MOISTURE PENETRATION IN CONCRETE WITH SURFACE COATINGS AND OVERLAYS

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Tests were made on concrete specimens coated with four waterproofing materials to determine how deeply the coatings penetrated into the concrete. Also, coated surfaces and overlaid specimens were ponded with salt water and tap water to determine the effectiveness of each in preventing the penetration of moisture into the concrete specimens. Freeze-thaw tests were made on asphaltic overlays to determine the effect of freeze-thaw cycling on the overlays and the portland cement concrete beneath the overlays. Shear tests were made to determine the shear strength of concrete overlays bonded to concrete test blocks. It was found that the deepest penetration of coatings, 0.054 to 0.062 in., was made by a mixture of linseed oil and kerosene. No damage was found under the asphaltic overlay after 59 freeze-thaw cycles. Shear bond strengths ranged from 61 to 578 psi when the cube surfaces were treated with surface coatings and from 367 to 597 psi when the surfaces with coatings were sandblasted before overlaying.

•MANY of the problems associated with durability of concrete bridge decks begin with the entry of water into the concrete through cracks and pores. Soluble chlorides are sometimes carried by the water. Electrochemical corrosion of reinforcing steel is enhanced by concentration of chloride ions resulting from chloride entry with water. De-icing salts and seawater are two common sources of chlorides. The depth of penetration of water into concrete is of interest because salt solutions that reach reinforcing steel will probably cause corrosion. The accumulation of corrosion products is sometimes so great that spalling (tensile failure of surface concrete) occurs in the vicinity of the corrosion.

Scaling of concrete surface mortar is the result, too, of water penetration. Alternate freezing and thawing of the water in pores and cracks cause gradual surface deterioration by flaking away the mortar.

Concrete that is kept dry is almost certain to be free of corrosive and freeze-thaw damage sometimes found in concrete bridge decks. This report covers a study to determine the depth that water penetrates concrete with and without protective coatings and with overlays. Tests were made also to determine how deeply the coating materials penetrated into the concrete. The depth of penetration is of interest particularly where abrasion from traffic is expected.

Tests and test results that were used in selecting the surface treatments for this study have been reported elsewhere (1). The overlay systems selected for this study are some of those that have been or are being considered for use by the Texas Highway Department.

Concrete specimens that had been coated with waterproofing materials were examined to determine how deeply the coatings penetrated. In other tests, coated surfaces and overlaid specimens were ponded with 5 percent salt water (the salt solution contained 5 percent sodium chloride and 95 percent tap water by weight) and with tap water

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to determine the effectiveness of each to resist the penetration of moisture into the concrete specimen. Table 1 gives the tests made in the study and the purpose of each test.

It was found that the overlay systems were in general effective in resisting moisture penetration, that the waterproofing materials served to slow down moisture penetration, and that the depth of penetration of the waterproofing materials differs. No correlation between depth of penetration and protection provided against freeze-thaw action was evident in the laboratory study.

MATERIALS AND TESTS

The portland cement concrete slabs, 10 × 10 × 2 in., were made of natural sand and gravel. The maximum size of aggregate was ³⁄₄ in. The concrete mix design for the slabs was as follows: gravel, 1,950 lb; sand, 1,295 lb; type 3 cement, 516 lb; and water, 300 lb.

Test Series 1

In laboratory tests, several materials were investigated as possible depth indicators. Those materials include oil-base dyes, sulfuric acid, printer's ink, and phenolphthalein.

Oil-Base Dyes—Three colors of oil-base dyes (red, orange, and blue) were used. One gram of the dye was added to 100 ml of coatings 2-a and 8-a prior to applications. After the coatings had dried, eight to 10 measurements of penetration depth were made over the 10-in. long broken and sawed surfaces.

Sulfuric Acid—A 50 percent solution of sulfuric acid was used as an indicator of depth of penetration with coating 2-a (method suggested by William Kubie, Oilseed Crops Laboratory, U.S. Department of Agriculture). It was applied evenly over the sawed and broken faces at room temperature, and the specimens were then baked in a 270-deg oven for 2½ hours. After removal from the oven, the specimens were allowed to cool before observations were made.

Printer's Ink—A mixture of 20 percent printer's ink was made with coatings 2-a, 7, and 8-a, and the mixture was applied to the top of the blocks. After drying, transverse surfaces, both broken and sawed, were made from each block. These surfaces were then observed under ultraviolet light to determine the penetration of the flourescent ink.

