Methods for Evaluating and Treating ASR-Affected Structures: Results of Field Application and Demonstration Projects

Volume I: Summary of Findings and Recommendations

Final Report

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16. Abstract

As part of the FHWA ASR Development and Deployment Program, nine field trials were conducted across the United States that evaluated mitigation measures applied to concrete structures and pavements already exhibiting ASR-induced distress. The findings from these trials served as the basis for the Volume I report and recommendations. In order to provide a technical underpinning for Volume I and to provide more detailed information on each of the trials (e.g., product types and application rates, treatment methods, monitoring program, etc.), the Volume II report was developed.

This document presents the findings and recommendations from the field trials concerned with the treatment of ASR-affected structures.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

Table of Contents

List of Figures

List of Tables

1. INTRODUCTION

Alkali-aggregate reactions (AAR) occur in concrete as a result of chemical reactions between the alkali (sodium and potassium) hydroxides in the concrete pore solution, which are supplied mainly by the cement, and certain mineral components found in some aggregates (coarse and fine). Alkali-silica reaction (ASR) involves the reaction of certain silica minerals such as opal, cristobalite, chert, microcrystalline quartz, and acidic volcanic glass, present in some aggregates. Alkali-carbonate reaction (ACR) involves the reaction of some argillaceous dolomitic limestones. Of the two types of reaction, ASR is far more widespread having occurred in most countries worldwide, all contiguous states of the United States of America, and all Canadian provinces. Under certain circumstances, these reactions cause internal expansion within the concrete which can result in (sometimes severe) cracking of the concrete impairing its function and shortening its service life. The resulting cracking can also accelerate other concrete deterioration processes such as freeze-thaw damage and corrosion of embedded reinforcement, especially for in service structures that are exposed to chlorides, such as deicing salts or seawater. ASR has been studied since 1940 and ACR since 1950, and today there are widely accepted methodologies for identifying potentially reactive aggregates and measures for limiting the risk of damaging reaction in new concrete construction. A standard practice for testing aggregates and selecting measures for preventing damage was recently published by American Association of State Highway and Transportation Officials as AASHTO Designation: PP 65-11 *Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction* (AASHTO 2011). The basis for the standard practice was produced under the Federal Highway Administration (FHWA) ASR Development and Deployment Program, and its development has been documented in detail elsewhere (Thomas et al. 2009; 2012a; 2013c).

Despite the availability of numerous guidelines and accepted technologies for minimizing the risk of damaging AAR in new concrete construction, there are many existing concrete structures throughout the world that are affected by AAR, particularly ASR, to varying degrees. These structures include buildings, foundations, dams, harbor works, airport runways, other major civil works, and all forms of transportation infrastructure including pavements, bridges, tunnels, and associated structures such as sidewalks, curbs, barrier walls, and retaining walls. The management of AAR-affected concrete structures raises a number of concerns including the following:

- Diagnosis: The extent to which ASR or ACR has contributed to the deterioration of the concrete and the contribution of other damaging mechanisms needs to be determined.

- Serviceability: The impact of ASR or ACR on the functionality and structural integrity of the structure has to be evaluated.

- Prognosis: The rate of future deterioration from AAR (and other contributing factors) may need to be assessed.

- Mitigation: Consideration should be given to implementing appropriate technologies for retarding or preventing the reaction, or for addressing the resulting symptoms.

One of the goals of the FHWA ASR Development and Deployment Program was to work with the varying State transportation agencies and provide tools to assist in the management of existing AAR-affected concrete structures. To this end, a number of documents have been developed under the program; these include:

- *Report on the Diagnosis, Prognosis, and Mitigation of Alkali-Silica Reaction (ASR) in Transportation Structures* (Fournier et al. 2009). This document describes an approach for the diagnosis and prognosis of alkali–aggregate reactivity in transportation structures. A preliminary investigation program is first proposed to allow for the early detection of ASR, followed by an assessment (diagnosis) of ASR completed by a sampling program and petrographic examination of a limited number of cores collected from selected structural members. In the case of structures showing evidence of ASR that justifies further investigations, this report also provides an integrated approach involving the quantification of the contribution of critical parameters with regards to ASR. This report is the basis for AASHTO PP 65-11 (AASHTO 2012).

- *Alkali-Silica Reactivity Field Identification Handbook* (Thomas et al. 2012b). This handbook serves as an illustrated guide to assist users in detecting and distinguishing ASR in the field from other types of damage.

- *Alkali-Silica Reactivity Surveying and Tracking Guidelines* (Folliard et al. 2012). This document is intended to serve as guidelines for State highway agencies (SHAs) to survey and track transportation infrastructure affected by alkali-silica reactivity (ASR). The focus of the guidelines is to assist engineers, inspectors, and users in tracking and surveying ASR-induced expansion and cracking in bridges, pavements, and tunnels. The guidelines are simple and are intended to collect, quantify, and rank typical signs of ASR distress, based primarily on visual inspection.

Through the FHWA ASR Development and Deployment Program field trials were conducted in various states to evaluate technologies for preventing ASR in new concrete construction and mitigating the reaction in existing ASR-affected concrete structures. This document only reports the findings from the field trials concerned with the treatment of ASR-affected structures.[1] Volume II of this report includes a more comprehensive summary of the evaluation and monitoring techniques, treatment technologies, and monitoring data and analysis for each field trial site (Thomas et al. 2013b).

1.1 OBJECTIVE

- The goal of the field studies reported here was to lay the foundation for gaining valuable knowledge about long-term efficacy and practicality of the technologies identified in the *Report on the Diagnosis, Prognosis, and Mitigation of Alkali-Silica Reaction (ASR) in Transportation Structures* (Fournier et al. 2009) and to validate the recommendations presented in that report.

- Treatment technologies and performance monitoring packages were implemented on various types of structures and at various sites across the country.

1.2 SCOPE

The nine sites investigated as part of this study were as follows (a more detailed summary for each site is provided in Chapter 4):

- Alabama: ASR-affected concrete arches on the Bibb Graves Bridge in Wetumpka, AL, treated with a combination of crack-filling, silane (hydrophobic) sealer and epoxy coating.

- Arkansas: ASR-affected concrete pavement near Pine Bluff, AR, treated with two types of silane sealer.

- Delaware: ASR-affected concrete pavement near Georgetown, DE, treated with a topical application of lithium nitrate.

- Maine: ASR-affected concrete bridge abutments, wing walls, and columns in Bangor/Brewer, ME, treated with two types of silane sealer and one type of

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[1] Two field exposure sites were constructed as part of the FHWA ASR Development and Deployment Program: one in Hawaii and the second in Massachusetts. At each of these sites, concrete blocks were constructed using locally-available and imported reactive aggregates, and various measures were employed to counteract damaging expansion (e.g., limiting alkali content, use of supplementary cementing materials, and use of lithium-based admixtures). The visual condition and length change of the blocks will be monitored over a period of at least twenty years. The development of these sites and the early findings will be documented in separate reports.

elastomeric coating; one column treated with lithium nitrate (electrochemical treatment); one column encapsulated with fiber reinforcement polymer (FRP wrap).

- Massachusetts: ASR-affected concrete barrier walls near Leominster, MA, treated with lithium nitrate (topical spray application and vacuum impregnation employed), various silane sealers or elastomeric coating.

- Rhode Island: ASR-affected concrete abutments, retaining walls, and barrier walls in Warwick, RI, treated with two types of silane sealer and one type of elastomeric coating.

- Texas (Houston): ASR-affected concrete bridge columns in Houston, TX, treated with lithium nitrate (vacuum and electrochemical treatment) and a range of sealers and/or coatings.

- Texas (New Braunfels): cracked precast beams near New Braunfels, TX, treated with silane. Note: petrographic examination revealed that the cracking was not due to ASR (or ACR) in this case; at the time of treatment, there was no consensus on the cause of cracking of these beams.

- Vermont: ASR-affected concrete barrier walls on a bridge in Montpelier, VT, treated with three types of silane sealer and one type of elastomeric coating.

The following tasks were conducted as part of the investigation at each site:

- A condition survey was conducted in accordance with the *Report on the Diagnosis, Prognosis, and Mitigation of Alkali-Silica Reaction (ASR) in Transportation Structures* (Fournier et al. 2009) and included visual inspections.

- A preliminary and detailed investigation program was conducted to select treatments/technologies for implementation according to the recommendations in the same report (Fournier et al. 2009). Extensive sampling and laboratory testing (petrographic examination, mechanical testing) and in-situ investigations were conducted.

- Monitoring at each site followed the guidelines in Fournier et al. (2009) and included: expansion measurements, internal concrete temperature and relative humidity measurements, and crack development evaluation.

The efficacy and practicality of treatments/technologies implemented on various structures was evaluated during the field trials, and updates to general guidelines for best practice based on the data gathered are formulated in this report.

2. TREATMENT TECHNOLOGIES

Three requirements need to be met to initiate and sustain alkali-silica reactions in concrete; these are:

- A sufficient concentration of alkali (sodium and potassium) hydroxides in the concrete pore solution, provided predominantly by the portland cement;

- A sufficient amount of reactive silica provided by the aggregate;

- A supply of water (usually in excess of that used to produce the concrete or, in other words, an external source of moisture).

If any one of these three requirements is eliminated, ASR can be prevented. In new construction ASR is usually prevented by either selecting a non-reactive aggregate or by controlling the availability of alkali in the concrete through the use of low-alkali cement and/or the use of supplementary cementing materials (such as fly ash, slag, silica fume, or natural pozzolans). Another option for reducing the risk of damaging expansion in new concrete is through the use of lithium compounds, such as lithium nitrate. The AASHTO *Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction* (AASHTO 2011), AASHTO Designation: PP 65-11, provides guidance on selecting and using these options in new concrete.

For existing ASR-affected structures, the first two requirements (sufficient alkali and reactive silica) are already present, and it is only feasible to attempt to control the supply of the third requirement (water) if the reaction is to be slowed or stopped. In certain circumstances, it may also be possible to introduce lithium into the hardened concrete and change the nature of the reaction. These are the only two remedies that are known to be able to stop or retard the reaction in existing concrete. Other techniques may be used to address the symptoms of the reaction. For example, problems caused by expansion of the concrete may be addressed by cutting slots or expansion joints into structures. Such action has been taken in some large hydraulic structures to relieve the stresses on embedded mechanical equipment such as gates or turbines. The expansion itself may be reduced by providing external restraint in the form of post-tensioning, reinforced concrete jacketing, or wrapping with fiber-reinforced polymer (FRP) composites. Cutting to allow expansion and provide stress relief, and wrapping or jacketing to confine expansion do not address the cause of the expansion (i.e., the chemical reaction) but provide relief (often only temporarily) from some of the symptoms. In some cases, it may be necessary to remove and replace some of the concrete damaged by ASR, especially where other deterioration mechanisms have exacerbated the damage in exposed areas of the structure. An example of this can be seen with ASR-affected concrete pavements where freeze-thaw action has further ravaged the concrete, especially in the vicinity of the joints. In such cases, patch or full-depth repairs are required in the area around the joints. Again, such a procedure does not address the cause of the problem but merely provides a temporary fix to the symptoms of distress.

2.1 CONTROLLING MOISTURE AVAILABILITY

Controlling the availability of water begins with a critical review of the drainage systems serving the affected members. Modifications could be implemented to allow water to drain away from the structure rather than onto or through parts of it (Hobbs 1988). Waterproofing membranes (e.g., polyvinyl chloride (PVC) geomembrane) have been installed on the upstream face of concrete dams to provide protection against ingress of water in the concrete (De Beauchamp 1995).

Filling macrocracks or construction joints with cement grout or epoxy resins is commonly done to restore structural continuity or to limit water penetration in AAR affected structures (Durand 1995; Bérubé et al. 1989; Charlwood and Solymar 1995) (see Figure 1); it is also commonly performed before applying a waterproof sealing or water-repellent agent. In a number of cases, the effectiveness of this approach in ASR-affected structures has been limited as cracks often reappear a few months/years after treatment (Bérubé and Fournier 1987; Ishizuka et al. 1989) (see Figure 1C and Figure 1D). Injection of modern flexible grouts may prove to be more effective than rigid epoxy resins to prevent leakage through joints or cracks in a concrete member where ASR expansion is still active.

Numerous studies have shown that ASR typically develops or sustains in concrete elements with internal relative humidity greater than 80 to 85 percent (BCA 1992; Stark 1990). Thin concrete elements are unlikely to be deleteriously affected by ASR when exposed to constantly dry indoor or outdoor conditions (i.e., with no external supply of moisture), or when immersed in fresh water or seawater because of the leaching of alkalis from the concrete pore fluid. On the other hand, massive concrete elements incorporating a reactive aggregate are often at risk of ASR, even those in arid conditions, because of the high internal humidity conditions maintained, at least periodically, in such elements (Stark 1990; Stark and Depuy 1987).

The effectiveness of surface treatments against ASR is influenced by the actual effectiveness of the specific product to control moisture exchange between the concrete and the atmosphere; coatings that permit the escape of water vapor are preferable to allow progressive drying of the concrete. Some silane and siloxane sealers have shown beneficial effect in controlling moisture content in concrete and the extent of deleterious expansion due to AAR (Bérubé et al. 2002a). Bérubé et al. (2002b) described the application of various types of sealers on highway median barriers affected by ASR (see Figure 2A). In some cases (e.g., some silanes), the treatment had a dramatic beneficial impact not only on the cosmetic appearance of the affected concrete member (see Figure 2B) but also contributed in progressively reducing internal humidity content and expansion of the concrete (Bérubé et al. 2002b). Grabe and Oberholster (2000) reported that a silane treatment on ASR-affected concrete railway sleepers has been effective in reducing the rate of deterioration due to ASR, thus extending their service life (see Figure 2C and Figure 2D).

Putterill and Oberholster (1985) have found that some surface film coatings, such as polyurethane coatings and water-repellent agents, e.g., water-based silicates, were ineffective in preventing long-term water penetration. Badly cracked concrete piers supporting the Hanshin Expressway in Japan were repaired at an age of 7 years by first filling the cracks with an epoxy resin injected under pressure and then either coating with an epoxy resin or impregnating with silane followed by a cosmetic coating of a polymer cement paste (Hobbs 1988). This approach did not suppress the expansion of the piers since, after only a few years of further exposure, some crack widening had been observed. Ono (1989) also reported limited effectiveness of crack injection followed by surface coatings on concrete structures in Japan.

