CASE STUDIES OF TREATING ASR-AFFECTED STRUCTURES WITH LITHIUM NITRATE

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Abstract

Lithium compounds have been found to be effective in reducing expansion of small, ASRaffected laboratory specimens, but there have been little, if any, data showing that lithium compounds are effective in field applications. The research described in this paper aims to fill in this gap in knowledge and focuses on the treatment of ASR-affected structures in the United States. The findings of this study show that topical applications of lithium nitrate are ineffective in reducing ASR-affected due to a lack of penetration of the lithium solution. Vacuum impregnation of lithium in field structures was also found to be ineffective, again due to a lack of lithium penetration. Electrochemical methods of driving lithium compounds into were found to be quite effective in increasing lithium penetration, but the observed migration of sodium and potassium from within the concrete to the reinforcing steel may negate the effects of increased lithium penetration.

KEYWORDS: lithium nitrate, topical application, vacuum impregnation, electrochemical, case studies, field structures

1 INTRODUCTION

The use of lithium in new concrete was first reported by McCoy and Caldwell in 1951 [1]. They cast mortar bars containing Pyrex glass as the reactive aggregate and evaluated a wide range of chemicals to determine which ones might be effective in reducing ASR-induced expansion. Over 100 different compounds were investigated, with some increasing expansion while lithium salts, when used in sufficient dosages, showed the most promise in suppressing expansion. Later, Lawrence and Vivian [2] reported using lithium hydroxide as an inhibitor against ASR-induced expansion. After these initial studies, lithium research was quite limited until the early 1990's. Since then, there has been renewed interest in using lithium compounds to control expansion when used as a chemical admixture and in applying lithium-based products to hardened, ASR-affected concrete as a post-treatment. A summary of some of the main laboratory and field evaluations on lithium compounds (both as an admixture and as a post-treatment for existing concrete suffering from ASR) can be found in Folliard et al. [3]. This paper focuses on the recent treatment of ASR-affected structures in the United States with lithium nitrate, applied topically, via vacuum impregnation, or by electrochemical methods. Before describing these field studies, a brief review of some past and ongoing laboratory-based studies will be presented to provide some background and context for the field trials (funded by the Federal Highway Administration or FHWA).It is has been well documented over the past 15 years or so that small laboratory specimens, when dried, fully immersed in lithium nitrate (or hydroxide), and then subjected to accelerated ASR testing (high temperature, high relative humidity, etc.) exhibited significantly less expansion than companion samples that were not immersed in lithium-based solutions [4,5,6]. Barborak et al. [6] further showed that treating small mortar specimens and subsequently immersing them in 1 N NaOH solution can also reduce subsequent expansion. Because of the efficacy of treating small laboratory specimens with lithium-based solutions, there has been keen interest in attempting to implement this technology on real field structures. The majority of structures that have been treated with lithium have been treated topically with a 30% lithium nitrate solution, typically by a spray truck. Considerably fewer field trials have focused on advanced methods of application, such as vacuum or electrochemical methods [3].

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Although there have been numerous applications of lithium on/to field concrete, especially pavements, there has unfortunately been very little monitoring of these trials. In an attempt to fill in these gaps in data, three field trials were initiated under FHWA funding, including a pavement section in Mountain Home, Idaho, a highway barrier in Leominster, Massachusetts, and bridge columns in Houston, Texas. These three test sites have been heavily instrumented and are being monitored for expansion, cracking, and changes in microstructure. Because each of these field trials were performed between 2004 and 2006, there has not been sufficient time to determine if any of the mitigation measures (lithium nitrate, silane, etc.) have effectively reduced the rate of expansion. The structures will continue to be monitored and reported in future publications. For the current paper, the main data presented are those for depths of lithium penetration for cores from these three sites. In addition, the results of testing on outdoor exposure blocks are presented, in which concrete containing a highly-reactive aggregate was treated with lithium over a several month period.