Phenolphthalein—Phenolphthalein has the property of reacting with alkaline substances to indicate a pink color. Thus, in intimate contact with alkaline concrete particles, a pink color is seen. If the particles are coated to prevent intimate contact with alkali, no such color is indicated. An indicator was prepared by mixing 5 grams of phenolphthalein crystals, 500 ml of isopropyl alcohol, and 500 ml of distilled water. This solution was mixed with coatings 2-a and 8-a to produce a mixture of 20 percent indicator and 80 percent coating. Because the indicator would not mix with coatings 7 and 9, a mixture of indicator was made with coating 2-a. The resulting mixture was applied evenly on the sawed and broken surfaces of the blocks coated with coatings 7, 9, and 2-a. A mixture of coating 8-a and indicator was applied evenly to the sawed and broken surfaces of the blocks receiving coating 8-a.

Both sawed and broken surfaces were observed by the aid of a variable-power microscope. Specimens were mounted on a traversing table, and the distance traversed from the surface to the observed penetration limit was read from a micrometer on the traversing mechanism. Depth measurements to 0.001 in. were recorded for the coatings given in Table 2 by using phenolphthalein as the depth indicator.

Test Series 2

Specimens containing Monfore (2) moisture gauge wells were used in this test series. A relative humidity probe inserted into the moisture wells was used to determine relative humidity at depths of ⅛, ²⁄₈, and ⅜ in. below the top surface.

The specimens in this test series were coated with coatings 0, 2-a, 7, and 8-a. After the coatings had dried, 8-in. diameter rings were bonded to the tops of the blocks.

All surfaces not ponded were exposed to laboratory air of approximately 70 F and 50 percent relative humidity. One set was ponded with a ½-in. depth of tap water and an identical set with 5 percent salt water. Relative humidity versus time was recorded until each moisture well had reached 100 percent relative humidity.

Test Series 3

In this series of tests, overlays were bonded to the surfaces of 10-in. square blocks to determine their effectiveness in resisting the passing of tap water and 5 percent salt water into the concrete base. All surfaces not ponded were exposed to laboratory air as in test series 2. The following overlays were included:

1. Epoxy mortar, ½ in. thick, made up of 15 percent GuardKote 250 epoxy and 85 percent natural sand was used for this overlay. The epoxy and sand were mixed in a 5-gal can using a beater type of blender attached to an electric drill. After being mixed for 5 min, the mortar was poured onto the block surfaces and smoothed. When the mortar lost its tackiness, it was rolled to provide compaction. After 1 day, the 8-in. diameter rings were bonded to the overlay, and relative humidity data were recorded until the overlays were 60 days old.
2. A ½-in. thick polyester resin mortar made of 15 percent commercial polyester resin and 85 percent natural sand was used for this overlay. The procedure for preparing the overlay was the same as for the epoxy except that a wood maul was used for compaction. A wood screed was then used for strike off.
3. Asphaltic concrete, 1½ in. thick, was used for this overlay. A seal coat of 120 to 150 penetration asphalt cement and intermediate-grade synthetic lightweight aggregate was applied to 10-in. square blocks. After 3 days, a tack coat of EA-HVMS (emulsified asphalt, high viscosity medium setting) with 2 percent latex rubber solids was applied to the seal coat. Time was allowed for the EA-HVMS to break, i.e., to permit water to evaporate; then the hot mix was applied on top of the tack coat. The hot-mix overlay was compacted 1 min by static pressure from a hydraulic ram with a force of 14,000 lb over the 10-in. square area.
4. A 1½-in. thick portland cement concrete overlay was bonded to 10-in. square block surfaces with a portland cement grout. The overlays were cured in a 73 F, 100 percent relative humidity chamber for 7 days, after which the overlaid blocks were placed in a 73 F, 50 percent relative humidity chamber. After 7 days in this chamber it became apparent that the drying would not be complete in time for the tests. The specimens were then removed to a 140 F, 25 percent relative humidity chamber where they remained 25 days until the relative humidity in the specimens reached 65 to 70 percent. The containing rings were then bonded to the overlay surface after the 25-day drying period. Tap water and 5 percent salt water were ponded in the rings, and relative humidity data were recorded. When the relative humidity in the moisture wells reached approximately 95 percent, the rings were removed and the overlaid blocks were returned to the 140 F, 25 percent relative humidity chamber for 14 days to reduce the relative humidity to about 70 percent. Coating 2-a was then applied to the overlays, and the test was repeated.