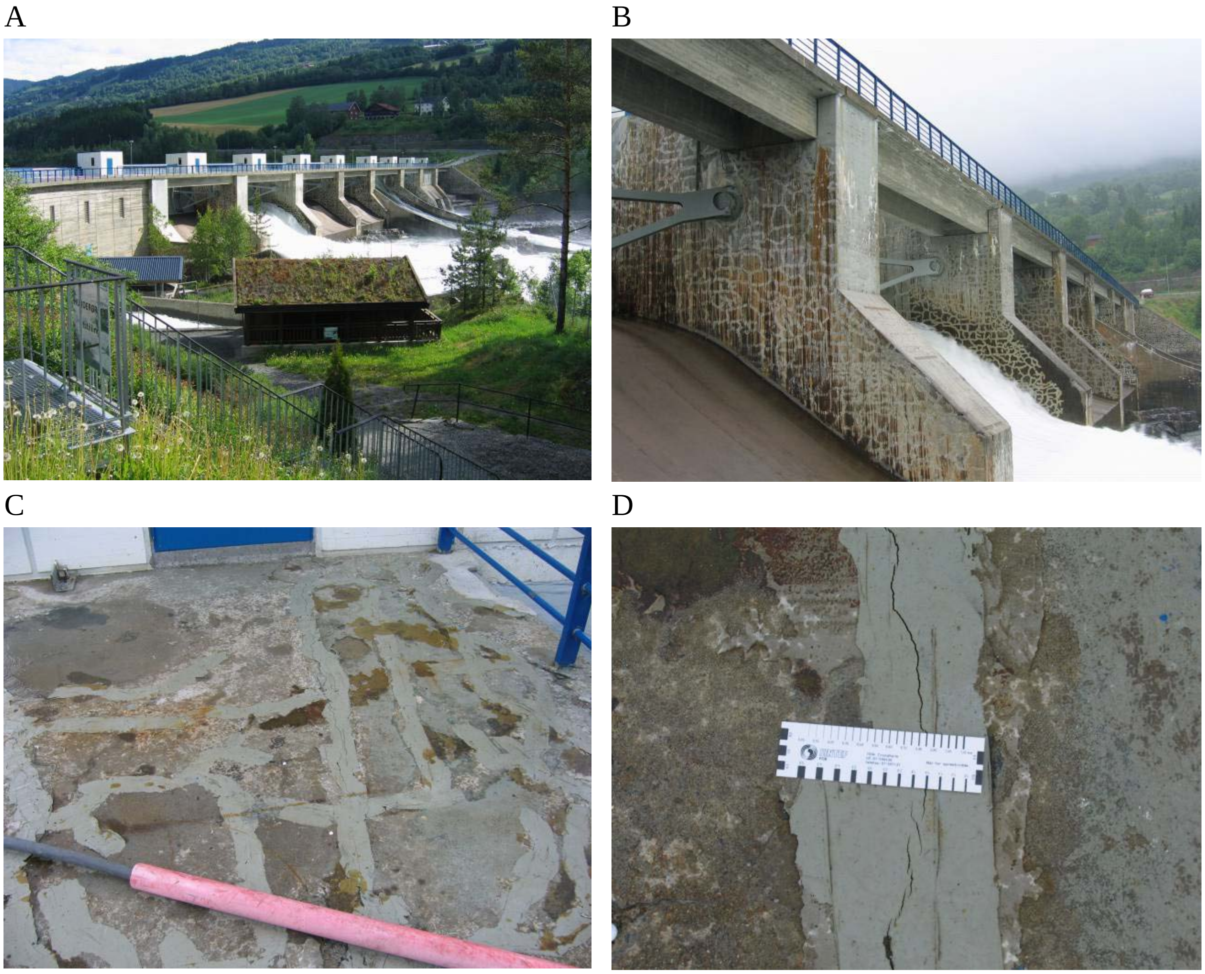

**Figure 1. Large hydraulic dam affected by ASR in Norway.
A: General view of the dam. B&C: View of the epoxy-injected pillars. D: Cracking reappearing in the injected cracks.**

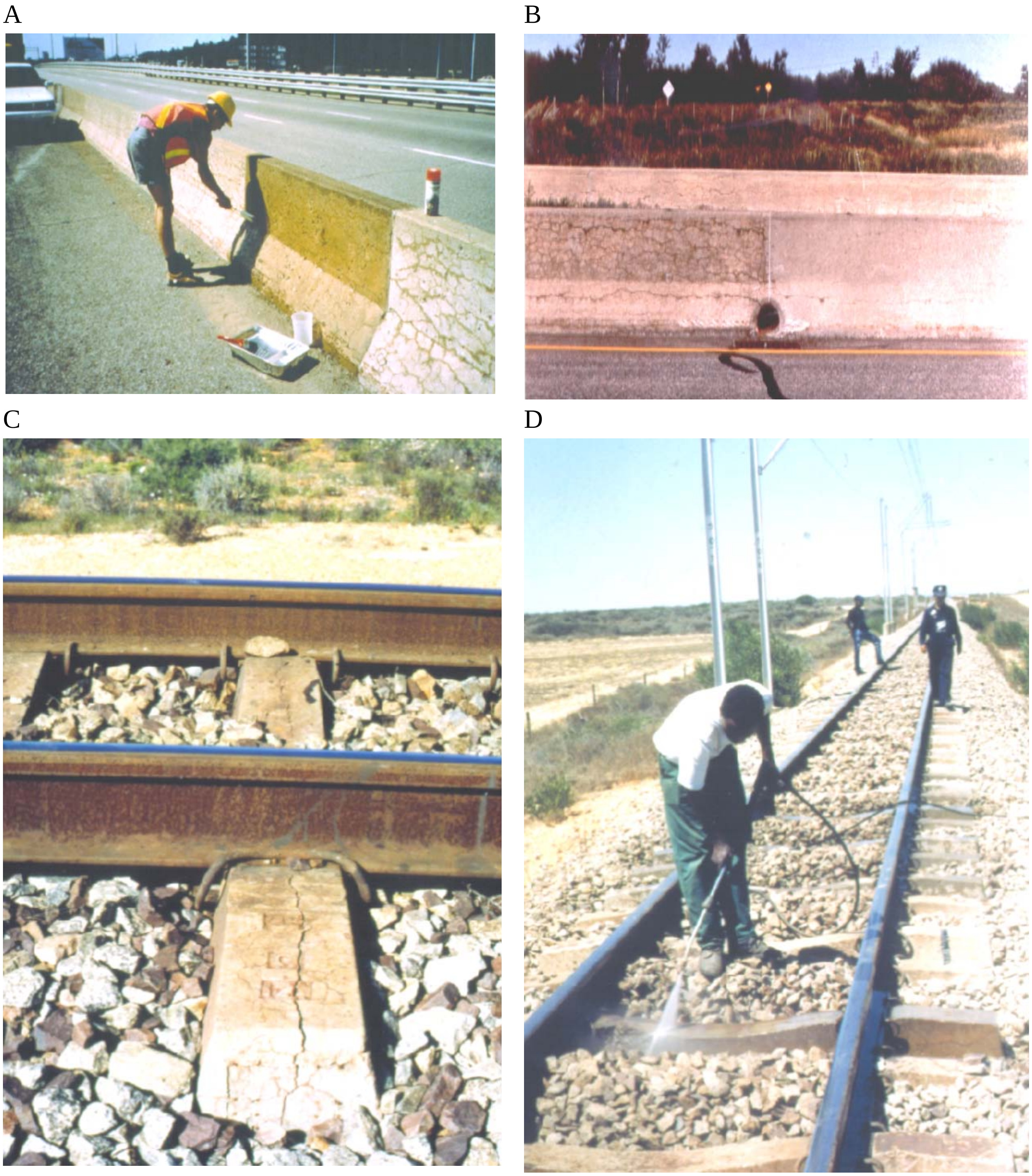

Figure 2. Median barriers and concrete sleepers.
A: Application of sealers on highway median barriers affected by ASR. B: Unsealed/control (left) and sealed (right) of a highway median barrier treated with silane (photos taken three years after treatment).
C: Condition of concrete sleepers affected by ASR in the Sishen-Saldanha railway line in South Africa. D: As part of the management program, a number of cracked concrete sleepers were treated with silane. (Pictures C and D: courtesy of R.E. Oberholster, PPC Technical Services, Cleveland, South Africa.)

Durand (2000) reported the results of monitoring ASR-affected concrete foundations of power-transmission towers that had been subjected to various types of repairs, including epoxy injection, impermeable coating, strengthening, and encapsulation. The data showed that the foundations to which a bituminous coating had been applied for the buried portions and the exposed parts coated with a flexible polymer membrane continued to expand at a significant rate after the repair work. Utsunomiya et al. (2012) reported the study of piers previously repaired with protective surface coating and found to have cracks attributed to post-treatment deterioration by alkali-silica reaction. Based on their findings, the authors reported that water repellent coatings had better deterioration suppression effect than that of waterproof coatings, presumably due to the more breathable nature of water repellent coatings. Impermeable surface coatings/membranes may represent an interesting approach to prevent further deterioration of concrete (e.g., due to frost action) when there is little or no potential remaining for future expansion due to ASR.

For structurally adequate pavements affected by AAR, maintenance and rehabilitation measures may include: (1) undersealing where voids exist beneath the slab, (2) joint and crack repair, (3) joint and crack sealing, (4) improvement of drainage, and (5) improvement of load transfer (ACI 1998).

2.2 USE OF LITHIUM COMPOUNDS

Since the pioneering work of McCoy and Caldwell (1951), several researchers have confirmed that lithium-based compounds can significantly reduce expansion due to ASR (Folliard et al. 2006; Thomas et al. 2006). Laboratory investigations have shown that the effectiveness of lithium to control ASR expansion is mainly a function of the concrete alkali content, and the type and reactivity level of the aggregate. Lithium-based admixtures have been used to (1) control ASR expansion in new concrete incorporating reactive aggregates, and (2) limit the progress of ASR in existing concrete structures. For the latter, lithium salts either sprayed on the surface of ASR-affected concrete pavements or introduced into the concrete by vacuum impregnation, or during the electrochemical chloride removal process, have been used (Folliard et al. 2006; Thomas et al. 2006; Stokes 1995; Stokes et al. 2003). Although early treatments used lithium hydroxide solution, lithium nitrate solution is now the preferred choice as it is pH neutral, easier to handle, and has better penetration rates.

2.2.1 Topical Application

Topical application has been the most common method of applying lithium to ASR-affected concrete (primarily pavements and bridge decks) in recent years (see Figure 3A). It is quite clear from past topical applications of lithium that the lingering question is whether or not topical treatment of lithium leads to sufficient penetration to reduce ASR-induced damage. The potential for lithium ingress is significantly influenced by the extent of deterioration of the concrete at the time of treatment. Cracking will clearly facilitate ingress of the solution, but, if the deterioration of the concrete has proceeded too far, it may be too late to treat the affected concrete.

Stokes et al. (2003) described the treatment of State Route 1 in Delaware. Approximately 6.4 km (4 mi.) of 8-year-old, ASR-affected concrete pavement was treated with six applications of 30 percent-$LiNO_3$ (lithium nitrate) at a rate of 0.24 L/m^2 (6 $gal/1000ft^2$) over a period of three years (two treatments per year). Control sections were left untreated at either end of the project. Four years after the first application, one of the control sections was showing severe deterioration in the form of excessive cracking and spalling at the longitudinal and transverse joints. Figure 3B shows photographs of the control and treated sections at this age, and it is evident that the treated sections exhibit less deterioration. One year later, this control section was rehabilitated by grinding the pavement surface and placing an asphalt overlay. The lithium profiles measured from cores taken four years after the first application indicate that the depth of penetration is a function of the extent of cracking. In the more heavily cracked areas (crack widths in the region of 1 mm (0.04 in.) at the surface), the lithium had penetrated to a depth of at least 50 mm (about 2 in.).

More recent studies conducted under the FHWA Lithium Technology Research Program (Folliard et al. 2008) showed it to be more challenging to get sufficient penetration of lithium into an ASR-affected concrete pavement even after repeated topical applications. In this study, 30 percent-$LiNO_3$ solution was applied at a rate of 0.24 L/m^2 (6 $gal/1000ft^2$) on three separate occasions on a pavement in Idaho, but sampling after the final application indicated that the treatment was only successful in delivering significant lithium (concentrations > 100 ppm) to the concrete within 3 to 4 mm (0.12 to 0.16 in.) of the pavement surface.

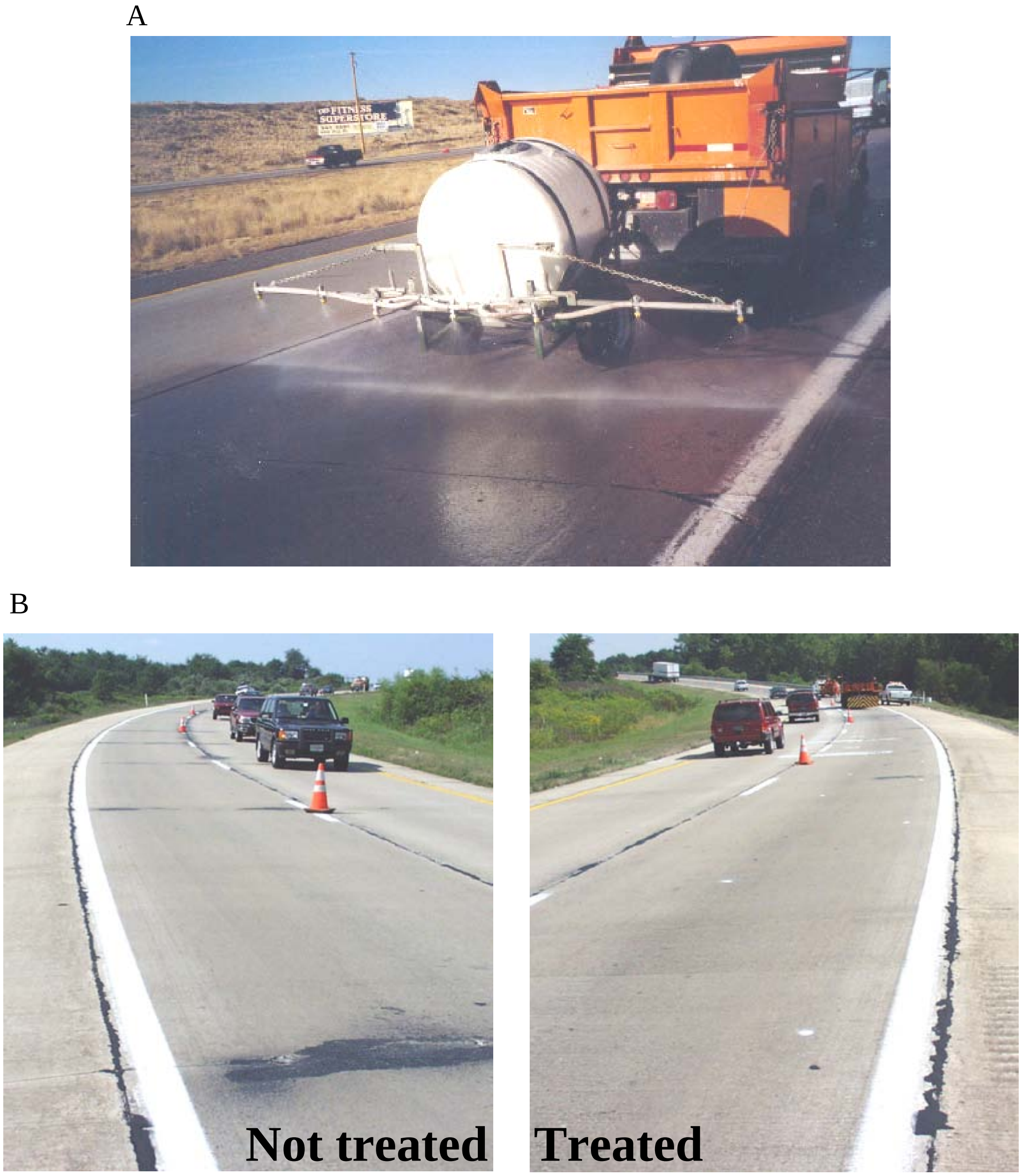

Figure 3. Concrete pavement affected by ASR.
A: Topical application of lithium-based solutions at the surface of a pavement section affected by ASR.
B: Condition of not-treated (control) and treated sections (after six topical treatments with lithium nitrate solution) of concrete pavement affected by ASR in Delaware. Spalling of concrete at joints in more frequently observed in the untreated sections.

