^3
- Water: 170 lb/yd^3
- Fine aggregate: 1,281 lb/yd^3 (wet weight)

- Coarse aggregate: 1,819 lb/yd^3 (wet weight) (1 in. topsize)
- Daravair R air entraining agent: 2.75 oz/100 lb
- Slump: 2.5 in.
- Net air content: 7.8 percent
- Unit weight: 141 lb/ft^3
- Water-cement ratio: 0.40 to 0.44

(Conversion factors are 1 lb = 0.454 kg; 1 yd^3 = 0.765 km^3; 1 ft^3 = 0.028 m^3; 1 oz = 29.57 mL; 100 lb = 45.4 kg.) The batch weights reported for the fine and coarse aggregates are the wet weights. The water-cement ratio could not be located; tests usually range from 0.40 to 0.44 in Indiana.

Surface Preparation

The field work for preparing and sealing the pavement sections was conducted on June 4, 1987. The weather conditions were fairly clear and warm with temperatures near 26.7°C (about 85°F). Before the test areas were sealed, the PCC surface of the evaluation strip was sandblasted by the INDOT Gas City Maintenance Section to remove the curing compound (i.e., a Type II AASHTO M148 curing compound), surface dirt, and cement latency. The curing compound was applied at approximately 3.69 m^2/L (150 ft^2/gal), and the pavement concrete was allowed to cure more than 28 days before PCC sealers were applied. The pavement surface was then swept and blown clean.

Application of Sealers

The sealing was performed by the Special Studies Section. Table 1 is given for reference purposes. The concrete sealers were all applied to the test areas at a rate judged to be necessary for complete and uniform coverage of the tinned concrete surface. As indicated by Table 1, this was typically heavier than what would normally be recommended by the manufacturer. Three 22.32 m^2 (240 ft^2) control areas (designated Controls 1, 2, and 3) were spaced along the test strip where no concrete sealer was applied. Two areas were delineated for the application of state-approved polysulfide type, epoxy penetrating sealers (EPSs).

These test areas (designated EPS 1 and EPS 2) were created to provide data from a known performer in sealing concrete. Figure 1 shows the locations and sizes of the various PCC sealer test and control areas. The various PCC sealers were applied as follows:

- Silane was poured across the 33.48 m^2 (360 ft^2) test area. A thick-napped roller was used to squeegee and spread it uniformly over the test area. The sealer was applied at a rate of 2.46 m^2/L (100 ft^2/gal), which is somewhat heavier than the recommended rate, which is 3.07 m^2/L (125 ft^2/gal).
- Blend was poured across the 33.48 m^3 (360 ft^2) test area. A stiff-bristled broom was used to spread the material uniformly over the test area. Then the material was groomed further to work the material into the concrete surface. The

TABLE 1 PCC Sealer Application Information

Test Areas by Type of Sealer	Manufacturer's Recommended Surface Preparation	Manufacturer's Recommended Application Equipment	Manufacturer's Recommended Application Rate (ft^2/gal)	Test Area Application Rate (ft^2/gal)
SILANE	Sandblast or Waterblast	Spray, roller, or Bristly broom	125	100
SILOX 1	14 day (minimum) concrete cure & "clean" concrete surface	Low pressure sprayer, roller, brush, or broom	75-125	100
SILOX 2	Clean concrete surface with high pressure water and cleaners	Low pressure spray (preferred) or saturated brush or roller or "broom"	125	90
BLEND	Waterblast or Sandblast	Push broom (preferred) must broom into surface	100-125	100
MODIFIED	Waterblast or Sandblast	Push broom (preferred) must broom into surface	100-125	85
EPS I	Sandblast	Flood surface and spread with roller	90-110	90
EPSII	Sandblast	Flood surface and spread with roller	90-110	90

