An *IPRF* Research Report

Innovative Pavement Research Foundation

Airport Concrete Pavement Technology Program

Report IPRF-01-G-002-03-10

Field Studies in Mitigating ASR in Existing Pavement, Topical Application of Lithium

Programs Management Office
5420 Old Orchard Road
Skokie, IL 60077

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Field Studies in Mitigating ASR in Existing Pavement, Topical Application of Lithium

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Mr. David Stokes	**FMC Corporation**
Mr. Toy Poole	**U.S. Army Corps of Engineers, ERDC**
Dr. David Gress	**University of New Hampshire**
Mr. Dan Johnston	**South Dakota DOT**
Dr. David Brill	**Federal Aviation Administration**

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EXECUTIVE SUMMARY

Alkali-Silica-Reactivity (ASR) is a problem exclusive to concrete where there is a reaction between hydroxyl ions (OH-) ions present in cement and/or other sources and specific reactive aggregates present in concrete mixtures. This reaction can be present in any concrete construction including roadways, bridges, building and wharves. There is a harmful aspect to this reaction where it causes an expansive gel that causes distress in concrete. This distress can be manifested in forms of cracking, scaling, delaminations and spalls. This is the area of concern when dealing with concrete airport pavements. The result of these distresses may range from excessive growth of concrete pavements, to creation of foreign object debris (FOD).

This study consists of the evaluation of surface applied lithium salts to prevent or slow down the deterioration of concrete pavements due to ASR. Lithium salts have shown the potential to mitigate the causes of the expansion of concrete as a result of ASR. This project consisted of a field study of treatment of concrete pavements already exhibiting ASR by the monitoring and evaluation of treated and control pavement sections. This project was intended to track changes in the serviceability of treated pavement test sections relative to the untreated control sections. Evaluating the ability of lithium salt solutions to maintain and extend the functional service life of existing airfield pavement and reducing the generation of foreign object debris (FOD) were the principal foci of this work.

Site selection included pavement in 3 geographically and geologically diverse areas of the country: Cheyenne, WY (CYS); Phoenix, AZ (PHX) and Atlanta, GA (ATL). These airports were selected based on the level of distress, environmental exposure and amount of area available to treat. Large areas were selected for full-scale topical application of lithium in order to provide an indication of overall effects and the potential for service life extension. At each of the airports initial characterization sampling of the concrete was completed to determine the physical properties that may affect the topical treatment. This included petrographic Damage Rating Index, density, absorption, voids, rate of absorption, coefficient of linear thermal expansion and measurement of the alkali content. In addition to the testing of concrete samples, the pavement surface was characterized by visual condition assessment of the pavement following ASTM and FAA procedures.

Lithium was applied in a full-scale application fashion at a rate of 4.5 gallons per 1,000ft^2 to give an indication of overall effects and provide a better indication of the service life extension that can be expected. Many trends were observed in the application of the lithium solution. The use of a pre-wetting phase did not show any added benefit, in either daylight or nighttime application. However there was a large benefit to the post-wetting phase. This prevented lithium salt crystallization on the surface of the concrete due to evaporation of the solution liquid which subsequently produced a slick and somewhat “greasy” surface. Also to prevent this effect, the application of was also completed in two applications of 2.25 gallons per 1,000ft^2 on subsequent days.

Initial alkali testing showed that in most cases the alkali content of the concrete was above the threshold required for further reactivity at the surface. Petrographic analysis of cores taken at the airports also showed that the initial ASR deterioration observed was likely due to alkali-silica reactivity and therefore all areas should continue to show deterioration due to ASR. In CYS and PHX the control zones showed less expansion in the transverse direction than the treated zones. While this might seem to be alarming, the treated areas in CYS were more deteriorated in the beginning of the testing and in the initial petrographic testing showed more reactive concrete.

The two types of visual surveys have given an insight into the level of deterioration of the concrete surface during the testing period. Where CYS showed an ever increasing level of deterioration, and a subsequent deterioration of serviceability, Atlanta and Phoenix's serviceability did not deteriorate at the same rate. Cracking and joint deterioration at CYS simply continued and was seemingly not kept in check by the topical application of lithium salts. This site was perhaps too far gone to receive any benefit. PHX and ATL began the testing with PCI ratings in the "Excellent" to "Very Good" range and during the testing changed very little. It may be concluded from this observation that whatever benefit is received from the application of lithium salts may best be served by airport pavements that are in the initial stages of deterioration. However no changes in deterioration or creation of foreign object debris was observed. This type of observation may only be seen after more years of service. If the treatment was effective in these cases, then after several more years it would be assumed that the deterioration would be more severe in the control zone.

At all sites, the penetration of the lithium salts into the concrete was measured. Lithium penetrated only the very top layer of the concrete. At no site did it penetrate any further than 18mm and this was only observed in a multiple application zone. Penetration was measured to be deeper in multiple application zones as compared to single application zones. However at none of the sites did it reach a molar ratio of 0.37 of lithium per alkali; the theoretical ratio for preventing ASR expansion in new concrete. Environmental exposure seems to have affected the lithium absorption at the three different sites. ATL is easily the most humid and receives the most precipitation, which would provide a mode of diffusion for the lithium salts to penetrate further into the concrete.

It is difficult to conclude if the topical application of lithium was successful at mitigating ASR in the tested airport pavements. Penetration depths were shallow, and as such cannot be expected to provide mitigation to the entire thickness of the concrete treated. No FOD generation was observed. Additional time is required to determine whether the treated areas will fare better than the control areas. In some cases the treated areas deteriorated less than the control areas when compared using the PCI rating system. In other cases the treated areas deteriorated more than the control areas when compared using the PCI rating system. With longer timeframe for observation it can be determined if there becomes a more marked difference between the control and treated areas. This also may be aided with the comparison of initial ROSAN test data with future evaluations. Additional evaluation at a later date would provide a clearer picture as to the performance of the topical application. Future testing would be beneficial to provide a more definite conclusion. Any benefit of the treatment will become measureable and apparent with time.

1. INTRODUCTION

Alkali-Silica-Reactivity (ASR) is a reaction between hydroxyl ions (OH-) ions present in cement and/or other sources and specific reactive aggregates present in concrete mixtures. The reaction produces an expansive gel that causes distress in concrete. In the case of airfield pavements, these resultant distresses may range from anywhere between excessive growth of concrete pavements, to creation of foreign object debris (FOD). While there are multiple options available for the construction of new airfield pavements in order prevent reactive aggregates from creating expansive gels, there are few to prevent the deterioration of existing pavements that have ASR tendencies.

Deterioration by ASR of existing pavements can be hazardous to airfield operations. When the deterioration or expansion is too excessive, the common response is to treat the symptoms of the ASR distress such as reconstruction of expansion joints, repairs to in-pavement structures, etc. This however does not treat the cause. Lithium salts have shown the potential to mitigate the causes of the expansion of concrete as a result of ASR. This report is in response to the IPRF Project 01-G-002-03-10, Field Studies in Mitigating ASR in Existing Pavement, Topical Application of Lithium. Therefore, this report is the study of the use of topically applied lithium salts to deter the further deterioration of in situ airport pavements due to ASR.

1.1 STUDY INTENT AND OBJECTIVES

The focus of this project was to study the effect of topically applying a lithium salt solution to existing concrete pavements suffering from alkali silica reactivity (ASR) at airfields exposed to various environmental conditions. Since this project was a field study of pavements already exhibiting ASR, the benefits of this type of treatment were evaluated in terms of a) a comparison of serviceability between treated and untreated pavements, and b) the relative service life of the control and test pavement sections. The bulk of the project resources were dedicated to the application and evaluation of lithium treatments in the field. Laboratory testing was used as required to complement the field-testing regime.

The important aspects of the field study have included:

- Initial characterization testing of control and treated sites.
- Initial and interim condition assessment surveys to compare treated and control sections using the assessment guidelines found in FAA Advisory Circular AC 150/5380-8 “Handbook for Identification of Alkali-Silica Reactivity in Airfield Pavements” and ASTM D5340-03 “Standard Test Method for Airport Pavement Condition Index Surveys”.
- Installation of instrumentation for pavement monitoring.
- Topical application of lithium salt solution to test areas in a uniform, repeatable manner using full-scale application equipment and techniques.

Monitoring and evaluation of the treated and control pavement sections was intended to track changes in the serviceability of the treated pavement test sections relative to the untreated control sections. The principal serviceability criteria consist of joint and surface deterioration. Since the pavements selected for this study have already suffered some physical distress from ASR, the focus of the study was the effectiveness of topically applied lithium salt solutions to minimize further deterioration of the concrete in order to extend the airfield's functional service life.

Evaluating the ability of lithium salt solutions to maintain and extend the functional service life of existing airfield pavement and reducing the generation of foreign object debris (FOD) were the principal foci of this work.

Site selection included pavement in 3 geographically and geologically diverse areas of the country. Three airports were selected based on the level of distress, and environmental exposure. At these airports, large areas were selected for full-scale topical application of lithium in order to provide an indication of overall effects and the potential for service life extension.