2.2.2 Electrochemical Treatment

Electrochemical techniques have been developed to remove chloride ions from reinforced concrete. This involves the application of low voltage DC electric potential to cause the migration of negatively-charged chloride anions away from steel and towards a surface-mounted anode. By making a few modifications to this system, it can be used to deliver positively-charged lithium cations into a structure (Whitmore and Abbott 2000). Various lithium compounds have been used to date as the electrolyte including lithium nitrate, lithium hydroxide, and lithium borate. Limited testing of bridge decks treated electrochemically have indicated that a significant quantity of lithium is absorbed from the electrolyte during treatment and that depths of penetration of at least 30 mm (1.2 in.) are possible (greater depths were not tested). Whitmore and Abbott (2000) described the treatment of five concrete pier footings of a bridge in New Jersey using an electrochemical system. The treatment involved installation of titanium mesh on the top surface of each footing, and the addition of several anode “reservoirs” and auxiliary cathodes (see Figure 4A) to accelerate migration of the lithium solution. The system ran for four weeks, with an average consumption of 7.9 L of lithium solution per m^3 of concrete (1.6 gal per yd^3) (Vector 2001) (see Figure 4B).

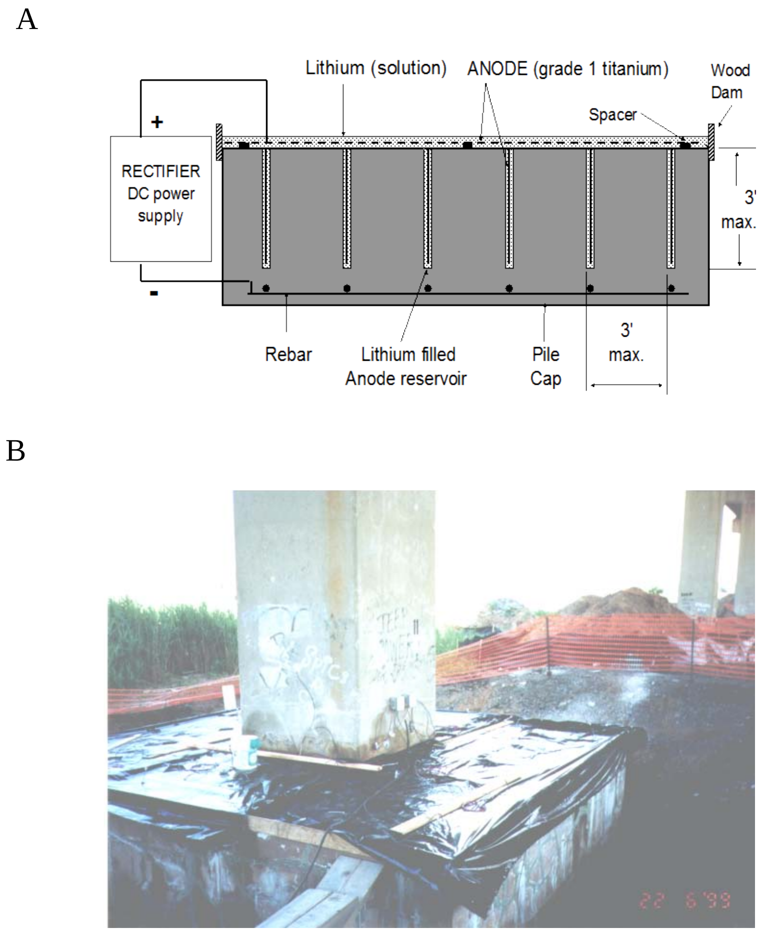

Figure 4. Repair of pier footings of a highway structure suffering from severe cracking and spalling due to ASR using an electrochemical system for lithium impregnation.
(Pictures A & B: courtesy of D.Whitmore, Vector Construction Group, Winnipeg, Canada.)

2.2.3 Vacuum Impregnation

Originally developed in Europe in the early 1970s, the vacuum injection/impregnation processes have been utilized in North America since the mid-1980s for the in-situ restoration of concrete, stone, and masonry structures. Under negative pressure, appropriately selected repair products and materials (e.g., lithium-based admixtures) can penetrate into the deteriorated system thus filling cracks, interconnected cracks, voids, and even microcracks. It has been reported that the vacuum processes can actually fill cracks as fine as 5 µm (0.0002 in.) using low-viscosity resins (Boyd et al. 2001). Vacuum injection/impregnation has already been used for repairing ASR-affected members. For example, in Southern California, the treatment of alkali-silica damaged high-line tower pier footings to a depth of ~4.5 m (14.8 feet) with minimal excavation (< 2 m [6.6 feet]) was reported; core drilling the member revealed interconnected lateral cracking at a depth of ~1.25 m (4.1 feet). In October 2003, the Pennsylvania Department of Transportation

(PennDOT) treated the abutment wall, sidewalk, the parapet, and the deck of a structure under the “Evaluation of Lithium Vacuum Impregnation on a Structure” (Lucas 2003).

2.3 STRENGTHENING

Physical restraint or containment (e.g., encapsulation of the affected member by a surrounding non-reactive concrete, applied stress, or reinforcement) can significantly reduce deleterious expansion due to ASR in the direction of restraint. Post-tensioning in one or two dimensions, or by encasement in conventional reinforced concrete, is currently used as a means to restore the integrity of the structure; however, it should generally be restricted to relatively small masses of structural concrete because of the huge forces that may result from the expansive process due to ASR (Rotter 1995; CSA 2000). Post-tensioned tendons or cables are considered to be an effective solution for thin arch dams (Singhal and Nuss 1991) or structural members of bridge/highway structures; however, they may be less attractive for large concrete structures because of the necessity of periodic destressing (Rotter 1995).

Methods to restrain expansion and movement in ASR-affected mass concrete foundations can include rock anchors and/or encapsulation. Bérubé et al. (1989) and Durand (2000) described the repair of a group of electricity tower concrete foundations affected by ASR in Quebec City, Canada. The foundations had suffered from significant swelling and cracking due to ASR. The repair program selected consisted in splitting the foundations in two blocks, followed by the encapsulation with reinforcing steel and silica-fume concrete. Durand (2000) showed that this type of treatment resulted in significant reduction in the expansion rate of the affected element. Care should be taken in designing the encapsulating element because, if sufficient reinforcement is not provided to control stresses due to AAR expansion, the only beneficial effect of encapsulation may be to limit the ingress of moisture (CSA 2000).

Strapping or encapsulation of AAR-affected reinforced concrete columns by or with composite materials may be an interesting solution provided sufficient structural strengthening is assured. Carse (1996) described the repair program of a bridge structure affected by ASR in Australia. Vertical cracking has been observed in the pre-stressed octagonal piles supporting the structure about 13 years after commissioning. The repair strategy consisted in monitoring progress of ASR expansion and then repair the piles in which ASR had nearly exhausted itself. Glass-fiber composite repair to 500 piles above high water level and concrete encasement to bed level was performed. As an alternate method to the glass-fiber composite, wrapping was also carried out with two layers of carbon-fiber composite materials (Carse 1996).

2.4 STRESS RELIEF

Cutting slots or expansion joints has been performed at a number of AAR-affected gravity dams and intakes in order to relieve stress build-up due to AAR (Charlwood and Solymar 1995). This may provide only a temporary solution for concrete structures in which the expansion process due to AAR is not terminated; re-cutting may then be necessary, thus increasing the cost of the rehabilitation program. A somewhat related form of stress relief applied to transportation structures could be the removal of regions around pavement joints that had been damaged by ASR-induced expansion. Because ASR-induced damage in jointed pavements tends to manifest itself at joints, failure typically initiates in this zone. Thus, removing the most damaged section will reduce stress in this region. However, as is the case with slot cutting dams, replacing only the concrete at and around the joints with ASR-resistant concrete does not prevent the remainder of the pavement from expanding, and subsequent repairs are inevitable.

2.5 STRUCTURES AND TREATMENT TECHNOLOGIES INVESTIGATED IN FIELD TRIALS

A number of technologies for mitigating ASR were used in the field trials under the FHWA ASR Development and Deployment Program. These were selected to evaluate different products from a generic standpoint rather than specific manufactured products. The locations of the field sites, the types of elements treated and the technologies evaluated are summarized in Table 1.

Table 1. Summary of field sites, concrete elements treated, and types of treatment under the FHWA ASR Development and Deployment Program.

Field sites	Elements Treated	Technologies Evaluated
Alabama	Concrete arches on a bridge (above the roadway)	• System incorporating 40% water-based silane, crack-filling caulk, and epoxy flood-coat on top surface
Arkansas	Concrete pavement	• 100% silane • 40% water-based silane
Delaware	Concrete pavement	• Topical lithium application
Maine	Bridge abutments, wing walls, and bridge columns	• 100% silane • 40% water-based silane • Elastomeric coating • Electrochemical lithium treatment • Carbon-fiber reinforced polymer (CFRP) wrap
Massachusetts	Highway barriers	• Topical lithium application • Vacuum impregnation with lithium • 40% silane in isopropyl alcohol • 20% silane in isopropyl alcohol • 20% silane in water • Lithium silicate-based penetrating sealer • Elastomeric coating
Rhode Island	Bridge abutments, retaining wall, and highway barriers	• 100% silane • 40% water-based silane • Elastomeric coating
Texas (Houston)	Bridge columns	• Vacuum impregnation with lithium • Electrochemical lithium treatment • 40% silane in isopropyl alcohol • Silane-siloxane blend, applied via vacuum impregnation • Sodium silicate, applied via vacuum impregnation
Texas (New Braunfels)	Precast beams (not in service and with no significant ASR)	• 40% alcohol-based silane
Vermont	Bridge barriers	• 100% silane • 40% water-based silane • Alcohol-based silane (40% solid; used by local contractor) • Elastomeric coating

The products used in the later field trials conducted in Arkansas, Maine, Rhode Island, and Vermont were selected on the basis of laboratory tests which indicated the products to be effective at reducing water absorption and, hence, the internal relative humidity of concrete. These products included two penetrating silane sealers containing (i) 40 percent active ingredient dissolved in water and (ii) 100 percent active ingredient (without solvent) and an acrylic-based, vapor-permeable elastomeric paint designed to bridge cracks. In earlier studies in Massachusetts and Texas, a wider range of sealers and coatings were used. A topical application of lithium was the only treatment evaluated in Delaware.

More details of the products used are provided in Chapter 2 of Volume II of this report (Thomas et al. 2013b).

3. EVALUATION AND PERFORMANCE MONITORING

A variety of techniques have been used to evaluate the candidate sites and monitor the post-treatment performance of the structures. Comprehensive details on the methodology and equipment used are provided in Volume II of this report (Thomas et al. 2013b) and in Fournier et al. (2009); the techniques are briefly summarized here.

3.1 DATA COLLECTION

The following protocol, documented in the *Report on the Diagnosis, Prognosis, and Mitigation of Alkali-Silica Reaction (ASR) in Transportation Structures* (Fournier et al. 2009), was followed for each of the field sites:

- Initial condition survey (visual examination). Each candidate structure was visited to determine the following: (i) extent of deterioration, (ii) nature of symptoms, (iii) probability of ASR being the major contribution, (iv) evidence of action of other deterioration processes, and (v) exposure conditions. Coring locations were also selected during the initial visit.

- Petrographic examination of concrete core(s) taken from the site. A detailed petrographic evaluation was conducted to confirm the presence of alkali-silica reaction and to determine the nature of the reactive aggregate. In most cases, the Damage Rating Index (DRI) method was used to provide a quantitative measure of the ASR damage. In some cases, cores were also taken for stiffness damage testing (SDT). The SDT provides a measure of the physical damage resulting from ASR-induced cracking and microcracking.

- Following the initial condition survey and petrographic examination of the concrete sections, the structures were selected for various treatments or to act as controls.

- The selected sections were then instrumented to permit the following measurements: (i) length change (expansion), (ii) Cracking Index (CI) and (iii) internal relative humidity (RH).

- After initial measurements (length, CI, and RH) were made the treatments (e.g., sealers, coatings, or lithium) were applied.

- The sites were then visited periodically to monitor changes in length, CI, and RH. In most cases, attempts were made to visit the structures twice a year, in the spring and the fall wherever possible, to minimize temperature extremes. In some cases, this was not possible for various logistical reasons and the site was only visited once a year.

3.2 INSTRUMENTATION

Length-change measurements were made using "DEMEC-type" strain gauges produced by Mayes Instruments in the U.K. (see Figure 5A). Although similar gauges are available from other sources, the gauges were used in this project because of familiarity of the project team with the Mayes gauges from previous laboratory and field experience. In most cases, a 500-mm (20-in.) gauge was used, the exception being in certain areas where the geometry dictated the use of a shorter gauge (e.g., vertical measurements on short barrier walls); in such cases a 150-mm (6-in.) gauge was used. Stainless steel reference pins were embedded in the structure using waterproof epoxy. In the case of circular reinforced concrete columns of a bridge structure in Maine, circumferential expansion measurements were taken along two lines separated by about 1 m (39 in.) (see Figure 5B).

Internal relative humidity (and temperature) measurements were made using a Vaisala HM44 Concrete Humidity Measurement System. Holes 16-mm (5/8-in.) in diameter were drilled to depths of 25, 50, or 75 mm (1, 2, or 3 in.). Although similar probes are available from other sources, the probes were used in this project because of familiarity of the project team with the Vaisala probes from previous laboratory and field experience. RH probes were inserted into the holes and sealed in place (see Figure 5C and Figure 5D) for a minimum period of 1 hour (to allow "moisture equilibrium" to be established) before recording the temperature and RH. The probes were then removed and the probe holes sealed until the next monitoring visit.

The Cracking Index (CI) was measured by recording and summing the crack widths measured along a set of lines drawn on the surface of the selected sections (see Figure 5E and Figure 5F). When possible, 1000-mm (39.4-inch) squares are drawn on the surface of the structures, and the cracks that cross the vertical, horizontal, and diagonal lines (6 total) of the square are counted and measured (width estimated using a magnifying glass and a crack-indicator card). A Cracking Index is then calculated, and an average crack opening per unit length of structure can be determined. Note that a 500-mm (20-in.) square was used when the space for drawing the grid was limited.

Figure 5. Expansion, RH, temperature, and CI measurements.
A: Length-change measurements using DEMEC gauge. B: Circumferential measurements using a PI-tape. C: RH and temperature measurements. D: Vaisala RH probes (photo courtesy www.vaisala.com). E: Grid pattern used for CI. F: Performing Cracking Index.

4. APPLICATION SITES

A summary of the details of each application site is provided here. Comprehensive details of each site investigated are provided in Volume II of this report (Thomas et al. 2013b).

4.1 ALABAMA

The Bibb Graves Bridge (built in 1931) is a reinforced concrete parabolic arch structure with a suspended roadway, with a total of seven arches supporting the roadway as shown in Figure 6. The bridge was visited in December 2005 as ASR was suspected as the cause of cracking in the concrete arch above the roadway in the 5th span (see Figure 7). No other arch is exhibiting ASR-related distress and the arch below the roadway in the 5th span is also undamaged. Petrographic evaluation of cores confirmed that ASR involving chert and quartzite coarse aggregate particles was the cause of damage to the concrete in the 5th span. DRI values of 1430 and 1081 in this concrete are indicative of a very high degree of ASR-related damage. Large amounts of ettringite were also found filling cracks in the cement paste of the deteriorated arch. However, it was also revealed that the concrete in the undamaged arches contained the same aggregate, and further testing revealed the water-soluble alkali content of ASR-affected and undamaged concrete to be equivalent. No explanation has been put forward to explain why significant ASR has only occurred in a single isolated arch and not in the other arches of similar composition and in the same exposure environment.