ft^2 = square feet = 0.093 meters squared; gal = gallons = 3.785 liters

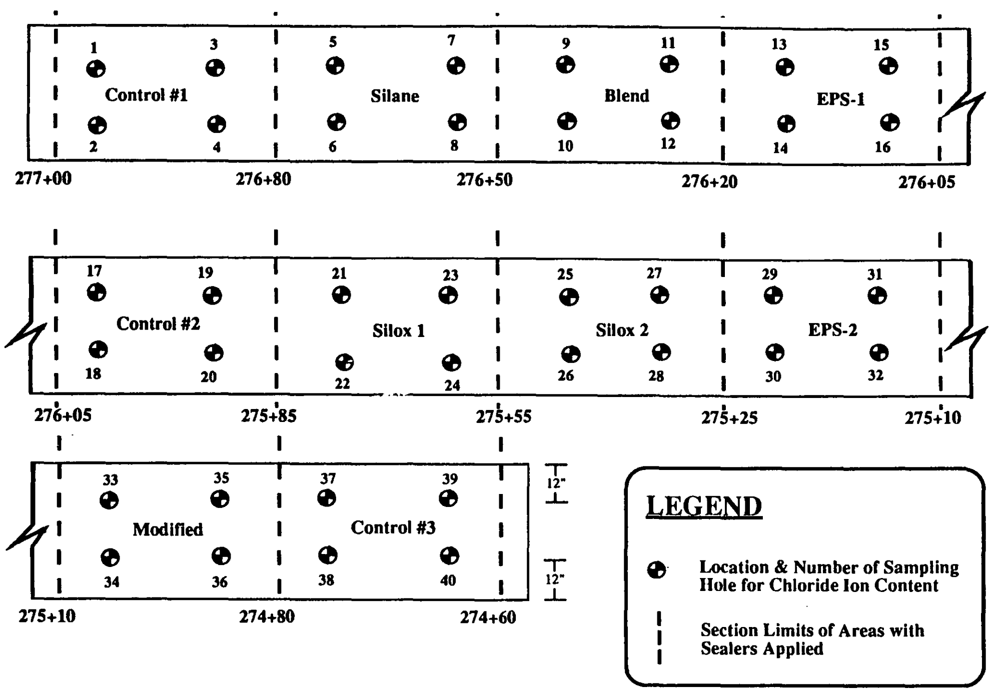

FIGURE 1 Plan view of field test site.

sealer was applied at a rate of 2.46 m²/L (100 ft²/gal), which is the heavier amount of the recommended range of 2.46 m²/L (100 ft²/gal) to 3.07 m²/L (125 ft²/gal).

- Modified was applied in the same manner as Blend. It was applied at a rate of 2.09 m²/L (85 ft²/gal), which is heavier than the recommended range of application rate, which is 2.46 m²/L (100 ft²/gal) to 3.07 m²/L (125 ft²/gal).
- EPS 1 and EPS 2 were applied on separate areas of the test strip. Each EPS was mixed after combining the resin and hardening components. Each EPS was applied by pouring the material across the 16.74 m² (180 ft²) test area, then a thick-napped roller was used to squeegee and spread the sealer uniformly over the test area. Each EPS was applied at a rate of 2.21 m²/L (90 ft²/gal); the recommended rate was 2.21 m²/L (90 ft²/gal) to 2.70 m²/L (110 ft²/gal). Once applied, the EPSs were allowed to begin the set before sand veneer was spread over the surface to add skid resistance.
- Silox 1 was poured across the 33.48 m² (360 ft²) test area. A thick-napped roller was then used to squeegee and spread the material uniformly over the test area. The sealer was applied at a rate of 2.46 m²/L (100 ft²/gal), which is the midpoint of the recommended range of application.
- Silox 2 was poured across the 33.48 m² (360 ft²) test area. A thick-napped roller was then used to squeegee and spread the material uniformly over the test area. This sealer was applied at a rate of 2.21 m²/L (90 ft²/gal), which is heavier than the amount recommended by the manufacturer—3.07 m²/L (125 ft²/gal).

