Coatings and Overlays for Concrete Affected by Alkali-Silica Reaction

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ABSTRACT: Alkali-silica reaction (ASR) affects numerous transportation structures, resulting in cracking that is unsightly and may create the appearance of a loss of structural performance. Extreme cases can lead to a loss of performance. Additionally, cracking provides easier access for aggressive agents such as chlorides to penetrate into the interior of the structure. The aesthetic and durability concerns caused by ASR may be mitigated through the use of coatings and overlays.

Field trials conducted by the U.S. Federal Highway Administration (FHWA) and the Texas Department of Transportation (TxDOT) to mitigate ASR in existing structures incorporated the use of breathable sealers. An outdoor exposure site at the University of Texas at Austin tested breathable sealers, waterproof membranes and pavement overlays on a variety of simulated field structures.

This paper will present the results of up to five years of post-treatment monitoring of field structures and over two years of exposure site testing.

1 INTRODUCTION

Alkali-silica reaction (ASR) is a leading cause of premature concrete deterioration. First discovered in California in the late 1930s and diagnosed by Stanton (1940), it has since resulted in deleterious expansion and cracking of numerous portland cement concrete transportation structures. The cracking is unsightly and can provide avenues of ingress for moisture and chlorides, which can lead to further deterioration of the structure. Expansion can lead to misalignment and crushing of adjacent elements.

The causes of ASR are now well understood and significant research has enabled the development of concrete mixture designs that will not result in expansive ASR. As a result, there should be few cases of ASR in new structures. However, there is a need for effective mitigation methods for structures already affected by ASR.

1.1 *Alkali-silica reaction*

ASR is a reaction that can occur between akali hydroxides (e.g. NaOH, KOH) in the concrete pore solution and certain forms of silica present in some aggregate particles. The reaction forms a hydrophilic alkali-silica gel that, in the presence of sufficient moisture, can expand with sufficient force to cause microcracking in the paste and aggregate. With sufficient expansion, this is manifested at the concrete surface as open macrocracking that may be accompanied by dark stains or white efflorescence.

Since expansive ASR requires a moist environment, transportation and hydraulic structures are particularly susceptible. Hydraulic structures such as dams are constantly exposed directly to moisture, while transportation structures experience wetting and drying cycles. Without sufficient moisture, the reaction can take place, but the gel will not be able to expand. Microclimate effects can often be observed, where portions of a structure that are more frequently exposed to rainfall show more severe signs of ASR, while unexposed portions show little, if any, signs of deterioration.

1.2 *Mitigation methods*

Research into mitigating ASR in existing structures has typically focused on either chemically inhibiting the expansive tendencies of the gel, providing mechanical restraint to the structure, or reducing the supply of external moisture. Lithium salts, particularly lithium nitrate, can be very effective in preventing further expansion (McCoy & Caldwell 1952, Stark 1992, Stokes et al. 1997). However, it is very difficult to introduce sufficient quantities into large concrete elements (Giannini 2009). Mechanical restraint can take the form of external prestressing (active restraint) or fiber-reinforced polymer wraps and steel frames (passive restraint). Reducing the supply of moisture can be as simple as improving drainage details; this should, in fact be performed wherever possible for ASR-affected structures. Other techniques include epoxy crack injection, the application of pavement overlays and coatings such as breathable sealers and waterproof elastomeric membranes.

Breathable sealers such as silanes have been studied extensively in recent years by the U.S. Federal Highway Administration (FHWA), the Texas Department of Transportation (TxDOT), and other agencies for their potential to prevent the ingress of external liquid moisture while allowing the passage of water vapor. Given sufficient dry periods, the net effect is to reduce the moisture content of the concrete (Fig. 1). Studies show that expansion is markedly reduced if the internal relative humidity is below 90%, and can be almost completely eliminated if reduced below 80% (Pednault 1996). Research by Jensen (2000) and Wehrle (2010) suggests that silanes are most effective if applied to thin concrete elements because the depth to which silanes can reduce relative humidity is limited. Experimental work and models by Kubo et al. (2000) suggests that the greatest effect is achieved within 10 cm of the treated surface. Silanes can also significantly reduce the aesthetic damage caused by ASR. Trial applications to sections of a highway median barrier near Québec City in 1991 were not only effective in reducing expansion (Bérubé et al. 2002), but also resulted in a much improved appearance compared to untreated control sections. Figure 2 shows a boundary between a treated and untreated section of barrier as it appeared in 2009. Some breathable sealers are more effective than others, so it is important to test several (Bérubé et al. 2002).

