FHWA Workshop

Alkali-Aggregate Reaction

Session 08: Mitigation Measures Applied to ASR-Affected Structures

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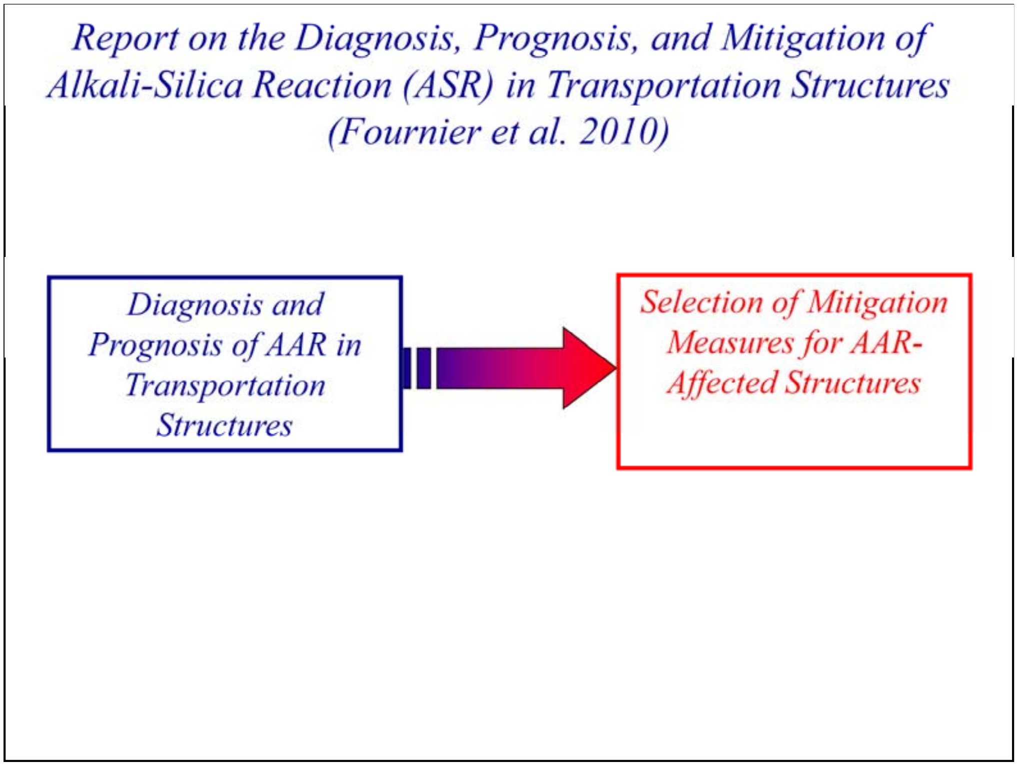
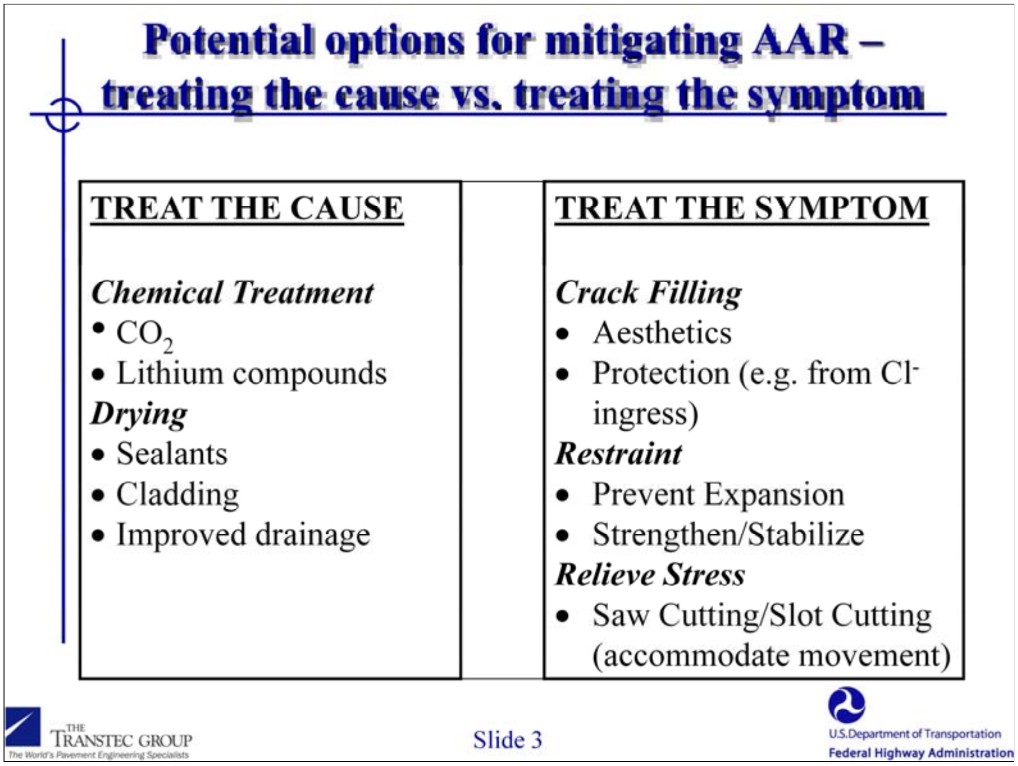


This session serves as a follow-up to the previous presentation on the diagnosis and prognosis of ASR-affected transportation structures.

This presentation will describe past and ongoing field trials that have attempted to reduce future expansion and cracking caused by ASR.

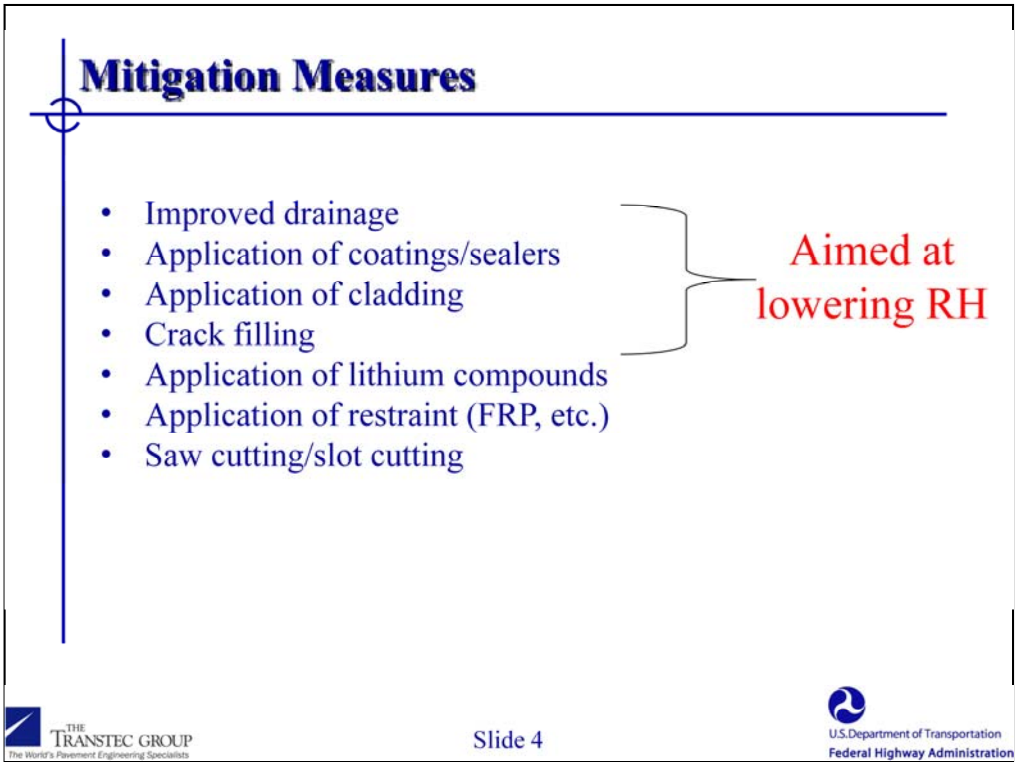
Both this presentation and the previous one are based on the Report on the Diagnosis, Prognosis, and Mitigation of Alkali-Silica Reaction (ASR) in Transportation Structures (Fournier et al. 2010). Those that are interested in more detail are referred to this FHWA publication.



When considering potential measures for mitigating ASR in transportation structures, one can look at it globally and consider options aimed at either affecting the cause(s) of ASR or the symptom(s) of ASR.

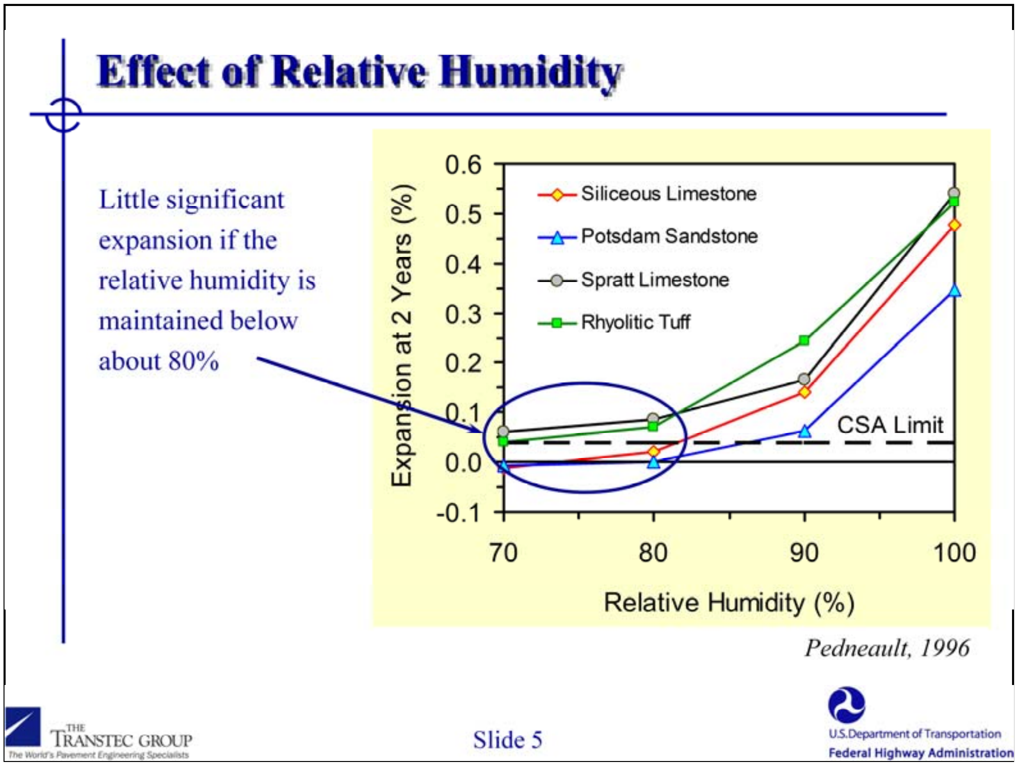
Examples of targeting the causes of ASR include drying the concrete (through sealers, coatings, cladding, etc.), lowering the pH (though CO_2 treatment), and attempting to change the nature of the gel, itself (through lithium treatment).

Examples of treating the symptoms of ASR include crack filling, external restraint, and stress relief (e.g., slot cutting).



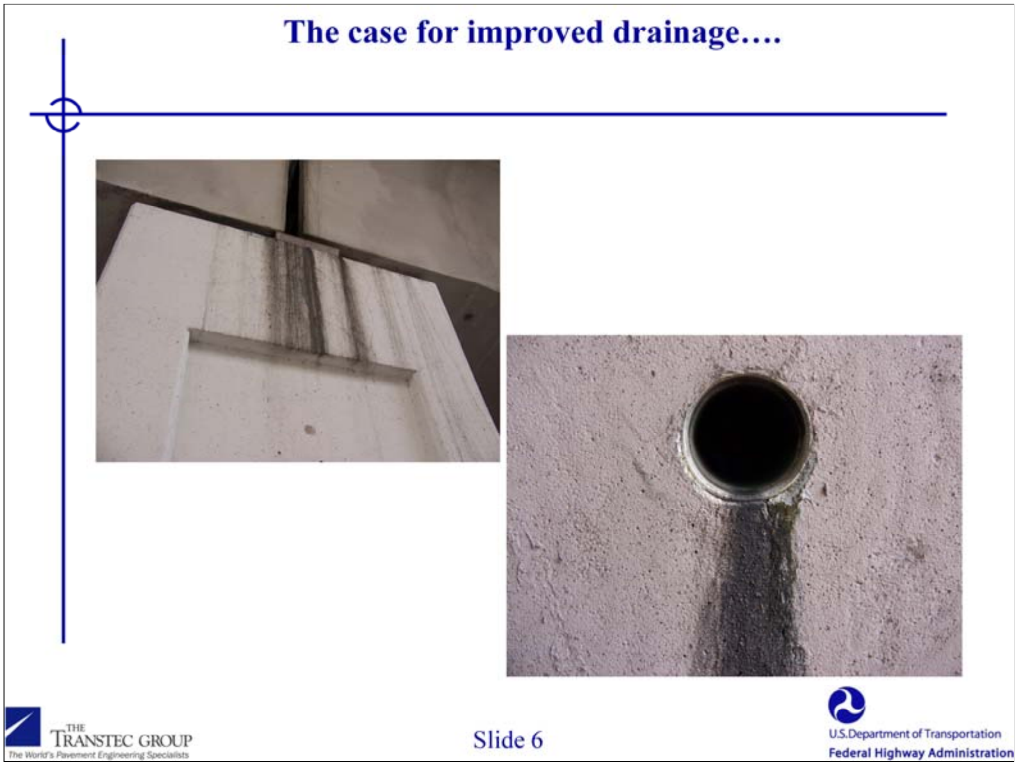
Various specific mitigation measures have been attempted on field structures affected by ASR-induced expansion and cracking. The first four methods shown in this slide all aim to lower the internal relative humidity in concrete. The last three bullets involve the application of lithium compounds, the application of external restraint, and stress relief.