As mentioned, the test area surfaces were clean and dry before the sealers were applied. On June 3, 1987, the day before the sealer was conducted, it was a sunny day with clouds. The temperature was about 15°C (in the upper 60's Fahrenheit); the wind blew 16.1 km (10 mph). Traffic was not allowed on the pavement for at least 4 hr after the applications. Several photographs were taken to document these application activities; the photographs are on file at the INDOT Division of Materials and Tests.

Field Sampling and Chloride Ion Determination

The sealers were applied on June 4, 1987, and field samplings were conducted on May 25, 1988; October 4, 1989; and May 18, 1990: at 12, 24, and 36 months, respectively. Sampling holes were drilled at locations illustrated in Figure 1 for each test and control area. Samples for chloride ion content were obtained according to the method described in AASHTO T260, except that sampling tools were not washed before each sampling. A rotary hammer drill was used to advance the bit in the concrete. The pulverized cuttings or dust were obtained at 12.7-mm (0.5-in.) increments of bit penetration to a total depth of 3 in. The sampling procedure used several hammer drill bits with diameters of 31.75 mm (1.25 in.), 25.4 mm (1 in.), and 19.05 mm (0.75 in.). Each bit was used to obtain two samples from each hole, thus creating a stepped sampling hole, to prevent contamination of successively deeper samples. The samples obtained from each drill hole were submitted to INDOT Chemistry Laboratory for the determination of chloride ion content using an automated method duplicating ASTM C114. The chloride ion content and the depth of sample increments was established for each sampling location per year of exposure. Each sampling location is just outside the wheelpaths. They are approximately 25.4 mm (1 in.) from the outer edge of the pavement or center longitudinal joint, as shown in Figure 2. The results are presented in Table 2. Each value in Table 2 represents the mean of four sample data for each sealer.