Expected predictors for a successful topical treatment include:

- Pretreatment condition rating of the pavement: whether treatment can prevent further deterioration of poor concrete.
- Porosity/absorption of the pavement surface: the depth of absorption of the lithium salts affects the performance of the material
- Effect of geographic location/environmental exposure: if treatment is effective in humid/wet areas to prevent accelerated deterioration
- Exposure to de-icing chemicals: de-icing chemical would accelerate deterioration
- Alkali content levels: high alkali content levels produce a more reactive environment for the reactive aggregates
- Lithium application details: if multiple applications are more effective in providing successful treatment

2. RESEARCH APPROACH AND IMPLEMENTATION

2.1 SITE SELECTION

Site selection consisted of three (3) airports in geographically and geologically diverse areas of the country. These airports met the qualification factors of being of different levels of distress as well as environmental conditions. Table 1 shows the site selection test matrix.

Table 1: Site Selection Test Matrix

	Test Matrix			
Location	Cool / Arid	Warm / Arid	Warm / Humid	Distress Level
Cheyenne Regional Airport (CYS)	X			Medium/High
Phoenix Sky Harbor International Airport (PHX)		X		Low
Hartsfield-Jackson Atlanta International Airport (ATL)			X	Low and Medium

2.1.1 Cheyenne Regional Airport (CYS)

The Cheyenne Regional Airport (CYS) in Cheyenne, Wyoming serves the City of Cheyenne and the southeastern portion of the state of Wyoming. It also provides service to the Wyoming Air National Guard and the Wyoming Army National Guard which are located directly next to the airport.

CYS was selected as the site which would be experiencing the "Cool/Arid" environmental exposure. From 2005-2008 Cheyenne Regional Airport received on average 14 inches of precipitation per year and was an average 52% relative humidity. After the initial site visit it was also determined that the level of distress was also quite high and therefore would be an excellent candidate to evaluate the effectiveness of a topical application of lithium to mitigate more severe ASR.

2.1.2 Phoenix Sky Harbor International Airport (PHX)

The Phoenix Sky Harbor International Airport (PHX) in Phoenix, AZ is a major hub airport for international and domestic travelers and provides a base for general aviation activity to support metropolitan Phoenix. Per day at PHX: nearly 1,500 aircraft arrive and depart, about 100,000 passengers arrive and depart, more than 700 tons of air cargo is handled (*from Phoenix Sky Harbor International Airport Website: http://phoenix.gov/aviation/*).

PHX was selected as the site which would be experiencing the "Warm/Arid" environmental exposure. From 2005-2008 Phoenix Sky Harbor International Airport received on average 7 inches of precipitation per year and had an average 33% relative humidity. After the initial site visit it was determined that the level of distress was somewhat low and but this site would be an excellent candidate to evaluate the effectiveness of lithium solutions to mitigate or delay damage caused by ASR.

2.1.3 Hartsfield-Jackson Atlanta International Airport (ATL)

The Hartsfield Jackson Atlanta International Airport (ATL) in College Park, GA has had the distinction of being "the world's busiest passenger airport". In 2008 ATL saw over 90 million passengers, over 655 thousand metric tons of freight and nearly a million aircraft takeoffs and landings (*from Hartsfield Jackson Atlanta International Airport Website: http://www.atlanta-airport.com*)

ATL was selected as the site which would be experiencing the "Warm/Humid" environmental exposure. From 2005-2008 Hartsfield-Jackson Atlanta International Airport received on average 45 inches of precipitation per year and had an average 63% relative humidity. There were many areas that are visually showing signs of ASR distress at ATL. Most of these areas were found on the southern runways and taxiways, with a few additional areas in the concourse ramp areas.

2.2 TEST SECTIONS

At each airport it was important for the treatment areas to be of sufficient size and the number of measurements to be taken within each area to be sufficient to provide statistically significant results. The large areas assured that the test areas were given a typical application regime and are not unnecessarily affected by treatment start-up, shutdown, or edge effects. The effects of the individual slab sizes and aspect ratios within the test sections on the testing results were not included in this study.

Moreover, the test sections

- Contained consistent thickness, construction details, and age throughout
- Did not contain significant areas of repairs or patches.
- Presumably received the same influence of uncontrolled variables such as traffic, thermal volume change, drainage, precipitation, etc. should be relatively constant in the entire area
- Were bounded by a lithium application start-up section and a stopping section (which consist of a single panel) in the travel direction of the application vehicle.

With the exception of ATL the sites consisted of test areas of three (3) zones. The large available area at ATL allowed for a control section for each test section. These zones consisted of a Control Zone, a Single Application Zone and a Multiple Application Zone. The Single Application Zone received a single application of lithium solution (nominal application rate of 4.5 gal/1,000ft^2) at the beginning of the testing, and the Multiple Application Zone received three applications of lithium solution at approximately six (6) month intervals.

2.2.1 Cheyenne Regional Airport (CYS)

At CYS, there were three main areas that visually showed signs of ASR distress. These consisted of a large ramp area adjacent to the terminal building, two short taxiways between Taxiway Bravo and either runway, and the western end of Taxiway Bravo. The third area, the western end of Taxiway Bravo, was the area selected for the test section at CYS. This section of taxiway was able to provide test and control zones of similar size. The number of measurements taken within each area was sufficient to provide statistically significant results. The two treated zones and the single control zone at CYS were 23,760 ft^2

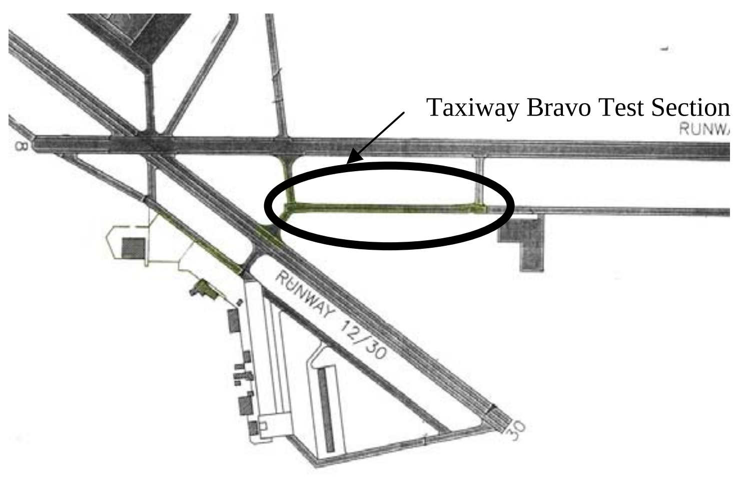

Figure 1: Test Area - Cheyenne Regional Airport

each. The size of the panels in this area is 15' x 18' and 10" thick. The test areas are outlined in Figure 2, and are shown to scale with detail in Appendix 6.

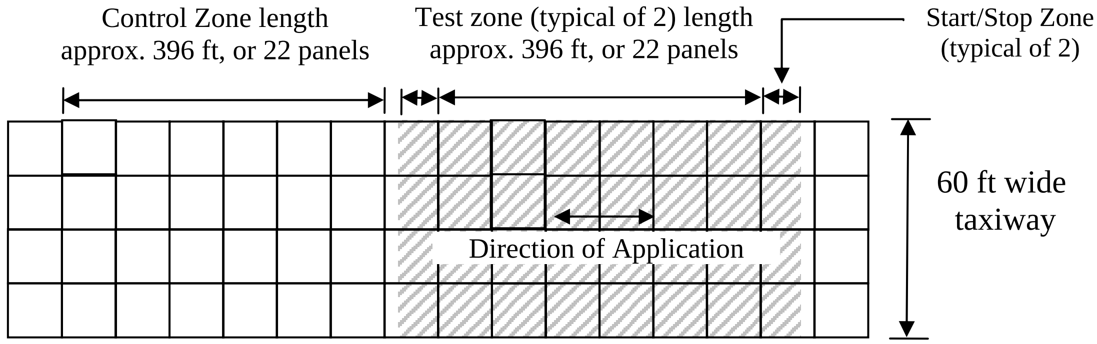

Figure 2: Schematic of Test and Control Zones on Taxiway Bravo at Cheyenne Regional Airport

The test area at CYS consisted of three (3) zones. As laid out from west to east: Control Zone (Zone 1), Single Application Zone (Zone 2) and Multiple Application Zone (Zone 3). Because the concrete of the taxiway was placed only half the width at a time over the full length, to maintain consistent properties of each zone, the zones were delineated width-wise along the length of the taxiway. This way each zone, including the control section, incorporated both concrete pours.