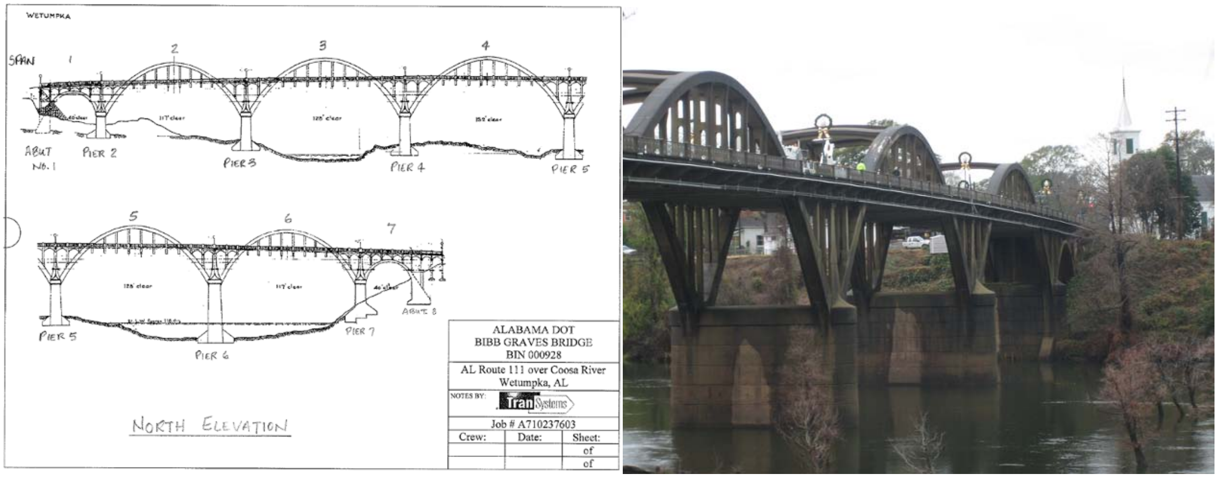

Figure 6. Sketch showing elevation and photograph of Bibb Graves Bridge (north face).

Figure 7. Cracking on top and underside of archway supporting 5th span.

Pins were installed at selected locations on the arches supporting the 4th and 5th spans in December 2005 to permit length-change measurements to be made. In December 2009, length-change measurements revealed that in some locations, the concrete in the arches supporting the5th span showed expansion rates estimated to be as high as 250 microstrains (or 0.025 percent) per year (0.120 percent length change between December 2005 and 2009). It was recommended that a detailed structural analysis be performed on the arch affected by ASR.

During the summer of 2010, Alabama DOT, FHWA, and Auburn University developed a repair procedure to retard (or stop) the ASR expansion in the arches of the 5th span, and the repair was implemented in the fall of 2010. The repair involved cleaning (water blasting) the affected concrete, applying a silane sealer, caulking all cracks greater than or equal to 1 mm (0.04 in.) in width and applying an epoxy “flood coat” to the top surface of the arch. The treatment was chosen to prevent rainwater ingress into the top surface of the concrete while allowing the concrete to dry out from the silane-treated sides and bottom faces of the arch. The treatment was performed in November 2010. Both the north and south arches of the 5th span were treated. In addition, the south arch of the 4th span was also treated in a similar manner. Instrumentation for length-change and RH/temperature measurements was installed in all 3 treated arches and the untreated north arch of the 4th span.

Length-change and RH measurements have been made on approximately one-month intervals by Auburn University. The data show that the treatment has had little impact on the internal RH and the rate of expansion approximately 2.5 years after treatment (Thomas et al. 2013b). In addition, new cracks have formed and existing cracks have widened since implementation of the treatment. These cracks provide for the ingress of rainwater which maintains a high humidity within the concrete, permitting the alkali-silica reaction to continue unabated. Given the rate of expansion of the concrete and appearance of new cracks to provide for moisture ingress, any attempt to dry the concrete would probably require the provision of external cladding over the concrete. Further attempts to “seal” the concrete with coatings are likely to prove to be ineffective because the water vapor within the concrete is not able to escape.

Given the extent of ASR, it is recommended that a structural analysis is conducted to determine the structural adequacy of the affected arches supporting the 5th span.

4.2 ARKANSAS

In November 2011, a 19.3 km (12-mi) stretch of jointed plain concrete pavement (JPCP) on Interstate 530 near Pine Bluff, AR was visually inspected for symptoms of ASR. Distress in the form of map-cracking, joint cracking and distress, and efflorescence/gel staining was quite common, with the extent ranging from minimal to moderate to severe (Figure 8).

Figure 8. Typical distress observed in concrete pavement near Pine Bluff, AR.

Petrographic examination conducted on five cores revealed that an alkali-silica reaction involving chert particles in the coarser fraction of the sand was occurring, with DRI values ranging from 254 to 489 indicating a low to moderate degree of ASR damage.

In May 2012 two sections of pavement, each approximately 550 m (1800 ft) long, were selected for treatment. Both sections were on the northbound lanes, and only the right (or driving) lane was treated. One section was selected to be representative of mild ASR distress and the other of moderate distress. Each section consisted of 120 slabs or panels which were treated as follows:

- Panels 1 through 40 were left as untreated controls.
- Panels 41 through 80 were treated by spraying with a silane (100 percent active content).

- Panels 81 through 120 were treated by spraying with a silane (40 percent active content in water).

Both products were applied at a rate of 3.1m^2/L (125 ft^2/gal) using a truck-mounted tank sprayer. The 100 percent silane was applied as a clear liquid and appeared to dry within an hour. The surface seemed somewhat slippery while still wet. After drying, walking on the pavement gave no indication of lasting slippery conditions. The 40 percent silane was applied as white liquid, and as it dried, it became clear. However, the surface of the pavement remained wet for an extended time and was very slippery while wet. To ensure the traveling public's safety, the lane-closure for this project was kept in place for 48 hours after the application of the 40 percent silane. Reports by the Arkansas State Highway and Transportation Department several weeks after the silane treatment confirm that the sections did not show any signs of being slippery once the lane-closures were removed, even after several rainfall events.

Monitoring was limited to length change, RH, and temperature. Data were collected immediately before spraying in May 2012 and in December 2012. A return visit is planned for the fall of 2013. Insufficient time has elapsed for the effects of the treatment to be determined. It is recommended that post-treatment monitoring be continued for at least five years to allow the efficacy of the treatment to be properly evaluated.

4.3 DELAWARE

In June 2009, 16 lane miles of concrete pavement along US 113 in Georgetown, DE, were treated with a topical application of lithium nitrate (30 percent solution) after it had been determined that the concrete was suffering damage due to alkali-silica reaction (ASR). Petrographic evaluation produced DRI values of 65 and 395, indicating an extent of ASR/damage in the concrete ranging from very low to moderate, and showed significant signs of ASR both in the coarse (gneiss) and the fine (chert) aggregates.

The pavement was overlaid with hot-mix asphalt in May/June 2011, which prevented any long-term monitoring (e.g., visual rating, crack survey, length-change or relative humidity measurements) of the treated pavement. Cores were taken to determine the depth of lithium penetration. Significant lithium concentrations ($\geq$ 100 ppm) were only found in the outer 6 to 12 mm (¼ to ½ in.) and concentrations returned to background levels at depths below 12 mm (½ in.). It is concluded that the topical application of lithium nitrate is not an effective ASR-mitigation technique for concrete pavements where ASR is distributed throughout the pavement depth. This has been confirmed in previous studies on concrete pavements performed by Folliard et al. (2008).

4.4 MAINE

In April 2009, a number of bridge structures along Interstate 395 near Bangor, ME were inspected for symptoms of ASR-related distress. The symptoms consisted of map cracking in abutments, wing walls, and columns; some preferred alignment (vertical) of cracks was observed in columns. The extent of damage ranged from mild to severe within a given structure depending on the nature of the exposure. Concrete that was directly exposed to rainfall exhibited very severe cracking in some cases, whereas the damage observed on parts of the same structure that were protected from rainfall by the bridge deck showed considerably less damage (see Figure 9).

Figure 9. I-395 and 5th Parkway bridges.
A: Bridge carrying I-395 over the Penobscot River showing (B) increased cracking on exposed part of pier.
C: Bridge carrying 5th Parkway over I-395 showing (D) increased cracking on wing wall and the exposed part of the abutment.

A total of 24 cores (100 mm [4 in.] in diameter) were taken from six bridges for petrographic evaluation, while 75 mm (3 in.) cores were taken from two bridges for stiffness damage testing (SDT). The presence of ASR was confirmed, and it was revealed that the concrete in all six bridges contained reactive greywacke/argillite in the coarse aggregate. DRI values ranged from 133 to 882, indicating a low to severe degree of ASR damage. SDT results also showed the extent of internal mechanical damage due to ASR ranged from low to severe. The DRI and SDT data are generally consistent with visual observations, the more severe damage being observed for concrete in exposed areas (see Figure 10).

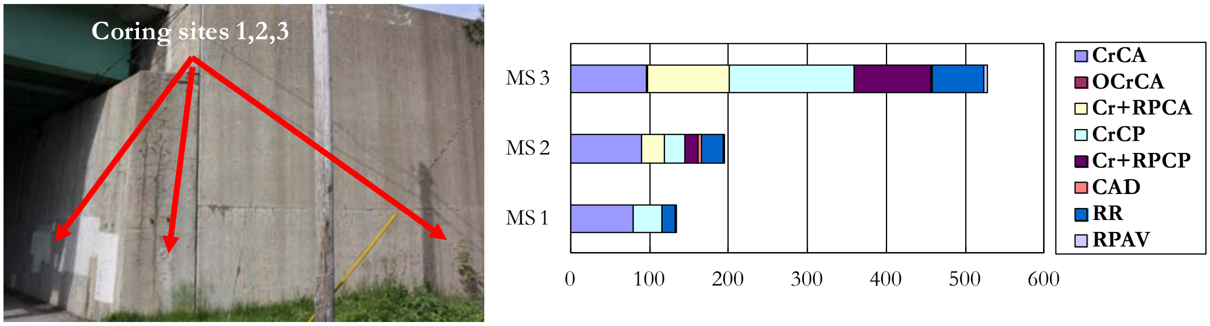

Figure 10. Results of petrographic analysis showing higher DRI values (i.e., higher damage) for exposed parts of the structure.

The following five bridges were treated in 2010:

1. I-395 over Main Street
2. 5th Parkway over I-395
3. Green Point Road over I-395
4. I-395 over the Penobscot River
5. South Parkway over I-395

The first three bridges were treated in a similar manner. In each case, the abutments and wing walls were split into four sections and treated as follows:

- 100 percent silane
- 40 percent water-based silane
- Elastomeric coating

For example, for the bridge over Main Street, the west abutment was divided approximately at the centerline of the bridge, and the abutment and wing wall to the south of the divide was left as a control (untreated) whereas the abutment to the north of the divide was treated with elastomeric coating. Similarly, the east abutment was divided into two sections, the south section receiving 100 percent silane and the north section 40 percent silane.

Three large piers supporting I-395 over the Penobscot River were treated either with 100 percent silane or 40 percent water-based silane; the third column was left as a control.

The six circular columns at the midspan of the bridge carrying South Parkway were numbered 1 to 6 from the west side of the bridge. This gave three similar damage and exposure conditions, with columns 1 and 6 showing the most damage as they only get moderate protection from the deck, columns 3 and 4 showing the least damage as they have the best protection from the deck (being closest to the center), and columns 2 and 5 being somewhere between in terms of damage and exposure condition. One of the most severely damaged columns (#6) was wrapped with four layers of a carbon-fiber reinforced polymer, one of the least damaged columns (#3) was treated with 40 percent water-based silane, and one of the intermediate columns (#2) was treated with lithium nitrate using an electrochemical technique to aid lithium penetration. The remaining three columns (#1, #4, and #5) were left as untreated controls.

Length-change, RH and temperature, and Cracking Index measurements were conducted prior to repair in May 2010 and during the summer (June or August) of 2011, 2012, and 2013. Analysis of the data produced during the three years since the treatment of the abutments and wing walls shows few consistent trends in the treated versus untreated portions of the bridges in terms of length change, RH, or cracking. It is not known whether moisture supply from the back side of the abutments and walls has masked any beneficial effect of applying sealers or coatings on the visible above-grade surfaces. It is possible that more time is needed for any beneficial effect to be revealed (see section 4.5 on treated barriers in Massachusetts).

Consistent trends in the length change, RH, and cracking data are also not observed for the treated versus untreated piers over the Penobscot River. In this case, it is possible that the massive nature of piers makes it difficult for surface treatments to have a significant impact. However, it is also expected that massive concrete elements will dry very slowly, and it may take many years for significant reductions in RH to occur.

Some trends are observed in the expansion data for the six circular columns supporting South Parkway. The three control columns appear to have expanded by values in the range from 0.08 to 0.18 percent in the three years since treatment. The lithium-treated column expanded between 0.21 and 0.23 percent during the same period, and the silane-treated columns by just 0.04 to 0.12 percent. It appears that lithium treatment may have increased expansion possibly as a result of the resaturation that occurs during the eight-week treatment. Similar trends were observed for the lithium-treated columns in Houston, TX (see section 4.7). On the other hand, the silane treatment may have had a positive impact slowing the rate of reaction. In a slender column, one might expect the confining steel to restrain the lateral expansion of the bulk concrete whereas the cover over this steel is relatively free to expand in the transverse direction. Retarding the rate of ingress of moisture into the cover zone might therefore be expected to have some impact on the circumferential expansion even if the effects of the silane are limited to the concrete closest to the surface. Further time is needed to confirm these trends in the expansion data.

Various non-destructive testing (NDT) techniques were used to monitor the performance of the control and treated sections of some of the structures in Maine. The techniques included ultrasonic pulse velocity (UPV), impact-echo (IE) and nonlinear acoustics. The data generally indicate that the quality of the interior concrete is satisfactory in most locations and that significant damage is restricted to regions close to the surface, especially for concrete in the more exposed locations.

Although some changes have been observed during the three years since treatment, there are no general trends that allow an assessment to be made on the effect of the treatments. Again, this can be attributed to the relatively short period of time that the structures have been monitored. The ASR damage that exists in these structures has accumulated over more than 20 years, and it is unlikely that significant or measureable changes will occur is just 3 years.

4.5 MASSACHUSETTS

In 2005, a section of concrete median barrier walls on State Route 2 near Leominster, MA was treated using a variety of products. The barriers showed extensive map cracking (Figure 11), and petrographic analysis of cores (Grattan-Bellew 2005) confirmed ASR as the main cause of deterioration, the reactive component being greywacke in the coarse aggregate. The initial treatment was conducted under the FHWA Lithium Technology Research Program, and when this program terminated it was decided to continue monitoring the barriers under the FHWA ASR Development and Deployment Program. There have been a total of three treatments as follows:

- In July 2005, approximately 40 sections of barrier wall were treated with a range of products including different silanes and lithium nitrate as described below; this is referred to as the “original test section.”
- Later in 2005, MassDOT treated additional barriers, beyond this original test section, with silane (40 percent silane, water-based); this is referred to as the “extended test section.” A selected number of these barriers were also monitored.
- In 2010, most of the barriers in the “extended test section” treated by MassDOT were subsequently treated under the FHWA Development and Deployment Program with an elastomeric paint that aimed to serve as a breathable, flexible coating that may provide additional resistance to freezing and thawing damage observed on the bottom sloping face of the barriers (see Figure 11).

Figure 11. Typical ASR damage on barrier walls (left) and barriers treated with elastomeric coating.

The original treatment included the following: (i) topical lithium application (30 percent $LiNO_3$ solution), (ii) vacuum impregnation with lithium (30 percent $LiNO_3$ solution), (iii) 40 percent silane in isopropyl alcohol, (iv) 20 percent silane in isopropyl alcohol, (v) 20 percent silane in water, (vi) lithium silicate-based penetrating sealer, and (vii) a combination of a topical application of $LiNO_3$ solution followed by 40 percent silane in isopropyl alcohol.