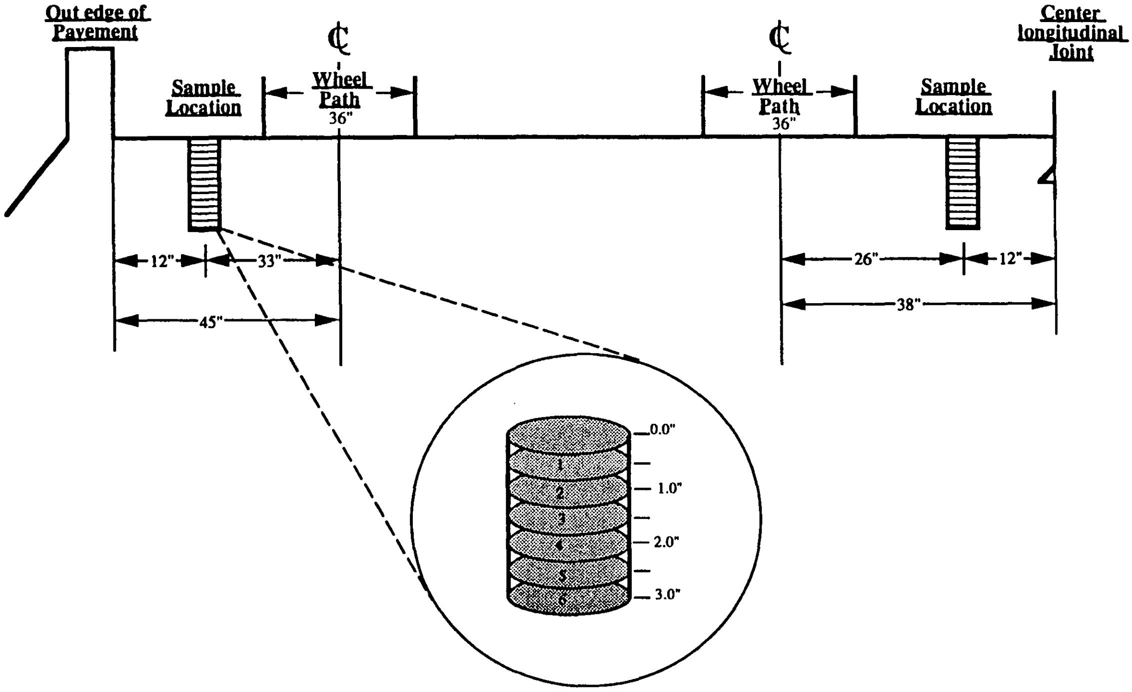

FIGURE 2 Typical wheelpath location on PCC pavement (1 in. = 25.4 m).

TABLE 2 Chloride Ion Content for Each Depth

Type of Sealer	Year 1						Year 2						Year 3					
Depth	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
Cont-1	5.31	2.81	1.57	1.98	1.50	1.61	7.43	7.12	2.92	1.89	1.58	1.74	11.00	9.52	4.18	2.30	1.57	1.61
Cont-2	5.30	3.45	2.40	1.85	1.49	1.93	8.69	7.44	3.05	1.70	1.90	2.20	10.20	8.69	4.07	2.03	1.58	1.94
Cont-3	5.56	3.28	2.05	1.72	2.02	1.71	7.15	7.11	3.51	2.11	1.71	1.84	8.88	8.01	3.60	2.24	1.78	1.63
Silox 1	1.99	2.27	1.94	1.55	1.55	1.72	3.97	4.90	3.21	2.29	1.73	1.60	4.75	5.74	2.86	2.01	1.69	1.91
Silox 2	2.51	2.31	1.77	1.91	2.04	1.63	4.85	5.84	3.24	2.27	1.70	1.69	5.45	6.40	2.55	1.60	1.65	1.46
Eps-1	2.69	2.19	1.56	1.70	1.50	1.67	4.15	3.79	2.35	1.87	1.69	1.58	5.00	4.02	2.75	1.93	1.75	1.45
Eps-2	3.14	2.63	2.14	2.01	1.39	1.28	5.13	3.85	2.92	2.48	1.75	2.53	5.33	4.18	2.21	1.66	1.55	1.76
Blend	2.59	2.10	2.14	1.57	1.99	1.73	5.80	6.36	2.63	1.75	1.59	1.72	6.67	7.88	3.83	2.21	1.78	1.59
Modified	3.58	2.57	1.55	2.26	1.83	1.59	6.46	6.58	3.10	2.29	1.92	2.03	7.15	8.58	3.82	2.07	1.77	1.55
Silane	1.69	1.90	1.61	1.64	1.49	1.73	2.31	2.82	2.13	2.33	1.90	1.68	2.88	3.46	2.27	2.01	1.47	1.75

1 pound = 0.454 kilograms, 1 cubic yard = 0.765 meters cubed

NOTE: Depth 1 = 0 to 12.7 mm (0 to 0.5 in.), Depth 2 = 12.7 to 25.4 mm (0.5 to 1.0 in.), Depth 3 = 25.4 to 38.1 mm (1.0 to 1.5 in.), Depth 4 = 38.1 to 50.8 mm (1.5 to 2.0 in.), Depth 5 = 50.8 to 63.7 mm (2.0 to 2.5 in.), and Depth 6 = 63.7 to 76.2 mm (2.5 to 3.0 in).

The surfaces of test and control areas were observed at the time of each sampling. After 3 years of exposure the first EPS test area had sealer still evident in the tinning. Most of the sealer appeared to be worn away on the surface. The second EPS had sealer still evident in the tinning and between wheelpaths. There were no significant signs of surface scaling or aggregate pop-outs in any test or control area along the evaluation strip.

Figures 3 through 7 illustrate the chronological sequence of the operation from blasting to applying the sealer and sampling. Both blasting and sealer application were done on the same day.