2.2.2 Phoenix Sky Harbor International Airport (PHX)

At PHX, there were several areas that visually showed signs of ASR distress. However, all these areas were found to be in the ramp areas between the terminal buildings at the airport. Of these areas, only a few provided a large enough area with the same construction details and level of deterioration to provide the area for treatment required. Finally it was decided that the western side of Terminal S3 would be an adequate area for treatment. This area was able to provide test and control zones of similar size. The number of measurements to be taken within each area would be sufficient

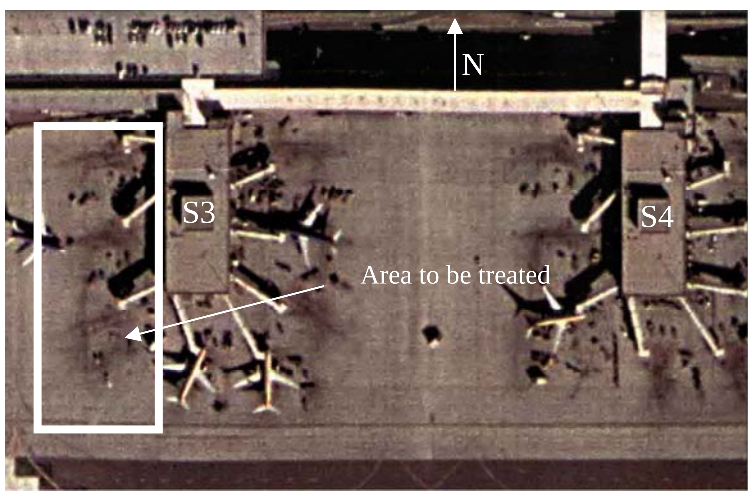

Figure 3: Aerial Photo of Phoenix Sky Harbor International Airport Terminals S3 and S4

to provide statistically significant results. The two treated zones and single control zone at PHX were 19,600 ft^2 each. The panels in this area are 20’ x 20’ and 18” thick. The test areas are outlined in Figure 4, and are shown to scale with detail in Appendix 6.

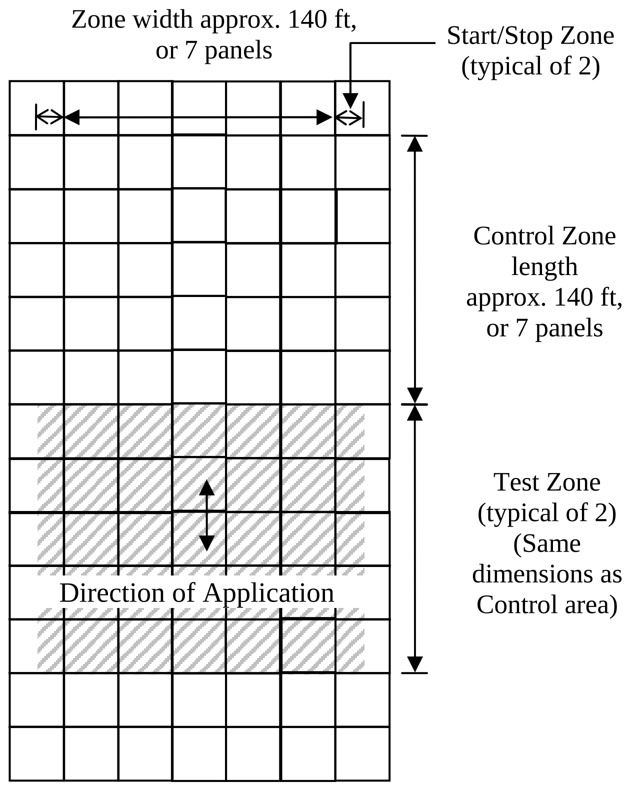

Figure 4: Schematic of Test and Control Zones at S3W at Phoenix Sky Harbor International Airport

The test area at PHX consisted of three (3) zones. As laid out from north to south: Control Zone (Zone 1), Single Application Zone (Zone 2) and Multiple Application Zone (Zone 3). Because of the type of exposure in the area that was chosen for the application, to maintain consistent properties of the concrete, the zones were delineated width-wise along the length of the terminal building. The level of deterioration was found to be higher closer to the terminal building where planes park for loading and unloading passengers. Therefore, to prevent any specific zone from concentrating on an area with possibly different levels of deterioration, each zone, including the control section, incorporated areas near the terminal building and outwardly towards the middle of the ramp area.

2.2.3 Hartsfield-Jackson Atlanta International Airport (ATL)

Because ATL was a large facility with many ASR affected areas, two test areas were chosen. Of the areas affected by ASR, few were large enough or uniform enough to provide value in results. The other limiting detail was to find areas that were not scheduled for future repairs or replacement. Finally it was decided that the western end of Runway 9L provided adequate area for treatment. It had the advantage of providing two distinct test areas somewhat close together: a newer constructed section which showed low levels of distress and an older section with slightly higher levels of distress. This area had the further benefit of not being scheduled for major repair work for the duration of this project.

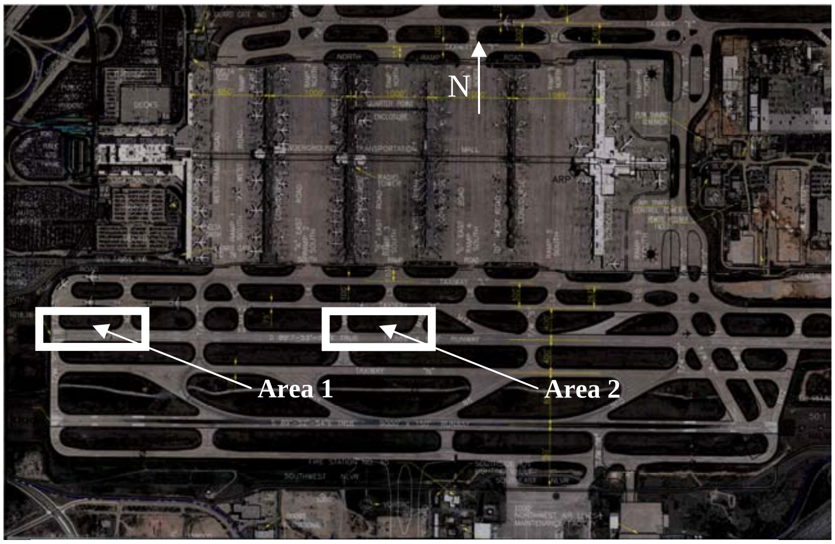

Figure 5: Aerial Photo of Hartsfield-Jackson Atlanta International Airport Concourse and Southern Runways

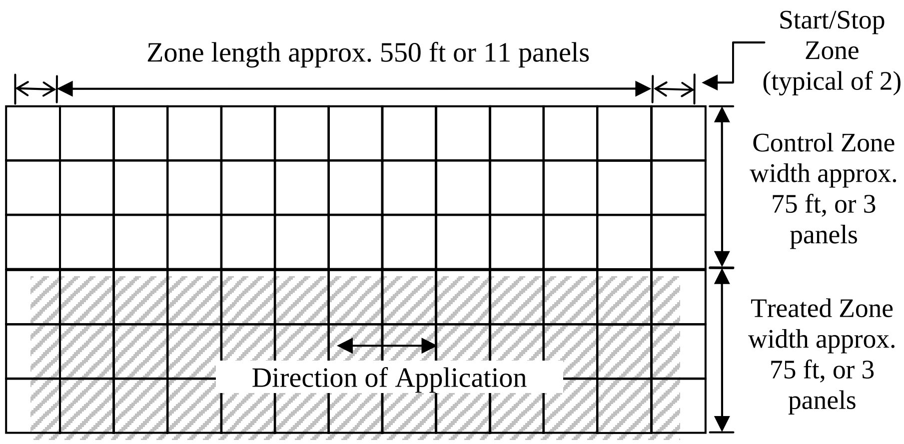

Figure 6: Schematic of Area 1 Control and Test Zone (Typical of 2) Layout at Hartsfield-Jackson Atlanta International Airport

Runway 9L was able to provide two test areas that each had test and control zones of similar size. The number of measurements to be taken within each area would be sufficient to provide statistically significant results. Each zone in Area 1 at ATL was 41,250 ft^2. The average size of the panels in this area is 25’ x 50’ and 16” thick. Each zone in Area 2 at ATL was 39,375 ft^2. The average size of the panels in Area 2 is 25’ x 75’ and also 16” thick. The test areas are outlined in Figures 6 and 7, and are shown to scale with detail in Appendix 6.

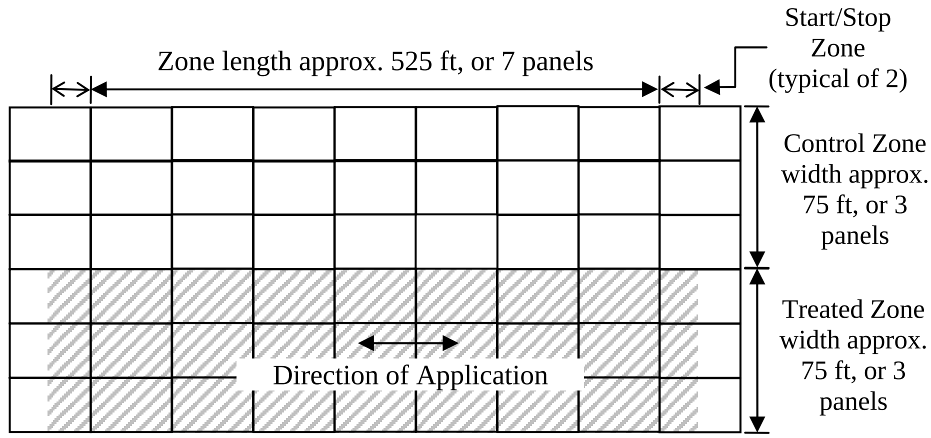

Figure 7: Schematic of Area 2 Control and Test Zone (Typical of 2) Layout at Hartsfield-Jackson Atlanta International Airport

Each test area at ATL consisted of four (4) zones. As laid out from west to east: the south half of the runway consisted of a Single Application Zone (Zone 1) and Multiple Application Zone (Zone 3) while the north half of the runway consisted of two Control Zones (Zone 2 and Zone 4). As it was previously suggested, the zone layout would consist of two long treated zones which would be located end-to-end with a lithium application start/stop buffer zone at each end. The length of the zones has been shortened from 1,000ft to 550ft, or 11 panels to accommodate the width of the runway. The level of damage due to ASR is more pronounced in the center panels therefore this treatment layout will allow consistency of measurement from the center outward in either the treated zone or Control Zone.

