Preformed Membrane Performance Under Control Conditions

IMAD L. AL-QADI, RICHARD E. WEYERS, AND N. LALITH GALAGEDERA

Recently, preformed membrane systems have been used extensively in the United States and Europe as a preventive technique to reduce the corrosion in reinforced steel in bridge deck structures. However, the membrane integrity and effectiveness have not been addressed sufficiently. Therefore, an extensive laboratory investigation was conducted to evaluate the membrane effectiveness as a chloride barrier. A total of 48 typical bridge deck slabs were cast in the laboratory: 36 of them were 5 × 5 ft and 12 of them were 5 × 4 ft. A total of four slabs were control, another 4 were overlaid with hot-mix asphalt, and the rest (40 slabs) were covered with three types of preformed membranes and overlaid with hot-mix asphalt. The membranes were installed with various perforation sizes and frequencies. The slabs were exposed to 9 months of deicing (2.3 percent salt) application simulating the average of two winters of salt application in the New England states. Also, twelve 1- × 1-ft specimens were cast for preliminary evaluation. Ultrasonic pulse velocity was used as a nondestructive testing technique to evaluate the installed membranes. Ground truth cores were obtained and powdered concrete samples at three different depths were taken to measure the chloride contents. A statistical model was developed to predict the membrane status using the transit time measured by ultrasonic-pulse velocity. Chloride contents of the unprotected slabs were found to be relatively high compared with those of the protected ones. The perforation-per-unit area in the membrane system was correlated with the chloride content, and a hole size of ¼ in. was found to be a critical size.

The severity of the bridge corrosion problem led to the advent of the 1972 policy (*1*) that requires that deck protective systems be applied to all federally aided structures. This policy resulted in many experimental techniques for both the construction of new bridges and the rehabilitation of existing structures, including membrane installation overlaid with hot-mix asphalt. Membrane systems can be classified as sheet systems and liquid systems. Liquid systems consist of one or two components of moisture or chemically curing solutions that are applied to the concrete surface. Sheet systems include the various preformed factory-manufactured rolls that are bonded to bridge decks to form a continuous membrane.

Membranes have been used extensively for the past two decades in the United States, especially in the New England states. Installation of membrane systems was one of the most convenient methods to comply with the FHWA requirements (*1*). However, a few problems were identified that prevent membranes from achieving their main objective as chloride barriers. These problems include temperature effects during application, membrane installation, blistering, irregularities in the concrete surface, wearing surface application, water absorption, and water and chloride transmission.

In a recent study (*2*), 22 states indicated use of membrane systems as standard in their bridge decks; among them Illinois, Vermont, and Kansas have conducted experimental field studies (*3–6*). An extensive study was performed on bridge deck membrane systems in Vermont on 69 different bridge decks; evaluating 33 different membrane systems (*7,8*). The membranes' performance was evaluated on the basis of the analysis of chloride-contaminated samples. The investigation concluded that membranes, in general, performed well over the investigated period, 14 years, and only 7 percent of the collected concrete samples revealed chloride contamination at 1- to 2-in. depths. The use of membrane systems on old bridge decks was investigated in Kansas over a period of 16 years (*5*). Most of the membrane systems installed performed well, including a membrane installed on a 50-year-old bridge deck. LaCroix (*6*) in his study on 20 bridges over a period of 7 years concluded that using membrane systems for at least 4.5 years is considered economical. In general, the three study cases supported the use of membrane systems as chloride barriers.

Although many studies have been conducted to investigate the membrane properties in the laboratory (*9,10*), no laboratory studies were performed to study the performance (integrity and effectiveness) of installed membrane systems under controlled conditions. This study investigated the integrity and effectiveness of preformed membranes as chloride barriers. The integrity and effectiveness are interrelated membrane properties. If the membrane remains whole, there is a high probability that it will be an effective chloride barrier. However, the bonding to the bridge deck and the hot-mix asphalt overlay are important factors. Although the integrity of the membrane is breached, the membrane may still effectively extend the corrosion initiation time. The study investigated the effectiveness of three types of preformed membranes and developed a methodology to evaluate the membrane effectiveness nondestructively.

SPECIMEN PREPARATION

Twelve specimens, 1 ft × 1 ft × 8 in., were cast using Virginia A4AE bridge deck concrete mixture (*11*). Each specimen was reinforced with three No. 4 rebars. Type A membranes (which consist of a bottom layer of rubberized asphalt with adhesive qualities, a polypropylene barrier sheet, and a top layer of rubberized asphalt-wax) with slits (⅛ in., ¼ in., and ⅜ in.) cut on the center, were placed on nine specimens. The specimens were overlaid with 2.5 in. of hot-mix asphalt, Virginia

---

Department of Civil Engineering, Virginia Polytechnic Institute and State University, 200 Patton Hall, Blacksburg, Va. 24061.

S-5 (*11*). The mix design for the hot-mix asphalt is presented in Table 1. The three remaining specimens were considered control specimens and were not overlaid with hot-mix asphalt; however, membrane was installed on one of them. The 12 specimens were cast to evaluate nondestructive testing methods.

A total of 48 large-scale typical bridge deck slabs were cast. Thirty-six slabs, 5 ft × 5 ft × 7.6 in., were cast with removable wooden forms. Twelve slabs, 5 ft × 4 ft × 9.6 in. were cast using galvanized steel-in-place (SIP) bridge deck forms. The total thickness, 9.6 in., includes a 2-in. SIP-thick form. The slabs were reinforced with No. 5 at 8-in. spacing and No. 4 at 12-in. spacing for the top and bottom rebar mats. The two reinforcing mats were electrically isolated. A reinforcing wire coated with epoxy was connected to the center reinforcing bars of the top and bottom mats. A type T thermocouple was also cast into the center of the slabs at a depth of the center No. 5 rebar in the bottom and top mat. The top cover depth of the slabs is 2 in., and the bottom cover depth is 1 in.

After 7 days of curing, four types of standard preformed membranes were placed on 40 slabs: A, B, C, and D. Preformed membrane A consists of a bottom layer of rubberized asphalt with adhesive qualities, a polypropylene barrier sheet, and a top layer of rubberized asphalt-wax. Preformed membrane B consists of a nonwoven fibrous mat between two layers of bituminous and synthetic resins. Preformed membrane C consists of an impregnated fiberglass mesh between layers of a bituminous mastic. Membrane D is the same as membrane A except that it was installed on 5- × 4-ft SIP slabs. The membrane systems were placed according to the manufacturers' recommendations.