The remainder of this presentation discusses each of these approaches, and when applicable, field trials currently being monitored under FHWA funding will be discussed.



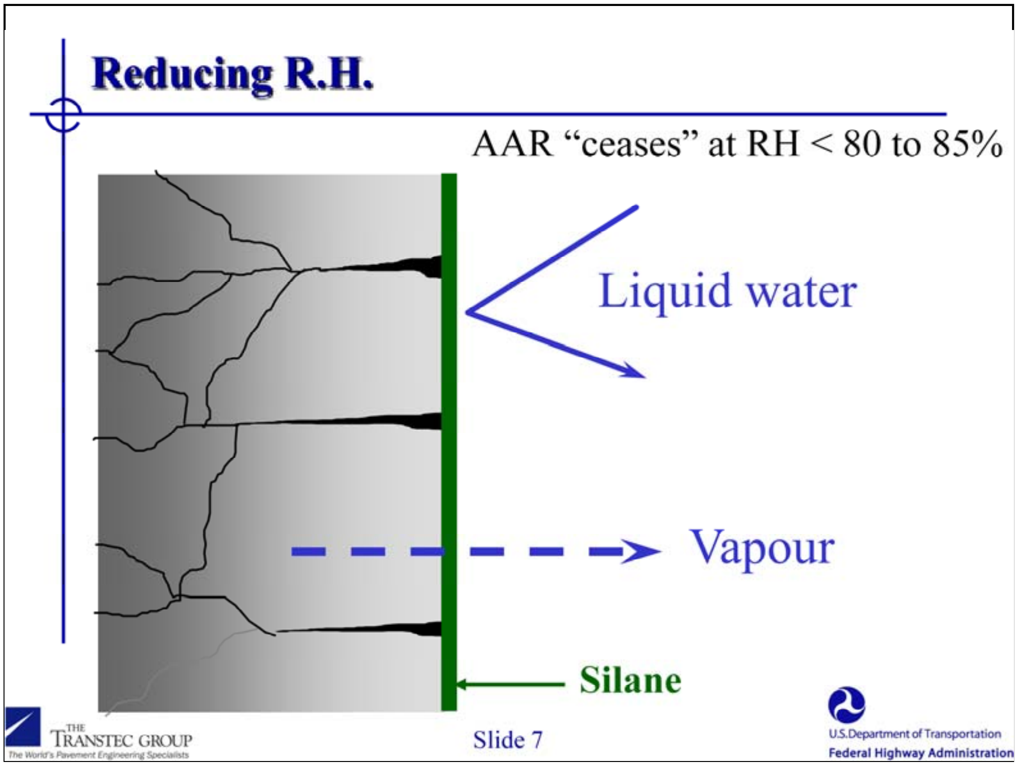
The graph in this picture shows some data from a laboratory study conducted at the University of Laval. In the study concrete prisms were produced with 5 different reactive aggregates (including an alkali-carbonate reactive aggregate) and were then stored at a range of different relative humidities.

The graph shows the expansion of the concrete after 2 years of storage plotted against the relative humidity of the storage. It is generally considered that ASR will cease once the relative humidity within the concrete has fallen below 80%.

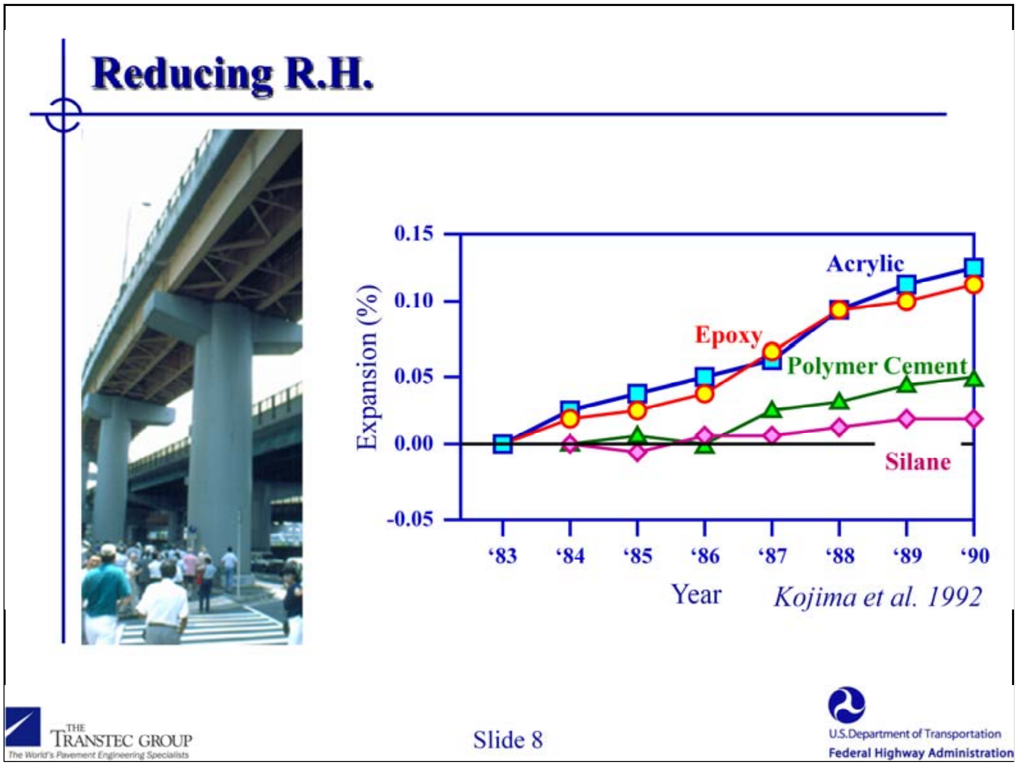


Improving the drainage of water away from ASR-affected structures is a simple, yet effective, method of reducing the internal relative humidity in concrete.

This slide shows a large reinforced concrete column that contained an internal drain pipe taking water from the deck above, through the column, to drainage pipes below the footings. However, upon examination, this drain pipe was clogged – simply unclogging the drainage pipe and restoring adequate drainage helped to reduce the availability of water to this ASR-affected column.



In some cases, it is not possible to improve drainage of water away from an ASR-affected element. In such instances, the application of breathable coatings, such as silanes, may prove helpful. Products such as silanes are effective in preventing liquid water from entering the concrete, while still allowing internal vapor to escape.



This graph shows data from the Hanshin Expressway in Japan. The graph shows that the application of silane effectively reduced ASR-induced expansion.

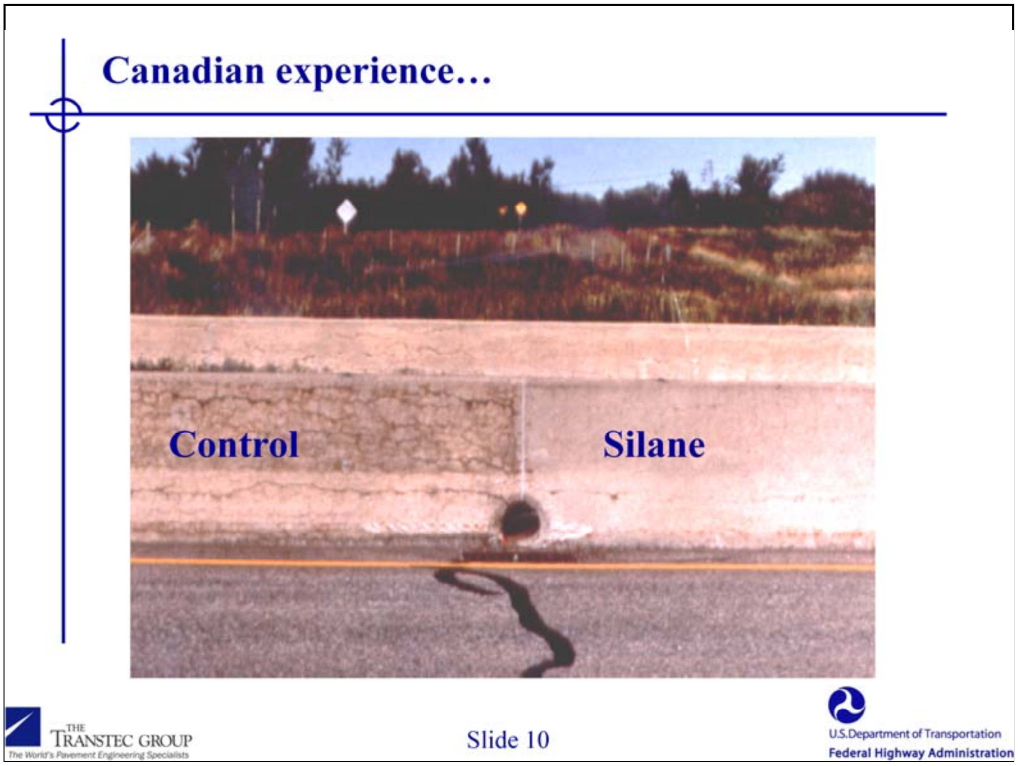
Other products that are not breathable, such as acrylic or epoxy, showed no benefits in terms of reduced expansion.

The data for this field study does not extend beyond 1990 because the bridge ultimately failed during an earthquake. It is not believed ASR contributed to the collapse of this structure.

A series of FHWA-funded field trials have been performed in recent years. Several of these trials will be described in this presentation.

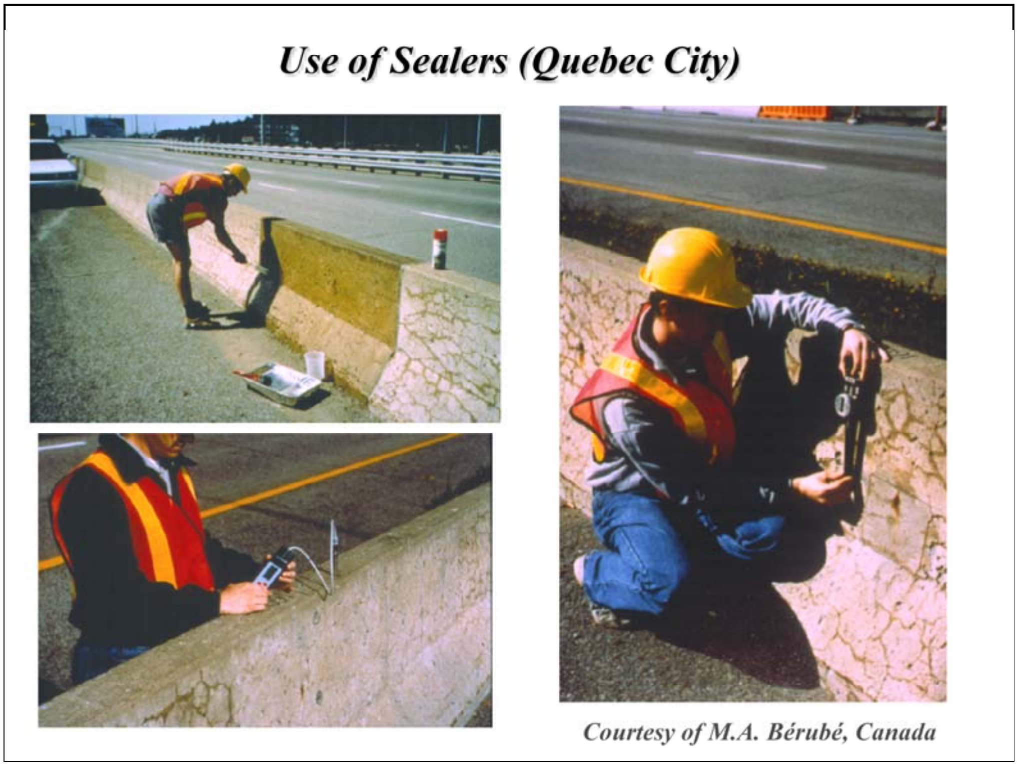
This photo shows the topical application of silane to highway barriers in Leominster, MA.

This study also included the application of other products, such as lithium compounds – this is discussed later in this presentation.