Test Series 4

In this series of tests, asphaltic overlays were bonded to the surfaces of the 10-in. square blocks as described in test series 3. Eight-in. diameter rings were bonded to the surfaces of the overlays, and 5 percent salt water was ponded within the rings. All surfaces not ponded were exposed to ambient laboratory conditions. The blocks were frozen in a 0 F chamber and were thawed in a 40 F chamber. One complete freeze-thaw cycle required 12 hours, and the cycling continued throughout the test. Once each week the blocks were removed to the laboratory where the old 5 percent salt water was discharged. The surfaces were flushed with tap water and brushed to remove any loose particles. They were then visually inspected for any signs of deterioration. If no signs of deterioration were found, the blocks were recharged with 5 percent salt water and the cycling was begun again. Cycling continued until 59 freeze-thaw cycles were completed.

Test Series 5

This series of freeze-thaw tests was made to determine the effect of coatings 0, 2-a, 7, and 8-a on the shear bond strength of old and new portland cement concrete.

TEST RESULTS

Results of tests are given in this section in the form of tables, charts, and discussion.

Test Series 1

Several methods were investigated in measuring the depth of penetration of various coatings. The oil-base dyes mixed well only with coatings 2-a and 8-a. On the broken and sawed surfaces, orange was the only effective indicator.

The 50 percent solution of sulfuric acid applied evenly to broken faces of blocks that had received coating 2-a produced carbon, black in color, when it reacted with the oil. The color gradually faded with depth into the block, making the limit of penetration difficult to identify under close inspection. Gast, Kubie, and Cowan (3) have reported using a 50 percent solution of sulfuric acid as an indicator of coating penetration. In tests on concrete with a sand and gravel to cement ratio by weight of 3, they reported sharp, even lines of penetration. In tests reported here, concrete with a sand and gravel to cement ratio by weight of 5.4 was used. Different coatings and different concretes possibly account for the difference in the results of the separate investigations.

When faces of blocks coated with mixtures of printer's ink and coatings 2-a and 8-a were viewed under ultraviolet light, fluorescence of the ink was evident. The depth was not well defined, however, making measurements difficult and accuracy subject to question. This test was not used for record measurements.

A chemical reaction that produces a distinctive pink color takes place when phenolphthalein and clean portland cement concrete come in contact. The sensitive solution caused no color change in that portion of the concrete penetrated by the coatings used in these tests, and it proved to be a good indicator of penetration depth. Because the phenolphthalein could not be made to mix with coatings 7 and 9, the mixture of phenolphthalein and coating 2-a was used to determine the penetration depths of those coatings.

Table 3 gives the penetration data recorded for coatings 2-a, 7, 8-a, and 9. Each of the coatings was applied to two blocks. Each block was then cut twice at random positions to give four faces from which penetration data were recorded. A statistical analysis of the data showed that there was no significant difference between blocks with a given treatment, no significant difference between faces within blocks, and a significant difference between coatings. Confidence limits for the mean penetration depth at the 95 percent level are given for each of the coatings.

Stewart and Shaffer (4) found no apparent correlation between depth of penetration of the sealer and the final rating of the concrete. Data presented here along with data from an earlier report (1) concur with that finding. In the Stewart and Shaffer test, penetration of linseed oil and mineral spirits was found to be less than 0.01 in. Penetration for linseed oil and kerosene reported above was found to be about 0.05 in. The difference in concrete used in the two tests and the difference in indicators possibly account for the difference in depth of penetration.

Heskin and Rheineck (5) have reported using a 2 percent paste of phenolphthalein indicator in a cellulose gel for determining depth of penetration of coatings. The paste became pink on the concrete areas and remained unchanged on the area penetrated by the coating.

Verbeck (6) discussed a phenolphthalein color test for estimating the depth of penetration of carbon dioxide in various types of portland cement specimens. He concluded that there appears to be no readily apparent physicochemical basis for this test and presumably indicates a combined net effect of extensive carbonation and leaching of alkalies.

In the tests reported here, a comparison of coated and uncoated specimens was not made because it was believed that the indicator would react with clean concrete, i.e., an uncoated concrete. If the concrete were coated, on the other hand, there would be no contact between the alkaline material and the phenolphthalein and, hence, no reaction. Later, tests were made in response to the suggestion of a reviewer that the neutralized products of carbonated alkalies would not react with the phenolphthalein indicator. In those tests, specimens of the same size and concrete mix as the original ones were prepared. After 7 days' moist curing and 21 days' dry curing at 73 F and 50 percent relative humidity one-half of the top surface of each of three specimens was coated with coating 2-a and the other half was left uncoated. The phenolphthalein indicator was applied on both halves of the specimens after they were broken to expose the interior of the blocks. The uncoated blocks displayed the pink color all the way to the top surface, whereas the coated ones had a line of uncolored material along the top surface. That uncolored line was taken to be material coated by the penetrating coating, and the interpretation given to the color on the uncoated blocks was that all of the material was still alkaline and, thus, reactive with the phenolphthalein.