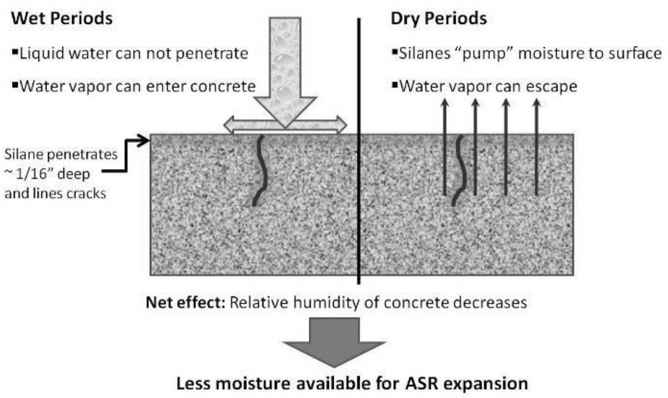

Figure 1. Mechanism of silanes.

Waterproof elastomeric membranes can effectively prevent the ingress of external moisture, but lack the breathability of silanes and therefore also prevent internal moisture for exiting the structure during dry periods. Therefore, it may be somewhat self-defeating with regard to its ability to prevent or slow future expansion. Any such coating must also be sufficiently ductile that it can accommodate additional expansion of the structure without cracking or debonding. Elastomeric coatings can also address the aesthetic damage of ASR-induced cracking by providing a fresh, uncracked surface.

Figure 2. Silane-treated (left) and untreated control (right) median barrier segments near Quebec City, Canada.

Pavement overlays present some of the same issues as waterproof membranes. They can limit moisture ingress, but also effectively prevent egress as well. However, the overlay does provide a new, uncracked surface for traffic. Unbonded concrete overlays have a flexible layer between the overlay and the damaged substrate concrete so that additional expansion can be accommodated. This is often accomplished with a thin layer of asphalt concrete. Asphalt concrete overlays can also be used to provide a new riding surface. With bridge decks, it is important that any overlay is of minimal depth to prevent adding excessive dead load to the structure. Thicker overlays can be used for pavements constructed on-grade. (Harrington, 2008)

1.3 *Research objectives*

The objectives of the research presented in this paper are to assess the effectiveness of a variety of breathable sealers, membranes and overlays on several types of transportation structures. Field trials were conducted on highway median barriers in Massachusetts and large columns supporting an overpass in Texas. An exposure site containing scaled column, bridge deck and on-grade pavement elements was constructed at the University of Texas at Austin to allow testing in a more controlled environment. The mitigation methods will be assessed by their ability to reduce expansion due to ASR. Breathable sealer should also reduce the internal relative humidity of the structure, while membranes and overlays should be able to accommodate continued expansion of the ASR-affected substrate.

2 FIELD TRIALS

The field trials in Massachusetts and Texas tested several breathable coating formulations on structures believed to be affected by ASR. Petrographic examination conducted prior to the field trials confirmed extensive signs of ASR in the Massachusetts median barriers and signs of developing ASR in the Texas overpass columns. The structures were instrumented and monitored for expansion and relative humidity for several years after the treatments.

2.1 *Massachusetts field trial*

Three silane treatments were applied to a total of 14 median barrier segments in October 2005. Each consisted of spray two applications at a rate 0.10 L/m^2. An isopropyl alcohol-based 40% silane sealer was applied to six barrier segments, designated T4-A/B/C and T5-A/B/C; three of these (T4-A/B/C) were in combination with a double spray application of lithium nitrate. Three segments, designated T6-A/B/C, were treated with an isopropyl alcohol-based 20% silane sealer. A water-based 20% silane was applied to five segments, designated T7-A/B/C, VB-1 and VB-2. Vacuum impregnation of lithium nitrate was also applied to VB-1 and VB-2.

The barriers were instrumented with embedded stainless steel gauge studs arranged in vertical and horizontal 500 mm gauge lengths. Expansions were measured using a DEMEC gauge with 0.001 mm precision. Sealed plastic tubes were embedded to a depth 50 mm to allow measurement of relative humidity as a function of depths using electrical probes. Instrumentation and initial measurements occurred at the same time as the treatments. Monitoring was conducted twice yearly through 2008 and data was also collected in May 2010.

Since the barrier segments were restrained horizontally by adjacent segments, the vertical expansion data was determined to be more significant. The average vertical expansions for each treatment type are shown in Figure 3. All silane-treated barrier sets experienced less expansion than the control sets.

Limited relative humidity data were obtained from this site, however data from May 2008 show that the silane-treated barriers had an average relative humidity of 85%, versus 88% for the control segments. Long-term humidity measurements are complicated by the difficulty of keeping the plastic sleeves sealed against external moisture between site visits.