2 CASE STUDIES OF APPLYING LITHIUM COMPOUNDS TO ASR-AFFECTED CONCRETE

The three aforementioned field trials (pavement, highway barrier, bridge columns) are briefly described in this section. A general summary of each of the test sections is provided, along with a description of the testing and monitoring programs. For each of the three field trials, depths of lithium penetration have been determined. Lastly, the testing of outdoor exposure blocks is described, in which concrete containing a highly-reactive aggregate was topically treated with lithium over a several month period.

2.1 Pavement section in Idaho (United States)

This section of I-84 is the most heavily instrumented and monitored section of pavement treated with lithium in the United States. This research is vital to the growing database for lithium used as a post-treatment for ASR-affected concrete. The site under investigation in Idaho is located just outside of Boise in Mountain Home. The Idaho Department of Transportation noticed that a significant stretch of highway on Interstate 84 exhibited cracking in certain areas after only a few years of service, mainly attributable to ASR. In 2004, a 4.8 km section of this deteriorating pavement was selected as a test section for topically-applied lithium nitrate (Figure 1).

This test site was ideal in that were large pavement sections with varying degrees of distress, and lithium was applied topically by Idaho highway department personnel to three different sections with varying levels of cracking. For each of these levels of distress, four test sections were included (note that one "application" is approximately 0.12 to 0.24 L/m² of 30% lithium nitrate solution), as shown below:

- Control (not treated with lithium nitrate solution)
- One topical application of 30% lithium nitrate solution
- Two topical application of 30% lithium nitrate solution
- Three topical application of 30% lithium nitrate solution

In addition to the primary focus on lithium nitrate application, smaller test sections were also treated with a silane-based product (40% silane) in an attempt to reduce internal relative humidity of the concrete. These results are not presented herein. For each test section, the following data are being collected as part of the ongoing monitoring program: surface expansion, cracking, and internal relative humidity, as described in detail elsewhere [8]. In addition, substantial laboratory testing has been performed on cores extracted from various sections of the test section, including determination of stiffness damage value, damage rating index, water-soluble alkali content, and lithium profiles. This test section is the most heavily instrumented and monitored section of pavement treated with lithium in the United States. This research is vital to the growing database for lithium used as a post-treatment for ASR-affected concrete.

As lithium penetration is the focal point of this paper, a brief description of how lithium profiles are measured from extracted cores is warranted. Cores (typically 100×200 mm) are extracted from structures, and safely packed and shipped to the testing laboratory. Using progressive milling, the top 1 mm of the test core is removed in the form of powder, collected, and labeled. The next mm layer is then removed and collected, and so forth. Lithium ion concentrations were then measured using acid digestion and subsequent analysis using ion chromatography. This same profiling methodology was used for all case studies described in this paper.

When evaluating lithium profile data, it is important to view it in context of how much lithium is needed to control expansion. Consider the following example: Assuming a plain concrete mixture contains 3 kg/m³ Na₂O_e, a "standard dose" of 30% lithium nitrate solution (4.6 L of solution per 1 kg

of Na₂O_e) would amount to 13.8 L/m³ of lithium nitrate solution. This dosage of LiNO₃ solution contains 504 g of Li, and assuming that half of this lithium gets bound in early hydration products (as well documented in literature), approximately 250 g of lithium per m³ will remain in the concrete to combat ASR. If one assumes a concrete density of 2350 kg/m³ the concentration of lithium ions in pore solution would be approximately 100 ppm, and this concentration would be enough to control expansion when used as an admixture. However, it should be noted that the "standard dose" of 30% lithium nitrate solution (4.6 L of solution per 1 kg of Na₂O_e) has been reported to be sufficient for controlling expansion in about half of the aggregates recently tested in North America [9]. Some aggregates, especially greywackes, still expand considerably at over twice the "standard dose." For the purpose of this discussion, it is assumed that the aggregate in the concrete being treated responds favorably to lithium (4.6 L of solution per 1 kg of Na₂O_e) and that 100 ppm would be required in pore solution for suppression of excessive expansion.