Test Series 2

Moisture penetration into dry portland cement concrete occurs quickly when no protective coating is provided. The moisture migration to the depth of a moisture well was evident when free moisture appeared on the gauge when inserted in that well. Tap water and salt water both can penetrate to a depth of $^3/_8$ in. within 3 hours, the penetration by 5 percent salt water being somewhat faster than that of tap water. Data shown in Figure 1 represent only one set of data and are intended to show a trend. The trend was the same for other data, but the magnitudes were different. When a protective coating is provided, the time required to penetrate $^3/_8$ in. can be extended to several days. Coating 7 provided approximately the same resistance to both tap and salt water, whereas coatings 2-a and 8-a were less resistant to tap water than they were to salt water. Of the three coatings tested, coating 8-a was the most resistant to both tap and salt water. Table 4 gives the times of penetration of 100 percent relative humidity to depths of $^1/_8$, $^2/_8$, and $^3/_8$ in. when various coatings are used.

Test Series 3

Results from this series of tests indicate that thin, bonded overlays can be effective in resisting moisture penetration into the concrete beneath the overlay. Generally, the ponded water remained on the overlays approximately 60 days. It is not likely that water would stand for any appreciable length of time on a well-drained bridge deck and even in low spots for more than 2 or 3 weeks. The 60-day time period then may be taken as a safe upper limit in time for surfaces to be covered with tap or salt water.

Thin, bonded overlays generally were effective in resisting moisture penetration into the concrete beneath them. The blocks covered with epoxy mortar overlays showed no appreciable change in relative humidity when subjected to ponded tap water, but there was an 8 to 10 percent increase in relative humidity over the test period when the blocks were subjected to ponded 5 percent salt water (Fig. 2). In blocks covered with polyester mortar overlays with a 30-day age, relative humidity of 90 percent gradually decreased to 85 percent at 60 days under ponded water. The only reason that can be offered for this decrease in relative humidity is that the sides and bottom of the concrete blocks were not sealed. In their exposure to the laboratory air, some moisture near the surfaces was lost, no doubt, but the moisture well nearest any exposed surface was covered with approximately 4 in. of concrete (Fig. 2).

The blocks covered with the $1^1/_2$-in. thick portland cement concrete overlays (Fig. 3) reacted practically the same when subjected to ponded tap and 5 percent salt water. The relative humidity had reached 90 to 95 percent after 7 days and remained almost constant at that level for an additional 20 days. The blocks were then stored in a controlled environment of 140 F and 25 percent relative humidity for 14 days. The relative humidity of the blocks was reduced from approximately 95 percent to approximately 70 percent. The blocks were then coated with coating 2-a. Results after the coating was applied are shown in Figure 4.

Table 1. Summary of tests and their objectives and results.

Test Series	Test	Objectives	Results
1	Penetration	To determine indicator(s) that may be used to ascertain depth of penetration and to determine the penetration of selected coatings	A mixture of phenolphthalein crystals, isopropyl alcohol, and distilled water was selected for an indicator. Penetration depths of the coatings ranged from 0.013 to 0.054 in.
2	Moisture penetration	To determine the effectiveness of waterproofing materials in retarding moisture penetration	Tung mix and LO mix[a] were most effective. Both more resistant to saltwater solution.
3	Moisture penetration	To determine the effectiveness of overlay systems in retarding moisture penetration	All overlay systems except the untreated concrete system were effective in resisting moisture penetration.
4	Freeze-thaw	To determine the effect of freeze-thaw action on asphaltic concrete overlay systems	No ill effects were noted.
5	Shear	To determine the effect of waterproofing materials on bond stress	All materials tested reduced the bond stress. Sandblasting of treated surfaces prior to overlaying helped to restore bond strength.

[a]LO mix is boiled linseed oil mixed with kerosene, 50 percent of each by volume.

Table 2. Description of coatings.

Coating Number	Description
0	No coating
2-a	Two coats of 50 percent linseed oil and 50 percent kerosene
7	Two coats of Thompson's Water Seal
8-a	Two coats of 50 percent tung oil and 50 percent kerosene
9	One coat of EpoXeal with a touch-up coat

Table 3. Indicated penetration of various surface coatings in concrete.

