STUDY OF REMEDIAL ACTIONS ON HIGHWAY STRUCTURES AFFECTED BY ASR

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ABSTRACT
This paper presents information of the different demonstration projects undertaken under FHWA's *Alkali-Silica Reactivity (ASR) Development and Deployment Program*, with an aim at implementing in the field a number of techniques for mitigating the deleterious effects of ASR in highway structures.

Keywords: Alkali-silica reaction, diagnosis, mitigation and repair, sealant material, electrochemical treatments.

1. INTRODUCTION

Mitigating the deleterious effects of ASR in existing concrete structures still remains a huge challenge for engineers worldwide. A number of different techniques, such as the application of impermeable membranes or metallic cladding, topical applications of breathable sealing materials/products, electrochemical/pressure impregnation of ASR-affected elements (CO_2, lithium-based admixtures, etc.), strengthening/encapsulation of the affected element with steel, reinforced concrete or composite materials, slot-cutting, etc., have been implemented over the years [1,2]. However, the efficacy of such technologies in successfully mitigating/eliminating the problem often remains uncertain as in-situ monitoring and "post-mortem" reports on the above treatments are not commonly available.

Under FHWA's *Alkali-Silica Reactivity (ASR) Development and Deployment Program*, an opportunity was given to gather some of the above technologies and put them into practice through field applications and demonstration projects, the objective being to ultimately gain valuable knowledge about their long-term efficacy and practicality [3]. In order to do so, a project team was put together to provide technical assistance to the State Departments of Transportation (DOT) in selecting field applications and demonstration projects, designing and implementing treatment and monitoring programs, evaluating and collecting data from the field test sites, and analyzing collected data to determine the efficacy of the technologies.

This paper provides details about the field implementation program through the description of selected case studies carried out in recent years. Despite the fact that it is too early to conclude on the efficacy of the different technologies/treatments implemented on ASR-affected structures in this studies, this paper will serve as a reference/basis for further technical papers that will, in time, report on their efficacy.

2. WORK PLAN

The project team first solicited participation from State DOT for FHWA's *ASR Development and Deployment Program*. A process for the selection, implementation and monitoring of field demonstration projects related to mitigating the deleterious effects of ASR in concrete structures, was developed based on the protocol for selecting ASR-affected structures for lithium treatment [4] and the report on the diagnosis, prognosis and mitigation of ASR in transportation structures [2], both developed by the team.

2.1 Field visit of potential project sites.

Field inspections were carried out by members of the team, along with State DOT and FHWA representatives, to evaluate potential project sites. When examining the structures, particular attention was paid to the environmental conditions and the nature/extent of features generally associated to ASR [4]. Based on the above observations, sampling sites were identified. They generally corresponded to badly-cracked concrete elements, often exposed to high moisture conditions, while cores were also collected from unexposed or mildly affected elements for comparison purposes.

2.2 Testing of concrete core samples

Confirming information for the diagnosis of ASR was generated by subjecting the core samples to petrographic examination using the *Damage Rating Inde*x (DRI) and, when a sufficient number of cores were available, to mechanical testing through the *Stiffness Damage Test* (SDT). The DRI is a count, under the stereomicroscope (18x magnification), of petrographic features of ASR identified in grid system (1cm x 1cm squares) drawn on polished concrete sections. The *DRI* represents the normalized value (to 100 cm^2) of the presence of these features after the count of their abundance over the surface examined has been multiplied by selected weighing factors [5]. The SDT consists in subjecting concrete cores to cyclic loading (five cycles in compression) up to a maximum stress of 10 MPa, the following parameters being used for characterizing the damage in concrete: 1) hysteresis area of the first cycle (or dissipated energy) (J/m^3) and 2) plastic deformation (µstrains) accumulated over the five loading/unloading cycles [6].

2.3 Selection and implementation of field treatments and performance monitoring program

Once ASR was identified as the primary cause of deterioration, the most appropriate mitigation measure(s) was (were) selected and implemented in the field, either directly by the project team or in collaboration with State DOT engineers/personnel and/or specialized contractors, based on the likelihood of success for the type of structure, the extent of deterioration and the funding available.