The patterns of membrane installation are presented in Figure 1. Nine slabs from each series, with membranes, were punched with various perforation sizes and frequencies. The tenth slab from each series had a sound membrane without perforations. Three hole sizes were used, ⅛ in., ¼ in., and ⅜ in., at three perforation frequencies, 0.5 percent, 1.0 percent, and 2.0 percent. All holes were located in a 1-ft^2 area at the center of each slab. Perforation sizes and frequencies are presented in Table 1, and a schematic diagram is presented in Figure 2. The eight remaining slabs were considered control slabs without preformed membranes. Four slabs, one from each series, were reinforced concrete without overlay, and the other four, one from each series, were reinforced concrete overlaid with hot-mix asphalt.

The sides of all slabs, at the concrete-asphalt interface, were coated with epoxy. A water-tight electrical box mounted on each slab housed the top and bottom rebar mat thermocouple, and a 10-Ω resistor was used to complete the electrical circuit between the mat. A 1-in.-high dike was placed on each slab surface 1 in. from the edges, and the areas outside the dikes were sealed with a Thoroseal, cement, lime, latex and quick-plug mixture. All slabs were covered with rooftops built from wood and covered with tar paper and plastic sheets to prevent any rainwater from ponding on the surfaces.

TESTING PROGRAM

The testing program included an investigation of the temperature effect on membranes, deicing salt application, nondestructive testing application, and investigating the pre-

TABLE 1 Membrane Perforation Size and Frequency

Series	Template	Membrane "A"	Membrane "B"	Membrane "C"	Membrane "A"
1	59 @ 1/8"	A1	B1	C1	D1
2	117 @ 1/8"	A2	B2	C2	D2
3	235 @ 1/8"	A3	B3	C3	D3
4	15 @ 1/4"	A4	B4	C4	D4
5	29 @ 1/4"	A5	B5	C5	D5
6	59 @ 1/4"	A6	B6	C6	D6
7	7 @ 3/8"	A7	B7	C7	D7
8	13 @ 3/8"	A8	B8	C8	D8
9	26 @ 3/8"	A9	B9	C9	D9
10	None	A10	B10	C10	D10
11	None (Asp + Con)	A11	B11	C11	D11
12	None (Con)	A12	B12	C12	D12

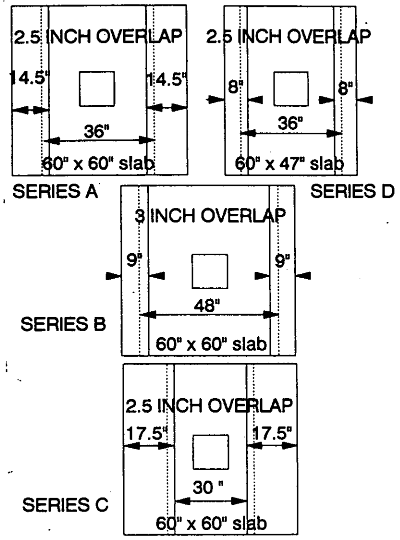

FIGURE 1 Membrane placement and series.

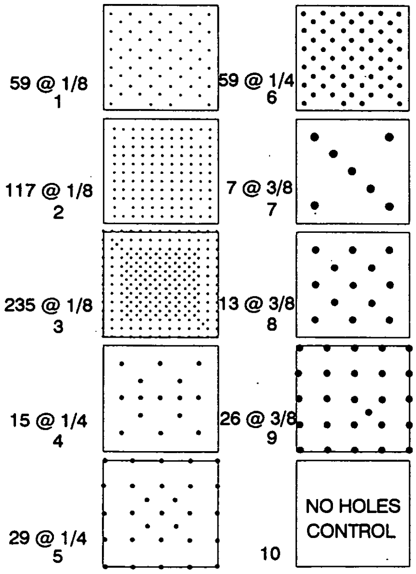

FIGURE 2 Schematic diagram of the membrane perforation frequencies and sizes.

formed membrane effectiveness using chloride content analysis of concrete samples.

Temperature Effect on Preformed Membranes

The temperature effect on preformed membranes was studied in two phases. The first one was preparing 4-in.-diameter membranes (from the three studied membrane types) and exposing them to various temperature levels. The temperature range used was 220°F to 270°F to simulate the laying and compaction temperature of the hot-mix asphalt in the field. A membranes showed a flow within the membrane system in which thin and thick spot areas were formed. These spots led to development of tiny holes in the membrane. B membranes experienced some shrinkages, especially at the edges. These shrinkages led to an uneven surface similar to a blistered membrane. C membranes showed minimum shrinkage and minimum flow within the system.

The second phase involved the preparation of 12 Marshall specimens overlaying membranes with various hole sizes and patterns. A ¼-in.-thick plexiglass sheet, which is temperature resistant up to 350°F, was placed over the Marshall mold's base. Membrane was placed over the plexiglass piece, which was used to evaluate the membrane holes through it. The following holes in the membranes were used: 1 × ⅛ in., five at ⅛ in. (ϕ), 1 × ⅜ in., and three at ⅜ in. (ϕ). The hot-mix asphalt, the same mixture as that for the slab overlay, was placed and compacted for 50 blows using an automatic Marshall compactor. The compaction was performed on one side; no compaction was performed on the plexiglass side.

For membrane A, the holes, five at ⅛ in. (ϕ) and 1 × ⅛ in., remained almost the same size after compaction. However, the three at ⅜ in. (ϕ) and 1- × ⅜-in. holes were increased dramatically in size. The bonding of the membrane to the hot-mix asphalt was satisfactory. The five at ⅛ in. (ϕ) and the 1- × ⅛-in. holes in membrane B remained almost the same after compaction, except that some tiny holes were developed in the second case. The three at ⅜-in. (ϕ) holes were almost the same, whereas an increase was noticed in the size of the 1- × ⅜-in. hole, and a development of tiny holes also occurred. The bonding of the membrane to the hot-mix asphalt was satisfactory. All holes in membrane C were almost the same size before and after the compaction, and the bonding to the hot-mix asphalt was satisfactory.

In general, membrane C performed the best in this experiment. However, an important factor was not studied at this stage: the bonding to portland cement concrete.