Cores were taken from sections exhibiting varying levels of deterioration and within these sections for different treatment regimes (no lithium, 1 treatment, 2 treatments, 3 treatments of lithium). Cores were generally extracted from each section directly over cracks to attempt to capture the highest possible concentrations of lithium in the pavement, as well as from non-cracked regions in the same test section. In addition, full pavement panels were extracted from the control sections, and from these panels, approximately $1 \times 1m \times$ full depth (0.3 m) sections were cut out shipped to the University of Texas at Austin for subsequent testing. Some of these panels were then treated with lithium nitrate in manners to mimic the actual field trial. Lithium penetration data on these pavement panels are presented later for sections with varying level of distress. In addition, to attempt to achieve as high a level of penetration as possible, selected panels were ponded continuously with lithium nitrate solution for up to six months (for conciseness, data not included in this paper).

2.2 Highway barriers in Massachusetts (United States)

Highway barriers near Leominster, Massachusetts (just outside of Boston) have exhibited significant ASR-related distress after only a few years in service. Figure 2a shows the general condition of the barriers, with obvious signs of ASR-induced map cracking (note ASR has been confirmed as prime cause of deterioration. Figure 2b shows the frost damage and salt scaling distress evident in bottom of selected barriers exhibiting severe ASR. In 2004, the authors initiated field evaluation of a subsection of the damaged barriers, as described in detail by East [8].

A total of 24 barriers (about 3 m long each) were topically treated by a contractor with various products, including 30% lithium nitrate solution, two silane-based products (40% silane content with remainder being either water or solvent), and a lithium silicate product. These coatings/sealers were applied manually (see Figure 3a) anywhere from one to four times over a 24-hour period as shown in Figure 3, with each treatment consisting of an application rate of 0.1 L/m². Lithium nitrate was also applied by vacuum to selected barriers (see Figure 3b), with vacuum pressure maintained for either 0.25 hour or 7.25 hours. A subset of these barriers that were treated by vacuum impregnation was subsequently treated with 40% silane (solvent-based) at a rate of 0.2 L/m². East [8] provides a detailed summary of this field test and monitoring program and parallel laboratory testing of cores extracted from the various barrier sections.

The data described in this paper are limited to lithium penetration results. To avoid any potential for diluting or removing the lithium from the extracted concrete, a rectangular section of one of the barriers was removed by dry sawing shortly after the long-term vacuum treatment was stopped. This section was selected for sampling as it was deemed to have the highest possible potential for lithium penetration. The results of lithium profiling on this sample are presented later in this paper. Based on this "dry cutting" and previous work, there is a negligible effect of "wet coring" when one measures depths of lithium penetration as only the outer perimeter of the core is in touch with water, and this effect is negligible when considering the amount of powder from each 1-mm thick layer removed for lithium concentration measurement. For conciseness, depths of penetration on cores extracted from various barriers within the test section are not included herein.

2.3 Bridge columns in Texas (United States)

Built in the late 1990s, the I-10 and I-45 interchange in Houston, Texas, was open to traffic in the year 2000. Within the past 7 years, significant cracks have developed in the columns supporting the interchange. The conditions of the columns and progression of the degradation has caused the Texas Department of Transportation (TxDOT) to be concerned. Six moderately-damaged and six severely-damaged columns (tapered columns with average cross-sectional dimensions of approximately 2×2 m) were selected for a field trial focusing primarily on lithium treatment (vacuum

and electrochemical methods), but also on application of silane-based products aimed at reducing internal relative humidity (see Table 1 for details of field test and Figure 4 for photo of electrochemical set-up for lithium application). More details of the electrochemical impregnation method, which involved connecting an anode (a 30%-lithium nitrate solution ponded at the surface of the concrete) to the imbedded reinforcing steel, which acts as a cathode, and driving lithium nitrate solution into the columns using 40V over the course of six to eight weeks, can be found in East [8]. The approach was to use essentially the same materials and methods for both sets of columns (moderately- and highly-damaged), and by doing so, one could evaluate the effects of the various treatments on future expansion and cracking, as a function of degree of distress at the time of treatment. All treatments to the columns were performed by contractors with significant experience in such techniques.