The project team also developed and implemented a monitoring program for treated and control sections, which included training of local State DOT personnel so they can continue to track the performance of the structures upon conclusion of the project. Monitoring activities include the following (Figure 1)[2]:

- Expansion measurements conducted by imbedding steel studs at different locations on the treated and control sections, and using a gage to regularly record changes of the nominal 500-mm gage lengths.
- Humidity/temperature measurements are done by drilling holes to different depths into the concrete. Probes are inserted into the holes and measurements taken upon equilibrium using a handheld reader.
- Severity of cracking on a 500-mm grid drawn on the surface of the treated/control elements. The number of cracks, along with crack widths, are recorded and used to create a Cracking Index (CI).
- Three non-destructive methods, i.e. impact echo, ultrasonic pulse velocity (UPV) and a non-linear acoustic technique [7-9], were applied to monitor internal damage in the concrete members evaluated.

3. DESCRIPTION OF FIELD CASE STUDIES

A total of nine field demonstration projects were carried out and are being monitored as part of this program. These include projects that were initiated under FHWA's lithium implementation program [10]. Table 1 gives an overview of the above projects; two of them will be presented in more details hereafter.

3.1 Bridge structures in Bangor/Brewer (Maine, USA)

The condition (visual) survey carried out in 2009 on six bridge structures along the Interstate 395 (I-395) revealed the abundance of typical symptoms of ASR. Sections or elements of the structures sheltered from direct exposure to rain and sun showed no or light visible cracking, while those exposed to the above elements (e.g. wing walls and exposed parts of the abutments) showed moderate to severe map/vertical cracking (Figure 2). The differences noted from the visual survey were confirmed by NDT measurements (impact echo and UPV); however, nonlinear acoustics yielded poor results on moderately- to severely-cracked surfaces since this method has rather been designed to detect early cracking. Figure 2G shows an example of a condition rating based on impact echo results obtained on three walls (abutment, side and center; wing wall). It is clear that the wing wall (exposed, higher visual damage) has a much lower number of measurement spots classified as "good concrete" compared to the other walls. The center (unexposed) wall has no spots classified as "poor concrete", while the other areas exhibit some. None of the three walls fell in the "excellent" category for concrete quality.

The petrographic examination of the cores extracted from several deteriorated structural elements confirmed the presence of petrographic features of ASR in the reactive greywacke/argillite coarse aggregate particles (Figure 2H). A total of 24 polished core sections were subjected to the DRI, with values ranging from low (DRI < 250) to high degree of ASR damage (DRI of 627 to 882), with the extent of ASR generally correlating well with the severity of the exposure conditions of the structural element (e.g. Figure 3A). A similar correlation was obtained for the SDT results, with the highest dissipated energy values (J/m^3) corresponding to the core samples extracted from severely exposed structural elements (Figure 3B).

Based on the results of the above field and laboratory investigations, a treatment plan involving the application of different types of sealers on various elements of five structures on the I-395 was implemented in 2010 (Tables 2 and 3). The Enviroseal® 40 and Protectosil® BHN materials were applied with a hand held pump pressure sprayer at a rate of about 150 ft^2/gallon , while the Sikagard® 550W material was applied with coats with a paint roller at a rate of 100 ft^2/gallon (Figures 3C-E). Sections/elements of similar degree of damage and exposure conditions were maintained untreated for comparison purposes.

The six columns at mid-span of the South Parkway structure provided an opportunity to evaluate additional types of remedial actions on a series of 7m-tall columns exhibiting different levels of ASR (Table 3). The column exhibiting the highest degree of deterioration (column no. 6; moderate-to-severe cracking – Figure 2F) was encapsulated using 4 layers of carbon fiber reinforced polymer (CFRP) strengthening wrap (Sikawrap Hex 103C System) (Figures 3F-3G). Electrochemical (lithium) migration technique was applied on the column no. 2 (moderate degree of cracking)(Figure 3H). The treatment involved the installation of a temporary anode system consisting of a series of titanium anodes placed into holes drilled in a grid pattern in the upper 6-metre portion of the column and a titanium mesh layer sandwiched between layers of geotextile felt that covered the concrete surface of the column. Both the temporary anode system and the embedded reinforcing steel, which acts as a cathode, were then connected to an AC/DC rectifier, which, once energized, applies a low voltage DC potential between the anode and the cathode to migrate lithium into the concrete from the electrolyte (30%-lithium nitrate solution) that is pumped onto the surface of the concrete column through a temporary irrigation system. The lithium impregnation system was sealed with polyethylene sheets to prevent evaporation or dry out over the 8-week treatment period.