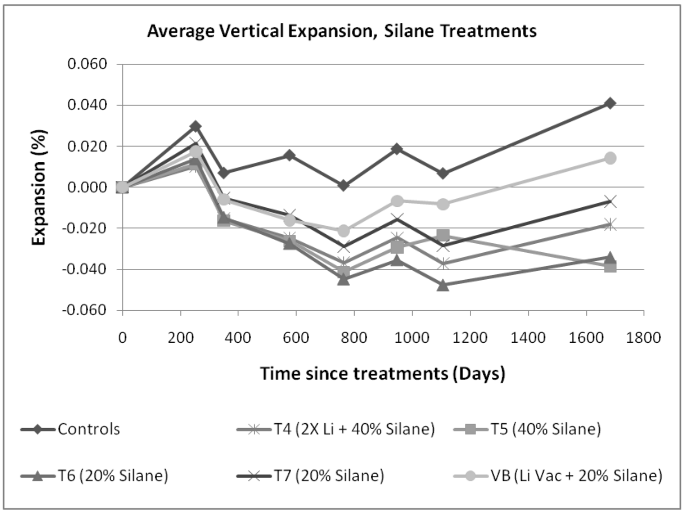

Figure 3. Vertical expansions of Massachusetts barriers.

2.2 *Texas field trial*

A single alcohol-based 40% silane sealer and a silane-siloxane blend were applied to a total of five columns in April 2006. Two untreated columns were selected as controls (columns 36 and 43). The columns were divided into moderate-severe damage (columns 32, 34 and 36) and low-moderate damage (columns 41 through 44), based on visual observations during initial site visits. In each set, one column was media blasted prior to silane application, while the other was left painted.

Columns 34, 42 and 43 were instrumented for expansion measurements in January 2006, while columns 32, 36, 41 and 44 were instrumented in May 2006, shortly after the treatments were applied. Expansions were measured over 500 mm horizontal and vertical gauge lengths on two of the four faces of each column. Plastic tubes for humidity measurements were installed at various times and embedded to depths ranging from 25 to 75 mm. The site was monitored approximately twice yearly from May 2006 to August 2009.

The horizontal expansions were determined to be most important because the columns were more heavily reinforced and bearing significant loads in the vertical direction, but restrained only by transverse reinforcement in the horizontal direction. Figures 4 and 5 show the horizontal expansion data for the moderate-severe damage columns and the low-moderate damage columns, respectively. With the exception of column 44, expansions were similar to the controls. Columns with silanes applied over paint experienced less expansion than those with silane applied on a blasted surface.

Relative humidity data was of limited usefulness. As with the Massachusetts field trial, it proved difficult to keep the plastic tubes free of water between site visits.

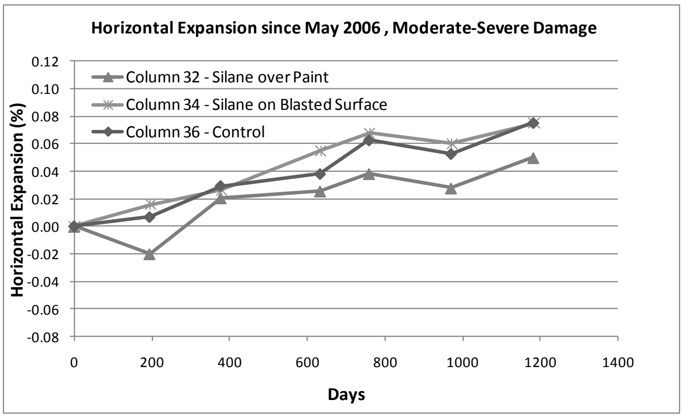

Figure 4. Horizontal expansion, moderate-severe damage columns.

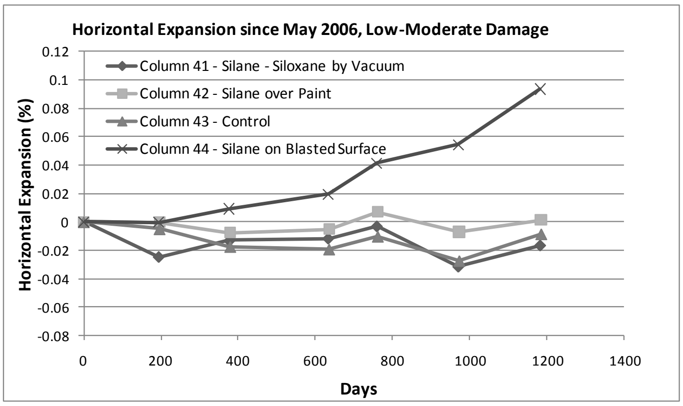

Figure 5. Horizontal expansion, low-moderate damage columns.

2.3 *Need for exposure site*

Although field trials offer the best opportunity for testing mitigation methods on full scale structures, they are limited by the need to travel to the site to take measurements, the time needed to obtain useful results and the lack of true control specimens. The latter is of greatest concern because it is difficult to evaluate a mitigation method if the treated specimen can not be compared to an identical untreated specimen.