Coating Number	Description	95 Percent Confidence Limits for Mean Penetration Depth (in.)
2-a	Two coats of 50 percent linseed oil and 50 percent kerosene	0.054 to 0.062
7	Two coats of Thompson's Water Seal	0.013 to 0.017
8-a	Two coats of 50 percent tung oil and 50 percent kerosene	0.041 to 0.045
9	One coat of EpoXeal with a touch-up coat	0.027 to 0.031

Note: N = 160, using the phenolphthalein indicating solution.

Figure 1. Penetration time for ponded tap and salt water on coatings 0, 2-a, and 8-a.

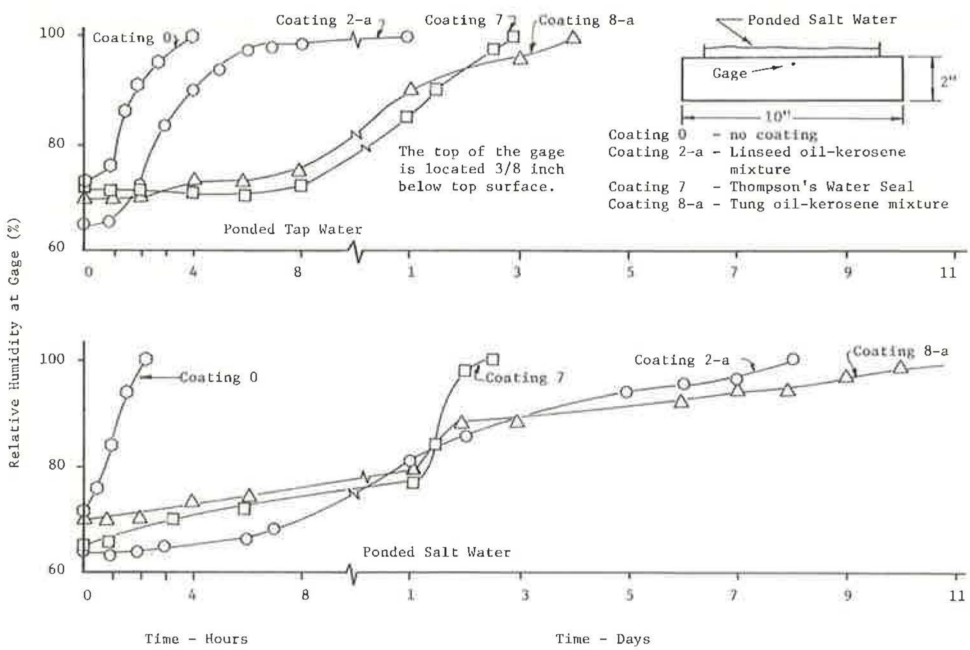


Table 4. Time for penetration to reach 100 percent relative humidity.

Coating Number	Type of Ponded Water	Penetration Time at Various Depths		
		$\frac{1}{8}$ In.	$\frac{2}{8}$ In.	$\frac{3}{8}$ In.
0	Tap	60 min	110 min	175 min
	Salt	20 min	60 min	150 min
2-a	Tap	30 min	7 hours	1 day
	Salt	90 min	$1\frac{1}{2}$ days	8 days
7	Tap	21 hours	27 hours	$2\frac{3}{4}$ days
	Salt	24 hours	27 hours	$2\frac{1}{2}$ days
8-a	Tap	2 hours	1 day	5 days
	Salt	8 days	10 days	13 days

Figure 2. Penetration time for ponded salt water on epoxy mortar overlay.