Data Analysis and Results

Table 2 shows the amount of chloride ion content found in samples from the various test holes. Each value represents the average annual value from four test holes of each test area. Six sample data were taken from each test hole. Because the study was only over 3 years, little chloride will penetrate below 50.8 mm (2 in.). Thus, the data analysis is based on the depths between 0 and 50.8 mm (0 to 2 in.).

Table 3 indicates the percentage of reduction of chloride ion due to the sealers applied to the surface of concrete test areas. For instance, the first-year value of 1.71 lb/yd^3 for

FIGURE 3 Sandblasting operation cleaning the concrete surface, removing the curing compound.

FIGURE 4 Applying sealers, flooding surface, uniformly distributing with roller.

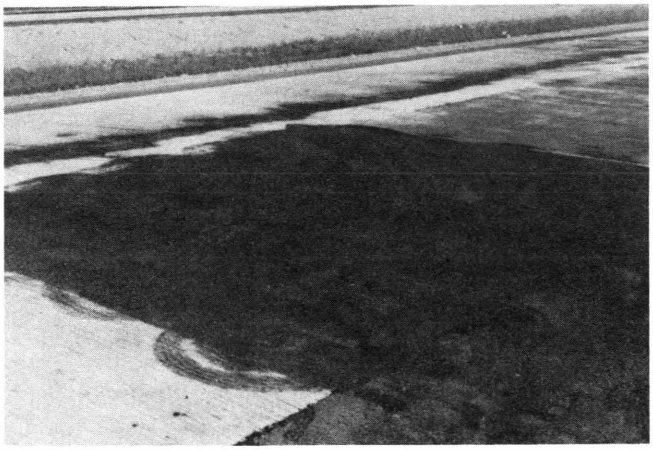

FIGURE 5 Epoxy sealer applied and sanded.

FIGURE 6 Finishing after all sealers applied in traffic lane.

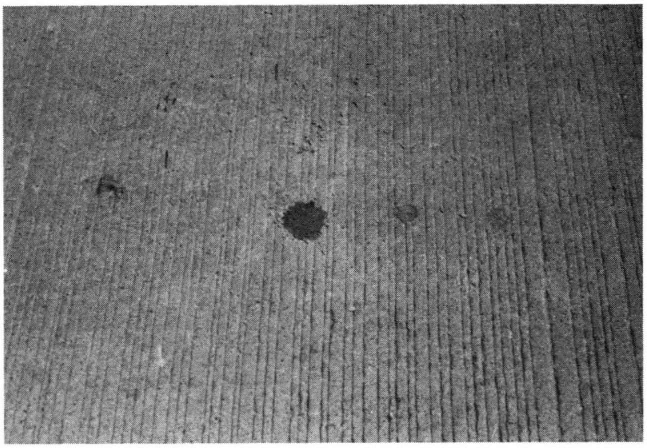

FIGURE 7 Close look at Location 30 after 3 years of sampling.

Silane is derived from Table 2. The average value of four depths, which represents depths from 0 to 50.8 mm (0 to 2 in.), is obtained by the calculation [(1.69 + 1.90 + 1.61 + 1.64)/4 = 1.71]. The corresponding reduction is obtained by comparing the average value of the Silane test area with the average value of the nearby controlled test areas, Sections 1 and 2. The reduction for the first year is 44.5 per cent [(3.08 − 1.71)/3.08 = 44.5 percent]. The percentage reduction for most treated test areas is increased each year. The last column contains the 3-year average. Silane has the comparatively highest reduction, and Modified has the lowest.