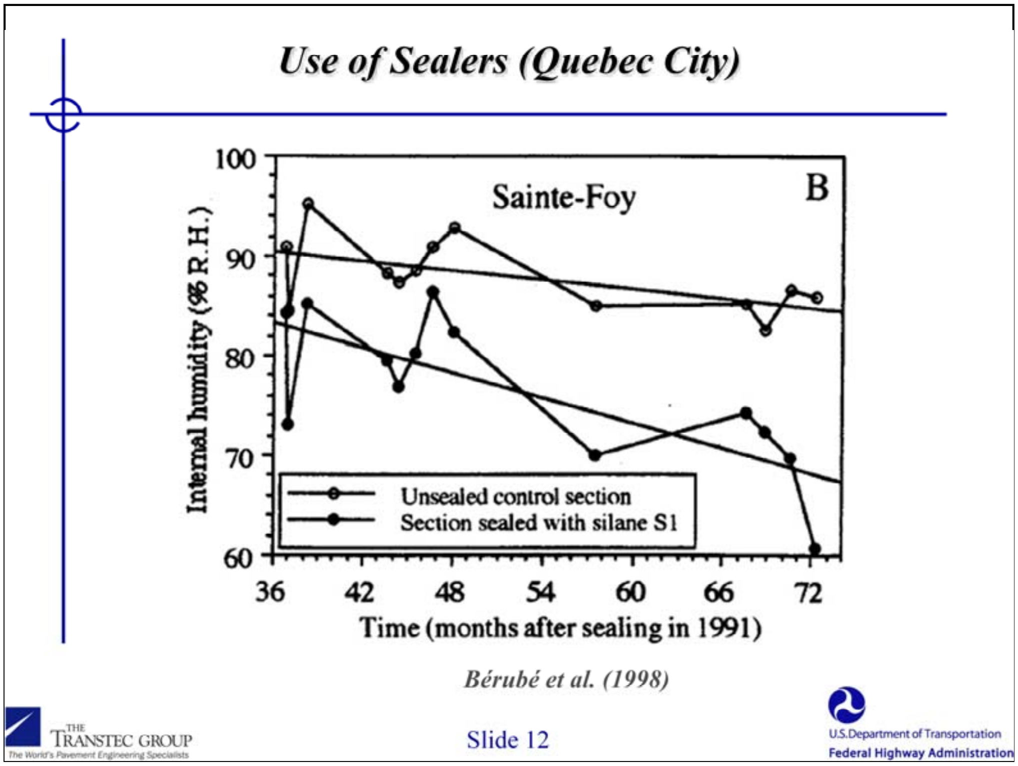
This photograph shows vividly the benefits of applying silanes to highway barriers near Quebec City, Canada.

Several years after treatment, there is a noticeable difference in visual appearance between the silane-treated section and an untreated control.



The highway barriers near Quebec City that were treated with silanes (and other products) were monitored for long-term expansion, crack development, and internal relative humidity.

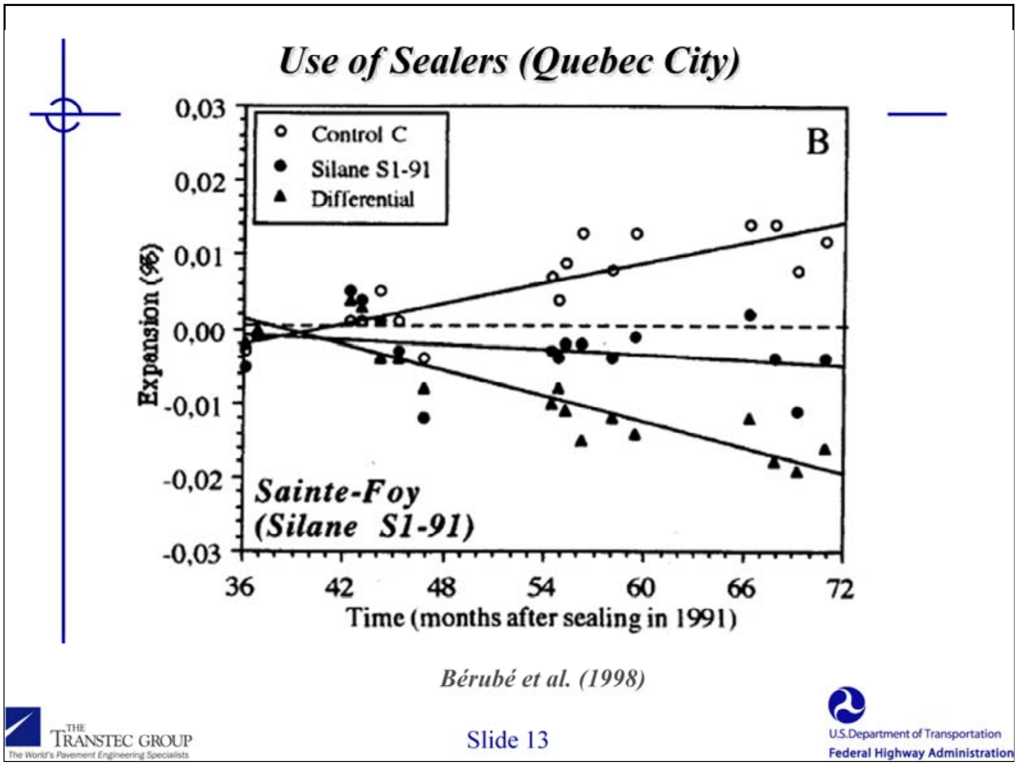
The results are presented in the slides that follow.



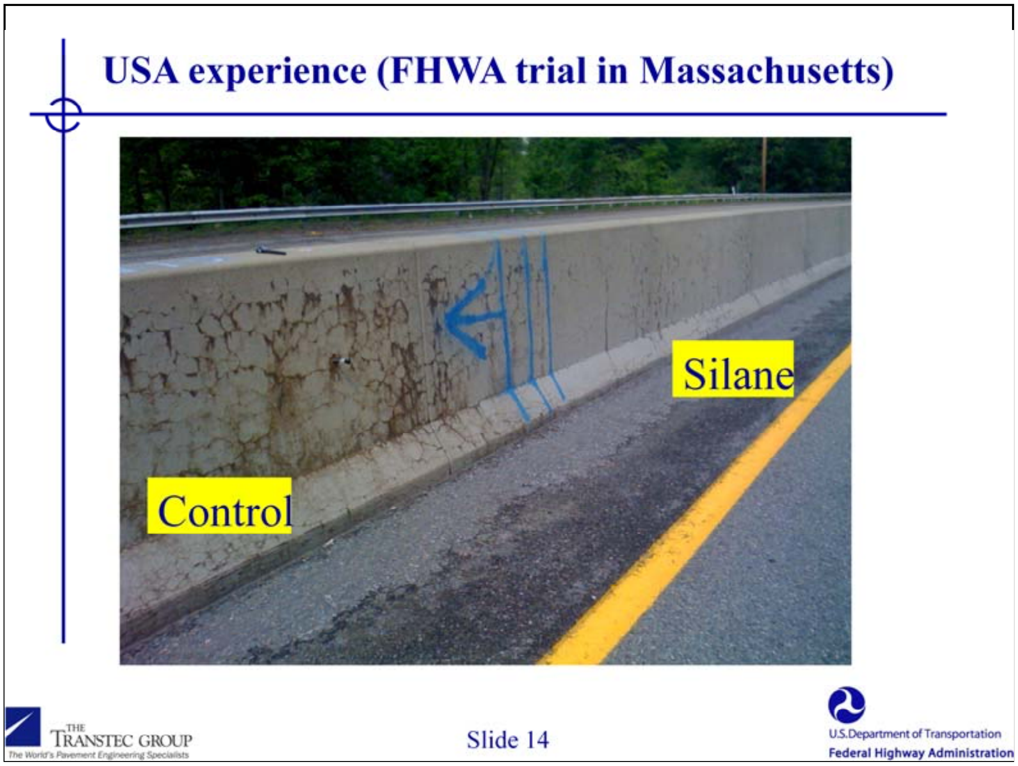
This graph shows that the application of silane to the highway barriers near Quebec City resulted in a lowering of the internal relative humidity.

The barriers treated with silane exhibit internal relative humidity values below 70 percent six years after treatment.

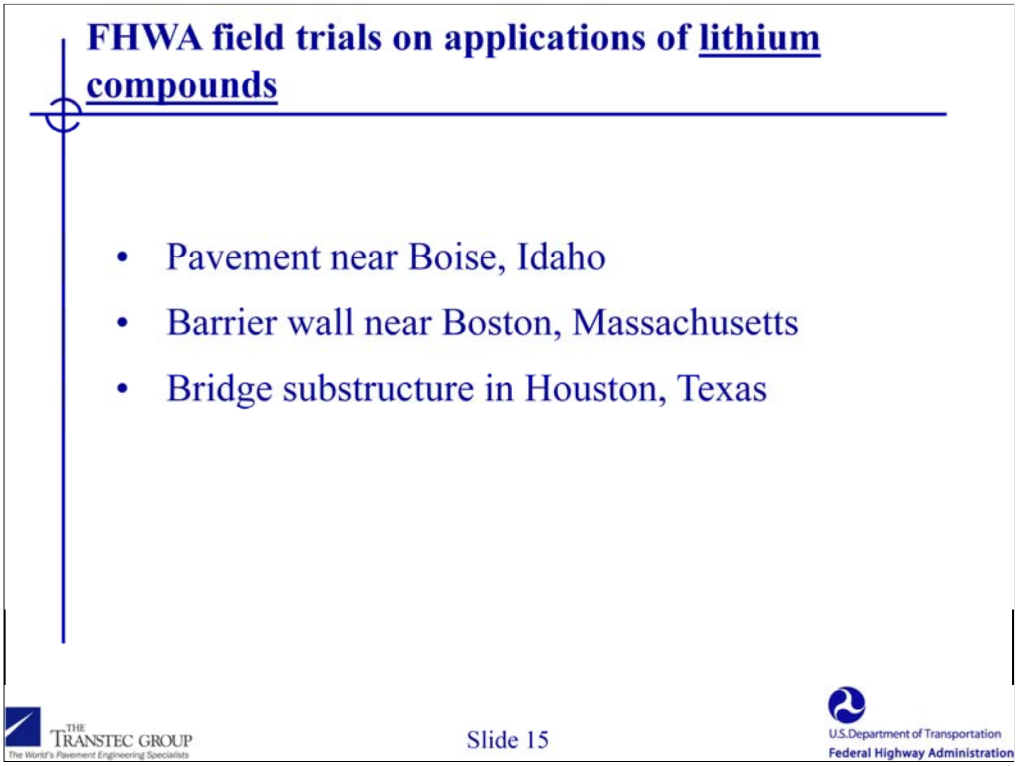
The control barriers still exhibit relative humidities above 80 percent, which is above the humidity level needed to sustain ASR-induced expansion.



Along with the reduced internal humidity came a reduction in the long-term expansion of the silane-treated barriers. In fact, after six years, the treated barriers had actually exhibited shrinkage, whereas the untreated barriers continued to expand during the monitoring period.



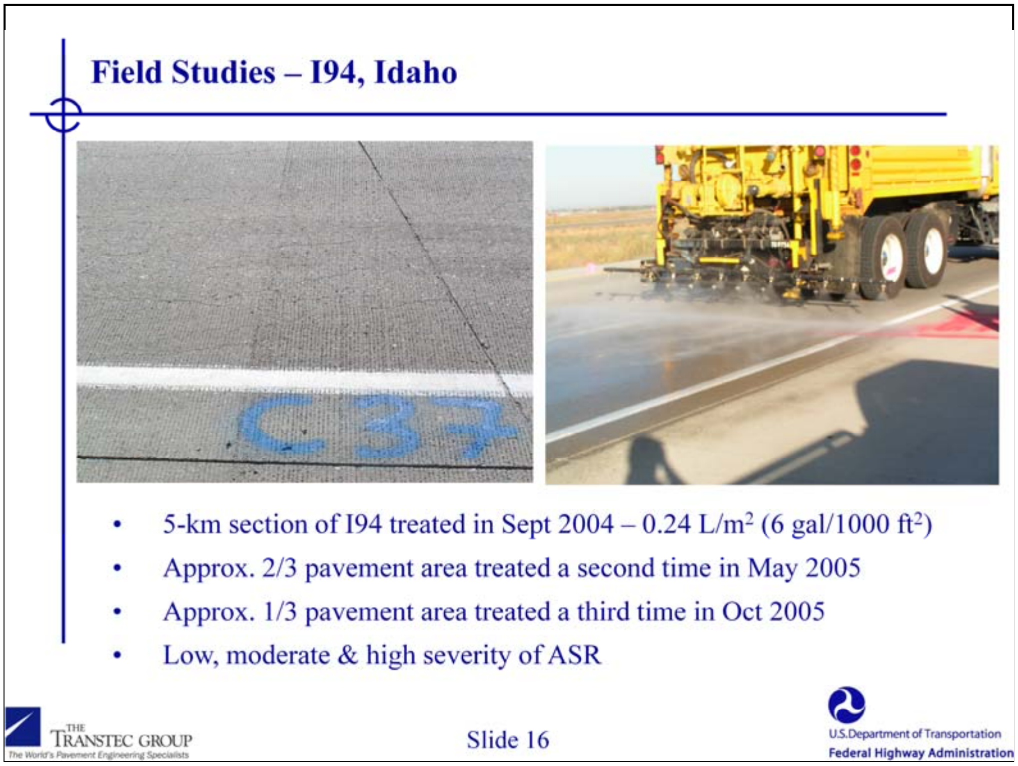
Coming back to the application of silanes under the FHWA project in Massachusetts, one can see that there is once again an obvious difference in the visual appearance of silane-treated and untreated barriers four years after treatment. Long-term monitoring has confirmed that the internal relative humidity has been reduced significantly for the silane-treated barriers.