An outdoor exposure site, however, can mimic field conditions while sets of nearly identical test specimens are monitored from the time of construction. Mixtures can be designed to yield more rapid results and ensure that ASR is the only deterioration mechanism present. Since there is no need to travel to the site, measurements can be taken in consistent climatic conditions.

3 EXPOSURE SITE TESTING

An exposure site was established at the University of Texas at Austin to study the effectiveness of various mitigation methods in a more controlled setting. This simulated field trial involved three types of structural elements and two reactive aggregates. All specimens were cast over a six day period in August 2008. The results of silane, waterproof membrane, concrete and asphalt overlay treatments will be presented in this section. Full details on the construction of the exposure site can be found in Bentivegna (2009).

3.1 *Materials and specimens*

Both reactive coarse and fine aggregates were included in this study, referred to as RCA and RFA, respectively. They consisted of a highly reactive natural sand from El Paso, Texas (RFA) and a moderate to highly reactive gravel from Bernallilo, New Mexico (RCA). The reactive aggregates were combined with local coarse and fine aggregates found to be non-reactive when tested in the ASTM C1293 concrete prism test. A high-alkali cement (Na_2O_e = 0.80%) was used and sodium hydroxide was added to the mixtures to produce an alkali content of approximately 1.25% Na_2O_e. Table 1 shows the mixture proportions used for each of the reactive aggregates.

Table 1. Mixture proportions for exposure site specimens.

Mix	w/cm	Water (kg/m^3)	Cement (kg/m^3)	Aggregate (kg/m^3) Coarse	Fine
RFA	0.42	176	420	1038	726
RCA	0.42	176	420	1038	751

*A water-reducing and retarding admixture was also used to provide sufficient workability.

Specimen types included 20 unreinforced on-grade slabs, 22 reinforced bridge decks and 14 circular reinforced columns. The unreinforced slabs were 910 x 910 x 286 mm in size. Reinforced bridge decks were 910 x 910 x 235 mm and contained two layers of two-way steel reinforcement typical of bridge deck construction. The columns were 1219 mm in height by 610 mm in diameter and contained both primary vertical reinforcement and secondary spiral reinforcement. The sides of the slabs and bridge decks were sealed with epoxy paint to ensure that moisture ingress could only take place through the top or bottom of the specimen.

The specimens were instrumented for measuring expansions and for selected specimens, relative humidity. Visual inspection of the specimens was frequently conducted as well. Embedded stainless steel gauge studs were installed on 500 mm gauge lengths for most expansion measurements and monitored using a DEMEC gauge. For the slabs and bridge decks, three horizontal gauge lengths on two sides of the specimens, in addition to four gauge lengths on the top surface (Fig. 6). The gauge lengths on the sides of the slabs were located at depths of 64, 143 and 222 mm from the top surface, while those on the bridge decks were 51, 105 and 184 mm from the top surface. Two vertical gauge lengths were monitored on opposite sides of the columns (Fig. 7). Additionally, circumferential expansion of the columns was monitored using a stainless steel tape marked with a vernier scale with 0.03 mm precision (Fig. 7).

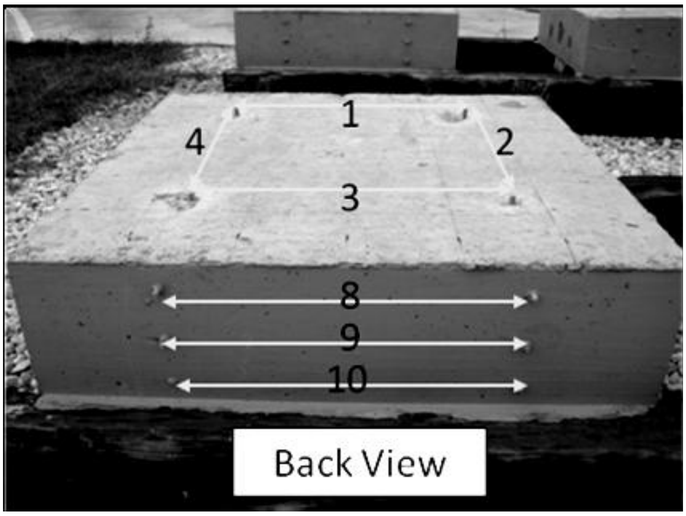

Figure 6. Expansion measurement locations on bridge deck specimen. A similar arrangement was used for the slabs. (Bentivegna 2009).