Figures 8 and 9 are the graphic representation of Table 3. The data shown in Table 4 are the reductions for the depth between 0 and 63.7 mm (0 to 1.5 in.) only. The reason for examining this layer is to attempt to compare the results with the results of *NCHRP Report 244* (*5*). In the report, the penetration of chloride ions in the concrete slabs subject to southern accelerated weathering exposure was examined between 6.35 and 31.75 mm (0.25 and 1.25 in.) below the concrete surface. The results in Table 4 are similar to the results in Table 3: the Silane test area has the highest percentage

TABLE 3 Present Reduction of Chloride Ion Penetration Between the Depth from 0.0 to 2.0 in. (Depths 1 to 4)

Type of Sealer	Year 1			Year 2			Year 3			Three Years		
	Avg.	SD	% Red	Avg.	SD	% Red	Avg.	SD	% Red	Avg.	SD	% Red
Silox 1	1.94	0.74	39.4%	3.59	1.09	29.5%	3.84	2.28	35.6%	3.12	1.76	34.2%
Silox 2	2.12	0.37	33.8%	4.05	1.45	20.4%	4.00	2.10	32.9%	3.39	1.73	28.6%
Eps-1	2.04	0.69	33.8%	3.04	1.27	39.6%	3.42	1.75	47.4%	2.83	1.47	41.8%
Eps-2	2.48	0.57	22.5%	3.59	1.14	29.5%	3.34	1.54	44.0%	3.14	1.25	34.0%
Blend	2.10	0.54	31.8%	4.13	2.03	17.9%	5.15	2.69	20.8%	3.79	2.34	22.1%
Modified	2.49	0.84	22.2%	4.60	2.07	9.6%	5.40	2.68	9.4%	4.16	2.36	12.4%
Silane	1.71	0.25	44.5%	2.40	0.78	52.3%	2.65	1.05	59.2%	2.25	0.87	53.7%
(C1+C2)/2	3.08	1.48		5.03	2.82		6.50	3.61		4.87	3.12	
(C2+C3)/3	3.20	1.49		5.09	2.68		5.96	3.25		4.75	2.83	

1 inch = 25.4 millimeters Avg.: Average SD: Standard Deviation Red.: Reduction

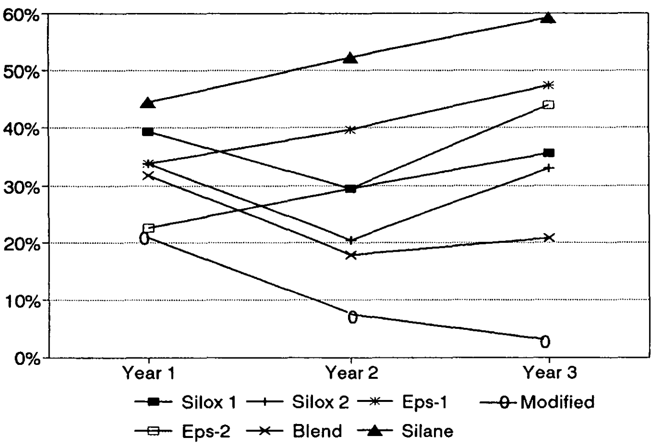

FIGURE 8 Yearly change of percentage of reduction.

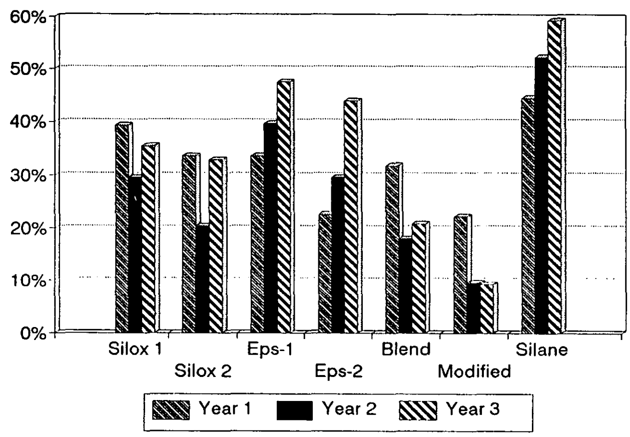

FIGURE 9 Comparison of percentage reduction for 3 years.