Deicing Salt Application

The 48 slabs were subjected to sodium chloride (NaCl) application. Each slab was ponded twice a week for 9 months, a total of 72 pondings. The slabs were salted at a rate of 11.4 tons/lane-mi/year using a solution of 0.25 lb of salt in 10.83 lb of water (2.3 percent); this rate simulates the average salt application rate for the New England states: Connecticut, 7.63; Maine, 6.40; Massachusetts, 18.34; New Hampshire, 13.49; and Vermont, 11.31 tons/lane-mi/year. During the deicing application period, the temperature of top and bottom rebar mats was measured monthly. The potential drop across the 10-Ω resistor was also measured monthly to monitor the corrosion activity.

Development of a Nondestructive Testing Methodology

No nondestructive testing method has been reported to determine defects in membrane systems. However, many nondestructive testing techniques have been used to detect defects in bridge decks (*12–17*). Three methods were used for feasibility study in this investigation: pulse radar, infrared system, and ultrasonic pulse velocity (V-meter).

A pulse radar using 1-GHz frequency was used to detect the holes in the membrane systems installed on the slabs. Because of the small thickness of the membrane sheets, the pulse radar was unable to detect any of the defects in the membranes. This can be explained by the low frequency used considering the membrane thickness and the similarity in dielectric properties between the membrane and the hot-mix asphalt.

Infrared technology was also unsuccessful because this technology is highly dependent on the surface condition and, therefore, will not be reliable in detecting any changes in the subsurface.

The ultrasonic pulse velocity (V-meter) evaluated has a frequency range of 20 to 500 kHz; the transmitter and receiver are operated at 54 kHz. The V-meter indicates the time taken for the earliest part of pulse sent by the transmitter and received by the receiver. The V-meter was first evaluated for 1- × 1-ft specimens using the direct method in which transducers are placed on the opposite sides of the specimen (top and bottom surfaces). In this method the path length is the specimen thickness; therefore, the method is the most accurate. The measurements were taken at three different positions. The average velocity for the nine specimens with preformed membrane and asphaltic concrete was 13,311 ft/sec. The maximum standard deviation between the three positions is 237, whereas the standard deviation of the pulse velocity among the nine specimens is 453. The average pulse velocity for the concrete specimen is 16,174 ft/sec, and its standard deviation is 42, whereas for concrete and membrane it is 14,969 ft/sec with a standard deviation of 18.

The successful use of the V-meter in the direct method led to the next stage of investigating its feasibility in the indirect method (both transducers on the same surface), which includes three different positions and four different distances between transmitter and receiver: 3.5, 5.0, 6.0, and 7.0 in. The study measured the transmittal time and detected the waveform. The measurements at the 3.5-in. distance were the most consistent and repeatable. However, because the measurements might be affected by the edge diffraction for 1- × 1-ft specimens, the measurements were repeated for the large-scale slabs.

On the large-scale slabs (only indirect method used), the 3.5-in. distance was also found to be the most repeatable and consistent. Therefore, a distance of 3.5 in. between transducers was used throughout the study. This distance is short enough to prevent the effect of reflected pulses from the bridge bottom and large enough to prevent detecting waves from the surface. According to Galan (*18*), the distance between transducers should be at least 0.9 the wavelength in the material. The average apparent velocity of the slabs is 13,311 ft/sec at a frequency of 54 kHz. Therefore, the apparent wavelength is 3.0 in. Thus, the minimum distance between transducers should be 2.7 in. This condition is satisfied by using a 3.5-in. distance.

The waveform was studied for the specimens and slabs. Voltage-time relationships for direct and indirect methods were obtained (*11*). A good correlation was found between the largest absolute amplitude and defects of the membrane for the specimens (1 × 1 ft) using the direct method. However, a lower correlation was found for the indirect method. The absolute amplitude is also affected by surface conditions. Therefore, no further analysis of this technique is discussed. However, using a network analyzer might indicate a better analysis of the waveform.

OVERALL INVESTIGATION

After 72 deicing applications on the slabs, half-cell potentials were measured for all the slabs. A grid was drawn on each slab to obtain an average of 20 to 25 half-cell potential measurements. An average of the CSE potential values for each slab is presented in Table 2. Potentials were measured through the overlay for slabs A1 through D11. The CSE potential values indicate corrosion initiation or uncertain corrosion activities in the unprotected slabs compared with a 90 percent probability of no corrosion activities in the protected slabs. This interpretation is in accordance with ASTM C 876-87.

Nondestructive Testing Investigation

V-meter measurements were taken for all slabs. The measurements were obtained at the center of each slab and at another two locations: at the overlap position and at the same distance from the center but perpendicular to the previous measurement (refer to Figure 2 for the overlap locations). The measurement at the center was labeled A, the second B, and the third C. The three measurements are presented in Table 3. After all the measurements were taken, ground truth cores were obtained. A water-cooled 3-in. diamond-core drill bit was used to drill through the hot-mix asphalt in the 40 slabs—A1 through D10. Two cores were extracted from each slab, one at the center where the V-meter measurements were taken and the other at one of the other two V-meter measurement locations; such as, at Slab A1 the second core was made at point B whereas the second core was extracted at point C for Slab A2.

The membranes were carefully evaluated in place and then removed and evaluated again. The criterion for membrane evaluation was a rating from 0 to 10. The 0 indicates an extremely deteriorated membrane with no bonding to the asphalt layer or to the concrete surface. The 10 indicates an excellent membrane condition with very strong bonding to the asphalt layer and the concrete surface. The rating from 7 to 10 indicates that membrane is in a good condition; the rating from 3 to 7 indicates that membrane is in a moderate condition and tiny holes or debonding, or both, exist that may affect the membrane performance; however, the membrane is generally in a satisfactory condition. A rating below 3 in-