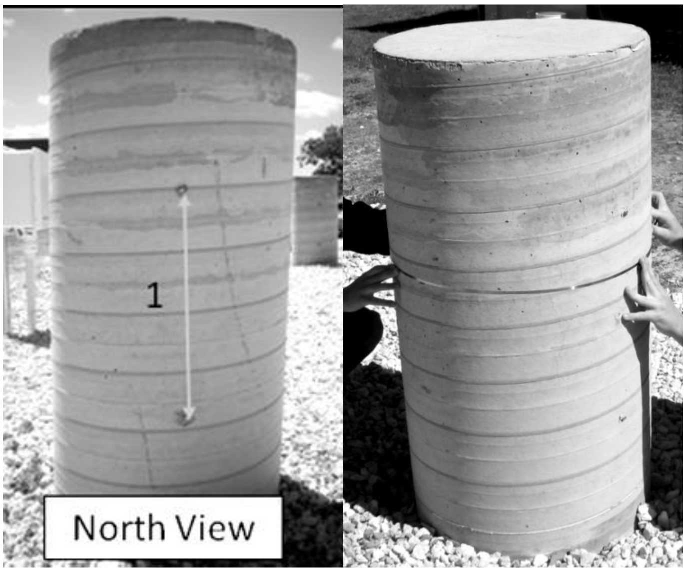

Figure 7. Column expansion measurements. 500 mm vertical gauge length (left) and circumference measurement (right). (Bentivegna 2009).

Monitoring was conducted under specific climatic conditions to minimize thermal and moisture effects on the data. An air temperature of 23 ± 1.5°C with cloudy or mostly cloudy skies was required. Measurements were not taken during or immediately after rainfall events. Initial measurements were taken at an age of seven days. Several measurements were taken throughout the first year, with less frequent monitoring thereafter.

3.2 *Mitigation methods*

A number of mitigation methods were applied to the exposure site specimens. The specimens were allowed to expand and crack prior to application of the treatment to simulate the timing of mitigation measures in real field structures. Table 2 lists these methods and the number of specimens tested for each. They are described in greater detail below.

Table 2. Specimens selected for each mitigation method.

Method	Slabs	Decks	Columns
Control (untreated)	2 RFA 2 RCA*	2 RFA 2 RCA	2 RFA 2 RCA
40% Silane	2 RFA 2 RCA	2 RFA 2 RCA	2 RFA 2 RCA
100% Silane	2 RFA 2 RCA	2 RFA 2 RCA	2 RFA 2 RCA
Membrane 1			1 RFA 1 RCA
Membrane 1 + 50 mm concrete overlay		2 RFA 2 RCA	
Membrane 1 + 50 mm asphalt overlay		2 RFA 2 RCA	
Membrane 2		2 RCA	
50 mm asphalt overlay	2 RFA 2 RCA		
300 mm unbonded concrete overlay	2 RFA 2 RCA		

*Material variations in RCA slabs led to significant differences in the untreated control specimens. Where possible, comparisons were made to the appropriate control.

Two silane products were used: a water-based 40% silane and an isopropyl alcohol-based 100% silane. For the latter product, the MSDS lists the solvent as 2.0% by weight; the solids content is thus likely 98%, not 100%. Both silane treatments were applied at a rate of 0.33 L/m^2.

Two waterproof membranes were tested. Prior to membrane application, the surface of the bridge decks and columns were grit blasted. Membrane 1 was a methylmethacrylate (MMA) flexible waterproof membrane that was sprayed onto the specimens in two layers. No. 8 size angular aggregate was broadcast into the top layer to improve bond to subsequent overlays on bridge decks. A bituminous tack coat was also applied to the decks which would receive the 50 mm asphalt overlay. Membrane 2 was a combination waterproof MMA membrane and wearing course designed to seal and provide a new riding surface for damaged bridge decks that is much lighter than an asphalt or concrete pavement overlay.

Several overlays were also tested. All concrete overlays utilized a non-reactive mixture design and new gauge studs for top surface expansion measurements were installed. Concrete and asphalt overlays 50 mm thick were placed on selected bridge decks treated with Membrane 1. Asphalt overlays 50 mm in thickness were also applied directly onto the top surface of selected slabs. Unbonded concrete overlays 300 mm in thickness were applied to selected slab specimens; an asphalt layer 25 mm thick acted as a bond breaker between the overlay and substrate concrete.

3.3 *Results*

A new system for measuring relative humidity based on the work of Jensen (2000) is under development and has not yet been implemented on the exposure site. Therefore, the two criteria on which the mitigation methods will be evaluated are expansion since the time of treatment application and visual observation. When possible, a set of measurements was taken around the time of treatment. The most recent expansion measurements were taken between November 2010 and April 2011.

The 40% silane treatment was applied to the RFA specimens in January 2009 at an age of 143 to 145 days. Expansions were measured ten days after treatment and most recently in March and April 2011 for a total of over two years of post-treatment monitoring. Since that time, the slabs have expanded an average of 0.57%, compared to an average of 0.65% for the controls. The bridge decks have expanded an average of 0.22% compared to an average of 0.24% for the controls. The columns expanded 0.07% vertically and 0.30% in circumference compared to 0.11% and 0.33% for the controls.