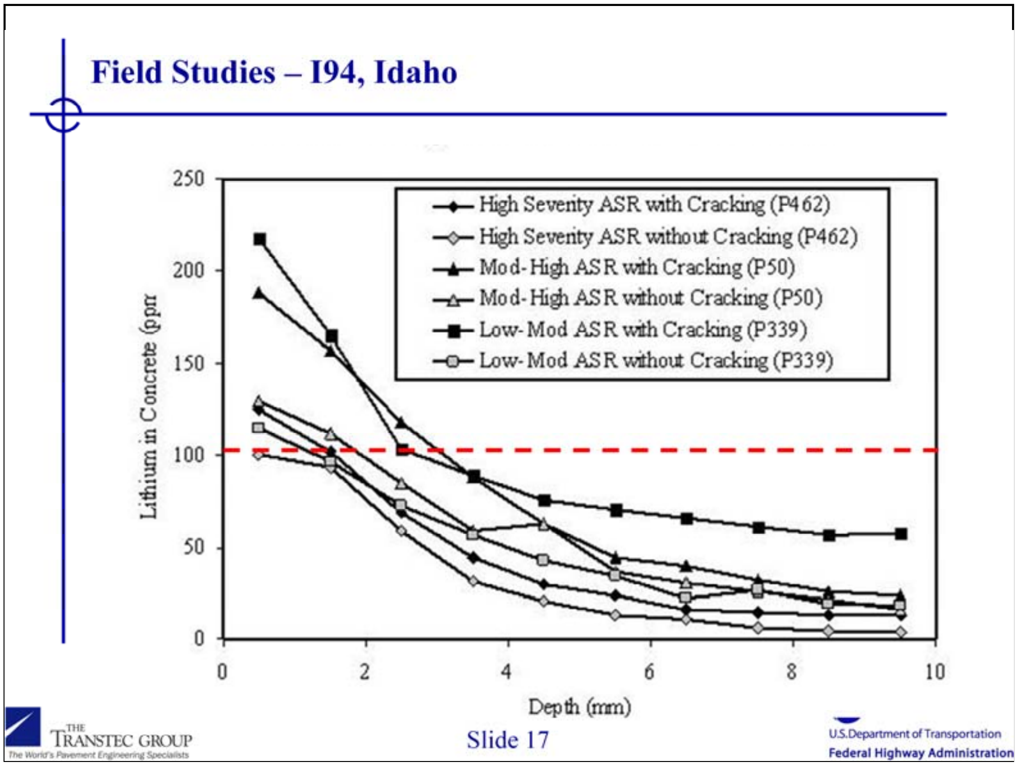
Switching gears, we will not consider the application of lithium compounds to field structures, with emphasis on three field trials performed under recent FHWA trials.

Previous laboratory research, using small bars and prisms, showed that when concrete is dried out and then soaked in lithium nitrate (or lithium hydroxide solution), subsequent expansion can be reduced (compared to control that was not immersed in lithium). It is believed that the lithium nitrate, upon exposure to ASR gel, reduces expansion by producing a non-swelling gel, although the exact mechanisms may not be fully understood.

In order for lithium to have an impact on ASR-induced expansion, it must penetrate considerably into concrete as a reduction in expansion will only be possible where lithium has reached in sufficient quantity to suppress expansion. Although it is feasible to dry small laboratory specimens and then soak them in lithium nitrate solution in order to reduce expansion, it is much more difficult to obtain sufficient lithium penetration and reduce the expansion of ASR-affected field structures and pavements, as discussed next.



In 2004, a large field trial was performed on ASR-affected pavements in Idaho (I94 in Mountain Home, ID). This study included the topical application of lithium nitrate, with various sections receiving different numbers of lithium applications (once, two or three topical applications). The trial also included various levels of ASR-induced damage within the test section (labeled as low, moderate, and high severity of ASR).



This graph shows the depth of penetration of lithium that was measured in various test sections in the Idaho pavement. The data include the results for pavements with all three degrees of distress (low, moderate, and high), and for each of these sections, data are shown from cores extracted through cracks and away from cracks.

Shown as a red, dashed line is the concentration above which it is estimated that lithium would efficiently reduce ASR-induced expansion. As can be seen in the graph, only the top 1 to 3 mm of the pavement contained lithium above this 100 ppm threshold. Based on the data from this field trial, it can be concluded that the lack of penetration of lithium into the pavement will prevent any substantial benefits from being realized.

Field Studies – I94, Idaho

Beams at University of Texas in Austin

- 15 beams placed on exposure sited
- Control, lithium treatment similar to I94 & continuous ponding
- 1 beam from each of the panels cut into three 1 x 1 ft x full depth sections and surface treated with 0.24 L/m^2 (6 gallons/1000 ft^3)
- Various pre- & post-treatments with water
- Cores extracted for lithium profiling

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Slide 18

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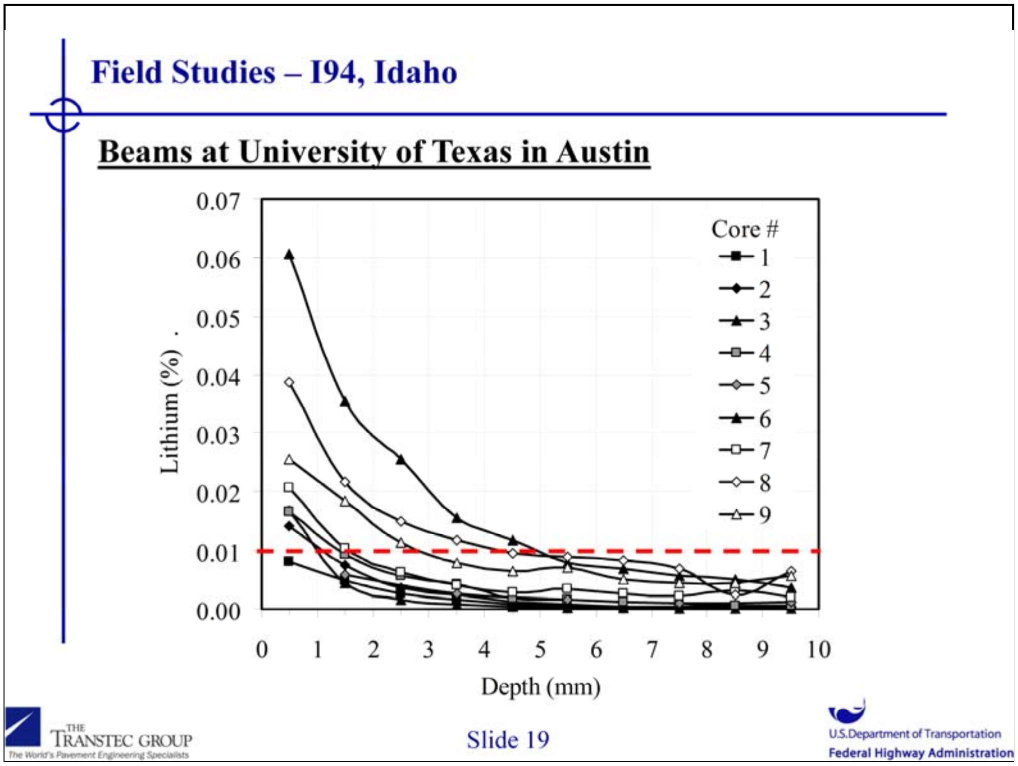
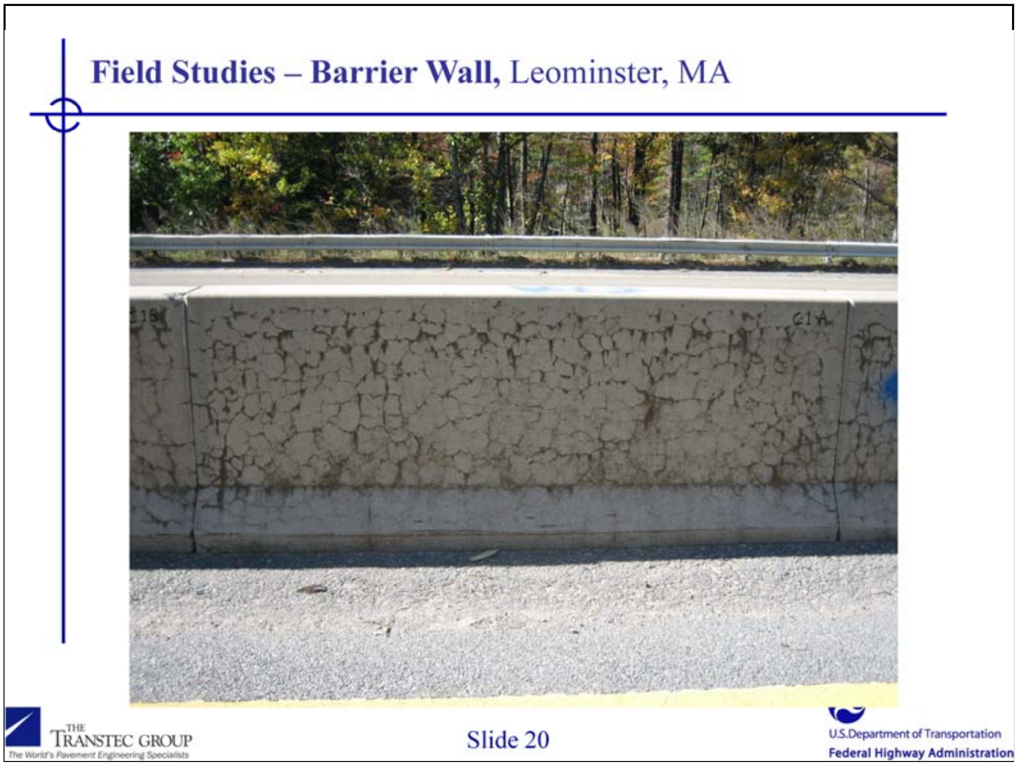
To complement the field trial in Idaho, the FHWA research team was able to procure full-depth beams from within the ASR field trial section. These beams were then cut into sections measuring 1 ft x 1 ft x full depth. Lithium nitrate was then applied to various beams, with concrete ranging from low to moderate to highly damaged, and with various numbers of lithium application. In total, nine beams were treated and then the concentration of lithium as a function of depth was determined for each beam, as shown on the next slide.



This graph shows comparable levels of lithium concentration as were observed for cores extracted from the treated sections. Using the same threshold concentration as before (0.01 percent lithium by mass or 100 ppm), this graph shows that lithium was only present above this concentration in the top 1 to 5 mm. This lack of penetration is quite consistent with not only the data obtained from the treated sections from this pavement but also from other laboratory data generated during the course of these FHWA field trials.



After completing the Idaho field trial, the FHWA research team initiated a comprehensive field trial on highway barriers in Leominster, MA. This trial included the application of lithium nitrate (topical and vacuum), and the topical application of various silane-based products.

Following are the results of applying lithium nitrate to these barrier walls, with discussion first on topical application and then on lithium applied via vacuum.