Finally, silane (Enviroseal® 40) treatment was applied on column no. 3 showing mild degree of cracking, while the other three columns (no. 1 (severe cracking), 4 and 5 (mild cracking) were kept as controls (Figure 3G). For all treated and untreated bridge elements, a monitoring program was implemented, involving regular (annual) length change, crack mapping and internal relative humidity measurements.

3.2 Bridge along the Interstate 89 in Vermont (USA)

The condition survey of two bridges (carrying two lanes in each direction) of Interstate I-89 over Dog River near Montpelier, Vermont (USA) was carried out in 2010 (Figure 4A). The parapet walls showed extensive map cracking consistent with ASR (Figure 4B), with no evidence of corrosion of embedded reinforcement or damage due to freeze-thaw. The petrographic examination of cores extracted from the barrier walls adjacent to the passing lane on both the northbound and southbound bridges revealed features of ASR associated to reactive particles in the coarse fraction of the sand (schist, microquartzite, sandstone and argillite)(Figure 4C). Moderate-to-high degree of deterioration due to ASR was obtained for cores S2 and S3, resulting in DRIs of 647 and 568, respectively; low to very low degree of deterioration/damage due to ASR was observed in cores I89-S1 and N1 to N3 (DRIs ranging from 53 to 202 - Figure 4D). No evidence of ASR was observed in the coarse aggregate consisting of a greyish granite.

Following the results of the petrographic examination of the cores, it was recommended that the barrier walls be treated with suitable coating/sealant systems to retard the rate of further deterioration due to ASR. The treatment program described in Table 3 was implemented on the Southbound bridge walls. The estimated length of the bridge wall is 955 feet long, and both bridge walls were treated. The bridge wall on the interior of the bridge had silane applied only to the side facing traffic while the outside bridge wall had both sides of the barrier wall treated with silane. The Enviroseal® 40 and Protectosil® BHN materials were applied, once again (as for the Maine demonstration project), with a hand held pump pressure sprayer at a rate of about 150 ft^2/gallon, while the Sikagard® 550W material was applied with a paint roller with 2 coats at a rate of 100ft^2/gallon(Figures 4E-H).

4. CONCLUSION

FHWA's *Alkali-Silica Reactivity (ASR) Development and Deployment Program* provided a unique opportunity to select a number of different types of highway structures affected by ASR, for implementing a number of different remedial actions. These consisted in controlling moisture access to the ASR-affected structures through the topical application of various types of sealant materials, chemical treatments (vacuum impregnation, electrochemical migration technique and topical application) using lithium-based admixtures, and strengthening of an ASR-affected column by CFRP wrap. Monitoring systems were installed on treated and control sections (expansion, humidity, progress of cracking) in order to monitor the performance of the above treatments and establishing their long-term efficacy and practicality.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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Table 1: List of demonstration projects as part of the program

Structure	Location	Comments
Pavement	Mountain Home, Idaho	• Mild to moderate ASR in the coarse aggregate (mixed volcanics, chert). • Treatment carried out in 2004 : topical application of $LiNO_3$. • Monitoring of expansion and humidity in treated/control sections.

Highway barriers	Route 2, Leominster, Massachusetts	• Moderate to severe ASR in coarse aggregate (greywacke)
		• Treatments applied on several barrier sections in 2005:
		  • Vacuum impregnation with $LiNO_3$
		  • Topical application of silane, or $LiNO_3$ (with/without silane)
		• Monitoring of expansion and humidity in treated/control barriers.