2.3 CHARACTERIZATION TESTING

Initial characterization testing of the test sites was performed. This included extracting a set of four (4), four inch (4”) diameter core samples from each test location zone. Three (3) of these cores were sent to the University of Toronto for standardized tests (Appendix 1), with the final remaining core was sent to Mr. Patrick Grattan-Bellew for petrographic ASR damage index determination (Appendix 2, 3 and 4). The Damage Rating Index has been determined using full depth cores using the petrographic methodology developed by Mr. Patrick Grattan-Bellew. All core samples were given an identification code to represent the location along the test section, and all core locations were repaired using a repair material with lithium admixture added to avoid free alkali in the repair material from aggravating ASR in the adjacent concrete.

The following tests have been performed on the core samples (1 core/zone):

- Petrographic Damage Rating Index
- Density, absorption, and voids - ASTM C 642
- Rate of Absorption - ASTM C 1585
- Coefficient of linear thermal expansion - CRD-C 39-81
- Measurement of the alkali content - using hot-water extraction by Marc-Andre Berube. The method was modified to obtain total alkali content.

In addition to the testing of concrete samples, the pavement surface was characterized using the following techniques:

- Visual condition assessment of the pavement following ASTM D5340-03 and FAA Advisory Circular AC 150/5380-8 “Handbook for Identification of Alkali-Silica Reactivity in Airfield Pavements”.
- Surface texture using ROSAN (ROadway Surface ANalyzer)

The visual condition survey was performed initially and repeated one (1) year after initial application and three (3) years after initial application. The use of the FAA Advisory Circular has been simplified for comparison purposes by using the visual inspection grading only. While the laboratory inspection and uranyl acetate fluorescence method (UAFM) field testing would be a valuable tool in determining the propensity of ASR where it is unevaluated, it was determined unnecessary in our evaluation. Other aggravating factors such as fly-ash, de-icing, freeze-thaw, average relative humidity and rainfall are also assumed relatively the same from year to year, and the majority of the use of the Advisory Circular is to track the appearance of the ASR-specific modifiers from year to year.

The second method of pavement surface characterization was the use of ROSAN (Roadway Surface Analyzer). Originally designed by FHWA’s Turner-Fairbanks Highway Research Center in partnership with the firm MGPS, ROSAN serves as a non-contact high-speed inertial profiler which uses a vehicle-mounted laser that can collect and analyze the concrete surface profile at a high speed of travel. The principal reading of relevance would be the Surface Texture (Mean Profile Depth Reading). Texture readings were taken at two different speeds, at 15 mph (with texture readings at 0.25mm (0.010inch)) and 30 mph (with texture readings at 0.50mm (0.020inch)). This equipment generates a digital version of the surface condition data that can complement a manual inspection. The data produced is reflective of ASTM Standard E1845, "Standard Practice for Calculating Pavement Macro-texture Mean Profile Depth". Vector personnel were trained in the use of ROSAN and were able to complete ROSAN testing initially at all sites as well one (1) year after initial application at PHX and ATL only. However, further testing with the ROSAN was discontinued due to logistical and budgetary reasons, and any results therefore are not presented in this report.

Testing for the depth of lithium penetration was performed at the end of treatment, three years after the initial treatment. At that time, one partial-depth (4-inch diameter x 10-inch long) core sample was extracted from each treated zone for lithium content profile determination. The lithium content was tested using a procedure similar to ASTM C1556 which is detailed in Appendix 5. Powder samples were obtained by profile grinding the cores. The lithium content, as well as alkali levels were determined in order to compare the results to those obtained in the initial cores.

2.4 INSTRUMENTAION

Surface expansion and movement measurements have been manually collected using a Geokon/Ealey Tape Extensometer which has an accuracy of ±0.001in and repeatability of ±0.004in. This approach was used to monitor the expansion of the concrete pavement panels. An adjustment using the average coefficient of thermal expansion from the characterization tests was used to correct surface measurements.

Figure 8: Extensometer Measurement at Cheyenne Regional Airport

Measurements were taken by measuring the distance between pins (survey points) that were screwed into concrete anchors placed a certain distance from the corner of the panel. Because expansion caused by ASR is not relegated to the transverse direction, it was deemed necessary to take measurements in different directions. The chosen configuration of the survey points provided measurements in many different directions and allowed the evaluation of different effects. The four points in a single panel evaluated how ASR is affecting expansion in a single panel. The line of survey points across the width of the test area allowed determination on closing or expanding of the joints between the panels. And finally, measurements across the individual panels allow understanding of changes in size created by the internal panels. Because ASR expansion is in all directions, it was deemed important not to limit the measurements in one direction only and therefore, each set of measurements consisted of between forty (40) and fifty (50) measurements per zone. However, after later examining the time taken to obtain these measurements, the final set of measurements consisted only of the longitudinal and transverse measurements in the four outer panels; a total of 16 measurements.

Figure 9: Humidity Wells Installed (12” Top, 6” Center, 2” Bottom) at Phoenix Sky Harbor International Airport

The panels with the survey points also delineate the areas for Pavement Condition Index (PCI) survey.

Temperature was measured using thermocouples embedded at three different depths in the pavement. Manual temperature readings coupled with the surface measurements in the treated and control sections were used eliminate bias in the data due to thermal expansion and contraction of the pavement. Thermocouple wires were included in the installation of the relative humidity wells.

Three concrete relative humidity wells were installed into the concrete pavement near the edge in the center of the overall test area. The tubes are recessed below the pavement surface to avoid interference with maintenance operations and are capped and sealed to provide access during manual inspections. Relative humidity measurements were recorded at the time condition surveys were performed.

2.4.1 Cheyenne Regional Airport (CYS)

The layout of the survey points for each zone is shown in Figure 10.

The panels with the survey points also delineate the areas for Pavement Condition Index (PCI) survey, an area of approximately 5400 ft^2.

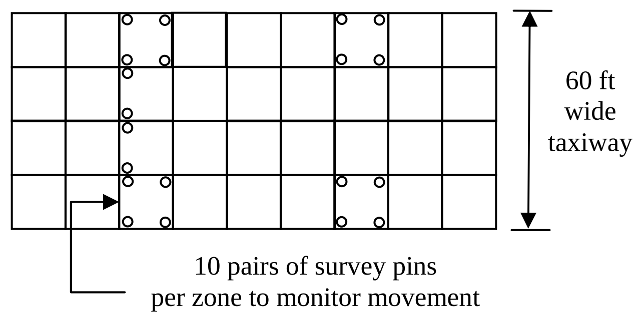

Figure 10: Schematic of Survey Point Layout at Cheyenne Regional Airport

It was observed during the removal of core samples for the characterization tests, that the taxiway consisted of a ten (10) inch thick concrete slab which was then followed by a further four (4) to six (6) inches of slurry concrete base. Therefore the humidity wells are installed at depths of two (2), five (5) and eight (8) inches in the top section of taxiway. The locations of the wells are included in the scale drawings in Appendix 6.

2.4.1 Phoenix Sky Harbor International Airport (PHX)

The layout of the survey points for each zone is shown in Figure 11.

Unfortunately, at the time of final measurements, a few of these survey points were found to be unusable due seizure of the screws left in the concrete anchors over time.

The panels with the survey points also delineate the areas for Pavement Condition Index (PCI) survey, an area of approximately 6400 ft^2.

Three concrete relative humidity wells were installed into the concrete pavement near the edge of

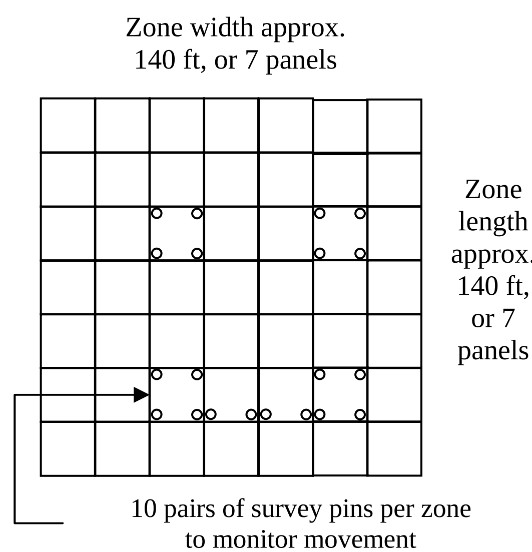

Figure 11: Schematic of Survey Point Layout at Phoenix Sky Harbor International Airport

Zone 2. The locations of the wells are included in the scale drawings in Appendix 6.