From all the data collected since 2005, the most revealing information regarding the effectiveness of the treatments is provided by the vertical length-change measurements together with simple visual observations. The horizontal length-change measurements are not too meaningful because expansion in the direction is restrained once the joints between wall sections have closed. Figure 12 shows the average vertical expansion for each of the treated sections. The data indicate some measure of ongoing expansion in the control (untreated) sections. The expansion of concrete treated with lithium (topical or vacuum impregnation) or lithium silicate is generally equal to or greater than control sections. The expansion of concrete treated with silanes is generally equal to or less than the control sections and, in some cases, the treated concrete exhibits an overall shrinkage over the course of the monitoring period. The section treated with lithium and silane also showed shrinkage after treatment.

Visual differences between sections treated with any of the three silanes became visually obvious about three to four years after treatment. An example is shown in Figure 13. In the treated sections, the cracking becomes less visible as moisture and exudation activity associated with the cracks begin to disappear.

Despite evidence that the silane applications have slowed ASR and reduced the extent of visible damage, there are still no consistent trends in the RH data between treated and untreated sections. In other words, there is no evidence that the silanes are working by reducing the internal humidity.

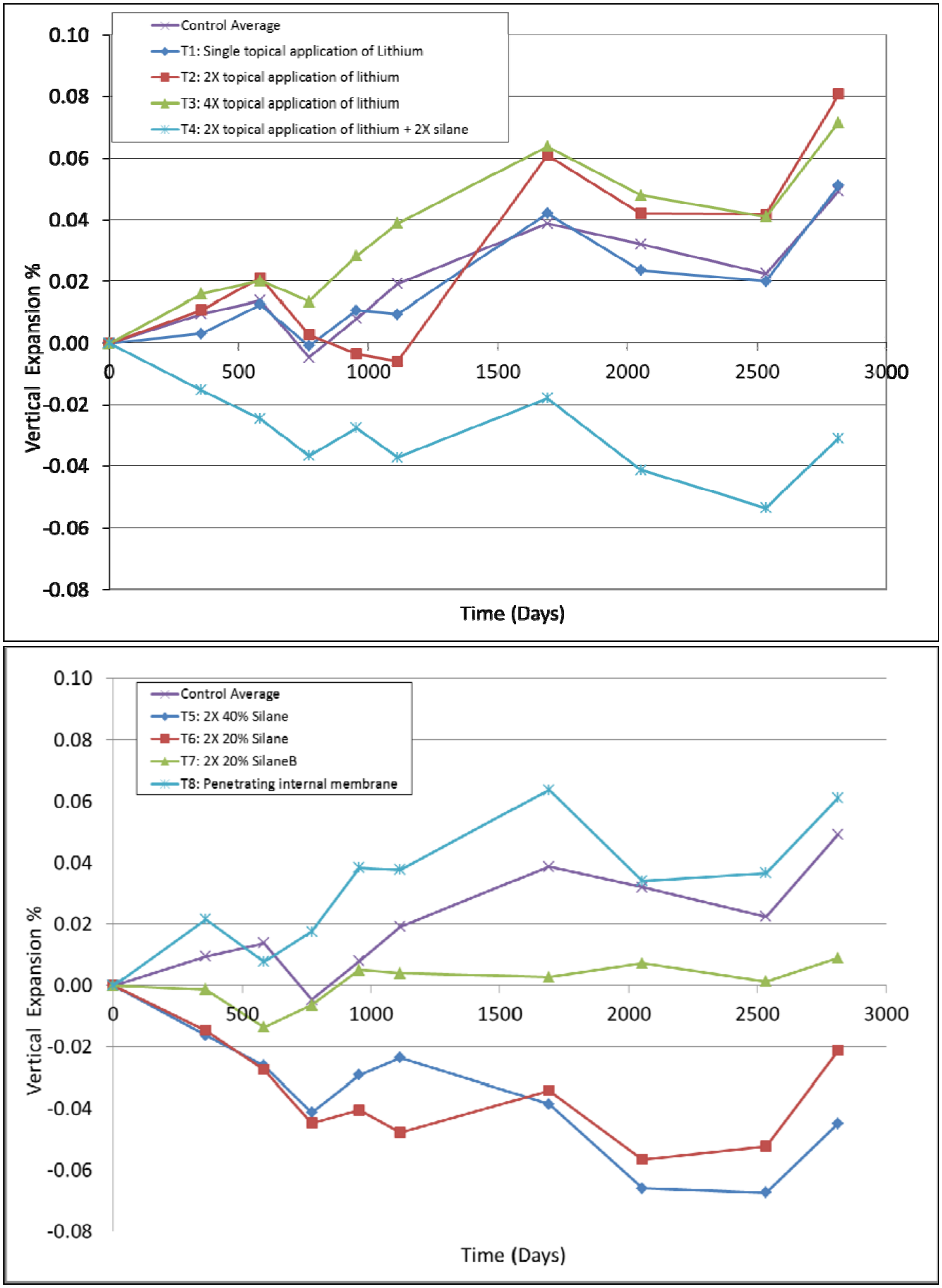

Figure 12. Average vertical expansion of treated and control barrier walls.

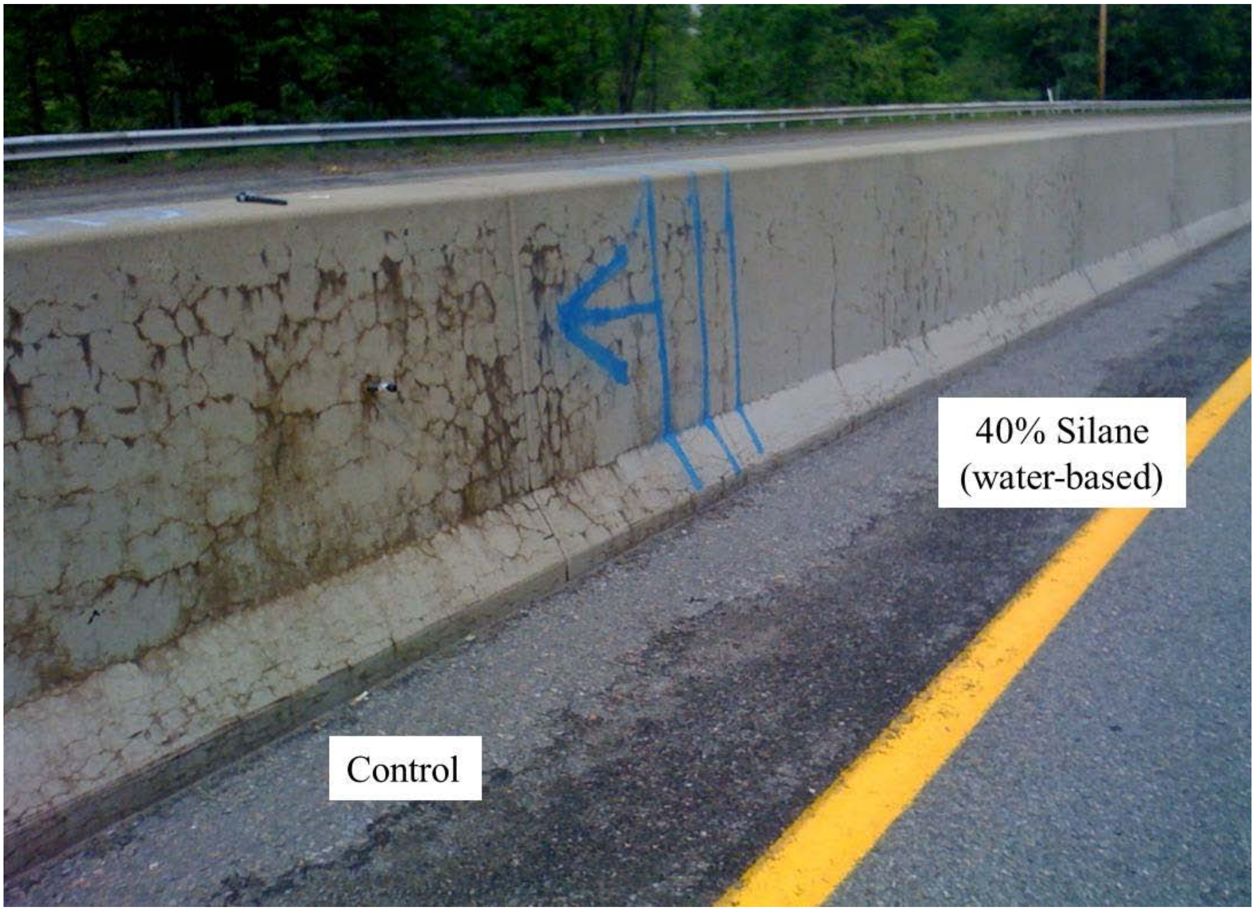

Figure 13. Visual contrast between the one of the control sections to the left and a section treated with 40% (water-based) silane by MassDOT in 2005.

It would appear that the treatment of these barrier walls with a one-time topical application of silane has been effective in reducing the ongoing ASR and reducing the extent of visible deterioration (cracking). It is not known whether improvements will continue without ongoing monitoring of the barrier wall.

4.6 TEXAS - NEW BRAUNFELS

The Texas Department of Transportation (TxDOT) identified several precast beams (or girders) that exhibited significant cracking that visually looked similar to that observed in ASR, even though the mixtures were cast under stringent ASR specifications, including limits on total alkali loading for plain cement mixtures and minimum required dosage of Class F fly ash. As a result, TxDOT was concerned about their current ASR specifications. Four of these beams had previously been rejected for use by TxDOT and were being stored at two different precast yards before being moved to outdoor storage along State Highway Loop 337 (TX SH Loop 337) in New Braunfels, TX for further monitoring. TxDOT engineers began monitoring these beams for expansion, and it was decided that the FHWA ASR Development and Deployment Program efforts would take over the monitoring of the beams (expansion and internal relative humidity), starting in November 2010, and expand the program to monitor the efficacy of silane-based products on portions of the distressed beams.

Core samples were taken in 2011 for petrographic examination. The cores showed no significant signs of ASR or noticeable deterioration, as indicated by the very low DRI values ranging from 36 to 66. The petrographic features identified essentially consisted of non-ASR related and very limited internal cracking within some coarse aggregate particles (mainly limestone/dolostone and some chert), a few reaction rims (surrounding some chert particles), and only a few air voids lined with ASR gel (adjacent to chert particles). No cracking was noticed in the cement paste, at least at the magnification used for the test (16x).

This case study is not discussed further here as there is no ASR-related distress, and monitoring has revealed that the cracking is not accompanied by an expansive reaction. However, details of the treatment and monitoring, including analysis of the monitoring data are included in Volume II of this report (Thomas et al. 2013b).

4.7 TEXAS - HOUSTON

In 2006, a set of bridge columns in Houston, TX were identified as possibly suffering from ASR-induced expansion and cracking. The initial evaluation and treatment at this site was conducted under the FHWA Lithium Technology Research Program, and monitoring the treated structures continued under the FHWA ASR Development and Deployment Program.

After inspecting various columns, cores were extracted from damaged sections. Petrographic evaluations confirmed that ASR was occurring in the various cores, and residual expansion testing showed the potential for future expansion. However, DRI values were relatively low, indicating a minor degree of ASR. Recycled concrete aggregate (RCA) had been used in the project and there was evidence of minor ASR in some of the RCA particles.

Based on these preliminary visual inspection and laboratory data, it was decided to select a total of 12 columns for treatment and monitoring; one set of six columns (Columns 31, 32, 33, 34, 35, and 36) was selected to represent moderate-to-severe visual damage, and a second set of six columns (Columns 41, 42, 43, 44, 45, and 46) was selected to represent slight-to-moderate visual damage. The types of treatment applied are summarized in Table 2.

Figure 14. Columns 32-35 in Houston, TX.

Table 2. Types of treatment used in Houston.

Column #	Treatment
Moderate to severe (visual) damage rating	
31	Sodium silicate vacuum impregnation over blasted surface
32	Topical silane over original painted surface
33	Lithium vacuum impregnation
34	Topical silane over blasted surface
35	Electrochemical lithium impregnation
36	Control
Slight to moderate (visual) damage rating	
41	Silane-siloxane blend vacuum impregnation over blasted surface
42	Topical silane over original painted surface
43	Control
44	Topical silane over blasted surface
45	Lithium vacuum impregnation
46	Electrochemical lithium impregnation

Analysis of the overall expansion results reveals some interesting trends and/or observations. First, columns treated with silane applied over the existing paint showed the lowest expansion in both sets of columns. This is surprising in that common practice is to remove existing paint prior to the application of silane (or similar coatings/sealers). However, the results of this investigation, as well as previous TxDOT-funded research (Wehrle 2010), are consistent in that applying silane over existing appearance paint reduced both the potential for future expansion and the internal relative humidity.

The two columns that were electrochemically treated with lithium exhibited relatively high expansions, at or near the maximum for each column set. This may be attributable to inherent differences between the columns in terms of materials, mixture proportions, and construction operations, or it may be due to the significant resaturation of the concrete that occurs during treatment. Lithium was driven all the way to the reinforcing steel (depth of 50 mm or 2 in.) in a concentration estimated to be sufficient enough to suppress ASR-induced expansion (100 ppm). However, the migration of other alkali ions (specifically sodium and potassium) leading to increased alkali concentration in the vicinity of the reinforcing steel (used as a cathode during treatment) was also observed. This will be accompanied by an increase in hydroxyl ions (and pH) as a result of the cathodic reaction and to maintain electro-neutrality of the concrete pore solution. This phenomenon could potentially exacerbate ASR-induced expansion and cracking in this region. More work is needed to determine if this redistribution of sodium and potassium towards the reinforcing steel has any adverse effects on long-term durability. There are insufficient data from this field trial alone to make this determination.

The expansion results for the columns treated with lithium nitrate by vacuum impregnation varied between the two column sets. In the first set of more distressed columns, the column treated with lithium by vacuum exhibited one of the lower expansions, but in the second set (columns 41-46) the same treatment resulted in some of the higher expansions within the set. Aside from the other possible reasons for varying column behavior in this field trial, it is likely that the lithium nitrate would penetrate more easily under vacuum through the more heavily cracked column. The application of lithium nitrate by vacuum impregnation increased its depth of penetration, with a penetration of about 8 to 12 mm (0.3 to 0.5 in.) of a concentration of lithium sufficient to reduce expansion (100 ppm). This penetration depth is higher than for typical topical applications of lithium nitrate, which tend to penetrate to depths of just 1 to 5 mm (0.04 to 0.2 in.). However, it seems unlikely that this increase in penetration depth can justify the need for the additional equipment, expertise, and cost needed for such vacuum applications.

When comparing the expansion of columns treated by silane over paint to the expansion of columns treated by silane after first removing paint, applying silane over paint resulted in lower expansions, which is in agreement with Wehrle (2010). The reasons for this are not known at this time, but one possible explanation may be that paint removal (either through sand blasting or wet media blasting) might adversely affect the surface of the concrete, potentially inducing microcracking or allowing for easier access of moisture. This is just postulation, but it is worth considering this as a potential issue in terms of transport mechanisms active at or near the concrete surface.

Although relative humidity measurements tend to fluctuate more widely than expansion measurements, some trends were evident. Columns treated topically by silane (over paint or with paint removed), or by vacuum with a silane-siloxane blend showed consistently lower relative humidities than the other test columns, and after seven years of monitoring, all columns treated with silane or silane-siloxane blends exhibited humidities below the 80 percent threshold often cited as a target below which ASR-induced expansion slows considerably. Columns treated with either lithium nitrate or sodium silicate generally exhibited similar RH values as the untreated columns.