Bridge columns	I-10 & I-45 interchange in Houston, Texas	• Moderate to severe ASR in the coarse aggregate (chert, quartzite)
		• Treatments applied in 2006:
		  • Lithium treatment (vacuum and electrochemical methods)
		  • Topical application of silane (blasted and painted surfaces)
		• Monitoring of expansion and humidity in treated/control columns.

Pavement	Route 113, Georgetown, Delaware	• Moderate ASR (coarse aggregate (schist, gneiss) and in sand (chert). • Treatment: topical applications of $LiNO_3$ (2009). • Overlaid with asphalt in 2011.

Bridge elements	I395, Bangor, Maine	• Moderate to high ASR in the coarse aggregate (greywacke/argillite).
		• Treatments applied in 2010:
		  • Topical applications of sealant materials.
		  • Electrochemical migration (lithium) technique.
		  • Carbon fibre reinforced polymer (CFRP) strengthening wrap.
		• Monitoring of expansion and humidity in treated/control elements.

Parapet walls, brige	I89, Montpelier, Vermont	• Moderate ASR in the coarse fraction of the fine aggregate (schist, microquartzite, sandstone and argillite). • Treatment in 2010: topical applications of sealant materials • Monitoring of expansion and humidity in treated/control walls.

Cconcrete arches, bridge	Wetumpka, Alabama	• Severe ASR in the coarse aggregate (chert, quartzite).
		• Treatment carried out in 2010 :
		  • Filling of large cracks with flexible sealant.
		  • Application of silane to all surfaces.

		• Application of epoxy flood-coat on the top face. • Monitoring of expansion and humidity in treated/control arches.
Abutments, retaining and barrier walls	Providence, Rhode Island	• Low to high degree of ASR in coarse aggregates (gneiss, quartzite) • Treatments applied in 2012: topical application of sealant materials • Monitoring of expansion and humidity in treated/control elements.
Concrete pavement	Little Rock, Arkansas	• Moderate ASR in the fine aggregate (chert) • Treatment carried out in 2012: topical application of sealant materials • Monitoring of expansion and humidity in treated/control panels.

TABLE 1 : Treatments applied on structural elements of three highway structures (Bangor/Brewer, Maine)

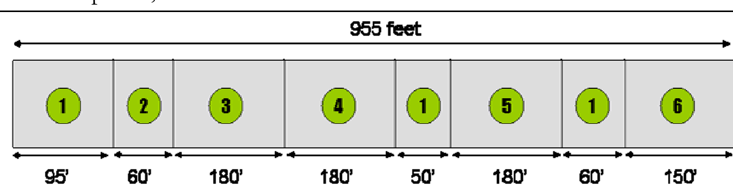
Elements	**I395 at Green Point**		**I395 at Robertson**		**O 395 over Main Street**	
	Eastbound	**Westbound**	**Eastbound**	**Westbound**	**Eastbound**	**Westbound**
Wingwall 1 + abutment 1	Sikagard® 550W	Protectosil® BHN	Control	Sikagard® 550W	Protectosil® BHN	Sikagard® 550W
Wingwall 2 + abutment 2	Enviroseal® 40	Control	Protectosil® BHN	Enviroseal® 40	Enviroseal® 40	Enviroseal® 40

- **Enviroseal® 40**: Clear water-based, VOC-compliant, 40% alkylalkoxysilane penetrating sealer (milky-white when applied) (typical coverage rate: 2.4 – 4.8 m^2/L)
- **Sikagard® 550W** : water-dispersed and acrylic-based elastomeric, crack-bridging coating, anti-carbonation, vapour permeable (typical coverage rate: 2.4 m^2/L);
- **Protectosil® BHN :** Clear, 100% active alkyltrialkoxysilane product (solvent-free), breathable VOC-compliant and water repellent material (typical coverage rate: 2.4 m^2/L.).