As described above, the main focus of this field test was to determine if silane or lithium nitrate can be effective in reducing expansion and cracking due to ASR, but TxDOT also expressed interest in trying other materials and techniques as part of this program. It was agreed that one column from each of the sets could be treated by TxDOT (through an outside contractor). It was agreed that the specific treatment regime would be selected entirely by TxDOT and the contractor, and that the role of the research team would be to only monitor the long-term effects of these treatments on expansion and cracking. The contractor that treated these two columns (Columns 31 and 41) was the same one that vacuum impregnated selected columns with lithium nitrate. Column 31 was vacuum treated with a silicate material, and Column 41 was vacuum treated with a silane/siloxane blend. It is unlikely that silicate will help to mitigate either ASR, and in fact, if the product is an alkali-based silicate, it could actually increase pore solution pH and worsen ASR. However, as stated above, the role of the research team will only be to monitor the behavior of the columns and not to provide guidance or input on the specific application materials or methods.

A wide range of testing and monitoring has been performed on these columns (e.g, expansion, crack mapping, relative humidity, petrographic evaluation, etc.), but for brevity, only data on depth of lithium penetration is discussed herein. Full details of this field test and a detailed description of field monitoring and parallel laboratory testing will be discussed in future publications.

2.4 Concrete blocks in Texas (United States)

Three outdoor exposure blocks (total alkali loading of 5.25 kg/m3) were cast in Austin, Texas containing a highly-reactive aggregate from El Paso, Texas (Jobe). All blocks were coated on the sides with a Bituthene®-based sealer, leaving just the top and bottom of the blocks uncoated. One block was ponded continuously from the top surface for 240 days with 30% lithium nitrate solution. Another block was treated topically 32 times on the top surface over the course of 240 days, with each treatment consisting of an application rate of 0.16 L/m^2 . The last block was an untreated control. The purpose of this study was to quantify the potential benefits of the topical application of lithium under the most favorable (yet unrealistic) conditions, specifically continuous ponding or weekly treatment over an eight-month period. The idea was to determine the best-case scenario for topical application of lithium. These tests are ongoing, and depths of lithium penetration have not yet been determined; however, data on the expansion of the blocks (measured on sides but the bottom) is presented herein.

3 RESULTS AND DISCUSSION

3.1 Pavement section in Idaho (United States)

Long-term monitoring of the test pavement section in Idaho is in progress, with the results of approximately three years of monitoring described by East [8]. It is too premature to make firm conclusions about the effects of topical lithium treatments on the expansion and cracking of this pavement section. However, significant data have been generated on depths of lithium penetration, only a small portion of which are presented herein. Lithium profiles have been measured on cores extracted from various portions of the test section, capturing a range of levels of deterioration (i.e, surface cracking) and number of lithium treatments. Some cores were intentionally extracted directly above cracks, whereas others were taken away from cracks. The penetration data from the various cores were quite similar, regardless of the above variations in pavement condition or lithium treatment details – the depths of lithium penetration were very limited in all cases, with lithium penetrating only into the upper few millimetres. Figure 5 shows typical lithium penetration data for sections of pavement that received three topical treatments of lithium (the most lithium applied for any of the test section). Using the aforementioned 100 ppm lithium concentration as a threshold index (above which lithium would be expected to suppress expansion), it is clear that only the upper few millimeters (less than 4 mm for all samples) have received enough lithium to effectively suppress ASR. Even when

looking beyond this threshold value of lithium concentration, it clear that very little lithium has penetrated much beyond this upper layer, which certainly raises doubt about the potential benefits of topical applications of lithium for this pavement section. The depths of penetration shown in Figure 5 are consistent with other data generated on full-depth pavement sections that were removed from service in Idaho and subsequently treated topically in the laboratory. Although long-term field monitoring will continue for this pavement test section in Idaho, the general lack of lithium penetration will almost certainly ensure that the topical application of lithium to this pavement section will have no effect on future ASR-induced expansion and cracking.