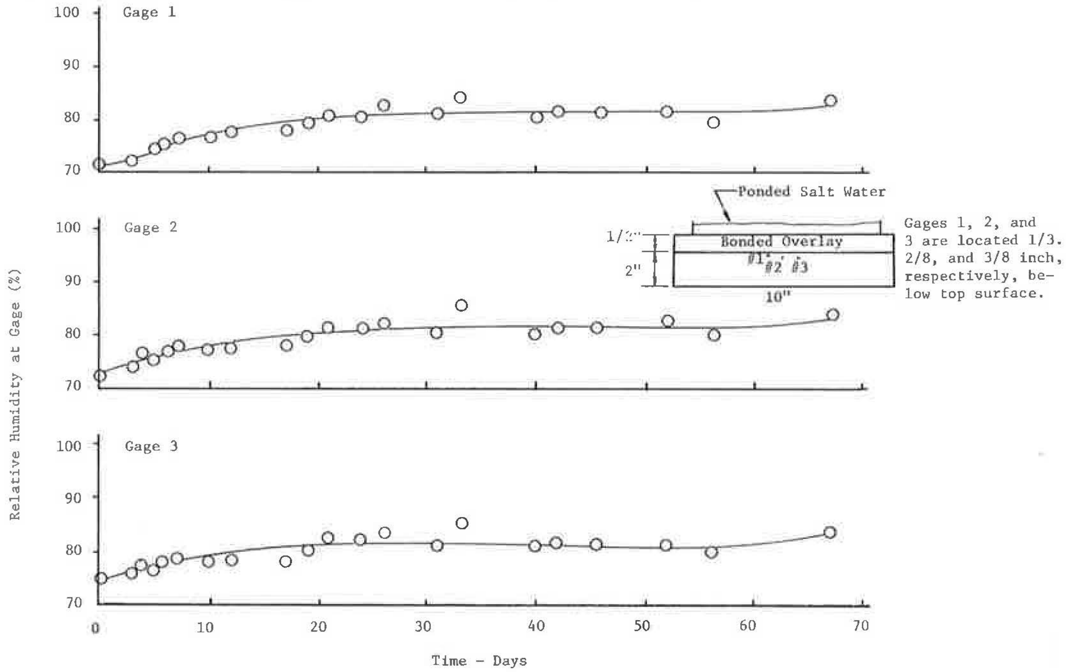
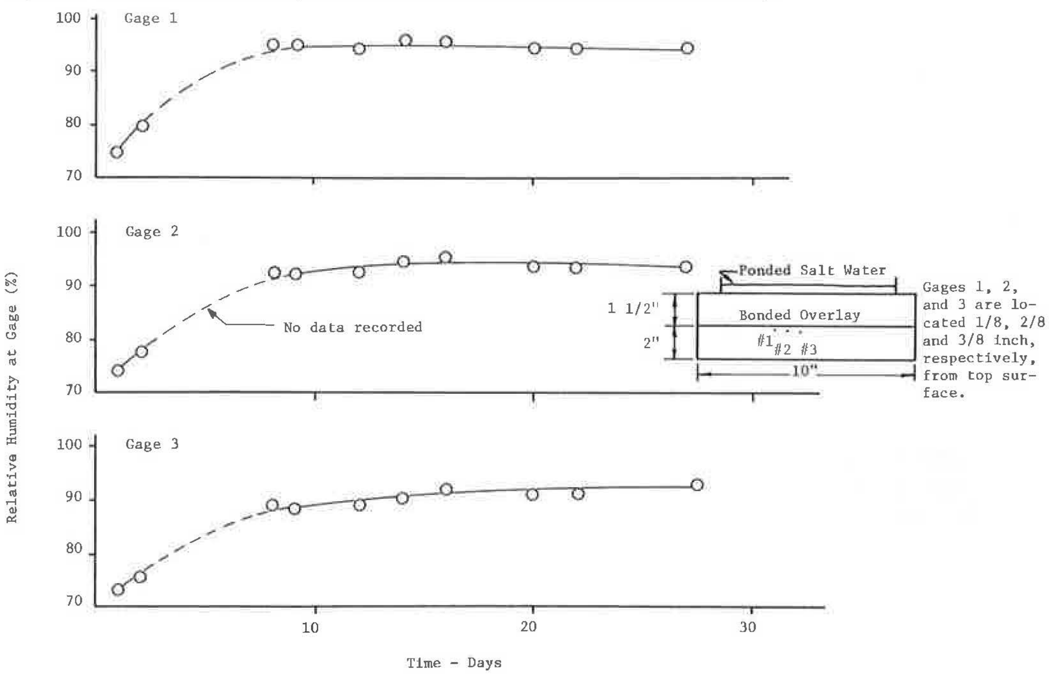


Figure 3. Penetration time for ponded salt water on 1½-in. thick concrete overlay.



The $1\frac{1}{2}$-in. thick asphaltic overlays were tested in the same manner as the other overlays. The relative humidities remained practically constant for the full 60-day period under ponded salt water. Figure 5 shows a typical plot of those data. It was assumed that the relative humidity in the moisture wells, being located near the ponded surface, was not influenced by exposed surfaces of the specimen.

Test Series 4

Tests reported in an earlier report (1) have shown that deterioration can develop under a seal coat when alternately frozen and thawed. In tests of this series, freeze-thaw cycling of the asphaltic overlays continued for 59 cycles. After 25 and 38 cycles, one of each type of overlay was removed in order to examine the concrete surface, which showed no signs of deterioration. The penetration of the 5 percent salt water into the broken overlay was observable from its damp and darker appearance, as compared to the remaining overlay, and, when measured with a ruler, penetration varied between $\frac{1}{4}$ and $\frac{1}{2}$ in. No apparent distress was evident when the blocks were removed from the test.