TABLE 2 Average Potentials for Slabs

Slab I.D.	Average Potential (-mV)	Stand. Dev.	Median Potential	Min. Potential (-mV)	Max. Potential (-mV)	Temp Top Mat (F)	Temp Bottom Mat (F)	Slab I.D.	Average Potential (-mV)	Stand. Dev.	Median Potential	Min. Potential (-mV)	Max. Potential (-mV)	Temp Top Mat (F)	Temp Bottom Mat (F)
A1	145.3	1.1	146.0	143.0	146.0	----	87.9	B1	146.8	11.6	149.0	120.1	172.1	----	88.8
A2	229.9	1.5	229.9	225.0	233.0	93.7	88.7	B2	107.7	10.1	109.1	86.7	128.9	95.3	93.3
A3	141.2	16.5	137.0	110.7	192.9	73.0	72.1	B3	129.5	46.3	109.5	97.3	278.3	72.5	72.5
A4	187.4	2.4	187.0	183.0	192.0	71.6	71.7	B4	104.9	17.0	106.3	34.5	126.2	81.8	----
A5	----	----	----	----	----	----	----	B5	102.4	17.2	104.5	70.3	127.3	98.2	91.5
A6	120.2	6.4	118.5	110.2	137.3	----	----	B6	127.2	12.7	130.3	90.0	144.8	90.6	84.3
A7	204.0	18.1	203.0	166.2	241.0	76.2	74.1	B7	----	----	----	----	----	95.0	----
A8	163.1	4.8	163.3	154.7	170.3	92.3	90.7	B8	158.9	13.0	157.8	132.3	194.4	97.5	90.5
A9	132.4	8.3	132.0	117.7	162.9	91.5	84.9	B9	----	----	----	----	----	----	----
A10	183.3	11.0	183.0	146.5	205.0	93.5	82.4	B10	121.7	9.4	122.4	97.5	136.0	----	97.7
A11	58.8	13.4	58.3	34.0	95.0	88.7	85.2	B11	81.1	23.1	72.2	37.9	118.9	86.0	79.8
A12	191.6	46.4	181.0	116.5	300.0	----	----	B12	116.3	6.3	116.9	100.8	129.0	98.9	89.9
C1	146.3	16.5	150.0	114.0	172.4	99.3	93.3	D1	147.9	21.9	155.3	103.6	182.6	----	----
C2	158.1	14.9	157.6	127.6	190.6	88.1	----	D2	114.4	17.7	116.8	57.6	142.6	105.4	97.1
C3	162.5	2.1	162.2	158.6	167.5	72.5	72.1	D3	81.5	13.2	78.0	65.3	116.4	103.6	95.5
C4	91.4	1.9	91.6	87.6	94.9	72.8	----	D4	126.5	19.1	132.3	85.9	154.6	104.0	95.2
C5	119.9	25.6	125.1	108.2	135.9	74.4	73.5	D5	117.0	18.8	119.7	70.1	140.1	103.4	95.9
C6	159.3	10.5	156.8	147.1	186.9	88.2	82.7	D6	115.2	14.6	110.8	98.8	138.4	102.0	95.1
C7	284.3	34.3	271.0	243.0	349.0	87.2	81.1	D7	128.9	19.0	121.5	110.4	173.8	103.4	92.6
C8	138.7	11.0	141.0	107.8	158.1	94.8	----	D8	70.0	35.0	64.9	11.8	174.4	----	98.9
C9	----	----	----	----	----	----	----	D9	----	----	----	----	----	----	----
C10	102.2	12.7	104.7	61.5	121.0	91.2	----	D10	158.3	9.8	157.0	140.7	179.2	98.2	89.2
C11	100.5	19.6	110.3	49.9	121.5	----	86.1	D11	100.9	48.8	106.9	20.6	198.2	----	92.6
C12	220.0	17.6	222.0	185.5	253.0	107.2	96.2	D12	345.1	80.5	316.5	266.0	511.0	----	88.3

---- Bad Connection

TABLE 3 V-Meter Measurements and Membrane Evaluation

Slab I.D.	Position A V-Meter Reading (10E-6 sec)	Membrane Rating	Position B V-Meter Reading (10E-6 sec)	Membrane Rating	Position C V-Meter Reading (10E-6 sec)	Membrane Rating	Slab I.D.	Position A V-Meter Reading (10E-6 sec)	Membrane Rating	Position B V-Meter Reading (10E-6 sec)	Membrane Rating	Position C V-Meter Reading (10E-6 sec)	Membrane Rating
A1	19.2	5.0	19.1	5.0	22.3	—	C1	19.0	5.0	20.6	6.0	20.3	—
A2	19.6	5.5	20.1	—	21.5	7.0	C2	19.2	5.0	20.9	—	21.1	6.5
A3	19.8	5.0	21.1	7.5	20.6	—	C3	18.6	4.5	20.9	6.5	20.3	—
A4	19.3	5.0	22.5	8.0	20.7	6.0	C4	19.6	5.0	20.1	—	21.3	7.0
A5	20.5	5.5	23.0	8.5	19.7	—	C5	18.6	4.5	20.2	6.0	19.6	—
A6	19.9	5.5	20.5	—	23.1	8.5	C6	17.5	3.5	18.9	—	19.6	5.5
A7	18.4	4.5	21.3	7.0	20.8	—	C7	18.1	4.0	20.8	6.5	21.2	—
A8	19.5	5.0	17.7	—	18.5	5.0	C8	19.4	5.5	20.5	—	21.4	7.0
A9	17.3	3.5	19.1	5.0	17.0	—	C9	18.1	4.5	21.5	7.0	22.1	—
A10	21.1	6.5	17.4	—	20.7	6.0	C10	20.4	6.0	19.3	—	20.8	6.5
B1	18.5	4.5	21.2	7.0	22.5	—	D1	18.5	4.5	20.7	6.0	20.5	—
B2	20.4	5.5	20.6	—	22.2	7.0	D2	19.6	5.0	23.1	—	20.3	6.0
B3	17.5	3.5	22.4	8.0	22.0	—	D3	18.9	5.0	20.0	6.0	21.2	—
B4	19.2	5.0	20.0	—	20.6	6.0	D4	19.9	5.5	21.5	—	20.2	6.0
B5	19.4	5.0	20.0	5.5	19.8	—	D5	19.2	5.0	21.9	6.5	20.1	—
B6	20.1	5.5	20.8	—	20.9	6.0	D6	18.3	4.0	19.9	—	19.3	6.0
B7	17.3	3.5	20.7	6.0	19.4	—	D7	18.0	4.0	21.5	7.0	21.5	—
B8	19.0	5.0	19.1	—	22.6	8.0	D8	18.0	4.0	19.4	—	19.3	5.5
B9	17.5	3.5	23.4	8.5	18.1	—	D9	18.6	4.5	19.8	5.5	19.0	—
B10	20.7	6.0	18.0	—	18.6	4.0	D10	20.1	6.0	20.6	—	20.2	6.0

— No Cores Obtained

dicates that the membrane is ineffective as a chloride barrier. The factors considered in the evaluation were the membrane condition, its deterioration, and the bonding to the asphalt and concrete layers. This approach was used because of the inability of the V-meter to detect small holes in membranes; however, the V-meter was found to be sensitive to debonding. Eventually, any holes that exist in membranes will lead to debonding because the air void in hot-mix asphalt is always between 3 and 5 percent; therefore, chloride and water will penetrate through the holes and cause the debonding of membrane from the concrete surface. The results are presented in Table 3.