4.8 RHODE ISLAND

In May 2011, a field visit to a series of concrete structures in Rhode Island was conducted. A number of structures (bridge abutment, retaining wall, and median barrier walls) along Post Road and Post Road Extension, in Warwick, RI, were identified as potentially suffering from ASR-induced cracking (Figure 15). Petrographic examination of cores confirmed ASR as a cause of deterioration, with the extent of the reaction ranging from low to moderate for the abutments, wing walls, and retaining walls, and moderate to high for the barrier wall. Aggregate particles in the cores show a wide variety of petrographic compositions (quartzite, granitic gneiss, sandstone).

Figure 15. Cracking in retaining wall (top left), wing wall and bridge abutment (top right), and median barrier wall (bottom).

For each structure, four sections were selected for monitoring (length-change, relative humidity and temperature, and Cracking Index), and these were subjected to one of the following treatments: (i) untreated control, (ii) 100 percent silane, (iii) 40 percent water-based silane, and (iv) elastomeric coating. The treatments were conducted in June 2012. The structures were revisited in October 2012 and June 2013 for monitoring purposes.

It is too early to draw any conclusions from the monitoring data at this time. It is recommended that the structures are monitored for at least five years to permit any effects of the treatments to be observed.

4.9 VERMONT

In May 2010, the twin bridges (each approximately 300 m or 900 ft long) carrying Interstate 89 over U.S. 2/State St. and the Dog River near Montpelier, VT were visited to examine cracking of the concrete barrier walls (see Figure 16). The barrier walls exhibit a mixture of map and aligned (longitudinal) cracking with severity ratings ranging from mild to severe. Concrete cores for petrographic examination were taken from locations showing either a moderate-to-severe or mild degree of damage. The presence of ASR was confirmed with reactive components (e.g., schist, microquartzite, sandstone, argillite, and other undifferentiated magmatic rocks) being found in the sand. DRI values ranged from low (53 to 202) to high (647 and 568), indicating that the extent of ASR varied from low to moderate to severe; the DRI values for cores were generally consistent with the extent of visible damage on the structure in the location where the cores were taken.

Figure 16. Bridges (left) carrying I-89 over U.S. 2/State St. and the Dog River near Montpelier, VT, and cracking on barrier walls (right).

The barrier walls were treated during the spring and fall of 2011. Three sealers were selected for application on separate sections of the above structures. The products correspond to a 100 percent silane, a 40 percent (water-based) silane, and an elastomeric coating. Some other sections of the wall were treated by a contractor conducting bridge repairs using a 40 percent (alcohol-based) sealer. Treated and untreated (control) sections were instrumented to allow monitoring of the post-treatment performance (length change, relative humidity, and Cracking Index).

Initial measurements for the barrier walls in the passing lane were taken in September 2010 (before treatment). Monitoring continued in July 2012 and May 2013. For logistical reasons, initial measurements could not be made for walls in the driving lane in September 2010, and data only were collected during the last two visits.

With only two years of monitoring data accumulated, it is currently too early to conclude on the efficacy of the above treatments at reducing the deleterious effects of ASR on the barrier walls treated. However, interesting trends have been identified, for instance possible reductions in the relative humidity values in the surficial portions of the barrier walls treated with penetrating sealers and elastomeric coating, and in general a better visual appearance of the treated barrier walls compared to the control sections. Long-term monitoring is expected to provide data on the effect of various types of surface treatments on the progress of ASR-related damage in the above elements. Figure 17 illustrates the barriers initially and in 2013, approximately two years after treatment. The elastomeric coating has covered up any sign of visible cracking, and a longer evaluation period is required to determine if this is a permanent improvement. The extent of visible cracking is much less on the barrier walls treated with silanes compared to the control (untreated) sections, and this is largely the result of reducing moisture and exudation activity in the vicinity of the cracks after treatment with a hydrophobic sealer (silane). Again, a longer study period is required to fully evaluate the long-term impact of the treatments on the service life of the barriers.

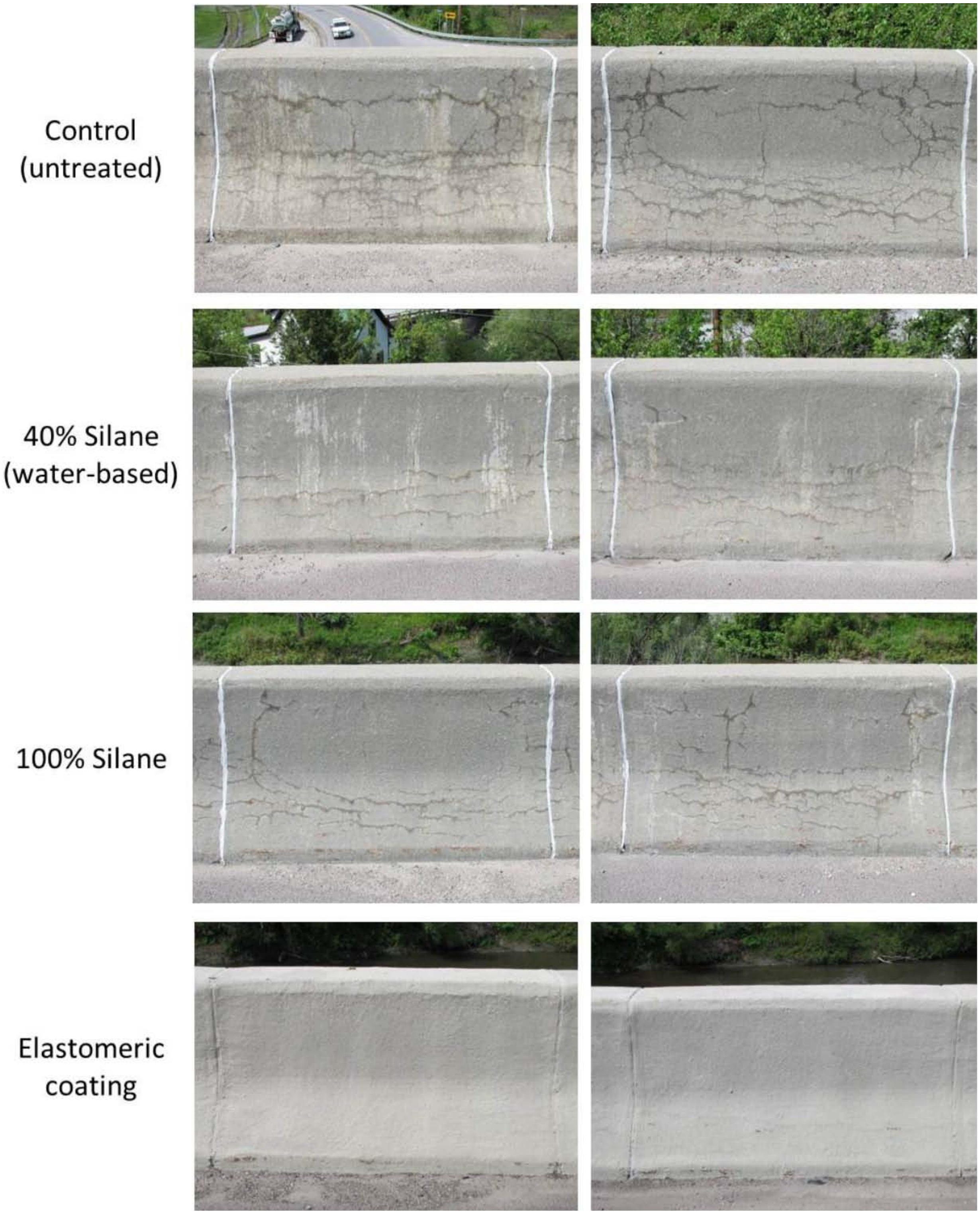

Figure 17. Barriers in 2013 (approximately two years after treatment).

5. KEY FINDINGS FROM THE FHWA ASR DEVELOPMENT AND DEPLOYMENT PROGRAM

A summary of the key findings from the nine field trials is presented next, including discussion on the diagnosis, treatment, and monitoring of the various transportation elements included in this program. Some of the most important findings from these trials include (see Table 3):

5.1 INVESTIGATIONS FOR DIAGNOSIS OF ASR

- A visual survey of the structure aims at identifying visual features that are commonly associated with ASR. The *Alkali-Silica Reactivity Surveying and Tracking Guidelines* (Folliard et al. 2012), the *Alkali-Silica Reactivity Field Identification Handbook* (Thomas et al. 2012b), and the *Report on the Diagnosis, Prognosis, and Mitigation of Alkali-Silica Reaction (ASR) in Transportation Structures* (Fournier et al. 2009) are documents intended to assist engineers, inspectors, and users in tracking and surveying ASR-induced expansion and cracking in bridges, pavements, tunnels, and other transportation structures. The guidelines are simple and are intended to collect, quantify, and rank typical signs of ASR distress, based primarily on visual inspection. The ASR Handbook serves as an illustrated guide to assist users in detecting and distinguishing ASR in the field from other types of damages. It should be noted that typical features of ASR are identified and quantified through visual survey, but a petrographic evaluation of concrete from the subject structure/pavement is required to confirm that ASR is the main cause of distress.

- Based on the results of a visual survey, structural elements showing symptoms of deterioration commonly/typically associated to ASR are selected for sampling. Elements exposed to excess moisture are commonly those suffering from the damaging effects of ASR and thus are often selected for investigation.

- Petrographic examination of cores extracted from the structure under investigation is a critical tool in evaluating and confirming the presence of ASR and its contribution in the damaging process of aging concrete structures. The use of the Damage Rating Index (DRI) as a tool to complement conventional petrographic examination and to quantify ASR-induced distress was found to be a useful tool in the diagnosis of ASR in concrete structures. This petrographic evaluation method quantifies petrographically the features most typical of ASR-induced expansion and cracking, and it was found to generate DRI values consistent with the levels of visual distress, as well as the effect of moisture on the development of ASR.

- The Stiffness Damage Test (SDT) was not used as extensively in these field trials, but this method was also found to be a useful tool in assessing the extent of damage to date for a given concrete element.

5.2 TREATMENTS OF ASR-AFFECTED CONCRETE USING SURFACE COATINGS AND/OR PENETRATING SEALERS

- Topically applying silane-based products to highway barrier walls in Leominster, MA was found to significantly reduce expansion, as well as visible cracking. In fact, most barrier walls treated with silanes (water- and solvent-based, with silane contents from 20 to 40 percent) exhibited a net shrinkage during the course of the seven-year field monitoring program completed as part of this program. Although significant expansion reduction has not been noticed yet, the monitoring of barrier walls on the twin bridges carrying I-89 over U.S. 2/State St. and the Dog River near Montpelier, VT suggests possible reductions in internal relative humidity values and a general better visual appearance of the barrier walls treated with penetrating sealers and elastomeric coating. These results, coupled with results from other studies where silanes were applied to highway barriers (Bérubé et al. 2002b), demonstrate that highway barriers are ideal candidates for silane treatment when ASR is deemed to be of concern. It is strongly recommended that the application of surface treatments be done when cracking is still somewhat minimal (in general terms of overall cracking density and especially crack thickness) because the efficacy of the treatments is likely to be limited as the severity of the ASR reaction and related cracking increases. For instance, the crack bridging capacity of the elastomeric coating may be limited when the product is applied on ASR-expanding barrier walls displaying severe degree of cracking. In addition, silanes and other breathable coatings that reduce the relative humidity content in concrete are also helpful in reducing the ingress of water and deicing salts, thus improving the frost resistance and scaling resistance of concrete.

- In the case of ASR-affected concrete columns in Houston, TX, the application of silane over the existing paint showed as much or more potential for reducing internal relative humidity and expansion than similar columns in which the paint was removed prior to silane application. This is surprising in that common practice is to remove existing paint prior to the application of silane (or similar coatings/sealers). However, the results of this investigation, as well as previous TxDOT research (Wehrle 2010), are consistent in that applying silane over existing appearance paint reduced both the potential for future expansion and the internal relative humidity. Paint removal is quite expensive and requires strict environmental standards in containing the removed paint, debris, dust, or liquid, and as such, it is quite advantageous to be able to apply coatings/sealers over the existing paint. However, the results included in this report and Wehrle (2010) do not automatically translate to all applications of silane over paint. The specific combination of paint and coating/sealer should be evaluated first to ensure that the underlying paint is breathable, that the silane is able to penetrate sufficiently, and that the combination reduces internal relative humidity or water uptake in accelerated tests, such as the NCHRP 244 Series II cube test (Pfeifer and Scali 1981), as described in detail by Wehrle (2010).

- It is not possible to determine yet the efficacy of silane treatment on concrete that has access to moisture from below or behind, such as pavements or abutment/wing walls. Treatments in Maine, Rhode Island, and Arkansas intentionally focused on this very issue, but more time is needed to monitor these sites to quantify the effects of silane treatment. However, visual evaluation confirms that structural elements or sections exposed to external moisture (e.g., rainfall) and sun exposure display more severe deterioration than "protected" sections (e.g., parts of abutment walls protected under bridge decks). This confirms the key role of "excess" moisture on the development of extensive cracking/damage due to ASR.

- Similarly, it is not possible to determine yet the efficacy of silane treatment on ASR-affected concrete pavements, especially regarding the medium-to-long term "abrasion" resistance of such surface treatment. Care should however be exercised to ensure the traveling public's safety when applying such surface treatments as the pavement can be very slippery while wet.

- Because it has only been about three years since selected barrier walls were coated with elastomeric paint (Massachusetts, Vermont, and Rhode Island field trials), it is premature to determine its efficacy in reducing relative humidity, ASR-induced expansion, and especially freezing and thawing damage, the latter being the primary motivation for applying this breathable, flexible paint over sections previously treated with silane in Massachusetts.

- In this study, treatments were made in accordance with manufacturers' recommended application rates. It is also recommended that the above products be applied on relatively clean surfaces. For example, in the case of the barrier walls in Rhode Island and bridge structures in Maine, the concrete elements were pressure washed prior to the applications. Non-breathable coatings, paints, or sealers should be removed prior to treatment, although this is not always feasible (note that paint removal was not feasible for the Rhode Island barriers). Also, since the above products aim at reducing internal humidity within concrete because of their hydrophobic properties, it is recommended, in order to optimize treatment efficiency, to apply the products on a dry concrete element, i.e., after at least 24 hours of dry weather.

- In the various field trials carried out in this study, the silane products were applied using a handheld pressurized container and spray nozzle. It was sprayed onto the surface of the various structural elements in a left-to-right-to-left pattern. The elastomeric coating product was applied like paint. Rollers and paint brushes were used instead of spray nozzles. For both products, one coat of material was applied as evenly as possible so that the entire area was covered. Such types of application methods are generally simple to implement.

5.3 CHEMICAL TREATMENT (LITHIUM-BASED ADMIXTURE)

- Lithium nitrate, applied either topically or by vacuum treatment, showed no tangible benefits in terms of reducing expansion or cracking when applied to bridge columns (Houston field trial) and highway barrier walls (Massachusetts field trial). This may be attributed primarily to the overall lack of penetration of the lithium nitrate into the concrete. The results show that the depth of lithium penetration was minimal, with lithium only present in a concentration above the 100 ppm threshold (needed to reduce expansion) in the outer 2 to 4 mm (0.08 to 0.16 in.) of barrier walls that were vacuum-impregnated for over seven hours with lithium nitrate, and about 8 mm (0.31 in.) in a column that was also vacuum-impregnated with lithium nitrate. Given the lack of lithium penetration, even when the application is done under vacuum, it is not surprising that no beneficial effects of the treatment were observed. This general conclusion is consistent with previous FHWA research that included the topical application of lithium nitrate to pavements, where depths of lithium penetration (at a concentration sufficient to reduce expansion) were reported to be in the range of 2 to 4 mm (0.08 to 0.16 in.) (Folliard et al. 2008).