The 40% silane treatment was applied to the RCA specimens in June 2009 at an age of 290 to 300 days. Expansions were measured approximately two months prior to the treatment and most recently in March and April 2011; nearly two years of post-treatment expansion data was recorded. The bridge decks have expanded an average of 0.02% compared to 0.10% for the controls. The columns expanded an average of 0.03% vertically and 0.06% in circumference, compared to 0.05% and 0.17% for the controls. Materials variations in several of the slabs selected for treatment made comparisons difficult.

The 100% silane treatment was applied to the RFA specimens at an age of 147 to 149 days. Expansions were measured six days after treatment and most recently in March and April 2011 for a total of over two years of post-treatment monitoring. Since that time, the slabs have expanded an average of 0.55%, compared to an average of 0.65% for the controls. The bridge decks have expanded an average of 0.17% compared to an average of 0.24% for the controls. The columns expanded 0.05% vertically and 0.30% in circumference compared to 0.11% and 0.33% for the controls.

The 100% silane treatment was applied to the RCA specimens at the same time as the 40% silane treatment; expansions were monitored on the same schedule as well. The bridge decks have expanded an average of 0.02% compared to 0.10% for the controls. Figure 8 shows the average expansions for the treated and control bridge decks. Note the lack of expansion following treatment. The columns expanded an average of 0.00% vertically and 0.12% in circumference, compared to 0.05% and 0.17% for the controls. Materials variations in several of the slabs selected for treatment made comparisons difficult.

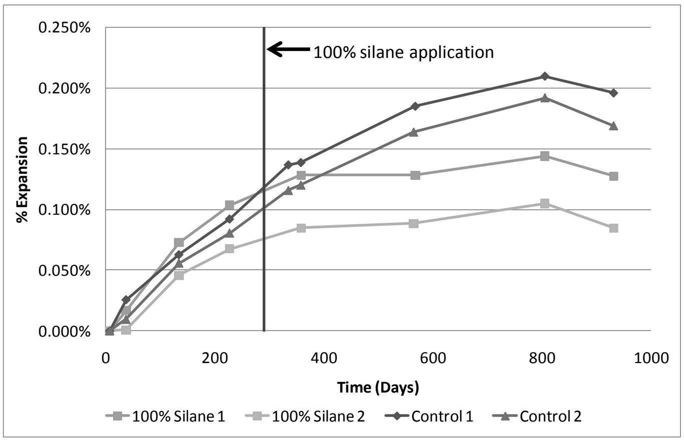

Figure 8. Expansions for 100% silane-treated and control RCA bridge decks.

Membranes 1 and 2 were applied to RFA and RCA specimens in March 2009 at ages ranging from 214 to days. Concrete overlays of specimens that received Membrane 1 (M1+C) were applied in June 2009 at ages of 283 (RCA) and 287 (RFA) days. Asphalt overlays (M1+A) were applied approximately two weeks later. Since the installation of membranes and overlays destroyed the gauge studs used for top surface expansion measurements, only the side measurements will be compared. Reference measurements were taken shortly after installation of the membranes but prior to installation of the overlays. The most recent measurements were taken in March 2011.

During the post-treatment monitoring period, the RFA control specimens expanded an average of 0.14%. RFA bridge decks receiving M1+C and M1+A expanded 0.11% and 0.15%, respectively. RCA control specimens expanded 0.08% during this period while bridge decks receiving M1+C and M1+A both expanded 0.07%. RCA bridge decks receiving Membrane 2 also expanded 0.07%. The RFA and RCA columns receiving Membrane 1 could not be monitored adequately for expansion in the post-treatment period.

The expansions of the top surface of the concrete overlays (M1+C) were also monitored during this period. The overlays on the RFA bridge d*ecks contracted* slightly more than 0.02% after installation, while those on the RCA bridge decks showed no measurable expansion.

The 50 mm asphalt pavement overlays and 25 mm debonding layers were applied to the RCA and RFA slab specimens in June 2009 at ages of 296 and 300 days, respectively. The unbonded concrete overlays on the RFA and RCA slabs were placed in September 2009 at 385 and 386 days of age, respectively. As with the bridge deck overlays, only the side expansions of the substrate concrete were monitored after the overlay was installed. Reference measurements were taken in April and May 2009, for the RCA and RFA specimens, respectively. The most recent measurements were taken in March 2011 for the RFA slabs and November 2010 for the RCA slabs.

The RFA control slabs expanded an average of 0.58% during the post-treatment monitoring period. RFA slabs receiving the concrete and asphalt overlays expanded 0.48 and 0.53% during this period, respectively. The top surface expansion of the concrete overlays were also monitored and contracted less than 0.01%. The RCA control slab expanded 0.42%, while those with concrete and asphalt overlays expanded 0.28 and 0.30% during this period. The top surface of the RCA concrete overlays expanded 0.01%.