TABLE 4 Present Reduction of Chloride Ion Penetration Between the Depth from 0.0 to 1.5 in. (Depths 1 to 3)

Type of Sealer	Year 1			Year 2			Year 3			Three Years		
	Avg.	SD	% Red	Avg.	SD	% Red	Avg.	SD	% Red	Avg.	SD	% Red
Silox 1	2.07	0.61	43.6%	4.03	0.94	34.6%	4.44	2.42	38.6%	3.51	1.32	38.2%
Silox 2	2.20	0.42	40.2%	4.64	1.23	24.6%	4.80	1.89	33.7%	3.88	1.18	31.8%
Eps-1	2.15	1.03	38.1%	3.43	1.30	43.8%	3.92	1.83	50.6%	3.17	1.39	45.8%
Eps-2	2.64	0.56	28.2%	3.96	1.05	35.7%	3.90	1.42	46.1%	3.50	1.01	38.5%
Blend	2.28	0.52	34.4%	4.93	1.77	19.3%	6.12	2.48	22.9%	4.44	1.59	23.9%
Modified	2.56	0.93	30.2%	5.37	1.86	12.8%	6.51	2.23	10.0%	4.81	1.67	15.3%
Silane	1.73	0.22	50.1%	2.41	0.86	60.5%	2.86	1.12	64.0%	2.33	0.73	60.0%
(C1+C2)/2	3.47	1.57		6.11	2.54		7.94	3.12		5.84	2.41	
(C2+C3)/2	3.67	1.49		6.16	2.34		7.24	2.86		5.69	2.23	

1 inch = 25.4 millimeters Avg.: Average SD: Standard Deviation Red.: Reduction

reduction, and the Blend test area has the lowest. Moreover, both the Blend and Modified test areas display a diminishing percentage reduction.

Table 5 exhibits the average yearly value of chloride ion content for both intervals from 0 to 50.4 mm (0 to 2 in.) and from 0 mm to 38.1 mm (0 to 1.5 in.).

An analysis of variances was performed to examine the differences among the exposures. The results demonstrate that they are significantly different at a 99.9 percent confidence level. Year 3 has more chloride ion penetration than Year 2, and Year 2 has more than Year 1. It is logical that the longer the exposure is, the more chloride ions penetrate.

Student-Newman-Keuls grouping was conducted to test the differences among the means of various test areas. The results in Table 6 indicate that all the means of control test areas are not significantly different. They can be considered as an identical group at a 99.9 percent confidence level. Blend and Modified test areas are separate groups; Silox 1, EPS 2, and Silox 2 are a group; EPS 2, Silox 2, and EPS 1 are another group; and Silane is a totally different group.

The INDOT test is similar to the test reported in *NCHRP Report 244* except that it is a field test rather than a laboratory test. Although the INDOT testing did not precisely follow the manufacturers' recommended application rate, the INDOT testing used a more conservative measure to ensure a better sealing effect by generally applying the sealer at a lower square-feet-per-gallon rate.

Table 7 summarizes the application information. EPS 1 and EPS 2 were not tested per *NCHRP Report 244*. The results

TABLE 5 Comparison of Yearly Chloride Ion Content Between the Depth 0.0 to 2.0 in. and Depth 0.0 to 1.5 in.

	0.0" - 2.0"		0.0" - 1.5"	
Year	Avg.	SD	Avg.	SD
1	2.42	1.10	2.62	1.18
2	4.04	2.10	4.69	2.03
3	4.65	2.88	5.53	2.81

1 inch = 25.4 millimeters
Avg.: Average SD: Standard Deviation

TABLE 6 Results from Grouping Test (for 0.0 to 2.0 in., or Depths 1 to 4)