Test Series 5

Surface condition plays a very important part in bonding of a portland cement concrete overlay. Sinno and Furr (7) showed that motor oil on the overlaid surface greatly reduces the bond capacity between new and old concrete when little or no surface preparation is made.

Overlays were sheared from cubes that had received coatings 0, 2-a, 7, and 8-a with no surface preparation and from cubes that had received coatings 2-a and 7 followed by sandblasting as the surface preparation (Table 5). The cube was fixed in a jig, and a shearing force was applied to the overlay. This force, parallel to the interface between overlay and base specimens, was gradually increased until the specimen failed. The bond stress, in force per unit area of bonded surface, was found for each specimen. When no surface preparation was made, the average bond stress was 578 psi for uncoated cubes, 61 psi for coating 2-a, 88 psi for coating 7, and 267 psi for coating 8-a. Cubes coated with coating 2-a and others coated with coating 7 were sandblasted after the coatings had dried. The resulting average bond stress for coating 2-a cubes was 367 psi and 597 psi for the cubes with coating 7.

Coating 8-a was not included in these tests on sandblasted surfaces. The shear bond strength of overlay over this coating without sandblast treatment was 267 psi. It has been established by Gillette (8) that 200 psi is an acceptable bond strength value for pavement overlay. Theoretical calculations (9) have shown that the bond between a 2-in. overlay and a 7-in. thick bridge slab when flexed under an AASHO H20 wheel is approximately 64 psi. Inasmuch as the 267 psi strength is greater than either of these values, further tests were not made. Had the test been made, it seems reasonable to assume that the bond stress would not have been lowered but increased.

The sandblasting seemed to have removed all of coating 7 but not all of coating 2-a. This is supported by data from test series 1 in which the depths of penetration were measured. Sandblasting removed approximately $\frac{1}{32}$ in. of the surface that included all of the concrete penetrated by coating 7 but only about 60 percent of that of coating 2-a.

CONCLUSIONS

The following conclusions are made on the basis of tests performed in this investigation. An explanatory note follows each conclusion.

1. Surface coatings of a mixture of 50 percent linseed oil and 50 percent kerosene penetrated almost $\frac{1}{16}$ in. into the portland cement concrete used in these tests. The two-coat application of boiled linseed oil and 50 percent kerosene penetrated to a depth of 0.05 to 0.06 in.; the mixture of 50 percent tung oil and 50 percent kerosene applied in two applications penetrated approximately 0.04 in.; EpoXeal, an epoxy penetrant, to 0.03 in.; and Thompson's Water Seal, to approximately 0.015 in.

Figure 4. Penetration time for ponded salt water on 1½-in. concrete overlay coated with coating 2-a.

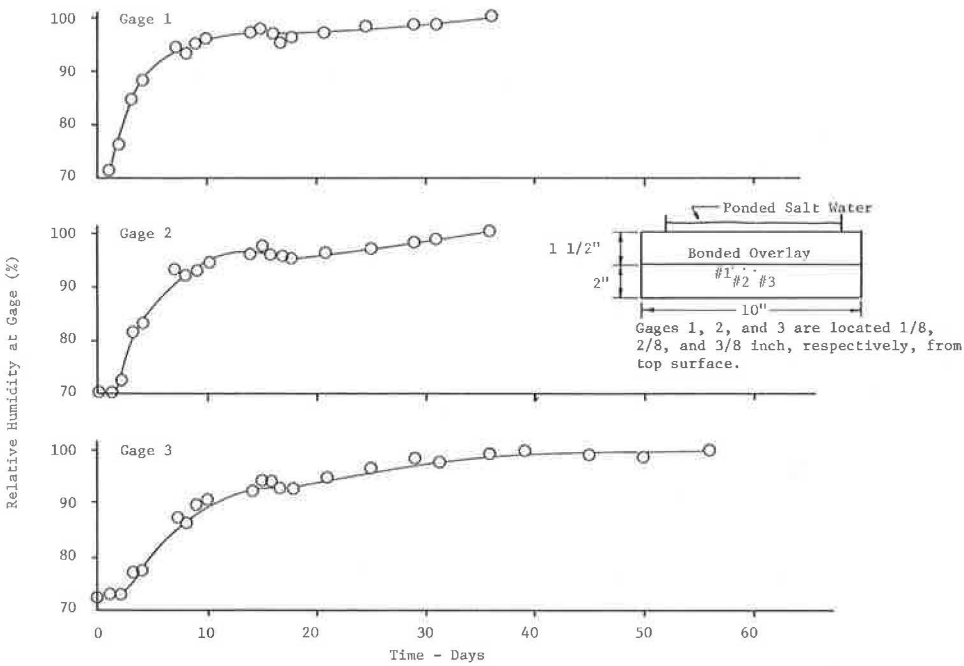


Figure 5. Penetration time for ponded salt water on asphaltic concrete overlay.