TABLE 2 : Treatments applied on the different highway structures (Bangor/Brewer, Maine)

Structure		**Reinforced concrete columns**					
		1	**2**	**3**	**4**	**5**	**6**
South Parkway over I 395		Control	Electrochemical Li treatment	Enviroseal 40	Control	Control	CFRP wrap
Penobscot River	North side	Enviroseal® 40	Protectosil® BHN	Control			
	South side	Enviroseal® 40	Control	Control			
Note: Application rate for Enviroseal and Protectosil materials similar to Table 1.							

TABLE 3: Treatments applied on the parapet walls of the Southbound bridge carrying I89 over Dog River near Montpellier, Vermont.



Section	Treatment	Application rate
1	Topical treatment with Protectosil® BHN, then Sikagard® 550W	150ft2/gal, 100ft2/gal
2	Control section (no treatment)	-
3	Topical treatment with Enviroseal® 40	150ft2/gal
4	Topical treatment with Protectosil® BHN	150ft2/gal
5	Topical treatment with Sikagard® 550W	100ft2/gal
6	Contractor's treatment	-

Figure 1: Monitoring equipment/set-up for evaluating the efficacy of mitigating treatments on ASR-affected concretes. A. Humidity probe and crack mapping grid. B. Temperature and humidity measurementsat different depths into the concrete elements. C. Expansion measurements. D. Impact-echo. E. Non-linear acoustic technique.

FIGURE 2 : Highway bridges (Bangor/Brewer, Maine). A. Cracking in the exposed portion of a large reinforced concrete column. B&C. ASR-affected bridge elements (abutment and wing wall). D&E. Cracking in the external (exposed) reinforced concrete columns. F. Coring sites in the abutment (not exposed (1), exposed (2)) and the wing wall (exposed (3)) of an ASR-affected bridge structure. G. Condition rating of concrete for three walls according to indirect velocities measured in the impact-echo test. Recurences correspond to the number of measuring spots falling into the different condition categories. H. Typical signs of ASR (cracking in aggregate particles and cement paste) in polished concrete sections.

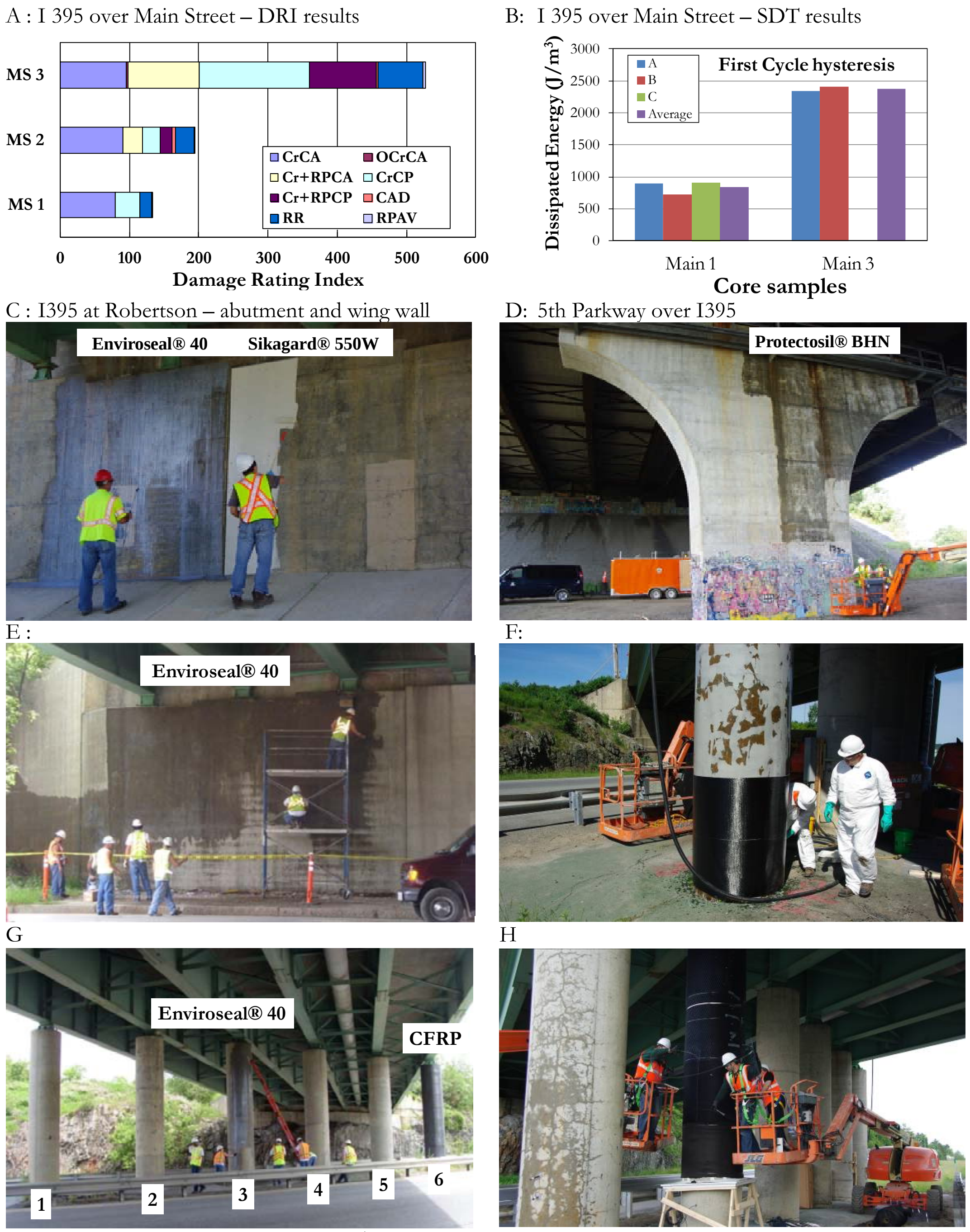
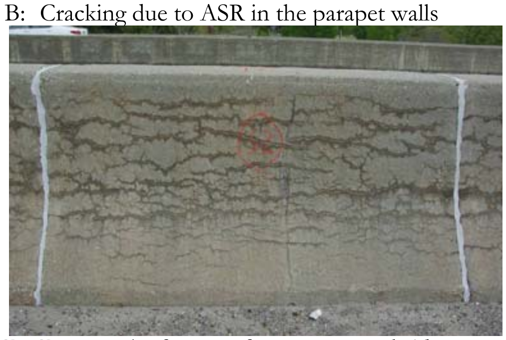