Topical application of lithium nitrate

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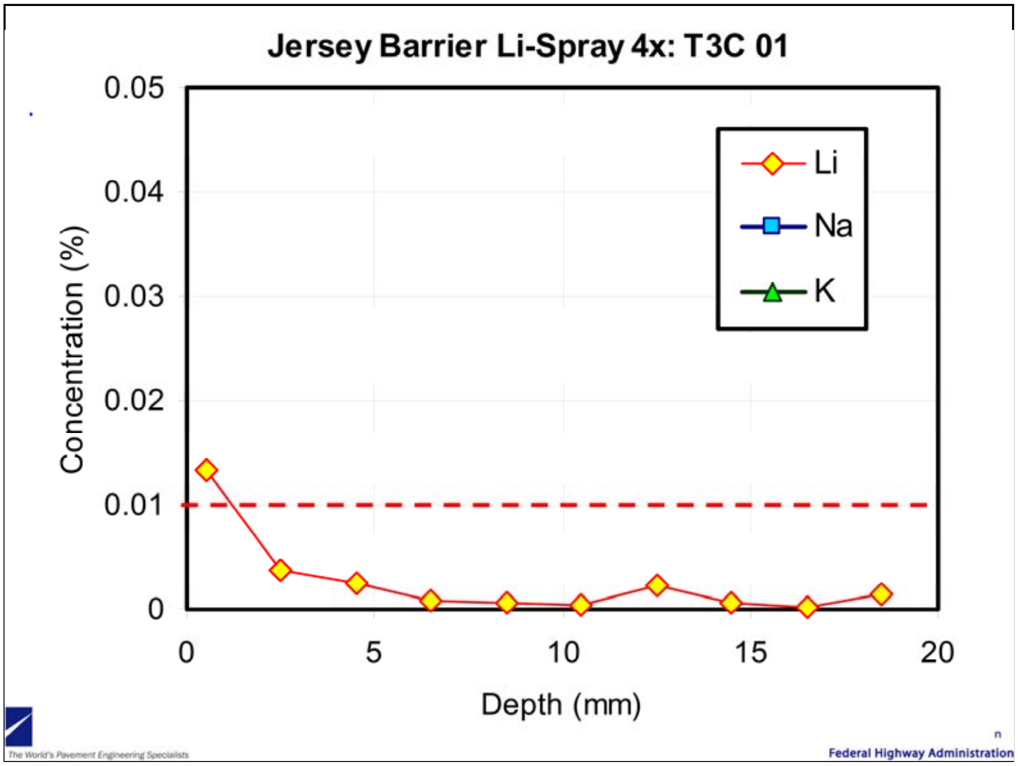
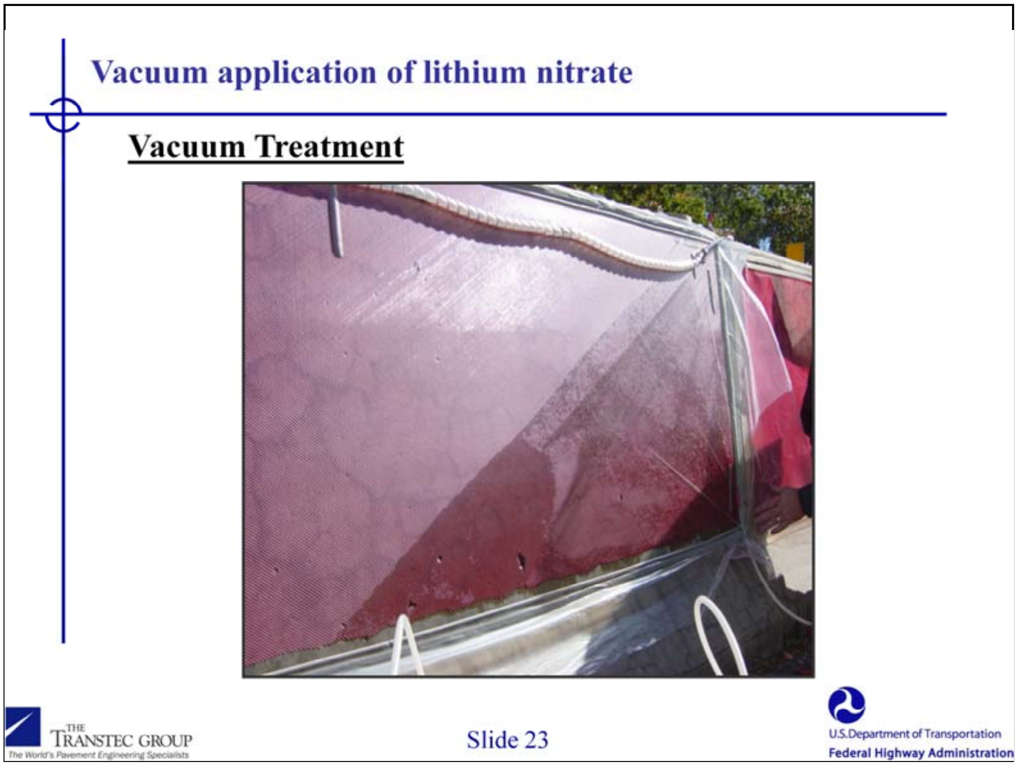
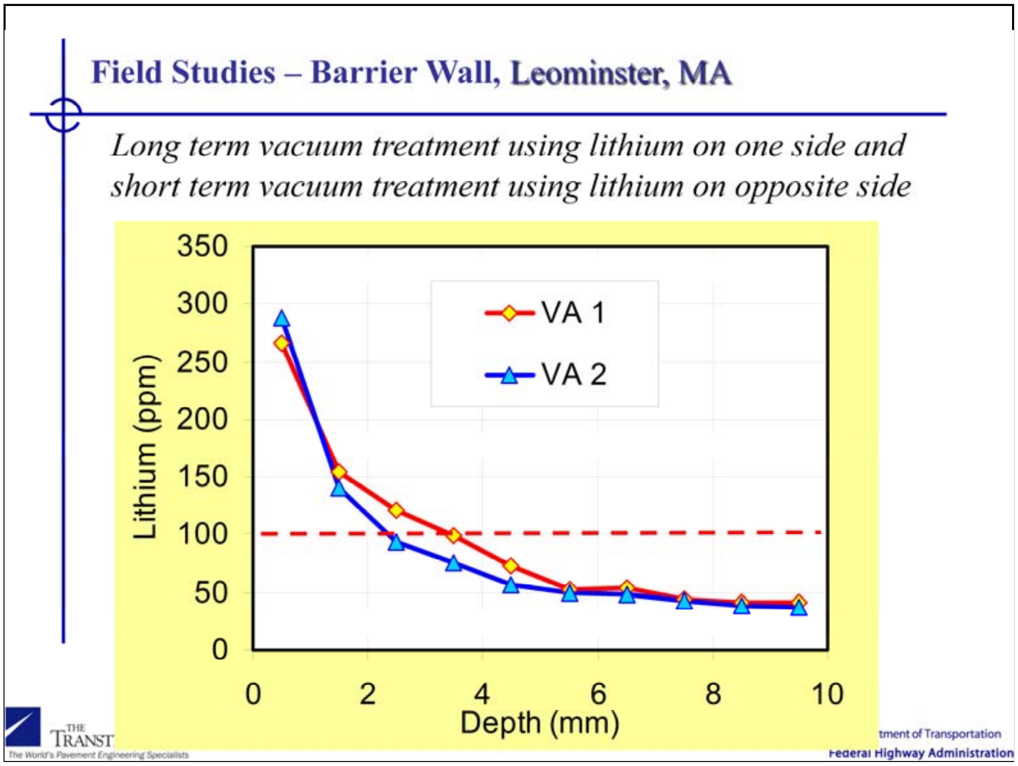
This photograph shows FHWA researchers applying a 30% lithium nitrate solution topically to the barriers in Leominster, MA.



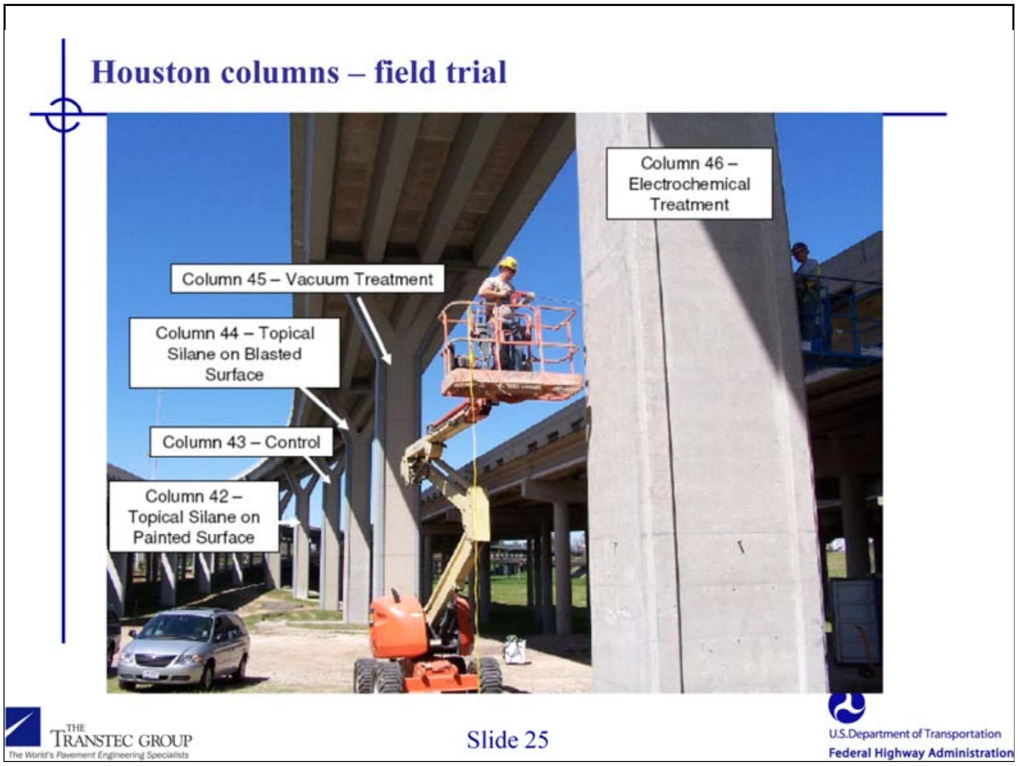
This graph shows the measured lithium profile from a core extracted from a barrier that was treated topically with lithium nitrate four times. Once again, the results are not encouraging. Lithium only was measured to be above the threshold value of 0.01 percent (by total mass) in the outer 2 mm or so.



Because only minimal depths of penetration were observed in previous field trials when lithium was applied topically, it was decided to try more aggressive means of driving lithium into concrete. A contractor who has years of experience in vacuum impregnating concrete with various products (mainly epoxy-based) was hired to attempt to drive lithium into these test barriers using a vacuum impregnation process. The photograph above shows the vacuum impregnation process. Different sections were treated with different levels of vacuum impregnation, ranging from holding a vacuum for only a few minutes to several hours.



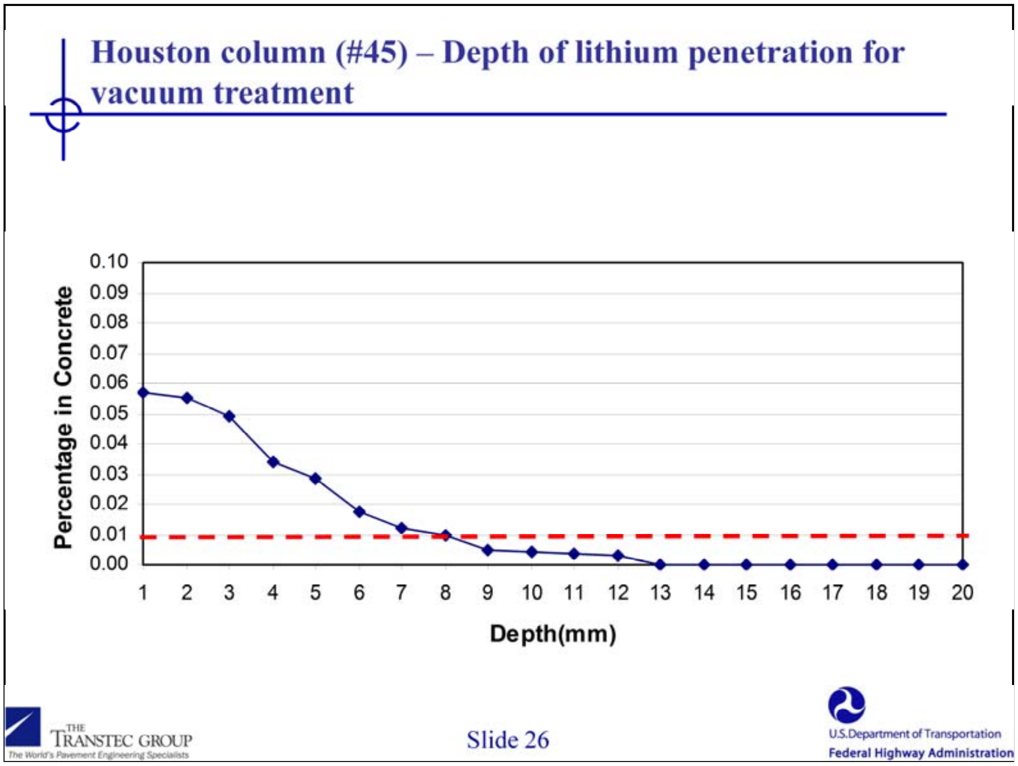
This graph shows the lithium profiles measured on cores extracted from a highway barrier that was vacuum impregnated overnight (the longest and most aggressive vacuum application within this field trial). Once again, the results were not very positive. Despite the significant resources used to attempt to achieve maximum lithium penetration using a long-term vacuum treatment, lithium was only found to be above the threshold value in the outer 2 to 4 mm of the barrier.



After the Leominster field trial, it was decided that future field trials would not include the topical application of lithium nitrate, as only minimal depths of penetration were measured in prior field and laboratory evaluations.