Type of Sealer	Mean	SD	Student-Newman-Keuls (SNK) Grouping					
Cont-1	4.83	3.21	A					
Cont-2	4.90	3.09	A					
Cont-3	4.60	2.62	A					
Modified	4.16	2.39		B				
Blend	3.79	2.36			C			
Silox 2	3.39	1.76				D		
Silox 1	3.15	1.75				D	E	
Eps-2	3.14	1.26				D	E	
Eps-1	2.38	1.49					E	
Silane	2.25	0.88						F

1 inch = 25.4 millimeters SD: Standard Deviation

TABLE 7 Comparison of Sealer Performances on Basis of Laboratory and Field Evaluations

Test Area	Laboratory Performance NCHRP No. 244, Series IV, SCE	INDOT Field Performance Based on 0" to 1 1/2" Sampling Interval (Similar to NCHRP No. 244, Series IV Criteria) 1-Year	2-Year	3-Year
SILANE	98.4%, 125 ft^2/gal.	50.1%	60.5%	64.0%
SILOX 2	92% to 93%,125 ft^2/gal	40.2%	24.6%	33.7%
BLEND	96% 125, ft^2/gal.	34.4%	19.3%	22.9%
MODIFIED	98.7%, 100 ft^2/gal.	30.2%	12.8%	10%
SILOX 1	89.30%, 100 ft$^{2/gal.}$	43.6%	34.6%	38.6%

1 ft^2 = 1 square feet = 0.093 meters squared
1 gal = 1 gallon = 3.785 liters
1" = 1 inch = 25.4 millimeter

in Table 7 indicate that the results from a field test could be significantly different from the results from a laboratory test. The laboratory results are not always applicable to the field, as the results from both test areas of Blend and Modified can verify. Both Blend and Modified sealers resisted chloride ion penetration very well under the reported laboratory atmosphere, achieving up to 96 and 98 percent reductions, respectively. However, the field tests for both demonstrated that their sealing effectiveness to reduce the chloride ion penetration diminishes under field conditions: they are on the 22.9 and 10 percent levels after 3 years of natural field exposure. It also appears that the severity of chloride ion penetration that resulted from laboratory testing is much greater than the 3 years of natural exposure.

The laboratory setup for accelerated weathering—which included acid, salt water, pounding, thermal heat, ultraviolet exposure, and drying (southern climate exposure)—appears to be much more severe than natural exposure from this study.

CONCLUSIONS

The following conclusions are based on the data presented in this report:

1. After 1 year of exposure, most of the test areas demonstrated effectiveness in resisting chloride ion penetration into the concrete. Silane and Silox 1 test areas demonstrated the highest effectiveness. The EPS 2 test area was not as effective as the other test areas, nor was the Modified test area.

2. After 2 years of exposure, the test area for Silane demonstrated the best effectiveness in maintaining resistance to chloride ion penetration in the concrete. The remaining sealer test areas demonstrated varying degrees of loss in effectiveness. Test areas for Blend and Modified had the most dramatic loss. The test areas sealed with Modified and Silox 2 did not perform as well as those areas sealed with the EPSs.

3. After 3 years of exposure, the test area for Silane continued to demonstrate the best effectiveness in maintaining resistance to chloride ion penetration in concrete. Both test areas for the EPSs demonstrated similar satisfactory effectiveness in reducing chloride ion penetration. Test area EPS 2 indicated a marked improvement from 2 to 3 years of exposure.

The test areas sealed with Silox 1 and 2 demonstrated similar effectiveness after 3 years of exposure. The Silox test areas were not as effective as the test areas sealed with the EPSs. These sealers' test areas also indicated an improvement in effectiveness from 2 to 3 years of exposure.

The test areas sealed with Blend and Modified demonstrated comparative effectiveness in reducing chloride ion penetration after 3 years of exposure, which was significantly below the effectiveness of EPSs.

4. The field test results are significantly different from the laboratory test results in this study. The laboratory test results cannot always be applied to the field. A measure should be developed to ensure that the results of laboratory tests are applicable to real-world situations.

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