2.4.3 Hartsfield-Jackson International Airport (ATL)

The layout of the survey points for the zones in each area is shown in Figure 12.

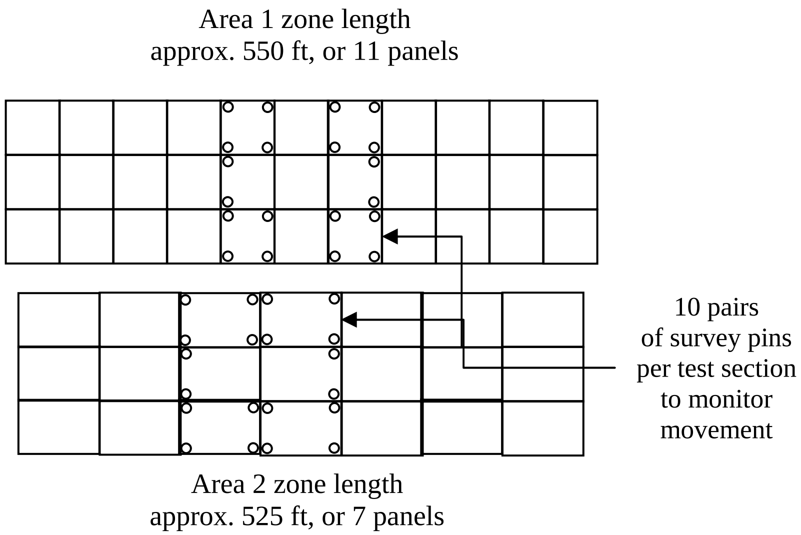

Figure 12: Schematic of Survey Point Layout at Hartsfield-Jackson Atlanta International Airport

Unfortunately, at the time of the second survey, and again at the final measurements, several of these survey points were found to be unusable due seizure of the screws left in the concrete anchors over time

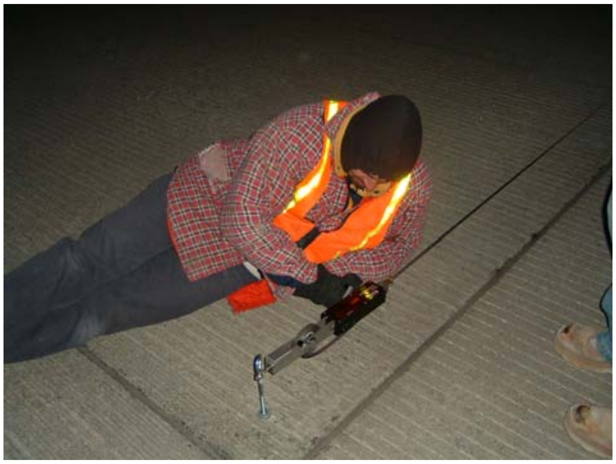

Figure 13: Extensometer Measurement at Hartsfield-Jackson Atlanta International Airport

The panels with survey points also delineate the areas for Pavement Condition Index (PCI) survey, an area of approximately 11250 ft^2 for both Areas 1 and 2.

In each test area, three concrete relative humidity wells were installed into the concrete pavement near the edge of the runway in the application start-stop edge panel between Zones 1 & 3. The locations of the wells are included in the scale drawings in Appendix 6.

3. LITHIUM APPLICATION

Lithium was applied by Vector Construction Inc., a certified lithium applicator. A large, full-scale application was used to give indication of overall effects and provide a good indication of the service life extension that can be expected of the treated in-situ concrete. The application was performed using an 80 gallon sprayer with a spray width of approximately eight (8) feet. This allowed the application to be performed using a conventional vehicle, in this case a pick-up truck.

3.1 CHEYENNE REGIONAL AIRPORT (CHY)

Figure 14: Application at Cheyenne Regional Airport

Initial application occurred in August of 2005. Upon suggestion from lithium distributor, the areas for application were pre-wetted prior to application. After the application of the lithium solution the area was then post-wetted. With the application occurring during the day, warm summer conditions allowed the solution to dry rapidly and crystallize on the surface of the concrete. The post-wetting allowed the lithium salts to be absorbed into the concrete, and prevented high levels of crystallization on the surface. It was observed that the lithium solution application initially caused the concrete surface to be slippery in areas where the solution was not fully absorbed. This was especially true where the surface of the concrete was painted with lines or other markings. Post-wetting of the treatment area allowed the lithium solution to be fully absorbed into the concrete and removed any immediate surface crystallization. Some crystallization confined to cracks in the concrete was observed the next day.

Figure 15: Zone 2 After Application at CYS

Figure 16: Zone 2 Following Day at CYS

Second (April 2006) and third (September 2006) applications occurred in much the same manner with the exception of the pre-wetting phase. In later applications at the other sites, pre-wetting seemed to contribute little to the absorption of the lithium solution and was therefore removed from the application process.

3.2 PHOENIX SKY HARBOR INTERNATIONAL AIRPORT (PHX)

Initial application occurred in September of 2005. The application was performed in two (2) coats of approximately 2.25 gal/1000 ft^2. This allowed better absorption and resulted in less crystallization of the lithium solution after a thorough post-wetting. No pre-wetting was performed, as it was determined that it seemed to provide no additional benefit. After each application the area was then provided with a post-wetting of the surface. The post-wetting allowed the lithium salts to absorb into the concrete, and prevented high levels of crystallization on the surface. Here too, it was observed that lithium solution application initially caused the concrete surface to be slippery in areas where the solution was not fully absorbed. Once again, post-wetting of the surface removed

Figure 17: Hand Application Around Facilities at Phoenix Sky Harbor International Airport

issues of incomplete absorption. Observations of the concrete the next day showed very few signs of remaining crystallization.

Second (March 2006) and third (September 2006) applications occurred in much the same manner. Locations around fixed equipment and facilities on the ramp area required some portions of the lithium solution to be hand applied.

Figure 18: Between Zone 1 (Control) and 2 After Initial Application at PHX

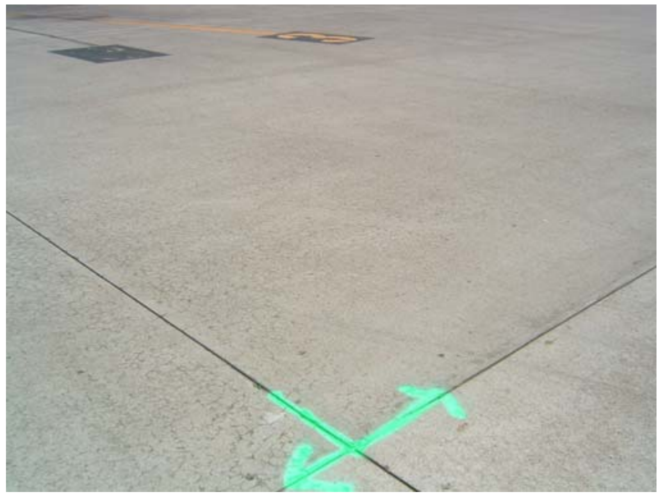

Figure 19: Between Zone 1 & 2 Next Day at PHX

3.3 HARTSFIELD-JACKSON ATLANTA INTERNATIONAL AIRPORT (ATL)

Initial application occurred in January of 2006. The application was performed in two (2) coats of approximately 2.25 gal/1000 ft^2. This allowed for complete absorption and reduced crystallization of the lithium solution after a thorough post-wetting. Post-wetting allowed the lithium salts to absorb into the concrete, and prevented high levels of crystallization on the surface. Because of the grooved surface of the concrete, issues regarding slipperiness and crystallization were not as evident as the un-grooved concrete at the other locations. Observations of the concrete the next day showed very few to no signs of crystallization.

Figure 20: Application On Runway and Runway Markings at Hartsfield-Jackson Atlanta International Airport

Second (August 2006) and third (December 2006) applications occurred in much the same manner.

Figure 21: Area 2 Zone 1 Following Day After Half Application

Figure 22: Post-Wetting of Concrete Surface

3.4 WORK ITEMS CHECKLIST

Table 2: Work Items Checklist

Work Item	Cheyenne Regional Airport	Phoenix Sky Harbor International Airport	Hartsfield-Jackson Atlanta International Airport
Survey Pin Installation	July 21, 2005	September 13, 2005	November 15, 2005
Characterization Testing Core Removal	July 21, 2005	September 15, 2005	November 14, 2005
ROSAN Scan	July 21, 2005	September 20, 2005	January 15, 2006
PCI Survey Initial	July 23, 2005	September 20, 2005	November 17, 2005
Thermocouple Installation	August 3, 2005	September 16, 2005	November 15, 2006
Humidity Well Installation	August 3, 2005	September 16, 2005	November 15, 2005
Extensometer Measurements Initial	August 4, 2005	September 18, 2005	January 19, 2006
Initial Lithium Application	August 6, 2005	September 22, 2005	January 21, 2006
Alkali Testing Core Removal (6 mo.)	April 20, 2006	March 10, 2006	September 1, 2006

2nd Lithium Application	April 21, 2006	March 10, 2006	September 2, 2006
PCI Survey Year 1	September 20, 2006	September 26, 2006	December 4, 2006
ROSAN Scan Year 1	N/A	September 26, 2006	November 29, 2006
Extensometer Measurements Year 1	September 20, 2006	September 28, 2006	December 8, 2006
3rd Lithium Application	September 22, 2006	September 28, 2006	December 6, 2006
PCI Survey Year 3	August 28, 2008	November 8, 2008	October 24, 2008
Lithium Profile Core Removal (3 yr)	August 28, 2008	November 6, 2008	October 26, 2008
Extensometer Measurements Year 3	August 28, 2008	November 7, 2008	October 26, 2008

4. TESTING RESULTS

4.1 LABORATORY SAMPLE TESTING

4.1.1 Cheyenne Regional Airport

Testing reports for the initial characterization cores removed September 15, 2005 can be found in Appendix 1. It includes the results of the Standard Test Method for Density, Absorption, and Voids in Hardened Concrete - ASTM C 642, of Rate of Absorption ASTM C 1585 and of CRD-C 39-81 Test Method for Coefficient of Linear Thermal Expansion of Concrete.