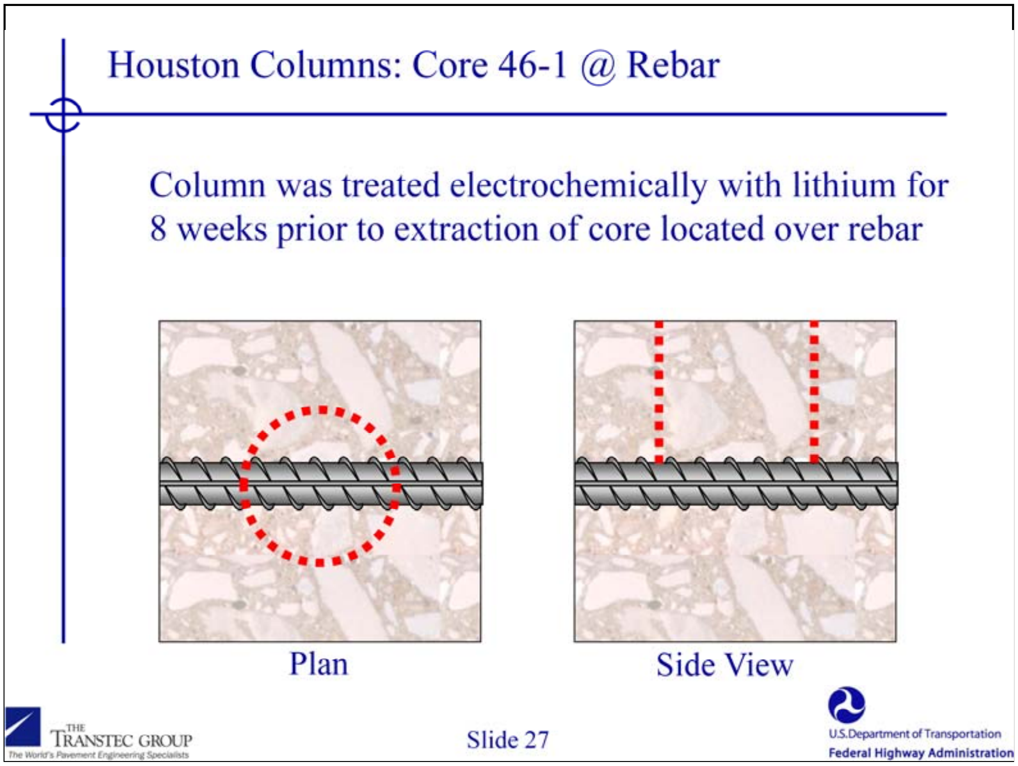
A comprehensive field trial was performed on a series of ASR-affected columns in Houston, TX. The trial included:

- Vacuum application of lithium nitrate
- Electrochemical application of lithium nitrate
- Topical application of silane



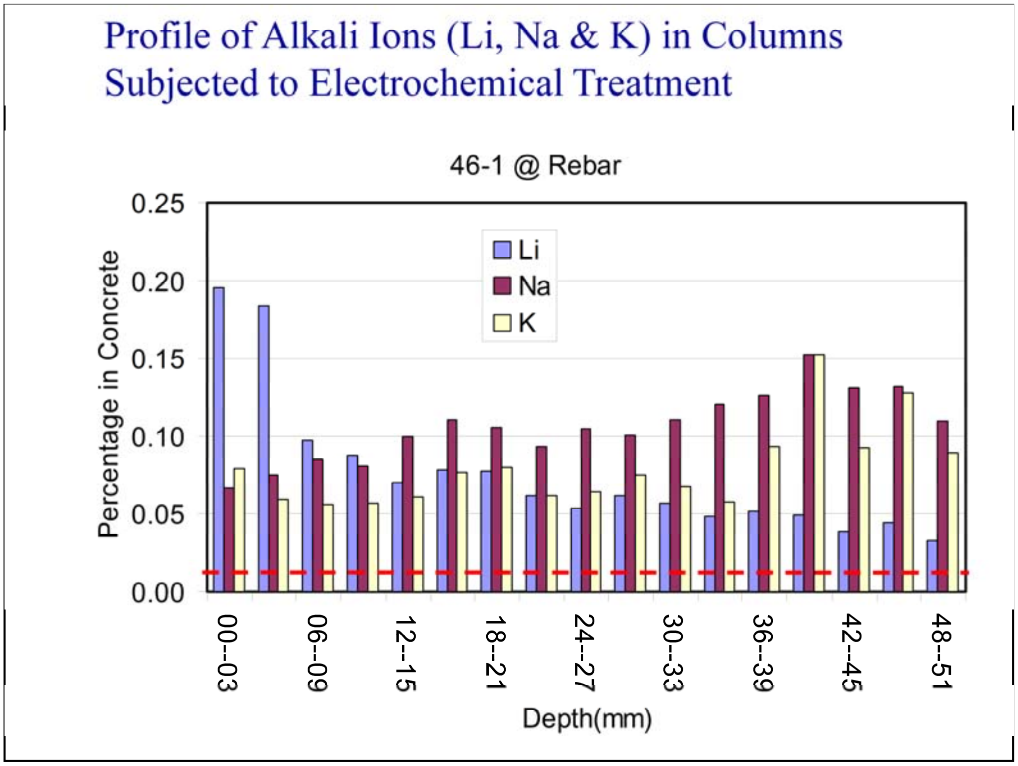
This graph shows the results of the vacuum application of lithium nitrate to an ASR-affected column in Houston, TX. The contractor hired for this field trial had previous experience with vacuum impregnation for repair applications, including the application of lithium nitrate to ASR-affected concrete.

Unfortunately, the results of this vacuum application were not encouraging. The depth of lithium penetration (above the threshold concentration) was limited to the outer 6-7 mm of this column. Although this penetration was slightly higher than those obtained from prior topical and vacuum applications, the increased penetration can not be justified based on the substantial resources (time, money, etc.) needed for this vacuum application.



As previously mentioned, electrochemical migration techniques were used on two of the Houston columns. Electrical contact was made with the reinforcing steel, 50 mm from the surface of the columns, and lithium nitrate was driven electrochemically into the concrete for eight weeks.

After the eight week treatment regime, cores were extracted from locations where the highest lithium concentration would be expected.



This graph shows the concentration of Li, Na, and K as a function of distance from the face of one of the electrochemically treated columns.

For the first time, significant lithium concentrations were observed beyond the near-surface region. Lithium concentrations well above the threshold lithium content (0.01 percent by mass) were detected all the way down to the surface of the steel.

However, what is concerning is that the creation of OH ions at the surface of the rebar, due to the electrochemical treatment, appears to be causing the sodium and potassium, already present in the concrete pore solution, to migrate to the rebar surface. This could potentially worsen the ASR potential at the rebar surface as the higher alkali contents may exacerbate ASR-induced expansion and cracking.

Summary of penetration data*…

State	Element	Treatment method	Depth to which "threshold" level of lithium was measured (mm)
ID (field-treated)	Pavement	Topical (3x)	1 – 4
ID (lab-treated)	Pavement	Topical (3x)	1 – 5
MA	Barrier wall	Topical (4x)	0.5 – 1.5
MA	Barrier wall	Vacuum ("long-term")	2.5 – 3.5
TX	Column	Vacuum	8
TX	Column	Electrochemical	50 (to depth of rebar)

*Similar experience with topical applications in lab….

This table summarizes the depth of lithium penetration measured on various cores extracted from FHWA field trials in recent years. The data that were the most promising were for the electrochemical treatment of the Houston columns – lithium was found to be in concentrations well above the threshold 50 mm from the treated surface. Although this is quite encouraging, it still remains to be seen if the migration of sodium and potassium, originally from the concrete pore solution, to the surface of the rebar will potentially worsen ASR at the rebar/concrete interface.

Jobe control

As a follow-up to the field trials, the FHWA-funded researchers cast a series of outdoor exposure blocks, containing a highly-reactive sand from El Paso. Three blocks were cast in total – one served as a control, one was sprayed once a week with lithium nitrate (for a total of 32 weeks), and one block was ponded continuously with lithium nitrate for 32 weeks. Expansion and cracking were then monitored for each of the blocks.

This slide shows the cracking observed on the control block – this block was never treated with lithium and serves as a point of reference for the slides that follow.

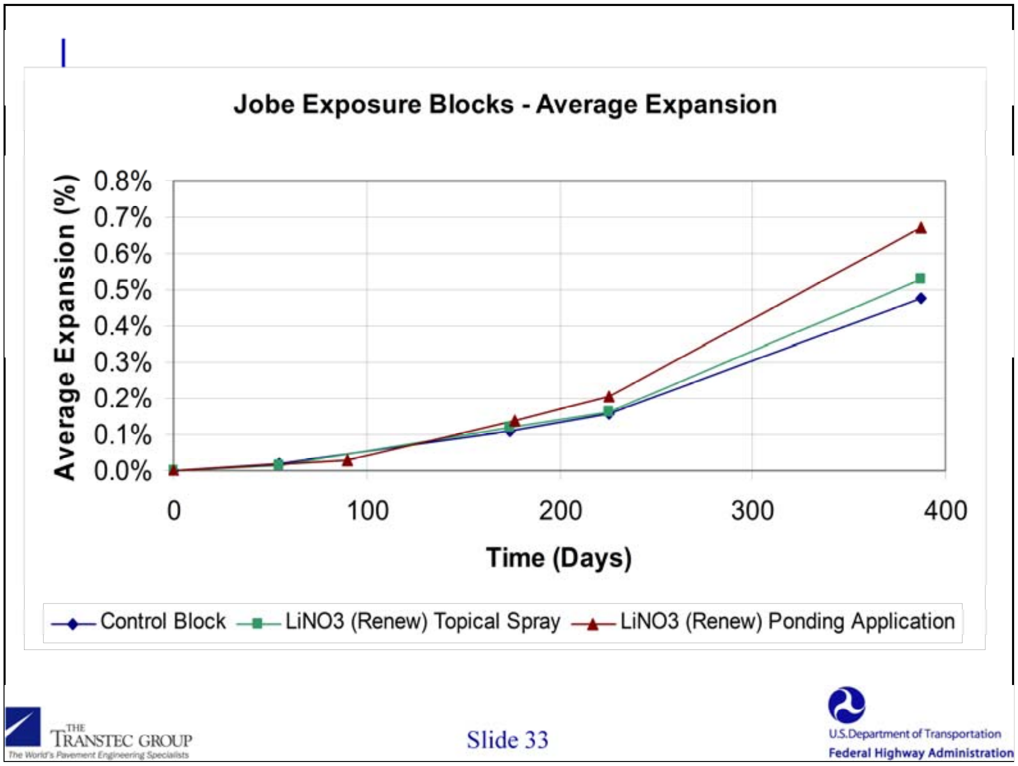
Jobe (ponded with lithium for 8 months)

Following up on this last slide, the block shown in this photograph is the block that was continuously ponded for 32 weeks with lithium nitrate solution. The cracking shown in this photo is comparable to the photo shown on the last slide of the control block.

It is quite interesting that even with continuous ponding for eight months with lithium nitrate solution, there was no visible benefit in terms of reduced cracking. Expansion data are provided later in this presentation.

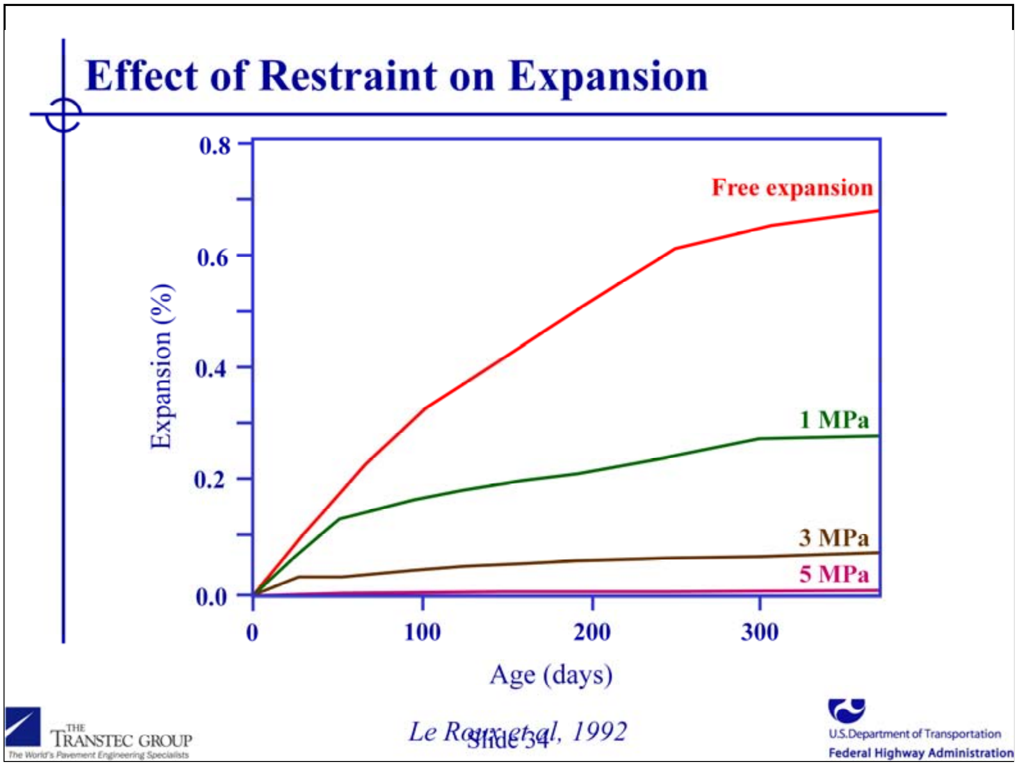
**Jobe (sprayed every week for 32 weeks –
4 gallons per 1000 sq. ft each treatment)**

This photo shows the top surface of the exposure block that was treated 32 times with lithium nitrate solution, over the course of eight months. There was very little, if any, difference between the cracking observed for this block and the control block.



This graph shows the average expansion for the three blocks shown on the last three slides.