- Electrochemical methods were found to be effective in significantly increasing the depth of lithium penetration when applied to bridge columns. Lithium was driven all the way to the reinforcing steel (depth of 50 mm or 2 in.) in a concentration estimated to be sufficient to suppress ASR-induced expansion. However, the migration of other alkali ions (specifically sodium and potassium) leading to increased alkali concentration in the vicinity of the reinforcing steel (used as a cathode during treatment) was also observed (e.g., reinforced concrete columns, Houston field trial). This will be accompanied by an increase in hydroxyl ions (and pH) as a result of the cathodic reaction and to maintain electro-neutrality of the concrete pore solution. This phenomenon could potentially exacerbate ASR-induced expansion and cracking in this region. More work is needed to determine if this redistribution of sodium and potassium towards the reinforcing steel has any adverse effects on long-term durability. There are insufficient data from this project alone to make this determination.

- More work is also needed to determine whether lithium-electrochemical treatment may result in increased expansion as a result of the resaturation that occurs during the multi-week chemical treatment. Some trends are indeed observed in the expansion data for the six circular columns supporting South Parkway. The lithium-treated column for the South Parkway bridge over I-395 (Bangor/Brewer corridor, Maine) expanded between 0.21 and 0.23 percent (circumferential expansion) during the first three years of the monitoring period. A similar trend was observed for the lithium-treated columns in Houston, TX.

5.4 ENCAPSULATION OR APPLICATION OF EXTERNAL RESTRAINT

- There was only one field trial that involved the application of external restraint, where in Maine an ASR-affected circular column was restrained by the application of a fiber-reinforced polymer (FRP) wrap. Because only limited time has passed since the application of this FRP wrap, it is not possible to draw conclusions on its efficacy.

5.5 PERFORMANCE MONITORING (OR PROGNOSIS OF ASR DETERIORATION)

- Visual surveys (including photographic records of the treated structural elements) and crack mapping (e.g., quantitative assessment using the Cracking Index) are useful tools in tracking distress in the form of visible (and recordable) cracks, gel exudation and staining, etc. However, more data for these field trials are needed for correlating the long-term degradation of a given structure to Cracking Index (CI) values or changes thereof.

- Measurement of length changes in structural elements can contribute to efficiently assessing the effect of various types of treatment on the progress of ASR expansion. Stainless steel studs can be inserted at selected locations in the control and treated elements to allow direct expansion measurements, using DEMEC gauges, at regular intervals. Because of the effect of restraint provided by reinforcement steel or adjacent parts of the structure elements, it is appropriate to monitor length changes in different directions (e.g., vertical, horizontal, longitudinal, etc.). Also, since temperature and humidity conditions at the time of field surveys can have a significant effect on length changes in concrete, it is recommended that similar periods/times of the year be selected for field measurements in order to reduce thermal effects. Several years of monitoring are generally required to establish trends for expansion or shrinkage in treated and control concrete sections.

- The results from internal relative humidity measurements were, for some field trials, complementary to expansion measurements, meaning that lower relative humidity values for silane-treated concrete resulted in reduced expansion after treatment. However, in some field trials (e.g., Vermont, Maine), the relative humidity measurements were somewhat inconclusive. Internal relative humidity measurements in field concrete are challenging, due to difficulties in maintaining the integrity of the measurement holes (e.g., keeping out water, ensuring protection against snow/ice impact in barrier walls), condensation that occurs within the measurement holes due to changes in ambient conditions, and logistical issues associated with reaching equilibrium after the initial hole is drilled (usually takes 24 hours or more) and after the relative humidity probe is inserted into the measurement sleeve/hole (usually 60 to 120 minutes). The latter issue is particularly a concern when access to instrumented structures (e.g., highway barrier walls) is limited and only allows for short-term lane closures in congested areas.

- In addition to these practical and technical challenges, it is also worth commenting on the overall reliance on periodic measurement of internal relative humidity in field structures. Even if the integrity of the hole since the last monitoring trip has not been compromised, and the measurements recorded are indicative of the actual equilibrium relative humidity within the concrete, the question remains as to what the values mean and can they be used to delineate between untreated (control) concrete and silane-treated concrete. Consider Figure 18, which shows the results of mass change measurements of concrete samples undergoing wetting and drying cycles as per NCHRP 244 Series II test method (Pfeifer and Scali 1981). The results shown are for an untreated (control) concrete mixture, compared to two concretes that were topically treated with silane (40 WBS in Figure 18) and a breathable silane cream/silicone resin paint (SCRP). The results clearly show that the two sets of treated specimens absorbed much less water during the soaking period, and after the soaking period, some of the moisture still present in the treated specimens was able to escape owing to the breathable nature of the two products. The important point relevant to this report is not that the treated product keep water out and allow vapor to escape, but rather that a snapshot at any one point in time may not identify the overall trend in behavior. For instance, if mass measurements and presumably internal relative humidity measurements were taken after, say, 50 days (shown on x-axis), there would not be such a tangible difference between the untreated and treated specimens. However, if measurements were taken after, say, 70 days, the results would be more dramatic, with the two treated specimens taking up much less water than the untreated specimens. Granted the real world is not the laboratory, but the results show that discrete snapshots of internal relative humidity may not tell the complete story. However, with repeated, accurate measurements over a long period of time, it is expected that the overall effects of silane treatment (or any other product that is effective in keeping external water out while letting internal vapor out) should be discernible through the measured reduction in internal relative humidity. Such long-term benefits in reducing internal relative measurements was indeed identified for ASR-affected barrier walls treated with silane in Quebec City (Bérubé et al. 2002b).

- Various non-destructive testing (NDT) techniques were used to monitor the performance of the control and treated sections of some of the structures for the field trial in Maine. The techniques included ultrasonic pulse velocity (UPV), impact-echo (IE) and nonlinear acoustics. Insufficient data were available from the limited field trials in this project to generate specific guidance on the application of NDT techniques to ASR-affected concrete elements.

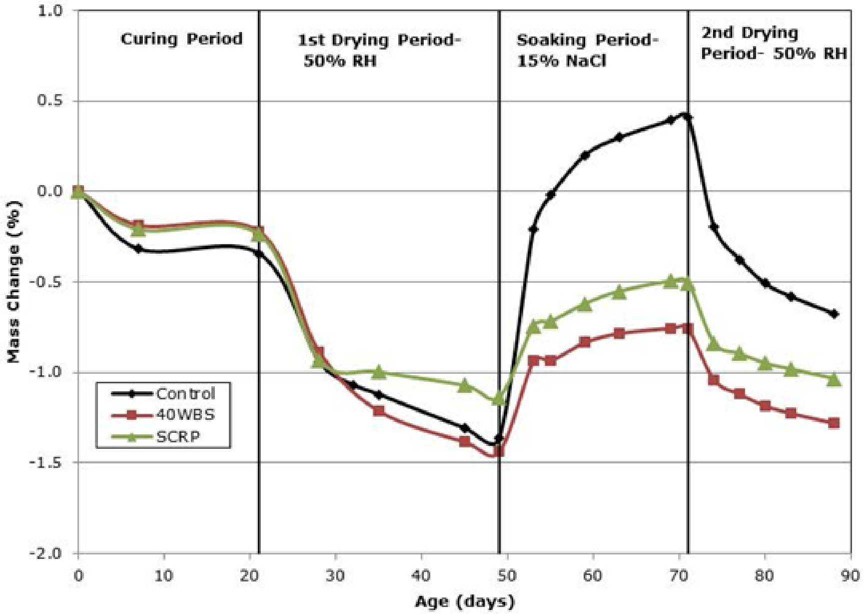

Figure 18. Mass change of specimens during NCHRP Series II testing. (After Wehrle et al. 2010.)

5.6 LESSONS LEARNED

As with any real-world project, there are always questions that are raised and lessons learned. Below are some of the lessons learned during the course of this nine-site field evaluation of mitigation measures for ASR-affected structures:

- **More time is needed.** This is an acknowledged cliché, but this is certainly true for monitoring field structures. In some cases, such as the highway barrier walls in Massachusetts, a long-enough monitoring period (eight years for oldest treatment) was sufficient for showing the efficacy of silanes in reducing expansion and cracking due to ASR. However, in most of the field trials, sufficient time has not passed since treatment to determine whether a given treatment was effective in reducing internal relative humidity, expansion, and visible cracking. Another point to consider is that most of the concrete structures and pavements evaluated in this study were fairly old at the time of treatment, say 20-years old, as an example. If a structure has been slowly exhibiting signs of ASR-induced for some or most of this 20-year period life, it is likely that the rate of distress is fairly slow and the chances of capturing changes in behavior over a short-term (say less than 3 years) are not very high. The longer the monitoring period, the more likely that the manifestations of ASR will yield discernible changes and allow for comparing the efficacy of various treatments on the progression of ASR.

- **Start monitoring as soon as possible.** The sooner monitoring begins, the more reliable baseline values will be prior to and after treatment. Measuring expansion, using embedded gauge studs and a DEMEC gauge, has been found to generate some of the most robust and insightful data during the field trials. Setting pins in the corners of a crack mapping station and measuring length change within the instrumented region as early as possible is recommended.

- **Expect the unexpected.** The inherent nature of field trials is to expect the unexpected. An example of this was that the 40 percent-silane product that was applied to a pavement in Arkansas created a slick driving surface that necessitated an extended lane closure. This was not expected as this and similar products had been tested in the past in the laboratory and field without need for such an extended drying period. In this particular case in Arkansas, the issue of slickness was identified and extended lane closures were put in place for about 48 hours, prior to safely opening to traffic. No slickness has been observed after opening to traffic, so this was just an issue observed shortly after application. Based on this experience, it is recommended that the potential for slick road surfaces be evaluated prior to the actual treatment to ensure safe opening to traffic.

- **Concrete sometimes behaves strangely in field trials.** An intriguing facet of monitoring and treating is that sometimes the results don’t make sense, or at least like they would if it were a controlled laboratory experiment with known materials. Sometimes one control column expands during monitoring, while a second control column does not, as was the case for columns treated and monitored in Houston, TX. The same was the case for two control pavement sections in Delaware (Stokes et al. 2003), where one section expanded considerably while the other essentially had no or very limited expansion. In Alabama, only one of five arches showed significant ASR-induced distress, even though it appears that the same materials, mixture proportions, and construction techniques were used. Why did only that one arch expand and not the others? These and other questions of the sort may never be answered, but that is the framework that defines field trials.

Table 3. Summary of findings – FHWA ASR Development and Deployment Program field trials.

Field sites	**Date treated**	**Treatment**	**Observations**
Alabama	**2010**	Treatment involved applying silane on all faces of the arch, caulking cracks ≥ 1 mm (0.04 in.), and applying epoxy coating on upper face of arch.	• Treatment of ASR-affected arches was **not** effective. • There has been no reduction in RH, and expansion continues unabated.
Arkansas	**2012**	Pavement treated with silanes.	• Too early to draw conclusions.
Delaware	**2009**	Pavement treated with a topical application of lithium nitrate.	• No ASR-performance data available. • DOT overlaid lithium-treated pavement with hot-mix asphalt before the impact of the lithium could be evaluated. • Testing of cores indicated very little lithium penetration and it is highly unlikely that the treatment would have impacted the course of ASR.
Maine	**2010**	Bridge abutments, wing walls, and columns treated with silane and elastomeric coating. One column treated with electrochemical lithium and another with FRP wrap.	• Too early to draw conclusions for abutments and wing walls, but it is possible that moisture supply from behind the treated elements masks any benefit of silane applied to the surface. • The application of a silane to a slender circular column may have reduced expansion, but electrochemical lithium treatment may have increased expansion. • Longer-term data required to confirm findings.
Massachusetts	**2005 and 2010**	Barrier walls treated with silane, lithium treatments (topical and vacuum impregnation), or elastomeric coating.	• Silanes appear to have been effective in reducing expansion and reducing the visual symptoms of ASR (“drying” of cracks). • Lithium treatments (topical or vacuum impregnation) have had no beneficial impact. • Elastomeric coating performing well. • Longer-term data required to confirm long-term performance.
Rhode Island	**2012**	Abutments, wing walls, retaining wall, and barriers treated with silanes and elastomeric coating.	• Too early to draw conclusions.
Texas (Houston)	**2006**	Bridge columns treated with lithium nitrate (vacuum and electrochemical) and sealers/coatings.	• The extent of ASR appears to vary significantly between columns tested, making it difficult to determine the impact of the treatment. • There is evidence that silanes have reduced the internal RH to some extent and may be expected to reduce expansion in the long term. • Electrochemical lithium treatment appears to have increased expansion. This may be due to a combination of the significant resaturation that occurs during treatment and the concentration of alkali-hydroxides around the steel (cathode).
Texas (New Braunfels)	**2010**	Beams treated with silane.	• Contrary to initial hypothesis ASR not confirmed and there is no evidence of an expansive process occurring in the concrete.
Vermont	**2011**	Barrier walls treated with silane sealers and elastomeric coating.	• Too early to draw conclusions. • Treatments have improved the visible appearance of the barriers. This is not surprising for the coating product, but the silanes have reduced the staining associated with the cracks giving the appearance of reducing the damage.

6. RECOMMENDATIONS FOR IMPLEMENTATION

Based on the findings from the nine field trials and monitoring programs, knowledge was gained on how to diagnose structures potentially affected by ASR, how to treat and monitor structures, and how to know what treatment options exist for a given transportation element. This chapter provides recommendations for implementing key findings from this field testing program and for continuing the monitoring program initiated under the FHWA ASR Development and Deployment Program.

It should be noted that the recommendations provided herein are based on the key findings from the nine field trials described in this report, as well previous work by the authors. These recommendations certainly will evolve with time, as more data are collected and analyzed and more mitigation measures are applied to field structures.

6.1 IMPLEMENTATION

This section describes how the key findings from these field trials should be implemented into other FHWA products, such as:

- *Report on the Diagnosis, Prognosis, and Mitigation of Alkali-Silica Reaction (ASR) in Transportation Structures* (Fournier et al. 2009).
- *Alkali-Silica Reactivity Field Identification Handbook* (Thomas et al. 2012b).
- *Alkali-Silica Reactivity Surveying and Tracking Guidelines* (Folliard et al. 2012).

The primary recommendations are presented in tabular form to allow for more efficient implementation into the above FHWA products. The three tables presented in this chapter are intended to serve as road maps for the diagnosis, treatment, and monitoring of ASR-affected transportation structures.

6.1.1 Diagnosis of ASR in Transportation Structures

Significant emphasis was placed on diagnosing the cause of observed distress in pavements, bridges, retaining walls, and barriers throughout this project. Table 4 summarizes the recommendations related to the diagnosis for ASR in transportation structures. References are included within Table 4 that direct readers towards specific field trials described in this report (Volume I or II (Thomas et al. 2013b)) that involved the use of a given method (e.g., crack mapping, DRI, etc.) or towards other FHWA products that include such evaluation tools.

Table 4. Summary of recommendations for the diagnosis for ASR in transportation structures.

Recommended Methods	Comments	Reference (FHWA documents)
Visual / routine inspection	• Identification of visual symptoms commonly associated with ASR (caution: cracking pattern is a function of exposure conditions and restraint). • Regular monitoring to determine the progress of ASR field symptoms. • Particular attention given to structural elements or parts of those that are exposed to excess moisture (e.g., rainfall) → increased probability of ASR distress. • Selection of best area(s) for sampling (coring) → zones exposed to moisture. Could be useful to core in non-deteriorated component (for comparison purposes).	• *Report on the Diagnosis, Prognosis, and Mitigation of Alkali-Silica Reaction (ASR) in Transportation Structures*, Appendix A (Fournier et al. 2009). • *ASR Field Identification Handbook* (Thomas et al. 2012b). • *ASR Surveying and Tracking Guidelines* (Folliard et al. 2012).