The Damage Rating Index was determined using full depth cores using the petrographic methodology developed by Mr. Patrick Grattan-Bellew. The report for the analysis of the initial cores taken from CYS confirmed ASR was present in all cores. The report also stated a mean DRI of 62 which corresponds to an expansion of ~0.09% and indicates the concrete should exhibit considerable cracking. The full report from the petrographic examination is included in Appendix 2. Figure 23 shows the DRI from the three cores. Note that Zone 1 (Control) has the lowest DRI and Zone 3 (Multiple Application) has the highest.

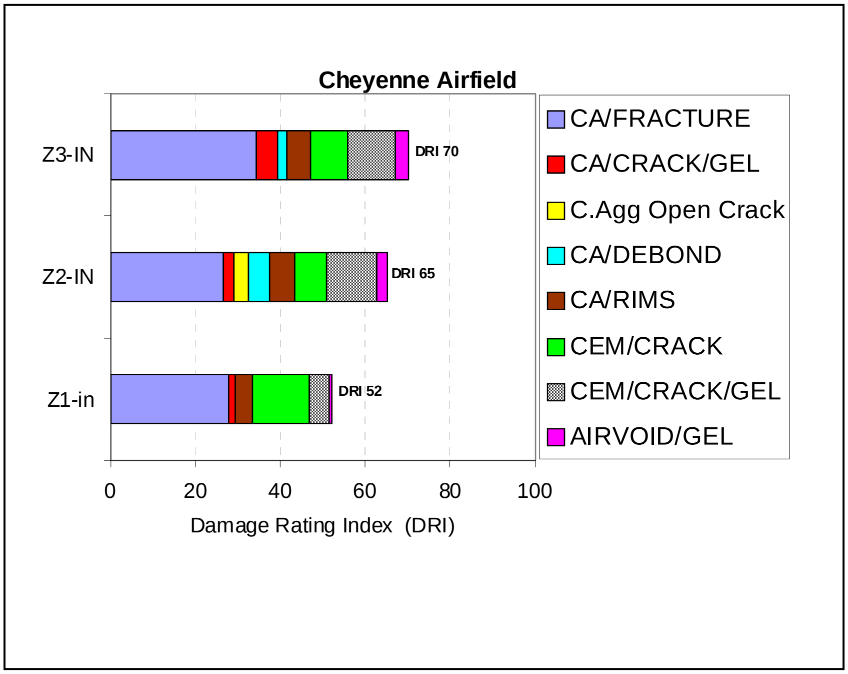

Figure 23: Chart showing Damage Rating Index (DRI) of cores from Cheyenne Regional Airport

Table 3 and Figure 24 show the sodium equivalent alkalis using "Measurement of the Alkali Content of Concrete Using Hot-Water Extraction by Marc-Andre Berube." from the initial characterization cores removed July 21, 2005.

Table 3: Initial Sodium Equivalent Alkalis - Cheyenne

Depth	Cheyenne Sodium Equivalent, kg/m^3		
mm	Zone 1	Zone 2	Zone 3
3.048	2.83	4.06	4.60
6.096	1.49	1.93	1.86
9.144	1.54	2.01	1.42
12.192	1.35	2.10	1.68
15.240	1.40	2.34	1.51
18.288	1.21	2.42	1.63
21.336	1.32	2.71	1.18
24.384	1.66	2.86	1.73
150.00	2.04	1.84	2.00
Averages	**1.65**	**2.47**	**1.96**

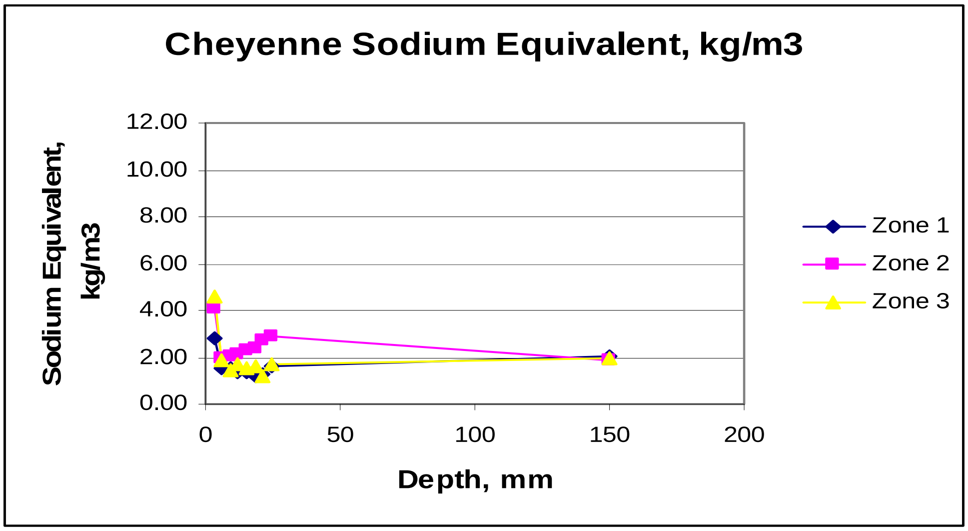

Figure 24: Graph Results of Alkali Sodium Equivalent at Cheyenne Regional Airport

The Canadian Standards guideline for the avoidance of ASR, A23.1 Appendix B5.2.3 of "Concrete Materials and Methods of Concrete Construction/Methods of Test and Standard Practices for Concrete" states that when using reactive aggregates in concrete having less than 3 kg/m3 of sodium equivalent alkali that no expansion will take place. As shown in Figure 24 the sodium equivalent of alkalis in the concrete are lower than the stated threshold at nearly all depths tested except near the surface of the cores. From this testing it can be concluded that there may not be potential for further reactivity in the concrete.

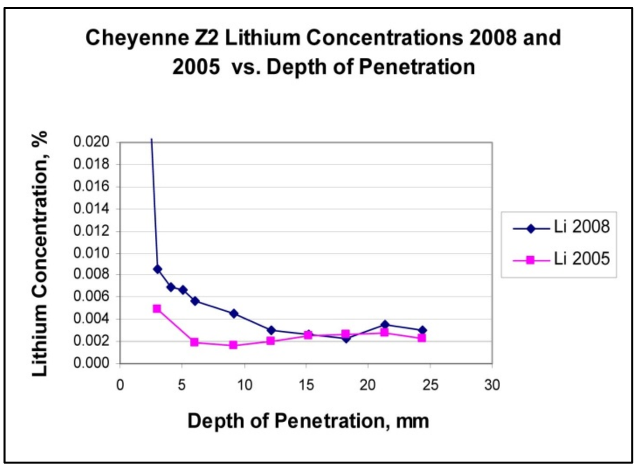

Figure 25: Graph Results Cheyenne Single Application - Lithium Concentration vs. Depth of Penetration 2005 & 2008

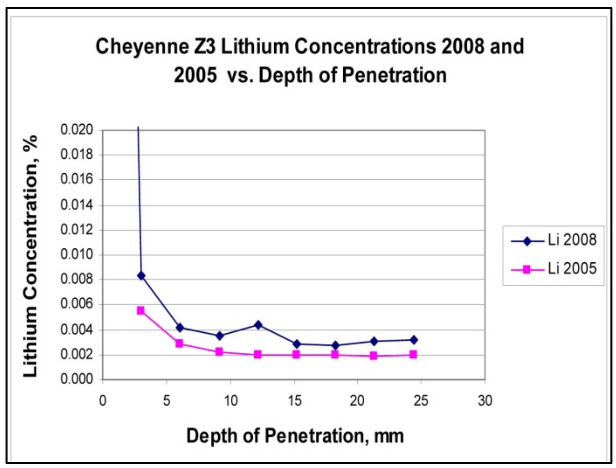

Figure 26: Graph Results Cheyenne Multiple Applications - Lithium Concentration vs. Depth of Penetration 2005 & 2008

The results of the lithium profile testing are shown in Figures 25 and 26 for Zone 2 (one lithium application) and Zone 3 (multiple lithium applications) respectively. They are compared to the 2005 results in % by mass of concrete. The core surfaces were noted to be visibly cracked. The full testing report is found in Appendix 5. From these results, it can be seen that multiple lithium treatments did not affect the depth of penetration over one application: both the Multiple Application Zone (Zone 3) and the Single Application Zone (Zone 2) had the same depth of lithium penetration (3mm). When comparing this data to the amount of alkali loading in the cores we can determine the molar ratio of lithium per alkali equivalent ratio.