The perforations in Membranes A and C remained almost the same size; however an enlargement in the hole size in Membrane B was occasionally noticed. Membrane C had the fewest changes in hole sizes. This observation was in agreement with the tests performed earlier to investigate the temperature effects. In general, the performance of the three membrane types was satisfactory regarding their condition; however, the bonding to the asphalt or concrete, or both, was varied. Membrane B experienced best bond to the concrete, whereas Membrane A bonded the best to the asphalt concrete. The bonding of Membrane C was the worst. This explains the unchanged hole sizes of Membrane C in the slabs and in Marshall specimens after laying down the hot-mix asphalt.

Regression analysis was performed to correlate the membrane rating and the V-meter measurements. The following model was developed:

$$\text{Memrate} = -10.6 + 0.816 \text{ V-meter} \qquad (1)$$

where Memrate is the membrane rating and V-meter is the V-meter measurement in microseconds.

The R^2-value of the above model is 85.9 percent (r = 92.7 percent), which indicates a good correlation between the membrane rating and the V-meter measurements. Also, the root mean square error, 0.447, indicates a strong correlation between the dependent and independent variables. A plot of the membrane rate versus V-meter measurement is presented in Figure 3. The level of significance for the two-tailed t-test concluded that both the slope and the constant are significant. Figure 3 also presents the 95 percent prediction interval of the regression model.

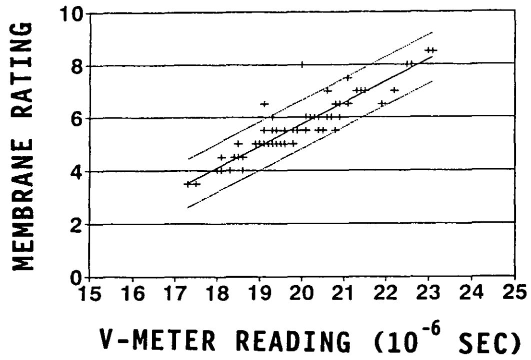

FIGURE 3 Membrane rating and V-meter measurement model with 95 percent prediction interval.

Chloride Content Measurements

After the membranes were removed from the cored locations in the slabs, half-cell potentials were taken directly at the concrete surface. The difference in potentials for a particular slab directly over the concrete or through the hot-mix asphalt overlays is insignificant (see data presented in Tables 2 and 4), which indicates that membrane sheets were able to provide continuity to measure half-cell potentials. However, they were sound enough to reduce the penetration of water and chloride as noted when the cores were removed; the salted water was accumulating between the membrane and the asphaltic layer, which may also explain the poor bonding between the asphalt layers and membranes.

Chloride contents were measured for each slab. Powdered concrete samples were obtained using a ⅛-in. vacuum bit that held the concrete powder in a collection unit. For a detailed procedure of collecting concrete samples, see Herald et al. (*19*). The concrete samples were obtained at three depths: 0 to ½, ½ to 1, and 1 to 1 ½ in. deep. The three depths are referred to as 1, 2, and 3, respectively. The chloride content was determined in each sample using the procedure developed by Herald et al. (*19*). The chloride contents in pounds per cubic yard of concrete and membrane ratings are presented in Table 5. The concrete samples for slabs A1, A2, and A4 were taken 5 days after the preformed membranes were removed. During that period, salted water was covering the holes, which again indicated the feasibility of membrane as a chloride barrier. The concrete samples obtained from these locations showed a high chloride content. Slab A11 indicated low chloride content, which was caused by some leak at the interface of the layers, whereas Slab A10 indicated a chloride content higher than expected. In general, the higher the percent of the perforation, the higher the chloride content. The chloride measurements at Depth 2 indicated that a hole size of ⅜ in. generally leads to a more chloride-contaminated concrete.

In Series B slabs, the chloride contents at B positions were the lowest. Position B is the location where membrane sheets overlap. This indicates that a thicker membrane is a better chloride barrier. However, an opposite observation was noticed in Series C: the overlap locations were more contaminated. This observation is in agreement with an earlier finding that membrane C demonstrated the least bonding. However, the membrane in Series C performed satisfactorily as a chloride barrier and indicated less chloride contamination compared with that of Series A and B. Of note here is that a membrane was installed on slab C11 by mistake. The membrane existence was first detected by the V-meter and then verified during the concrete sampling. The control slabs experienced a very high chloride content compared with that of the other protected slabs. The identification A, B, C, D, or E was used in control slabs to indicate that concrete samples were obtained at random locations.

The results of the effects of the hole size for all membranes are presented as an average for a specific location in Table 6. The average results showed that a ¼ in. hole is a critical size when considering the average chloride content (*1*). The chloride contents of the slabs with membranes of a hole size of ¼ in. and larger are two to three times the chloride content of the slabs with membranes of hole sizes of ⅛ in.