Qualitative visual inspection of the silane-treated specimens gave little indication of the performance of this method. The appearance was generally similar to the control specimens.

For the membrane- and overlay-treated specimens, visual inspection yielded some useful information. As seen in Figure 9, the expansion of the RFA bridge deck was sufficient to crack the first layer of Membrane 1, however the crack has not passed through the second layer or resulted in reflective cracking of the concrete overlay at this time. Figure 10 shows cracking that extended completely through Membrane 1 on an RFA column. The cracked area is above the top of the reinforcement cage and expansions in this region are likely higher than those measured in the central portion of the column. At the time of this writing, no failures of Membrane 1 have been observed on RCA bridge decks and columns. All asphalt and concrete overlays installed on the bridge decks appear to be in good condition. Some minor surface crazing is evident on the top surface of the concrete overlays, but no open cracks exist.

RCA bridge decks treated with Membrane 2 exhibit no signs of damage to the membrane at this time.

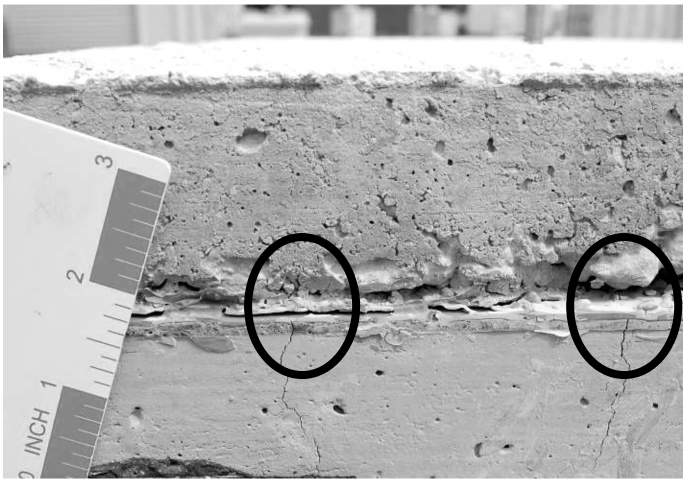
Figure 9. Cracks (circled) in substrate concrete extending into the first layer of Membrane 1 on RFA bridge deck.

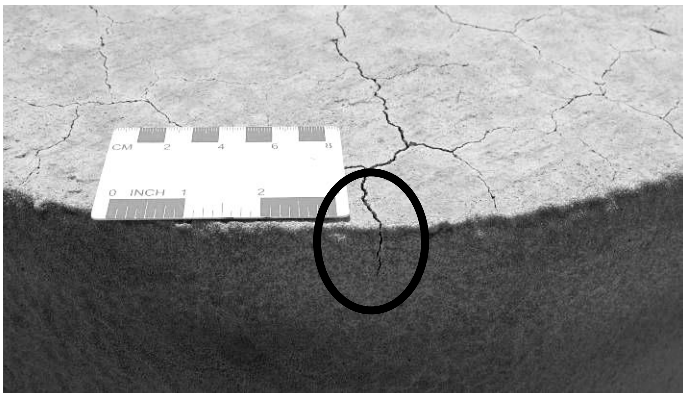
Figure 10. Crack (circled) that has passed completely through Membrane 1 on an RFA column.

At the time of this writing, all asphalt and concrete overlays on the slab specimens appear to be in good condition, despite the continued and significant expansion of the substrate concrete. Figure 11 shows an RFA specimen with a 300 mm unbonded concrete overlay. The asphalt debonding layer is clearly visible and appears to have prevented reflective cracking of the overlay.

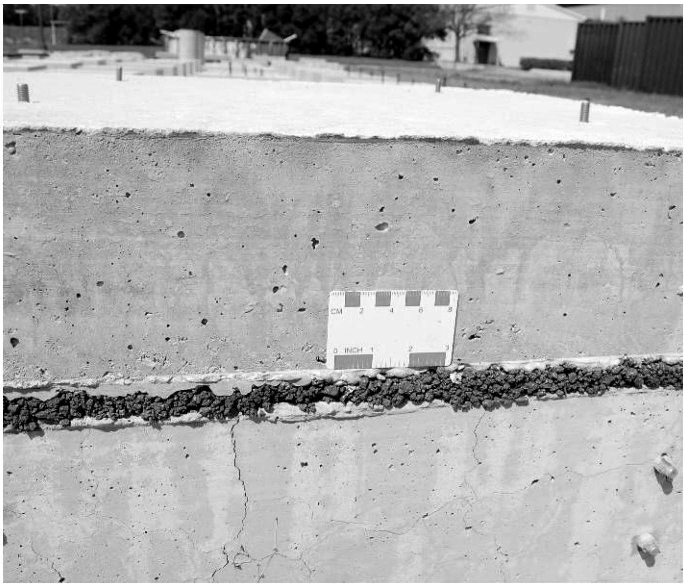
Figure 11. RFA slab with 300 mm concrete overlay and 25 mm asphalt debonding layer.