FIGURE 3 : Highway bridges (Bangor/Brewer, Maine). Results of the petrographic examination (A) and mechanical testing (B) of samples from 3 coring sites (Figure 2G). C. Application of surface treatments (silane and elastomeric paint) on the abutment. D. Application of surface treatment (silane) on the reinforced concrete column. E. Application of surface treatment (silane) on the abutment and wing wall. F. Wrapping of column with carbon fibers (CFRP wrap). G. Various treatments on the reinforced concrete columns (see Table 2). H. Electrochemical (lithium) treatment on the reinforced concrete column no. 2 of figure G.

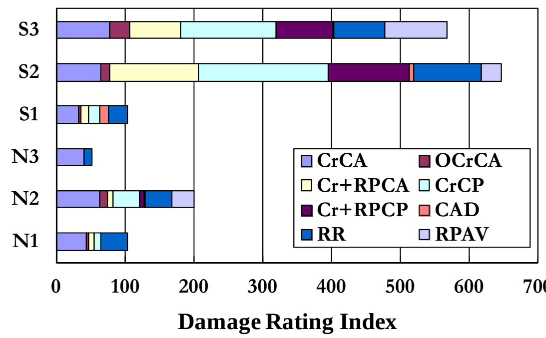
A : Bridge on the I89 over Dog River

B: Cracking due to ASR in the parapet walls



C : Petrographic features of ASR

D: DRI results for core from Vermont bridge



E : Application of Protectosil BHN

F: Application of Sikagard

G : Application of external barrier with Lift truck

H : Control section next to Sikagard section

FIGURE 4 : A. General view of the structure. B. Typical cracking in the parapet wall of the bridge structure (Section of sample S2). C. Cracking in the reactive sand particles (with silica gel) and in the cement paste. D. Summary of DRI results for the six core samples examined. E. to H. Application of different products.