3.2 Highway barriers in Massachusetts (United States)

Figure 6 shows the lithium profile data for the ASR-affected barrier that was impregnated with lithium via vacuum (7.25 hours under pressure). As described earlier, the samples extracted for lithium profiling were removed from the barrier without the use of water as a lubricant, ensuring that any lithium contained in the sample would not be diluted. As can be seen in Figure 6, the depth of lithium penetration was limited to only the outer few millimetres, with duplicate samples containing lithium at the "threshold" concentration only in the first 2 to 4 mm from the treated surface. As with the field trial in Idaho, this pronounced lack of lithium penetration will, in all likelihood, yield little, if any, positive benefits in terms of reduced expansion and cracking. However, the barriers will continue to be monitored (expansion, cracking, internal relative humidity, etc.), with the results reported on the lithium and silane treatments in future publications.

3.3 Bridge columns in Texas (United States)

Figure 7 shows the lithium profile data for bridge columns treated with 30% lithium nitrate solution, either by vacuum or electrochemical impregnation. The depth of penetration to which the "threshold" concentration of lithium (100 ppm) was attained for the vacuum-treated column was approximately 8 to 10 mm, which was higher than the penetration achieved in previous topical and vacuum applications (Sections 3.1 and 3.2). However, given the added cost and complexity of the vacuum impregnation apparatus, it remains to be seen whether this increased depth of penetration can be justified. It is too premature to determine whether these vacuum treatments have reduced expansion and cracking of these large elements (approximately 2×2 m in cross section), but continued monitoring will ultimately quantify the benefits of vacuum treatment on these two columns.

The lithium profile data shown in Figure 7 are quite encouraging for the electrochemically treated columns. Lithium was driven all the way to the reinforcing steel (depth of 50 mm) in a concentration estimated to be sufficient enough to suppress ASR-induced expansion. This is the most encouraging lithium penetration data generated under these FHWA-funded efforts and certainly suggests that electrochemical methods hold promise for treating ASR-affected structures with lithium compounds. However, one "side effect" of this process must be addressed. Figure 8 shows the sodium and potassium profiles, alongside the lithium profiles. Lithium ions were clearly driven to the reinforcing steel, as was the intention, but because the steel serves as a cathode in the electrochemical process, hydroxyl ions are produced at the surface of the reinforcing steel. To maintain charge neutrality and to offset the production of hydroxyl ions at the reinforcing steel surface, sodium and potassium ions from within the concrete migrated towards the steel surface. This increase in the hydroxyl ion concentration and subsequent increase in alkali (sodium and potassium) concentration near the surface of the reinforcing steel may exacerbate ASR-induced expansion and cracking in this region. Future monitoring of these columns (expansion, cracking, microstructural evaluations aimed at regions near the concrete/steel interface) should help to determine if the potentially detrimental side effects of electrochemical impregnation outweigh the benefits of the significant lithium penetration, as shown in Figure 8. Future publications will present the long-term data generated on these electrochemically-treated bridge columns.