To study the effect of perforation, the chloride contents were investigated considering the perforation percent regardless of the hole size and frequency (Table 7). The effect of perforation was very pronounced for Series C slabs, which is the only series in which the hole size did not change after overlaying the hot-mix asphalt and that showed the least bonding to asphaltic overlay and concrete surface. This effect was obvious for the chloride measurements at the three depths for that series. The chloride at Depth 2 for the other series showed a correlation with the perforation percent. However, no correlation was observed when the chloride was considered at Depth 3. The reasons for the variation are that some of the slabs were not completely leveled, the hot-mix asphalt-layer thickness was varied, and some of the hole sizes were changed after laying the asphalt concrete. In general, the chloride contents in Series A and B slabs were high compared with that of Series C and D slabs. However, when all the

TABLE 4 Potential Measurement of Evaluated Slabs Directly on Concrete Surfaces

Slab I.D.	Position A	Position B	Position C	Slab I.D.	Position A	Position B	Position C
A1	-180.0	-157.0	----	B1	-162.0	-165.0	----
A2	-225.0	----	-227.0	B2	-107.0	----	-105.0
A3	-161.0	-173.0	----	B3	-168.0	-164.0	----
A4	-197.0	-196.0	-196.0	B4	-135.0	----	-128.0
A5	----	----	----	B5	-78.0	-90.0	----
A6	-143.0	----	-146.0	B6	-137.0	----	-147.0
A7	-208.0	-205.0	----	B7	-168.0	-142.0	----
A8	-179.0	----	-189.0	B8	-164.0	----	-107.0
A9	-177.0	-176.0	----	B9	-95.0	-99.0	----
A10	-189.0	----	-178.0	B10	-124.0	----	-115.0
C1	-153.0	-154.0	----	D1	-165.0	-146.0	----
C2	-161.0	----	-160.0	D2	-111.0	----	-84.0
C3	-158.0	-169.0	----	D3	-54.0	-140.0	----
C4	-121.0	----	-117.0	D4	-115.0	----	-140.0
C5	-125.0	-120.0	----	D5	-96.0	-147.0	----
C6	-161.0	----	-151.0	D6	-82.0	----	-52.0
C7	-229.0	-229.0	----	D7	-130.0	-143.0	----
C8	-149.0	----	-146.0	D8	-74.0	----	-49.0
C9	----	----	----	D9	-78.0	-94.0	----
C10	-115.0	----	-110.0	D10	-186.0	----	-205.0
				D11	-89.0	-87.0	----

TABLE 5 Chloride Content of Evaluated Slabs

Slab	Cl (1) (lb/cu.yd)	Cl (2) (lb/cu.yd)	Cl (3) (lb/cu.yd)	Membrane Rating	Slab	Cl (1) (lb/cu.yd)	Cl (2) (lb/cu.yd)	Cl (3) (lb/cu.yd)	Membrane Rating
A1-A	12.988	25.903	31.871	5.0	B1-A	3.813	0.724	1.053	4.5
A1-B	18.329	11.493	6.433	5.5	B1-B	0.705	0.024	0.009	7.0
A2-A	12.088	1.955	0.772	5.5	B2-A	0.595	0.934	0.487	5.5
A2-C	9.668	2.537	0.791	7.0	B2-C	1.033	0.595	0.934	7.0
A3-A	0.731	<0.04	<0.04	5.0	B3-A	3.504	1.558	1.558	3.5
A3-B	0.397	<0.04	<0.04	7.5	B3-B	1.278	0.993	0.993	8.0
A4-A	17.193	7.572	3.267	5.0	B4-A	2.190	0.212	<0.04	5.0
A4-B	7.766	0.753	0.849	8.0	B4-C	4.953	1.536	1.195	6.0
A5-A	1.303	<0.04	<0.04	5.5	B5-A	5.607	1.134	1.033	5.0
A5-B	2.094	<0.04	<0.04	8.5	B5-B	2.494	0.895	0.800	5.5
A6-A	6.238	<0.04	<0.04	5.5	B6-A	1.603	—	1.093	5.5
A6-C	3.010	0.415	<0.04	8.5	B6-C	4.575	0.954	1.154	6.0
A7-A	1.281	<0.04	<0.04	4.5	B7-A	2.442	1.013	0.974	3.5
A7-B	2.069	<0.04	<0.04	7.0	B7-B	3.065	0.954	1.033	6.0
A8-A	3.194	0.528	0.694	5.0	B8-A	3.194	0.528	0.694	5.0
A8-C	3.493	0.528	0.583	5.0	B8-C	3.493	0.528	0.583	8.0
A9-A	2.354	0.113	0.063	3.5	B9-A	2.606	0.230	0.732	3.5
A9-B	3.034	0.334	<0.04	5.0	B9-B	1.667	0.675	0.510	8.5
A10-A	6.520	0.180	0.163	6.5	B10-A	2.796	0.351	0.456	6.0
A10-C	3.179	0.457	0.096	6.0	B10-C	1.024	0.601	0.564	4.0
A11-A	0.548	0.096	0.096	—	B11-A	2.660	0.403	0.299	—
A11-B	1.907	0.282	0.047	—	B11-B	0.984	0.403	0.492	—
A12-A	10.612	1.362	0.299	—	B12-A	8.682	0.546	—	—
A12-B	15.188	2.484	0.475	—	B12-B	12.693	0.656	0.163	—
A12-C	8.680	3.854	0.404	—	B12-C	12.763	2.660	0.113	—
A12-D	13.348	5.488	1.427	—	B12-D	9.667	0.675	0.163	—

Slab	Cl (1) (lb/cu.yd)	Cl (2) (lb/cu.yd)	Cl (3) (lb/cu.yd)	Membrane Rating	Slab	Cl (1) (lb/cu.yd)	Cl (2) (lb/cu.yd)	Cl (3) (lb/cu.yd)	Membrane Rating
C1-A	ERR	ERR	ERR	5.0	D1-A	0.488	0.104	<0.04	4.5
C1-B	0.230	0.247	0.385	6.0	D1-B	0.506	0.087	<0.04	6.0
C2-A	0.213	0.299	0.113	5.0	D2-A	0.561	0.380	0.275	5.0
C2-C	0.213	0.333	0.196	6.5	D2-C	0.711	0.206	0.155	6.0
C3-A	2.005	0.528	0.474	4.5	D3-A	0.654	0.362	0.292	5.0
C3-B	0.846	0.247	0.063	6.5	D3-B	0.432	0.398	1.027	6.0
C4-A	0.403	0.196	0.213	5.0	D4-A	1.278	0.309	0.223	5.5
C4-C	2.553	0.316	0.247	7.0	D4-C	0.206	0.155	0.257	6.0
C5-A	0.368	0.528	0.368	4.5	D5-A	0.673	0.327	0.104	5.0
C5-B	1.488	0.456	0.583	6.0	D5-B	0.808	0.327	0.309	6.5
C6-A	1.554	0.385	0.456	3.5	D6-A	0.292	0.189	0.071	4.0
C6-C	0.656	0.299	0.130	5.5	D6-C	0.172	0.172	<0.04	6.0
C7-A	0.350	0.524	0.000	4.0	D7-A	0.172	0.223	0.488	4.0
C7-B	0.687	0.687	0.761	6.5	D7-B	0.344	0.240	0.104	7.0
C8-A	1.070	0.780	0.780	5.5	D8-A	0.155	0.121	0.257	4.0
C8-C	0.837	0.687	0.669	7.0	D8-C	0.172	<0.04	0.104	5.5
C9-A	0.687	0.614	0.507	4.5	D9-A	0.344	0.292	<0.04	4.5
C9-B	1.464	0.560	0.524	7.0	D9-B	0.309	0.275	0.189	5.5
C10-A	0.578	0.650	0.542	6.0	D10-A	0.257	0.071	0.087	6.0
C10-C	0.507	0.507	0.650	6.5	D10-C	0.415	0.275	0.155	6.0
C11-A	1.336	0.780	0.560	—	D11-A	0.598	<0.04	0.054	—
C11-B	1.336	0.669	0.385	—	D11-B	0.926	0.087	0.054	—
C12-A	15.097	13.304	7.182	—	D12-A	9.012	1.153	—	—
C12-B	20.455	7.884	1.729	—	D12-B	11.944	2.094	0.170	—
C12-C	22.019	12.139	5.589	—	D12-C	10.524	2.810	0.291	—
C12-D	22.563	8.632	2.740	—	D12-D	10.962	3.970	1.303	—
C12-E	18.704	7.645	2.152	—	D12-E	11.944	1.217	0.052	—