Petrographic examination	• Identification of typical petrographic symptoms of ASR in polished concrete sections, broken core surfaces, thin sections.
	• Quantification of the extent of concrete deterioration due to ASR using the Damage Rating Index (DRI). The method consists in counting, under the stereomicroscope, the number of typical petrographic features of ASR on a grid drawn at the surface of a polished section.
	• The method can be used to:
	  • Confirm ASR as being a significant source of distress.
	  • Compare the condition of concrete cores from one concrete element (or portions of) to another (e.g., effect of exposure conditions).
	  • Quantify the progress of damage in concrete cores as a function of time – coring at some location at regular intervals.
	• A classification for DRI values (quantifying the extent of damage due to ASR) has been recently proposed.
		• *Report on the Diagnosis, Prognosis, and Mitigation of Alkali-Silica Reaction (ASR) in Transportation Structures*, Appendix C (Fournier et al. 2009).
		• *Methods for Evaluating and Treating ASR-Affected Structures: Volume II*, section 2.1.1 (Thomas et al. 2013b).
		• *Methods for Evaluating and Treating ASR-Affected Structures: Volume II*, section 7.1, Table 34, and Figure 65 (Thomas et al. 2013b).

Mechanical testing	• Compressive strength is not a good indication of the extent of damage in ASR-affected concrete cores.
	• Quantification of the extent of concrete deterioration due to ASR using the Stiffness Damage Test (SDT). The test consists in subjecting a set of concrete cores to five cycles of uniaxial loading/unloading up to a maximum of 10 MPa (1450 psi). Method proposed in Fournier et al. (2009).
	• Recent studies have shown that better diagnostics can be obtained by using the following options instead of a fixed (10MPa – 1450 psi) (modified SDT):
	  • 40% of the design strength of the concrete, or
	  • 40% of the strength obtained from cores extracted from non-deteriorated (or non-exposed) portions of the structure under investigation.
	• The following parameters are then proposed to quantify the degree of damage in the concrete using the SDT: (1) the energy dissipated (measurement of the surface area) during the five cycles (hysteresis loop), and (2) the accumulated plastic strain over the five cycles.
		• *Report on the Diagnosis, Prognosis, and Mitigation of Alkali-Silica Reaction (ASR) in Transportation Structures*, Appendix E (Fournier et al. 2009).
		• *Methods for Evaluating and Treating ASR-Affected Structures: Volume II*, section 2.1.2 (Thomas et al. 2013b).
		• *Methods for Evaluating and Treating ASR-Affected Structures: Volume II*, section 7.1 (Thomas et al. 2013b).
		• *Study of the Parameters of the Stiffness Damage Test for Assessing Concrete Damage Due to Alkali-Silica Reaction* (Sanchez et al. 2012).

6.1.2 Treatment of Transportation Structures Affected by ASR

Table 5 summarizes the various treatments or mitigation measures that have been applied to different transportation elements, primarily under the FHWA ASR Development and Deployment Program, but also including other reported field studies. The table provides interim recommendations on the various options available for treating ASR-affected structures. Only those treatments that have been shown to significantly reduce ASR-induced expansion and cracking are “recommended” in Table 5; however, as other data become available from well-documented field trials, other treatments for specific transportation will likely be recommended in the future.

6.1.3 Monitoring of ASR-Affected Transportation Structures

Table 6 summarizes the techniques recommended for the monitoring of ASR-affected structures. The table provides references to the use of such techniques in the field testing program.

6.2 FUTURE MONITORING OF FIELD SITES

It is recommended that the monitoring program initiated under the FHWA ASR Development and Deployment Program be continued for as long as possible, but at least for an additional three to five years. Based on the experience in Leominster, the benefits of silane treatment took several years to manifest themselves in terms of reduced expansion and visible cracking. Highway barriers are ideal candidates for silane treatment as both sides of the barrier can be treated, the barriers are relatively thin in cross section, and frequent wetting and drying cycles help to engage the mechanisms by which silanes function. It is likely that other elements, such as pavements, large columns, or bridge abutments, would require even more time for the efficacy of treatments to become discernible.

Table 5. Summary of recommendations and comments on potential mitigation approaches for ASR-affected concrete structures.

Structural Type	Potential Mitigation Approaches	Status	Issues / Comments	Reference / Field Trial
Pavements	Topical lithium treatment.	- Not recommended.	- Lack of lithium penetration.	Delaware (Vol. I, section 4.3; Vol. II, chapter 6)
	Topical silane application.	- Field trial in progress. - Recommendation pending.	- Treated surfaces may be slippery following the application. - Treated surface may suffer from abrasion in pavement and bridge deck applications; may need to reapply more frequently. - May need retreatment; no recommendation on the frequency (could be based on when internal relative humidity begins to increase significantly for those pavements being monitored over time).	Arkansas (Vol. I, section 4.2; Volume II, chapter 5)
	Overlay with hot-mix asphalt.	- Has been done. - Recommendation pending.	- Long-term efficacy still uncertain (long-term monitoring needed). - Potential exists for increase in ASR-induced expansion due to trapping water in affected concrete pavement and due to increasing pavement temperature caused by dark HMA overlay. - Take into consideration that the pavement will increase in depth which might be an issue for height clearances.	Delaware (Vol. I, section 4.3; Vol. II, chapter 6)
	Patch or full-depth repairs in the area around the joints.	- Has been done. - Sometimes necessary to maintain serviceability.	- Does not address the cause of the problem but merely provides a temporary fix to the symptoms of distress.	Delaware (Vol. I, section 4.3; Vol. II, chapter 6)
Barrier Walls	Topical or vacuum lithium treatment.	- Not recommended.	- Lack of lithium penetration.	Leominster (Vol. I, section 4.5; Vol. II, chapter 8)
	Topical silane application.	- Recommended.	- Proven beneficial effect in reducing internal RH in concrete, expansion, and improving visual appearance. - No treatment immediately after days of rainy weather – wait until concrete dries out. - May need retreatment; no recommendation on the frequency (possibly after 6 years).	- Leominster (Vol. I, section 4.5 ; Vol. II, chapter 8) - Vermont (Vol. I, section 4.9; Vol. II, chapter 12) - Rhode Island (Vol. I, section 4.8; Vol. II, chapter 11)
	Topical elastomeric coating.	- Recommended.	- Potential beneficial effect in reducing internal RH in concrete and proven improvement in visual appearance. - Can help in extending service life in cold environment (freeze-thaw action) by bridging existing cracks.	- Vermont (Vol. I, section 4.9; Vol. II, chapter 12) - Rhode Island (Vol. I, section 4.8; Vol. II, chapter 11)
Bridge Abutment and Wing Walls, Retaining Walls	Topical silane application. Topical elastomeric coating.	- Field trial in progress. - Recommendation pending.	- Impact on reducing internal concrete RH may be limited because of moisture access from backfill. - Potential beneficial impact on expansion and visual appearance (to be confirmed with continuing monitoring of field trials).	- Maine (Vol. I, section 4.4; Vol. II, chapter 7) - Rhode Island (Vol. I, section 4.8; Vol. II, chapter 11)
Precast Beams	Topical silane application.	- Field trial in progress. - Recommendation pending.	- Field trial in progress has limited ASR-related distress.	- New Braunfels (Vol. I, section 4.6; Vol. II, chapter 9)

Table 5 (cont'd). – Summary of recommendations and comments on potential mitigation approaches for ASR-affected concrete structures.

Structural Type	Potential Mitigation Approaches	Status	Issues / Comments	Reference / Field Trial
Bridge Columns	Topical and vacuum lithium treatment.	• Not recommended.	• Lack of lithium penetration.	• Houston (Vol. I, section 4.7; Vol. II, chapter 10)
	Electrochemical lithium treatment.	• Not recommended.	• Significant lithium penetration has been reported. • Possible migration of alkali ions (Na^+, K^+) towards the rebar, which may increase the potential for rebar corrosion; risk of maintaining ASR (impact to be evaluated). • Possible increase of ASR expansion due to resaturation during chemical treatment (impact to be confirmed).	• Houston (Vol. I, section 4.7; Vol. II, chapter 10) • Maine (Vol. I, section 4.4; Vol. II, chapter 7)
	Topical silane application.	• Recommended.	• More beneficial for smaller diameter columns. • Application has shown to work over existing painted surface without sandblasting the column surface.	• Houston (Vol. I, section 4.7; Vol. II, chapter 10) • Maine (Vol. I, section 4.4; Vol. II, chapter 7)
	Strengthening (e.g., FRP wrap or other methods).	• Has been done. • Recommendation pending.	• Long-term monitoring still required to confirm the efficacy of FRP wrap. • Likely to be beneficial when properly designed - can provide moisture control as well as physical restraint.	• Maine (Vol. I, section 4.4; Vol. II, chapter 7)
Bridge Decks	Topical silane application.	• Recommendation pending.	• Treated surfaces may be slippery following the application. • Treated surface may suffer from abrasion in pavement and bridge deck applications; may need to reapply more frequently. • May need retreatment; no recommendation on the frequency (could be based on when internal relative humidity begins to increase significantly for those bridge decks being monitored over time).	Not investigated as part of FHWA Development and Deployment Program
	Topical lithium application.	• Not Recommended.	• Lack of lithium penetration	
	Overlay with hot-mix asphalt or concrete.	• Has been done. • Recommendation pending.	• Long-term efficacy still uncertain (long-term monitoring needed). • Take into consideration that the bridge deck will increase in depth which might be an issue for height clearances. • Potential exists for increase in ASR-induced expansion due to trapping water in affected concrete bridge deck and due to increasing deck temperature caused by dark HMA overlay.	
	Electrochemical lithium treatment.	• Not recommended.	• Possible migration of alkali ions (Na^+, K^+) towards the rebars; risk of maintaining ASR (impact to be evaluated). • Possible increase of ASR expansion due to resaturation during chemical treatment (impact to be confirmed). • Would have to close the bridge deck or provide protection (e.g., ramp) and lower vehicle speed to allow the ponding of lithium on the roadway surface.	

Note: For Vol. II, see Thomas et al. 2013b.

Table 6. Summary of recommendations for performance monitoring of ASR-affected transportation structures.

Recommended Methods	Comments	Reference (FHWA documents)
Visual inspection	• Visual examination of treated sections of the structure → perform regular picture survey of selected portions; allows monitoring the progress in damage.	• Volume II, chapters 5, 7, 8, 10 to 12 - examples.
Cracking Index (CI) Method	• The method consists in quantifying surface cracking by recording and summing the crack widths measured along a set of lines drawn (crack map) on the surface of the selected sections. Minimum dimension of crack map: 500 x 500 mm (20 x 20 in.). • Insert stainless steel studs with DEMEC point at the corners of the crack map to allow direct comparison with length changes.	• *Report on the Diagnosis, Prognosis, and Mitigation of Alkali-Silica Reaction (ASR) in Transportation Structures*, Appendix B (Fournier et al. 2009) - detailed description of the Cracking Index method. • Volume II, section 2.2.2 - summary of the CI method. • Volume II, chapters 7, 8, 10 to 12 - examples of the use of the method.
Expansion measurements	• Length change measurements are carried out on the same grid (crack map) developed for CI measurements. • Thus, the recommended dimension for expansion grid (vertical and horizontal readings) is 500 x 500 mm (20 x 20 in.). When such a dimension is not possible (e.g., barrier wall in the vertical direction), a smaller size grid (500 x 150 mm [20 x 6 in.]) can be used. • Other types of measurements, e.g., circular measurements using a Pi-tape, can be used to monitor length changes in circular structural elements (columns).	• *Report on the Diagnosis, Prognosis, and Mitigation of Alkali-Silica Reaction (ASR) in Transportation Structures*, Appendix D (Fournier et al. 2009) - detailed description of the procedure. • Volume II, section 2.2.1 - summary of the CI method. • Volume II, chapters 4, 5, 7 to 12 - examples of the use of the method.
Temperature and humidity measurements	• The method allows the measurement of temperature and relative humidity (RH). Plastic sleeves inserted to different depths, e.g., 25 to 75 mm (1 to 3 in.) within concrete elements. • The method is useful to monitor the possible beneficial effect of surface treatments to control ASR expansion (by reduction of RH in concrete). • Select monitoring sites where the plastic sleeves are not going to be exposed/subjected to the impacts from cars, ice and snow removal, or be accessible to individuals who could damage the setup. • In moderately and severely cracked concrete elements, as well as when moisture is available from backfill material (e.g., abutment, wing, and retaining walls), water will likely accumulate in the holes, thus making reliable readings impossible. Moisture can also accumulate in the holes because of water condensation. In such circumstances, the holes should be left open until the holes dry out. An internal RH re-equilibrium period (few hours) is then required before any reliable data can be obtained.	• Volume II, section 2.2.3 - detailed description of the CI method. • Volume II, chapters 4, 5, 7 to 12 - examples of the use of the method.

Note for all of the above:

- To avoid high variability in results, carry out regular measurements (twice a year):
  - By the same operator or trained operators.
  - Under similar weather conditions.
- Because of the effect of climatic conditions, several years (minimum 3 years, ideally 5 years) of monitoring are required to establish significant trends.
- For Volume II, see Thomas et al. 2013b.

Table 6 (cont'd). Summary of recommendations for performance monitoring of ASR-affected transportation structures.

Recommended Methods	Comments	Reference (FHWA documents)
Non-destructive techniques	• The non-destructive techniques (NDT) provide an indirect measurement of the concrete conditions. The techniques used in this project are based on the propagation of stress waves, which are primarily dependent on concrete's Young modulus and the concrete density. • Ultrasonic pulse velocity (UPV) in indirect configuration can be used to assess the surface condition where only one face is accessible. When opposite faces are accessible, UPV will provide an evaluation of the global condition of the concrete. • Impact-echo can be used to assess the global condition when the opposite face is parallel to the surface (cannot be used on circular columns, for instance). • Nonlinear acoustics: this method is not recommended at this stage because of 1) the complexity of the method and of signal processing, and 2) the lack of long term data. • All NDT methods must be performed by skilled and qualified operators. Data should always be analyzed by experienced engineers. • In cases of severely cracked massive elements, NDT may not work because of the attenuation of the signals.	• Volume II, section 2.2.4 - summary of the CI method. • Volume II, sections 7.3 and 7.4 - examples of NDT results and their analysis.

Note for all of the above:

- To avoid high variability in results, carry out regular measurements (twice a year):
  - By the same operator or trained operators.
  - Under similar weather conditions.
- Because of the effect of climatic conditions, several years (minimum 3 years, ideally 5 years) of monitoring are required to establish significant trends.
- For Volume II, see Thomas et al. 2013b.

7. CONCLUDING REMARKS

This report described the results of nine field trials in which ASR-affected structures were treated with various techniques aimed at reducing the future potential for ASR-induced expansion and cracking. Collectively, these field trials represent the most comprehensive field evaluation of mitigation measures applied to ASR-affected transportation structures. Recommendations were developed under this project on refining and improving methods for diagnosis and prognosis of ASR-affected structures, and a substantial database of laboratory and field data was developed for a range of treatments and technologies. It is hoped that continued monitoring of these nine field trials will provide information to further advance the ability to diagnose structures affected by ASR, to select mitigation measures for a given transportation element, and to treat and monitor structures affected by ASR. It is also hoped that other researchers and practitioners engaged in field trials or mitigation of ASR-affected structures find the various tools developed under the FHWA ASR Development and Deployment Program beneficial.

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