3.4 Concrete blocks in Texas (United States)

As described in Section 2.4, a study was performed to quantify the effects of lithium treatments (topical or continuous ponding) on outdoor exposure blocks. Figure 9 shows the expansion results for three blocks cast from the same reactive concrete mixture: an untreated control block, a block topically treated with 30%-lithium nitrate solution 32 times over a 240-day period (each treatment consisting of an application rate of 0.16 L/m^2), and a block ponded continuously with 30%-lithium nitrate solution for 240 days. The aggregate contained in these blocks, a highly-reactive sand from El Paso, Texas, has been shown in previous studies to respond reasonably well to lithium when

used as an admixture and was incorporated in these blocks to attempt to generate the "best case" scenario for using lithium as a post-treatment for ASR-affected concrete.

As shown in Figure 9, the block topically treated 32 times over a 240-day exhibited essentially the same expansion as the control block. Interestingly, the block that was continuously ponded for 240 days with lithium nitrate solution has expanded considerably more than the control block. Additional work is in progress to study this in more detail, and the mechanisms responsible for this increased expansion are not fully understood. It may be possible that through continuous ponding, lithium nitrate was able to suppress expansion near the upper surface of the block that was in contact with the solution, while at the same time, the concrete below this upper portion continued to expand. It is possible that a more pronounced gradient between the highly expansive core of the block and the less expansive surface of the block resulted in more tensile stresses on the surface, resulting in more severe cracking and expansion. More research is needed to understand this behaviour. These blocks are still being monitored for expansion and cracking, and as such, cores have not yet been extracted for lithium profiling.

4 CONCLUSIONS

This paper summarized the findings of several case studies involving the treatment of ASRaffected structures with lithium nitrate solution using various treatment methods (topical, vacuum, and electrochemical methods). The case studies described in this paper are ongoing, with significant monitoring in progress and scheduled to continue through 2009. Although firm conclusions can not be drawn at this point, some preliminary conclusions can be drawn, especially those related to depths of lithium penetration. Some of the key findings to date include:

- Minimal depths of lithium penetration were observed in an ASR-affected pavement treated topically with lithium nitrate solution. Lithium concentrations estimated to be sufficient to suppress expansion were only detected in the upper 4 mm of the treated pavement section. These results are consistent with laboratory treatments of full-depth pavement sections from the same highway section and with parallel testing on laboratory-produced concrete that was topically treated with lithium nitrate solution. Given the minimal depth of lithium penetration observed in both the laboratory and the field, it is highly unlikely that topical treatment of ASR-affected concrete would be effective in reducing future expansion and cracking.
- The vacuum impregnation of ASR-affected structures (highway barriers and bridge columns) resulted in deeper lithium penetration, compared to topical treatments. However, lithium concentrations estimated to be sufficient to suppress expansion were only measured in to depths of 2-4 mm (highway barriers) and 8-10 mm (bridge columns). Although these penetration depths exceeded those for topical treatments, it is not clear at this point in time if the increased cost and complexity of the vacuum impregnation process is justified. The monitoring of expansion and cracking of these treated elements should provide data in the future to better assess the potential for using vacuum-based techniques for treating ASR-affected structures with lithium compounds.
- The most promising technique for achieving deeper lithium penetration was found to be electrochemical impregnation. Lithium concentrations well in excess of the value estimated to be sufficient for suppressing expansion (100 ppm) were detected all the way down to the depth of the reinforcing steel, 50 mm from the treated surface. However, it was also found that internal alkalies (sodium and potassium) were drawn to the surface of the steel because the steel serves as a cathode in the electrochemical process, resulting in the formation of hydroxyl ions. As such, it is possible that ASR may be exacerbated in the concrete adjacent to the reinforcing steel, due to the local increase in hydroxyl, sodium, and potassium concentrations. More research is needed to determine if the potential benefits of increased lithium penetration outweigh the potential negative effects of increased pore solution pH near the imbedded reinforcing steel.
- Repeated topical applications (32 treatments over a 240-day period) of lithium nitrate solution were found to have negligible effects on ASR-induced expansion and cracking of outdoor exposure blocks containing a highly-reactive aggregate. Surprisingly, continuous ponding of lithium nitrate solution for 240 days actually resulted in significantly more expansion and cracking than an untreated control block. More work is in progress to further investigate this behavior, and underlying mechanisms are not fully understood. It may be possible that continuous ponding of lithium nitrate solution suppressed expansion near the treated surface but resulted in a more pronounced gradient between the highly expansive core of the block

and the less expansive surface of the block. This may have led to the generation of higher tensile stresses on the surface, resulting in more severe cracking and expansion.