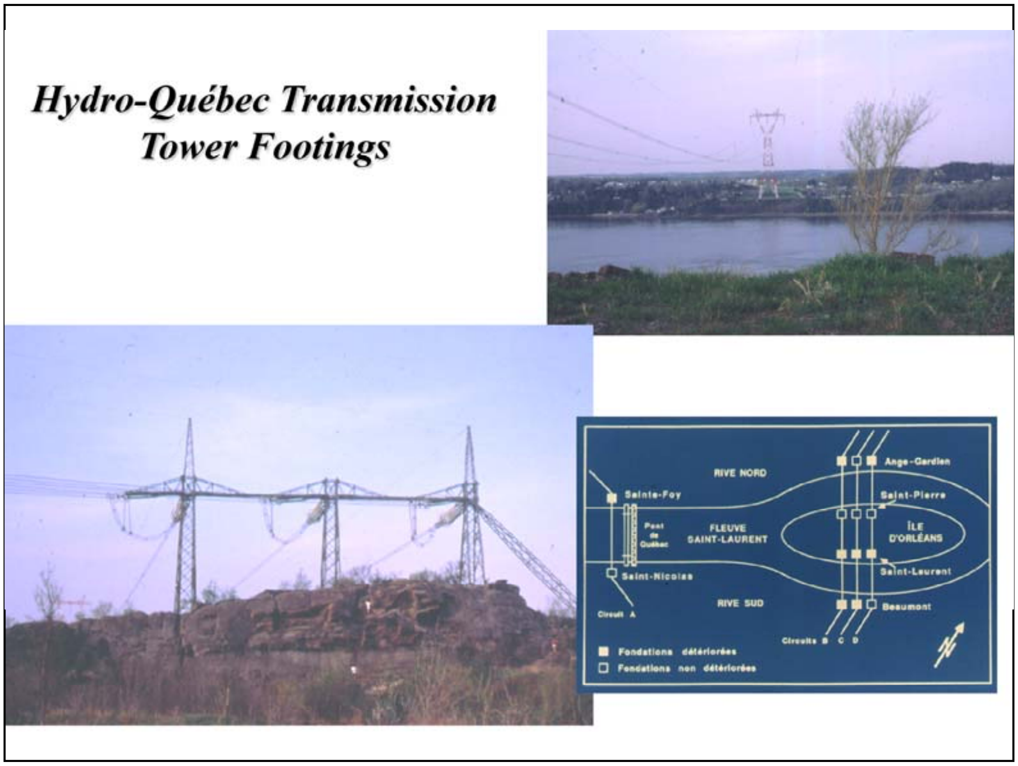
Interestingly, it appears that the lithium treatment may have actually increased expansion, compared to the control block. It may be that long-term ponding with lithium nitrate may increase expansion because the product used is 70 percent water and 30 percent lithium nitrate. Perhaps, the contribution of the water to ASR from the lithium nitrate solution may do more harm than the good that the lithium component (30 percent) of the product might bring to the table.



We will now switch gears and discuss some other methods that have been used in the laboratory and/or field to attempt to reduce the future expansion of concrete structures already affected by ASR.

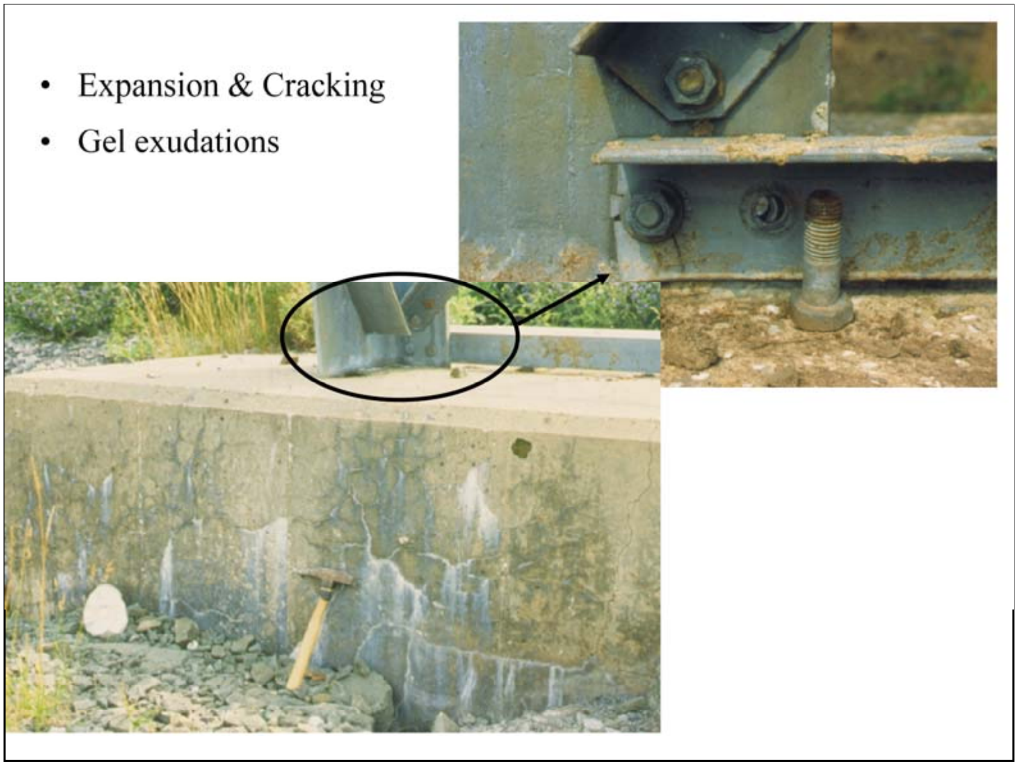
The first approach that I will discuss is the application of external restraint.

Work done by LeRoux et al. (1992) showed that applying axial restrain on the order of 3 to 5 MPa (450 psi to about 750 psi) can adequately restrain ASR-induced expansion.



The application of external restraint to ASR-affected structures is demonstrated in this slide and a couple that follow.

These slides describe work done by Hydro-Quebec in which various tower footings were repaired by removing the ASR-affected concrete, installing additional rebar, and casting a new, high-performance concrete around the original footing.



This slides shows a couple photographs showing the symptoms of ASR within these footings, prior to repair.

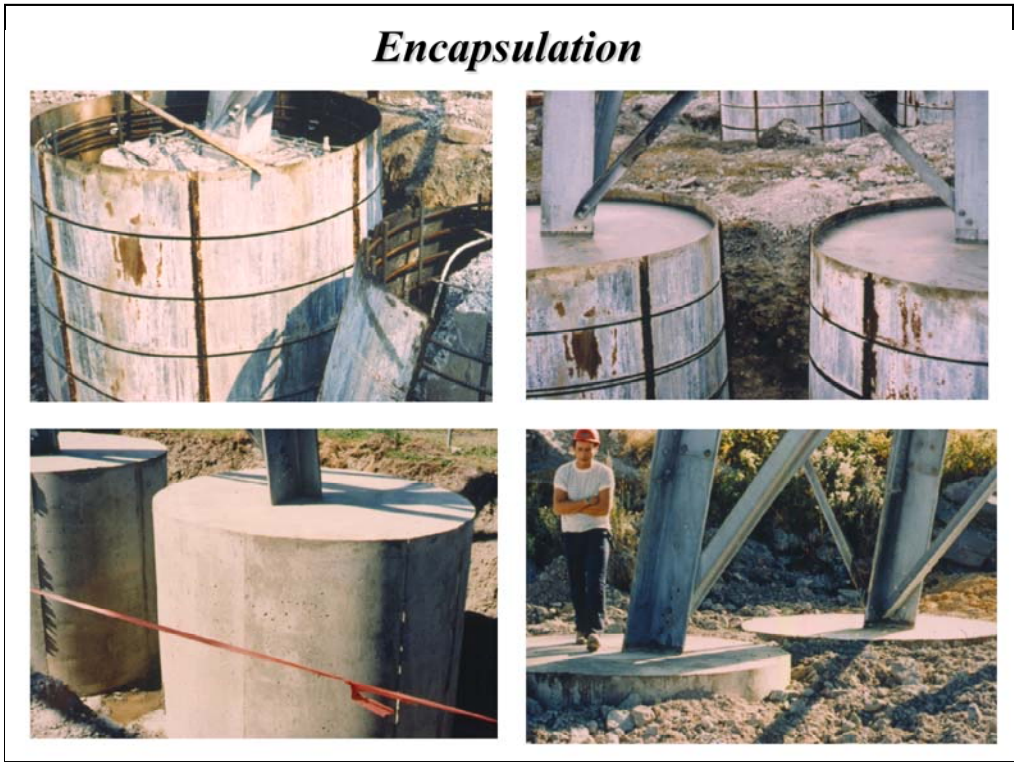
Gel exudations are quite visible, and significant cracking is clearly visible as well.

Concern was voiced regarding the performance of these tower footings as the concrete was particularly damaged in the locations in which the towers are anchored into the concrete footing. As such, repair was planned for these footings, with a prime emphasis on the application of external restraint.

Management Actions

- Encapsulation with silica fume concrete
- Post-tensioning
- Other foundations: impermeable membrane

These photos show the removal of the damaged concrete and the placement of the rebar cage (around original footing).



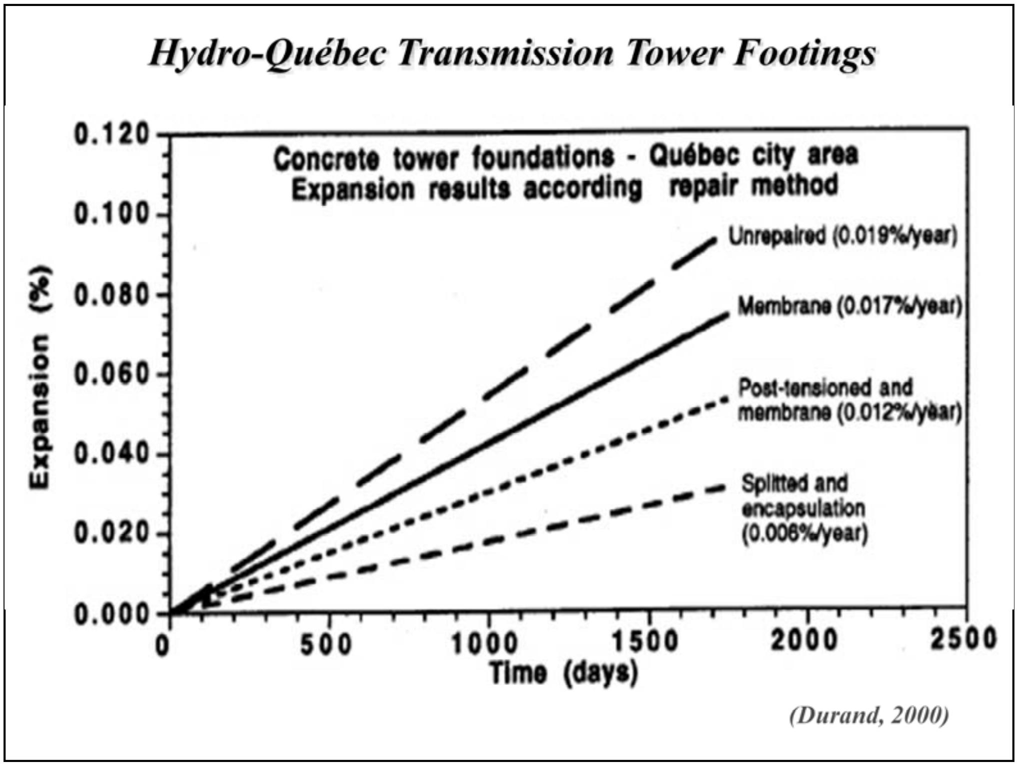
This slide shows the placement of external formwork around the footings, on top, and the final product, on the bottom, once the forms were removed.

Post-Tensioning

Some of the damaged footings were also post-tensioned, as part of the repair regime. This post-tensioning was passed through the original footing and anchored and tensioned to provide active restraint.

Membrane

Other footings from the same field trial were enveloped with a water-proofing membrane, with the overall objective of decreasing the availability of water to the ASR-affected concrete.



This graph shows the expansion data for the Hydro-Quebec field trials on tower footings. The data shows that all mitigation measures reduced expansion relative to the untreated control footing. The most effective method was found to be the encapsulation of ASR-affected footings with strong, dense, reinforced concrete. Post-tensioning also was found to be a viable means to reduce expansion.

(Courtesy of W.S. Langley, Halifax, Canada)

These are the before (left) and after (right) photographs of the repair of the ASR-affected footings using reinforced concrete encapsulation (around the original footing, after damaged concrete was removed).

Application of physical restraint against expansion - strengthening with steel plates and drilled-through bolts - *Bridge affected by ASR in Scotland*

(Courtesy of J. Wood, UK)

These photographs show another case study where external, physical restraint was applied to attempt to mitigate the effects of ASR damage in this arch bridge in Scotland.

In this case, as one can see in the photo on the right, steel plates and drilled-through bolts were used to physically restrain expansion near the top of the bridge.