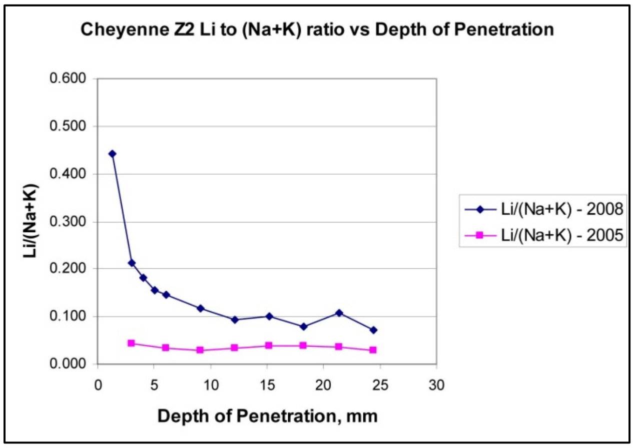

Figure 27: Graph Results Cheyenne Single Application - Lithium to Alkali Equivalent Ratio vs. Depth of Penetration 2005 & 2008

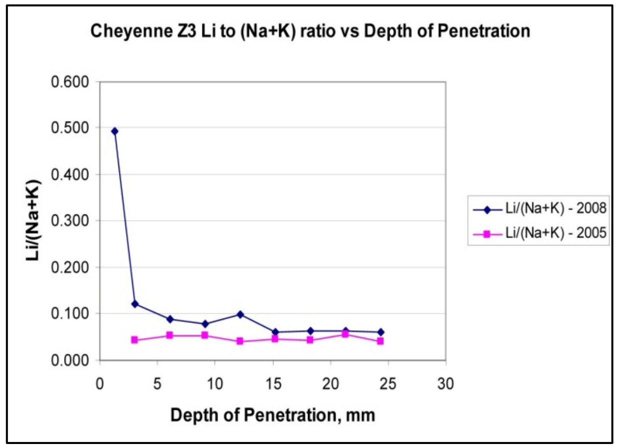

Figure 28: Graph Results Cheyenne Multiple Applications - Lithium to Alkali Equivalent Ratio vs. Depth of Penetration 2005 & 2008

The test report explains that a typical molar ratio of 0.74 for lithium per alkali (Li/N+K) is the guide for the use of lithium as an admixture in new concrete in order to prevent ASR expansion of concrete in for new construction. It was also suggested that approximately half of that amount of lithium would be bound during cement hydration and it suggest a ratio of 0.37. Therefore a measurement of successful treatment could be to compare the molar ratios achieved from the application of lithium. From Figures 27 and 28 it can be seen that this ratio is exceeded only in the shallowest depths.

4.1.2 Phoenix Sky Harbor International Airport (PHX)

Testing reports for the initial characterization cores removed September 15, 2005 can be found in Appendix 1. It includes the results of the Standard Test Method for Density, Absorption, and Voids in Hardened Concrete - ASTM C 642, of Rate of Absorption ASTM C 1585 and of CRD-C 39-81 Test Method for Coefficient of Linear Thermal Expansion of Concrete.

The Damage Rating Index has been determined using full-depth cores using the petrographic methodology as developed by Mr. Patrick Grattan-Bellew. The report for the analysis of the initial cores taken from PHX confirmed ASR was present in all cores. Figure 29 shows the DRI from the three cores. Because the thickness of the concrete in the ramp area was longer than the length of the available core bit, each core location consisted of two parts. P1 is the top piece whereas P2 is the bottom piece. In the case of Zone 3 P1 and P2 the notation was erroneously reversed due to a notation error. The report stated an unexpected result where DRI of the top portion of Zone 1 was 127, the bottom portion was 50 and the mean for Zones 2 and 3 was a DRI of 43. This unexpectedly high number may be simply a sampling error and therefore may be considered an outlier in these results. The results of the remaining cores suggest the concrete may exhibit some mild cracking. The full report from the petrographic examination is included in Appendix 3.

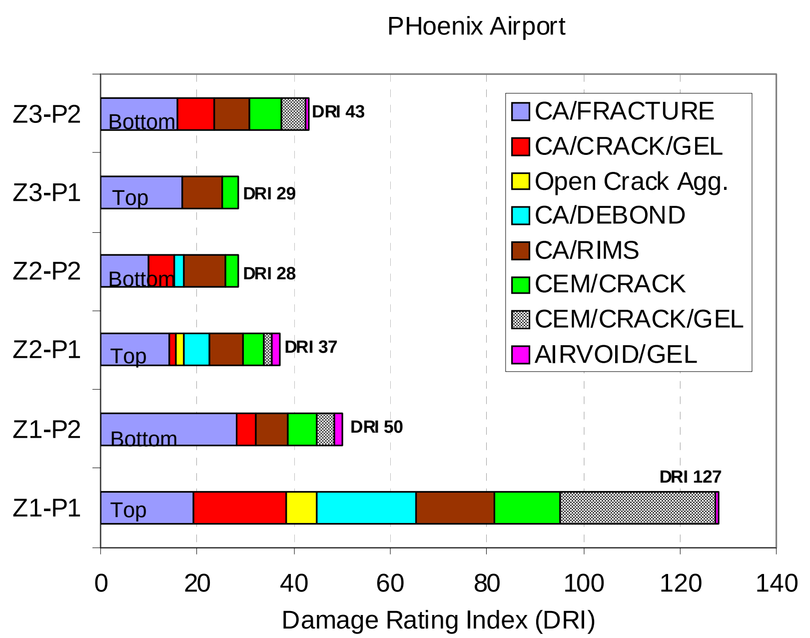

Figure 29: Chart showing Damage Rating Index (DRI) of cores from Phoenix Sky Harbor International Airport

Table 4 and Figure 30 show the sodium equivalent alkalis using "Measurement of the Alkali Content of Concrete Using Hot-Water Extraction by Marc-Andre Berube." from the initial characterization cores removed September 15, 2005.

Table 4: Initial Sodium Equivalent Alkalis - Phoenix

Depth	Phoenix Sodium Equivalent, kg/m^3		
mm	Zone 1	Zone 2	Zone 3
3.048	7.18	8.07	6.53
6.096	4.47	9.66	8.03
9.144	3.36	10.28	6.33
12.192	2.66	4.85	4.61
15.240	2.25	3.89	3.73
18.288	***	3.48	3.47
21.336	***	3.51	3.35
24.384	***	4.23	3.15
150.00	3.14	2.91	2.62
Averages	**3.84**	**5.65**	**4.65**

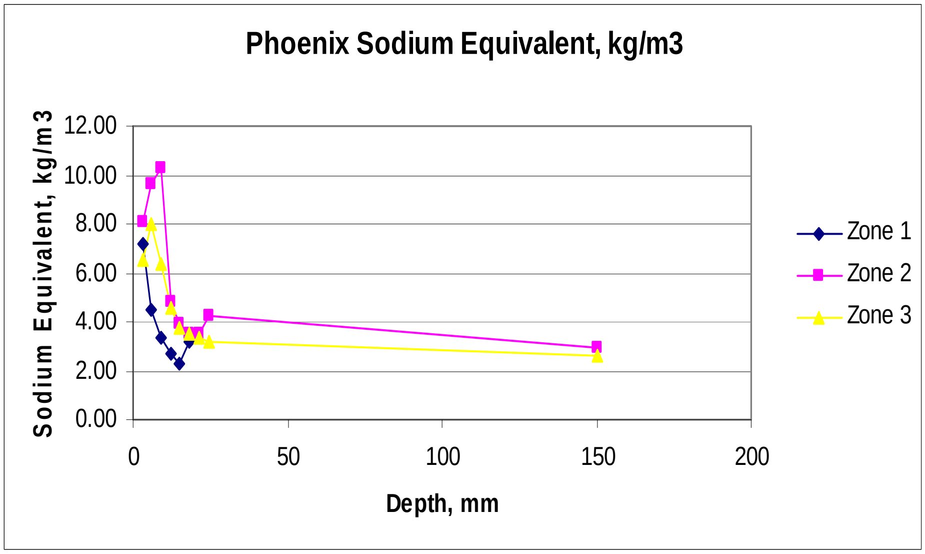

Figure 30: Graph Results of Alkali Sodium Equivalent at Phoenix Sky Harbor International Airport

Figure 30 shows the sodium equivalent of alkalis in the concrete in all zones was near or above the Canadian Standards guideline stated threshold (3.0 kg/m^3) at the depths tested on the cores. From this testing it can be concluded that there is a potential for further reactivity in the concrete.

The results of the lithium profile testing are shown in Figures 31 and 32 for Zone 2 (one lithium application) and Zone 3 (multiple lithium applications) respectively. They are compared to the 2005 results in % by mass of concrete and are shown in Figures 29 and 30. The core surfaces were noted to be visibly cracked. The full testing report is found in Appendix 5.