TABLE 6 Average Chloride Content for Slabs at a Specific Location

Position On Slab	Avg. Cl (1) (lb/cu.yd)	Std	Avg. Cl (2) (lb/cu.yd)	Std	Avg. Cl (3) (lb/cu.yd)	Std
1A	1.533	1.604	0.417	0.240	0.472	0.428
1B	0.472	0.193	0.421	0.377	0.275	0.157
2A	0.444	0.177	0.550	0.279	0.275	0.145
2C	0.641	0.342	0.354	0.165	0.118	0.067
3A	1.730	1.152	0.629	0.590	0.590	0.586
3B	0.747	0.369	0.432	0.354	0.550	0.472
4A	1.297	0.739	0.236	0.055	0.157	0.086
4C	2.555	1.942	0.668	0.613	0.550	0.444
5A	1.985	2.127	0.511	0.405	0.393	0.385
5B	1.730	0.625	0.432	0.314	0.432	0.283
6A	2.437	2.272	2.083	0.145	0.432	0.425
6C	2.123	1.785	0.472	0.295	0.354	0.464
7A	1.061	0.904	0.472	0.369	0.393	0.389
7B	1.533	1.093	0.472	0.354	0.472	0.417
8A	1.887	1.325	0.472	0.240	0.629	0.200
8C	2.005	1.521	0.432	0.252	0.511	0.216
9A	1.494	0.991	0.314	0.189	0.354	0.299
9B	1.612	0.963	0.472	0.165	0.314	0.204
10A	2.555	2.492	0.314	0.220	0.314	0.200
10C	1.336	1.097	0.472	0.114	0.354	0.252

series are considered, the chloride contents at all depths are proportional to the perforation percent, as presented in Table 7. The chloride content drops dramatically from Depth 1 to Depth 2; however, the decrease in chloride content between Depths 2 and 3 is insignificant.

To investigate the effect of membrane type on the chloride content a regression analysis was performed. Considering chloride contents at Depth 1, R^2 was 10 percent (r = 32 percent); for chloride content at depth 2, R^2 was 38 percent (r = 62 percent); and for chloride at depth 3, R^2 was 50 percent (r = 71 percent). These values are considered low, and no strong correlation exists between the membrane type and the chloride content.

FINDINGS AND CONCLUSIONS

To investigate the integrity and effectiveness of preformed membrane systems, a comprehensive laboratory investigation was conducted. Three types of preformed membranes were installed on large-scale slabs and studied under controlled conditions. The membranes were perforated with various hole sizes at varying frequencies and percent of perforation per unit area. The slabs were overlaid with hot-mix asphalt and exposed to deicing salt ponding. The potential drop in the slabs and temperature were monitored throughout the study. The effects of temperature on membrane systems were also investigated. An evaluation of nondestructive testing methods was performed, and the ultrasonic pulse velocity measurements were strongly correlated with membrane status. Concrete powder samples were obtained from two locations of each slab at three depths to determine chloride contents.

Findings

The temperature was found to have an effect on the preformed membrane sheets. At 220°F to 275°F, Membrane A showed liquidity within the system and an increase in the hole sizes at ⅜ in. Membrane C experienced some shrinkages at the edges of the membrane sheet without any changes in the hole sizes, whereas Membrane B performed the best but showed an increase in the hole sizes at ⅜ in.

The ultrasonic pulse velocity (indirect method) was able to detect debonding and defects of the membrane systems, whereas pulse radar and infrared failed to identify the membrane systems in the slabs. A statistical model was developed to correlate the ultrasonic pulse velocity and the membrane status for the large-scale slabs with a correlation of 92.7 percent (R^2 = 85.9).

A major difference was found in the chloride contents between the protected and unprotected slabs. The unprotected slabs experienced a high chloride content compared with the protected slabs. The chloride content results indicated that the chlorides were relatively higher at the overlapping location for C membranes, which indicates its weak bonding property, whereas B membranes that showed high bonding property resulted in relatively less chlorides at the overlapping locations. The hole size of ¼ in. was observed as a critical size. The percent of perforation was found to correlate with the amount of chloride content. However, the effect of membrane type was found to be minimum.