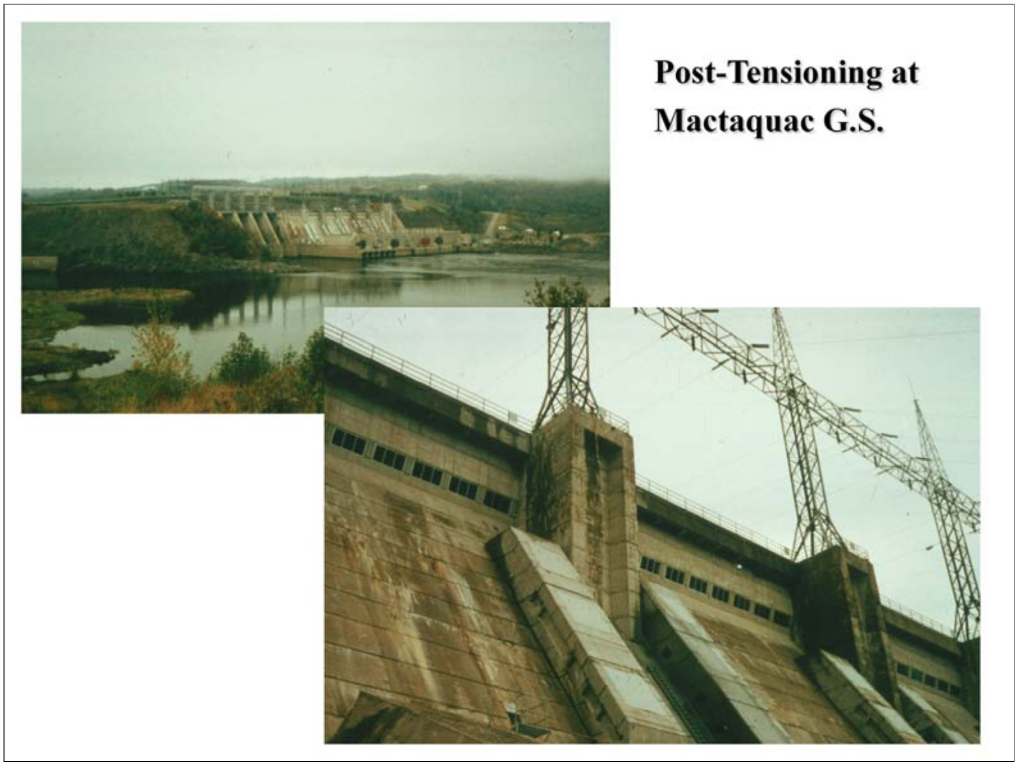
Bridge structure affected by ASR in Brisbane, Australia. The piles were wrapped with composite materials. The piles selected to be repaired by this method were those in which the ASR process was almost completed. It was also selected to try to minimize further deterioration due to corrosion (exposure to marine environment)

(Courtesy of A. Carse, Brisbane, Australia)

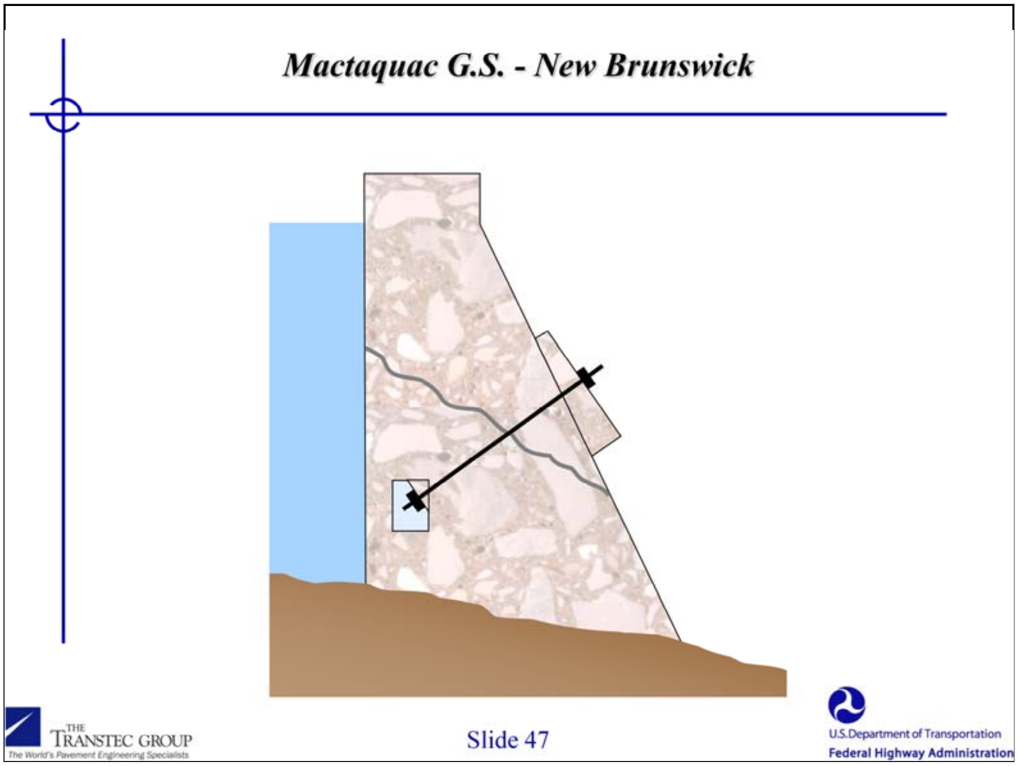
This photograph shows a bridge in Australia in which the columns were suffering from ASR-induced expansion and cracking. Cracking was particularly of concern as the bridge is in a very aggressive environment, especially with regard for corrosion of the reinforcing steel.

FRP wraps were used for the columns as shown in the highlighted portion of this photo and the next slide.

This slide shows the application of FRP wraps as a form of external restraint to ASR-affected columns. Again, this example is from a bridge in Australia.



Another interesting case study related to providing external (or internal) restraint is the Mactaquac Dam in New Brunswick, Canada. This dam has been suffering from ASR for quite a few years, and for a time, there was concern about some larger cracks that could affect the structural performance and safety of the dam. Post-tensioning was selected as a methodology for this dam, as discussed next.



As shown in this depiction, post-tensioning rods were inserted through a dam and were anchored in the interior of the dam and at its downstream face. This repair seems to have adequately addressed the concern regarding the large crack through the dam. However, because of operational difficulties, this dam is slated for replacement in the next 10-20 years.

Repair – Relieving Stress

Mactaquac G.S. – New Brunswick, Canada

Aggregate passed ASTM C 227 – “non-reactive”

- Remediation due to ASR costs ~ $6M per year
- Approx 18 inches of concrete removed from the intake structure
- Dam grown in height by approximately 7 inches

Another interesting technology that has been used in the Mactaquac Dam is the use of stress relief in the form of “slot cutting.” What is done is a diamond wire is drawn through the entire cross section of the concrete dam, removing material as it goes through. The removal of this concrete helps to relieve the pressure that was accumulating, due to ASR-induced expansion. To date, about 18” of the dam has been removed in order to keep this dam in operation. This does nothing to address the root cause of ASR, but rather it just tries to lessen the impact of ASR on the operation and safety of this dam.

This photograph shows the equipment used for “slot cutting.” The procedure itself is not fancy, but it is effective.

Ongoing FHWA Field Trials

State	Structure	Mitigation/Prevention Technique
Alabama	Historic bridge arch	Silane sealer
Arkansas	Pavement	Silane sealer
Delaware	Pavement	Topical application of lithium nitrate
Delaware	Pavement	Monitoring an asphalt overlay of pavement with lithium nitrate
Hawaii	Aggregates	Testing aggregates and development of field exposure site
Massachusetts	Median barrier	Silane sealers; topical application of lithium nitrate
Massachusetts	Aggregates	Testing aggregates and development of field exposure site
Maine	Bridge abutments and piers	FRP wrap; silane sealer; electrochemical application of lithium nitrate
Texas	Bridge Columns	Electrochemical application of lithium nitrate; vacuum impregnation of lithium; silane sealers
Texas	Precast Bridge Girders	Aggregate testing and investigation of specific mixture designs
Vermont	Bridge barrier walls	Silane sealers

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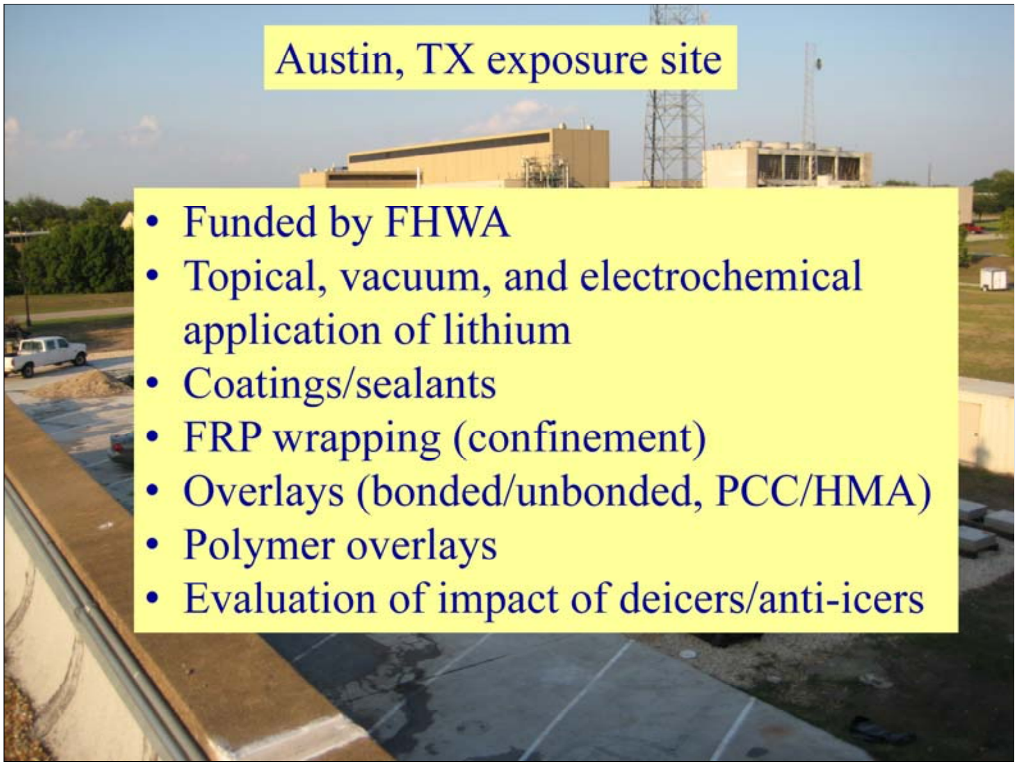
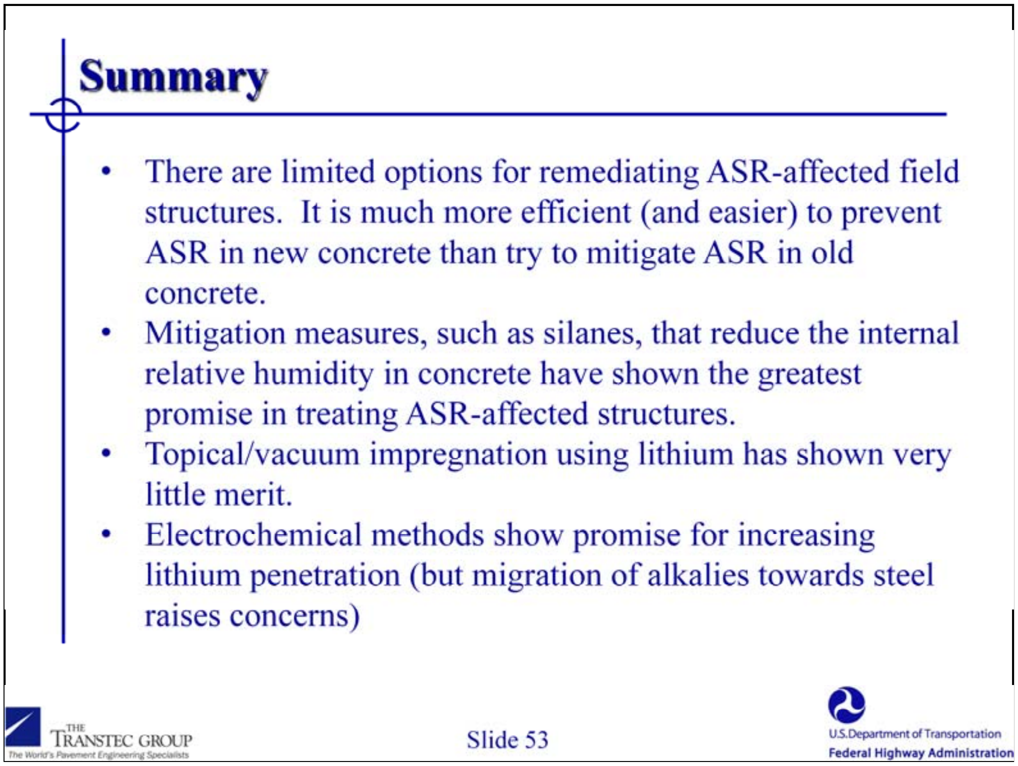
To attempt to advance the state of the art and the state of the practice, FHWA has funded a wide spectrum of field trials aimed at mitigation ASR in field structures. Several of these projects have already been discussed as part of this presentation.

In addition to the field trials on existing structures, the FHWA research team has developed two outdoor exposure sites aimed at evaluating local aggregates and preventive measures – these studies are being performed in conjunction with state highway agencies in Hawaii and Massachusetts.

Lastly, there is a relatively new ASR field site in Austin, TX, where the primary focus is on triggering ASR in simulated field structures and then trying to slow down the reaction through various treatments and technologies.



Several mitigation measures were applied to this FHWA field exposure site, including the use of lithium compounds (topical, vacuum, electrochemical), silanes and other coatings, FRP wraps, and overlays (polymer, concrete, or hot-mix asphalt). The true results of this study will not be known for several years to the nature of ASR and the need for long-term monitoring of the various treatments. Nevertheless, it is hoped that this study will help to guide future trials and projects aimed at slowing down ASR in field structures already affected by this durability problem.



In summary, this presentation attempted to discuss the most common methods of treating ASR-affected structures and pavements.

Silanes and similar products seemed to have the most positive outcome, resulting in reductions in internal relative humidity and expansion.

Lithium compounds were not found to be effective in treating ASR-affected concrete when applied topically or via vacuum, mainly due to very little penetration of lithium into the concrete. However, lithium did penetrate significantly into concrete when applied electrochemically. However, more work is needed to determine whether the increase in Na and K concentrations at the rebar surface may have any adverse effect on the performance of reinforced concrete structures.