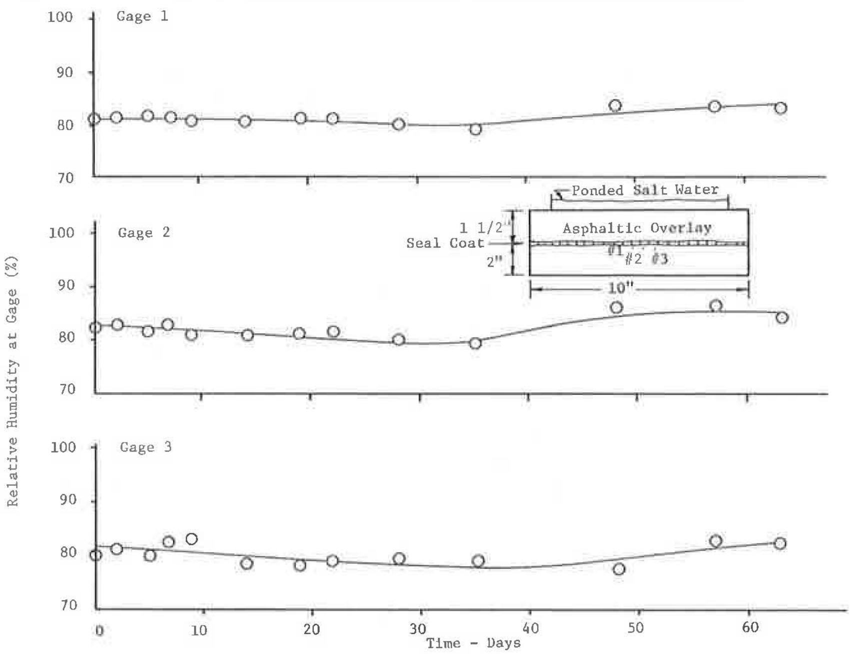


Table 5. Shear bond strength.

Coating Number	Surface Preparation	Bond Stress[a] (psi shear)	Range of Bond Stress (psi)
0	None	578	506 to 658
2-a	None	61	34 to 81
7	None	88	65 to 100
8-a	None	267	235 to 314
2-a	Sandblast[b]	367	255 to 650
7	Sandblast[b]	597	530 to 694

[a]Average of five specimens.
[b]Sandblasted after coating had been applied and curing.

2. Surface treatment of concrete with a mixture of kerosene and either boiled linseed oil or tung oil (50-50 basis) delays the penetration of both tap water and 5 percent salt water into concrete. Relative humidity measurements taken at $^3/_8$ in. from the horizontal surface of the portland cement concrete showed that tap water penetrated $^3/_8$ in. of uncoated concrete within 3 hours, whereas from 1 to 5 days were required for tap water penetration of the linseed-oil- and tung-oil-treated surfaces. Penetration of 5 percent salt water to $^3/_8$ in. was delayed up to 13 days.

3. Thin, uncracked, nonporous resinous and rubberized asphaltic overlays provide effective barriers to entry of moisture into concrete, and a portland cement concrete overlay retards the entry of moisture. Overlays of epoxy mortar and polyester mortar concretes $^1/_2$ in. thick were effective in maintaining the relative humidity below about 85 percent when ponded over with 5 percent salt water for the 60-day period of the test. The $1^1/_2$-in. thick portland concrete overlay retarded the flow of water for a period of about 10 days. A rubberized asphaltic overlay filled with expanded shale, limestone, and field sand provided a nearly complete seal to the laboratory concrete.

4. Surface treatments designed as moisture barriers can measurably reduce the shear bond strength of an overlay applied to the freshly treated concrete surface. The shear bond strengths of a portland cement concrete overlay placed on a concrete surface treated with the linseed oil-kerosene mixture, tung oil-kerosene mixture, and Thompson's Water Seal are reduced from about 578 psi for the untreated surface to 61, 267, and 88 psi respectively for the freshly treated surfaces. Sandblast conditioning of the linseed-oil- and Thompson's Water-Seal-treated surfaces restored them to 367 and 597 psi shear strength respectively.

5. No freeze-thaw deterioration developed after 59 freeze-thaw cycles on concrete surfaces overlaid with the rubberized asphalt used in the tests.

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