TABLE 7 Relationship Between Average Chloride Content and Perforation

PERCENT HOLES (%)	AVG. Cl (1) (LB/CU.YD)	STD DEV	AVG. Cl (1) (LB/CU.YD)	STD DEV	AVG. Cl (1) (LB/CU.YD)	STD DEV
0.5 (SERIES A)	----	----	----	----	----	----
1.0 (SERIES A)	2.240	0.943	0.275	0.236	0.373	0.334
2.0 (SERIES A)	3.105	2.311	0.079	0.035	0.039	0.020
0.5 (SERIES B)	2.791	0.711	0.629	0.342	0.708	0.464
1.0 (SERIES B)	3.145	2.056	0.865	0.263	0.747	0.224
2.0 (SERIES B)	2.555	0.770	0.904	0.668	1.140	0.338
0.5 (SERIES C)	0.354	0.197	0.393	0.134	0.197	0.114
1.0 (SERIES C)	0.550	0.377	0.550	0.193	0.432	0.275
2.0 (SERIES C)	1.415	0.558	0.511	0.094	0.472	0.020
0.5 (SERIES D)	0.708	0.421	0.236	0.083	0.236	0.177
1.0 (SERIES D)	0.472	0.220	0.275	0.114	0.236	0.075
2.0 (SERIES D)	0.432	0.169	0.393	0.244	0.118	0.102
0.5 (ALL SERIES)	1.297	1.124	0.377	0.287	0.342	0.366
1.0 (ALL SERIES)	1.533	1.655	0.507	0.318	0.444	0.307
2.0 (ALL SERIES)	1.887	1.627	0.432	0.425	0.472	0.464

Conclusions

This study concluded that membrane systems will protect the bridge decks by reducing the chloride and water intrusion. The following conclusions resulted from this study.

1. The use of membrane sheets is a desired technique to protect bridge deck structures.
2. Holes in preformed membranes increased chlorides and water intrusion; however, the effectiveness of membranes is significantly affected by perforation of a hole size of ¼ in. or larger.
3. The membrane integrity is affected by its bonding to the concrete surface and hot-mix asphalt overlay.
4. Membrane A had the strongest bonding to the asphaltic overlay, whereas membrane B had the strongest bonding to the concrete. Although Membrane C showed the weakest bonding, the system was least affected by the overlay application.
5. The membrane status can be evaluated in place nondestructively using the indirect ultrasonic pulse velocity method that can be used in a developed model to predict the membrane status.

ACKNOWLEDGMENT

The authors would like to express their thanks to Mike Otegui, Marcia Votour, and Chuck Sublet for their assistance in collecting the data.

REFERENCES

1. *NCHRP Synthesis of Highway Practice 57: Durability of Concrete Bridge Decks*. TRB, National Research Council, Washington, D.C., May 1979.
2. W. P. Chamberlin. *Summary of the Field Survey Questionnaire*. SHRP C-103 Project, Task 1. Strategic Highway Research Program, Washington, D.C., June 1989.
3. R. I. Frascoia. Performance of Waterproofing Membranes on New and Rehabilitated Bridge Decks. Presented at 4th Annual International Bridge Conference and Exhibition, Bridge Deck Rehabilitation Seminar. Pittsburgh, Pa., June 22–24, 1987.
4. R. I. Frascoia. *Performance of Waterproofing Membranes on Chloride Contaminated Bridge Decks*. Interim Report 90-3. State of Vermont Agency of Transportation Materials and Research Division, Feb. 1990.
5. I. I. Bukavatz and C. F. Crumpton. Kansas's Experience with Interlayer Membranes on Salt-Contaminated Bridge Decks. In *Transportation Research Record 962*, TRB, National Research Council, Washington, D.C., 1984.
6. J. E. LaCroix. Bridge Deck Condition Survey Phase V. Long-Term Performance Evaluation. Report 100. Illinois Department of Transportation, Feb. 1985.
7. R. I. Frascoia. Field Performance of Experimental Bridge Deck Membrane Systems in Vermont. In *Transportation Research Record 962*, TRB, National Research Council, Washington, D.C., 1984.
8. R. I. Frascoia. *Evaluation of Bridge Deck Membrane Systems and Membrane Evaluation Procedures*. Report 77-2. State of Vermont Agency of Transportation Materials and Research Division, 1977.
9. A. R. Price. *A Field Trial of Waterproofing Systems for Concrete Bridge Decks*. Report 185. Transportation and Road Research Laboratory, Berkshire, United Kingdom, 1989.
10. A. R. Price. *Laboratory Tests on Waterproofing Systems for Concrete Bridge Decks*. Report 248. Transportation and Road Research Laboratory, Berkshire, United Kingdom, 1990.
11. I. L. Al-Qadi, R. E. Weyers, N. L. Galagedra, and P. D. Cady. *Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion. Volume 4: Deck Membrane Effectiveness and a Method for Evaluating Membrane Integrity*. Final Report. Strategic Highway Research Fund, Washington, D.C., 1992.
12. R. G. Liptai and D. O. Harris. Acoustic Emission—An Introductory Review. *Materials Research and Standards*, Vol. 11, No. 3, March 1971, pp. 8–10.
13. I. L. Al-Qadi, P. E. Sebaaly, and J. C. Wambold. New and Old Technology Available for Pavement Management System to Determine Pavement Condition. In *Pavement Management Implementation*. Special Technical Publication 1121. ASTM, Philadelphia, Pa., 1991.
14. R. F. Paetzold, G. A. Mutzkanin, and A. DeLos Santos. Surface Soil Water Content Measurement Using Pulsed Nuclear Magnetic Resonance Techniques. *American Journal of Soil Science Society*, Vol. 49, No. 3, pp. 537–540.
15. D. Manning and F. B. Holt. Detecting Deterioration in Asphalt Overlaid Bridge Decks. In *Transportation Research Record 899*, TRB, National Research Council, Washington, D.C., 1984.
16. T. Chung, C. R. Carter, D. C. Manning, and F. B. Holt. *Signature Analysis of Radar Waveforms Taken on Asphalt Covered Bridge Decks*. Report ME-84-01. Canada Ministry of Transportation and Communications. June 1984.
17. G. Clemena. Non-Destructive Inspection of Overlaid Bridge Decks with Ground Penetrating Radar. In *Transportation Research Record 899*, TRB, National Research Council, Washington, D.C., 1984.
18. A. Galan. *Combined Ultrasound Methods of Concrete Testing*. Elsevier Science Publishing Company, Inc., New York, 1990.
19. S. E. Herald, M. Henry, I. L. Al-Qadi, R. E. Weyers, M. A. Feeney, and S. F. How Lum. *Chloride Content of Concrete*. Report 9133. Pennsylvania Transportation Institute, Pennsylvania State University, University Park, Pa., Aug. 1991.

This paper represents the views of the authors only, which are not necessarily reflective of the views of the National Research Council or the views of the Strategic Highway Research Program (SHRP) or its sponsor. The results reported here are not necessarily in agreement with the results of other SHRP research activities. They are reported to stimulate review and discussion in the research community.

Publication of this paper sponsored by Committee on General Structures.