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Numerical Identification of Column	Set Designation (Severity of Damage)	Treatment Details
31	Severely Damaged	Sodium-silicate blend applied using vacuum
32	Severely Damaged	40% Silane, applied topically over existing paint
33	Severely Damaged	Lithium nitrate applied using vacuum
34	Severely Damaged	40% Silane, applied topically after removal of existing paint
35	Severely Damaged	Lithium nitrate applied using electrochemical technique
36	Severely Damaged	Control
41	Moderately Damaged	Silane-Siloxane blend applied using vacuum
42	Moderately Damaged	40% Silane, applied topically over existing paint
43	Moderately Damaged	Control
44	Moderately Damaged	40% Silane, applied topically after removal of existing paint
45	Moderately Damaged	Lithium nitrate applied using vacuum
46	Moderately Damaged	Lithium nitrate applied using electrochemical technique

Table 1: List of columns, severity ratings, and treatment details for Houston, Texas field trial



Figure 1: Topical application of lithium nitrate to pavement in Idaho



(a) General condition of ASR-affected barriers

ral condition of ASR-affected barriers (b) Close-up of damage at bottom of barrier due to ASR and subsequent freeze/thaw and scaling distress Figure 2: ASR-affected highway barriers near Leominster, Massachusetts





(a) Topical application of lithium nitrate (b) Vacuum treatment of barriers with lithium nitrate Figure 3: Topical and vacuum application of lithium nitrate to highway barriers



Figure 4: Summary of electrochemical treatment of Houston columns -- (a) Irrigation tubes, wood splices and metal strips are placed on the column. The metal strips are attached to titanium mesh that runs inside holes drilled into the side s of the column; (b) A cellulose layer is being applied to the side of the column; (c) Plastic sheeting is placed on all sides of the column. The gutters under the sheeting collect excess lithium to be reused.



Figure 5: Depth of lithium penetration for Idaho pavement section. Dashed line (100 ppm) indicates concentration of lithium estimated to suppress ASR-induced expansion.



Figure 6: Depth of lithium penetration for Massachusetts highway barrier (vacuum impregnated with lithium nitrate). Plots are duplicate samples extracted from barrier that had been vacuum impregnated with lithium nitrate for 7.25 hours). Dashed line (100 ppm) indicates concentration of lithium estimated required to suppress ASR-induced expansion.



Figure 7: Depth of lithium penetration for Houston bridge columns (vacuum impregnated or treated electrochemically with lithium nitrate). Dashed line (100 ppm) indicates concentration of lithium estimated to suppress ASR-induced expansion.



Depth (mm)

Figure 8: Lithium, sodium, and potassium profiles for Column 46 (electrochemically impregnated with lithium nitrate solution). Note that the lithium profile shown here is the same as in Figure 7 (electrochemical over rebar). This figure shows clearly that lithium ions were driven all the way to the reinforcing steel (depth of 50 mm from concrete surface) and concentrations well exceed target concentration of 100 pm; however, Na⁺ and K⁺ from within the concrete migrated towards the steel surface as the steel acts as a cathode in the electrochemical impregnation process.



Figure 9: Effects of lithium treatment on outdoor exposure blocks. Values shown are average expansions at top of block. Topical applications of lithium (32 applications of 30%-lithium nitrate solution, each at application rate of 0.16 L/m^2) had little, if any, impact on expansion. Interestingly, the block that was ponded continuously with 30%-lithium nitrate solution for 240 days actually expanded significantly more than the control block.