4 DISCUSSION

4.1 *Field trials*

In the Massachusetts field trial, all silane products were successful in reducing expansion relative to the control barriers. The isopropyl alcohol-based silanes were slightly more effective than the water-based silane in this limited study. However, the expansions of the control barriers were still quite minimal over the course of the monitoring period. A slight reduction in internal relative humidity was measured, but the data are extremely limited.

In the Texas field trial, painted concrete columns treated with silane had similar or slightly less expansion relative to the untreated columns. Columns that were media-blasted prior to silane application had similar or significantly greater expansions than the untreated columns. This study was complicated by the lack of true control specimens. However, a comparison of blasted versus painted columns suggests that paint should not be removed from concrete prior to application of a silane.

4.2 *Exposure site: silane sealers*

The 40% silane had minimal impact on the RFA specimens, but resulted in a significant reduction in expansion of the RCA specimens. In the case of the RCA bridge decks, expansion almost completely ceased following the treatment. The 100% silane resulted in a modest reduction in expansion of the RFA specimens relative to the controls and significant reduction in expansion of the RCA specimens. Expansion of the RCA bridge decks and vertical expansion of the RCA columns ceased or nearly did so.

Both silanes were more effective when used on reinforced specimens. It should be noted that vertical expansion was not measured on the bridge decks and may have been much greater than the horizontal expansions as no reinforcement was provided in this direction. Since the RFA control specimens exhibited greater expansions than the RCA specimens, it is unsurprising that the silane treatments were more effective in controlling expansion of the RCA specimens. Additional cracking caused by continued expansion after application of the silanes is likely to have provided avenues of moisture ingress so that the concrete was no longer waterproof; this has also been suggested by Kubo et al. (2000). Finally, since the bottom of the bridge decks were not sealed and the base of the slabs were exposed to ground moisture, moisture could still enter the concrete and contribute to expansion.

4.3 *Exposure Site: membranes and overlays*

The waterproof membranes applied to the bridge decks were unsuccessful in significantly reducing expansion, however they do manage to cover the cracked surface and therefore mitigate the aesthetic damage caused by ASR. More importantly for bridge decks, they also provide a substantial barrier for chloride ingress and therefore could delay or prevent the onset of corrosion in the reinforcement. The lack of expansion in the concrete overlays is an encouraging sign that Membrane 1 is able to accommodate expansion in the substrate concrete without transmitting this expansion to the overlay. However, the cracks observed to extend from the substrate through the first layer of Membrane 1 is cause for concern. Additional monitoring is required to determine how much expansion the membrane can tolerate without complete failure. The failure of Membrane 1 near the tops of the RFA columns should not yet be treated as a major cause of concern because the failure occurred in an unconfined region of the specimen.

The performance of Membrane 2 has been satisfactory, as it has fully accommodated the expansion of the substrate with no signs of distress. It should be noted that Membrane 2 was only tested on the less expansive RCA specimens and not the more expansive RFA bridge decks.

The asphalt and concrete overlays applied to the on-grade slabs have resulted in a small reduction in expansion relative to the control specimens. This is somewhat surprising considering that the membrane- and overlay-treated bridge decks saw no reduction in expansion. A significant amount of expansion still occurred in the substrate concrete of all slabs with overlays; the treatment was still unable to have a major impact on expansion. The debonding layer has been effective in preventing transmission of expansion and cracking of the substrate to the concrete overlays installed on both the RFA and RCA slabs.

A final concern with respect to overlays and impermeable membranes of any material is the total movement that must be accommodated when the substrate concrete is still expanding due to ASR. The pavement and bridge deck specimens could be considered full scale with respect to their depth, but not to their length and width. Even if the strain gradient can be accommodated locally, ASR can cause considerable damage if the structure runs out of room to accommodate movement. This can result in closing of and crushing at expansion joints. The impact of this can not be simulated with the specimens used in the exposure site study.

5 CONCLUSIONS

The following conclusions can be made from these studies:

- Breathable sealers such as silanes have the greatest potential for mitigating expansion due to ASR in existing structures.
- Some silanes are more effective than others. Testing or a database of past test results is needed to identify the most effective.
- Silanes can also mitigate the aesthetic damage caused by ASR.
- Continued expansion and uncoated surfaces can limit the effectiveness of silanes.
- Waterproof membranes and overlays are unable to significantly mitigate expansion due to ASR, but can mitigate some of the aesthetic damage.

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