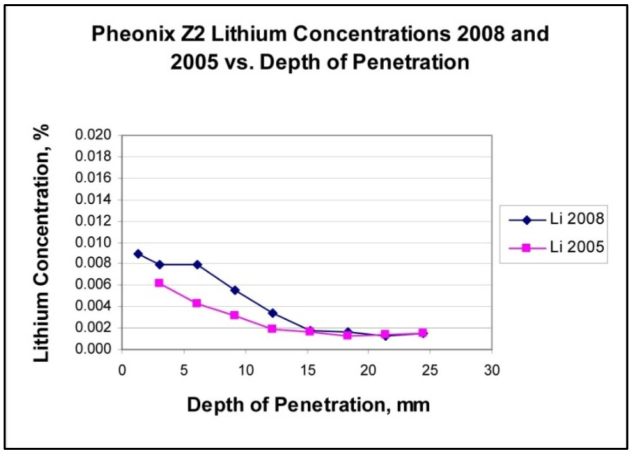

Figure 31: Graph Results Phoenix Single Application - Lithium Concentration vs. Depth of Penetration 2005 & 2008

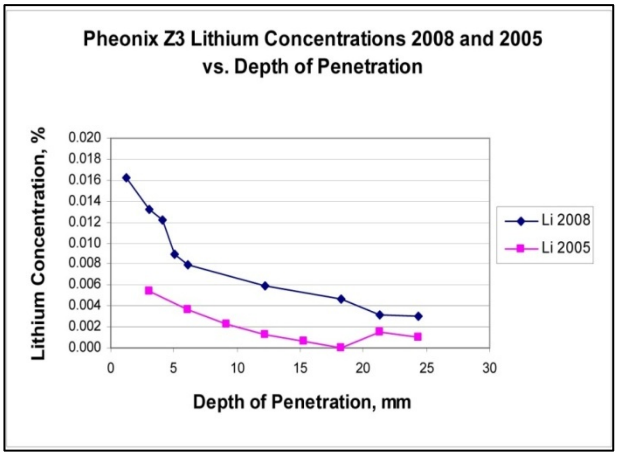

Figure 32: Graph Results Phoenix Multiple Applications Lithium Concentration vs. Depth of Penetration 2005 & 2008

From these results, it can be seen that multiple lithium treatments have increased the depth of penetration over one application: the Multiple Application Zone (Zone 3) penetrated deeper (21 mm) and the Single Application Zone (Zone 2) had not penetrated as deeply (14 mm). When comparing this data to the amount of alkali loading in the cores we can determine the molar ratio of lithium per alkali equivalent ratio.

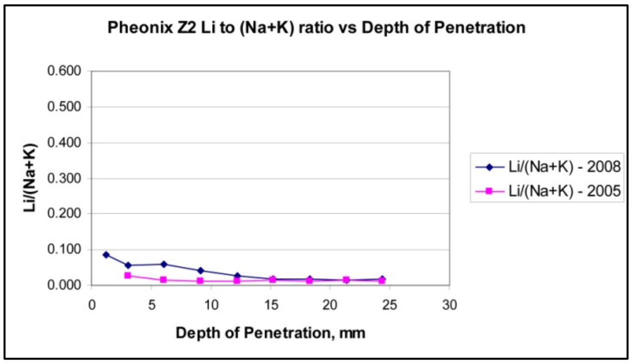

Figure 33: Graph Results Phoenix Single Application - Lithium to Alkali Equivalent Ratio vs. Depth of Penetration 2005 & 2008

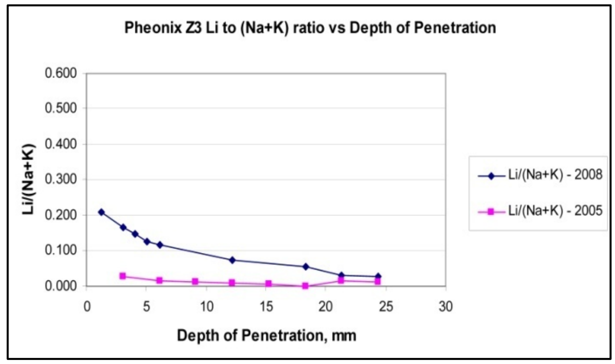

Figure 34: Graph Results Phoenix Multiple Application - Lithium to Alkali Equivalent Ratio vs. Depth of Penetration 2005 & 2008

Comparing the resultant ratio of lithium per alkali equivalent of the treated zones we can see that the Multiple Application Zone has a higher ratio. However either location fails to reach the theorized level: from Figures 33 and 34 it can be seen that this ratio isn't ever exceeded.

4.1.3 Hartsfield-Jackson Atlanta International Airport (ATL)

Testing reports for the initial characterization cores removed November 14, 2005 can be found in Appendix 1. It includes the results of the Standard Test Method for Density, Absorption, and Voids in Hardened Concrete - ASTM C 642, of Rate of Absorption ASTM C 1585 and of CRD-C 39-81 Test Method for Coefficient of Linear Thermal Expansion of Concrete.

The Damage Rating Index was determined using full-depth cores using the petrographic methodology as developed by Mr. Patrick Grattan-Bellew. The report for the analysis of the initial cores taken from ATL confirmed signs of ASR were present in all cores. The report also stated a mean DRI of 14 for Area 1 and 37 for Area 2 which corresponds to an expansion of ~0.02% and ~0.05% respectively. This would indicate in Area 1 there would be little cracking dues to ASR and only mild cracking in Area 2. The full report from the petrographic examination is included in Appendix 4. Figure 35 shows the DRI from all cores. Note the difference in Area 1 and Area 2 cores. The DRI from the cores supports the difference between the two ages of runway.

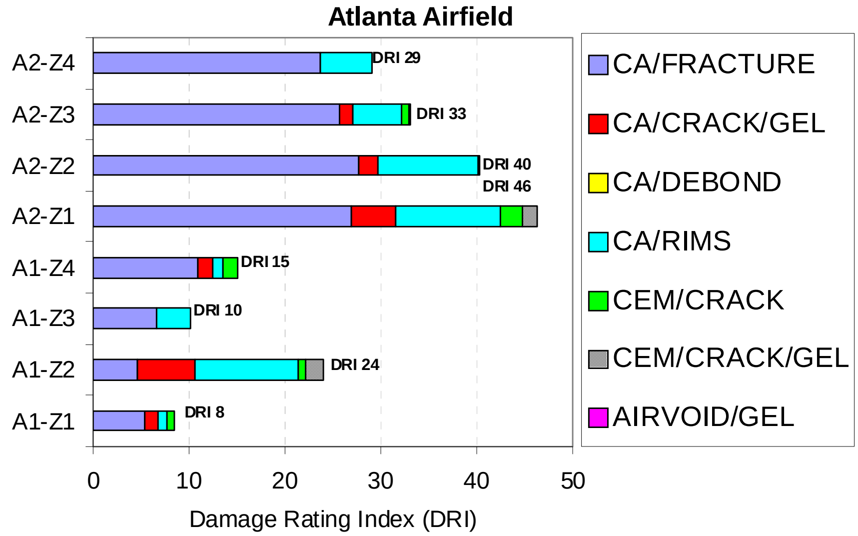

Figure 35: Chart showing Damage Rating Index (DRI) of cores from Hartsfield-Jackson Atlanta International Airport

Tables 5 and 6 and Figures 36 and 37 show the sodium equivalent alkalis using "Measurement of the Alkali Content of Concrete Using Hot-Water Extraction by Marc-Andre Berube." from the initial characterization cores removed November 14, 2005.

Table 5: Initial Sodium Equivalent Alkalis - Atlanta Area 1

Depth	Atlanta (Area 1) Sodium Equivalent, kg/m^3			
mm	Zone 1	Zone 2	Zone 3	Zone 4
3.048	1.99	3.01	2.44	1.97
6.096	2.52	2.94	2.66	1.88
9.144	2.98	1.97	2.85	1.80
12.192	2.65	1.79	2.30	2.00
15.240	2.22	1.59	2.10	2.02
18.288	2.35	2.18	2.45	1.97
21.336	2.59	2.27	1.87	2.16
24.384	2.33	1.58	2.89	2.10
150.00	2.30	2.65	1.95	2.69
Averages	**2.44**	**2.22**	**2.39**	**2.07**

Table 6: Initial Sodium Equivalent Alkalis - Atlanta Area 2

Depth	Atlanta (Area 2) Sodium Equivalent, kg/m^3			
mm	Zone 1	Zone 2	Zone 3	Zone 4
3.048	4.03	3.77	4.53	5.18
6.096	2.45	2.76	2.90	3.21
9.144	1.94	2.71	2.71	2.95
12.192	2.05	2.60	2.76	2.97
15.240	2.02	2.72	2.80	2.77
18.288	2.06	2.73	2.95	2.92

21.336	2.07	2.69	3.15	3.09
24.384	2.55	2.86	3.24	3.38
150.00	2.24	3.07	2.69	3.00
Averages	**2.38**	**2.88**	**3.08**	**3.27**

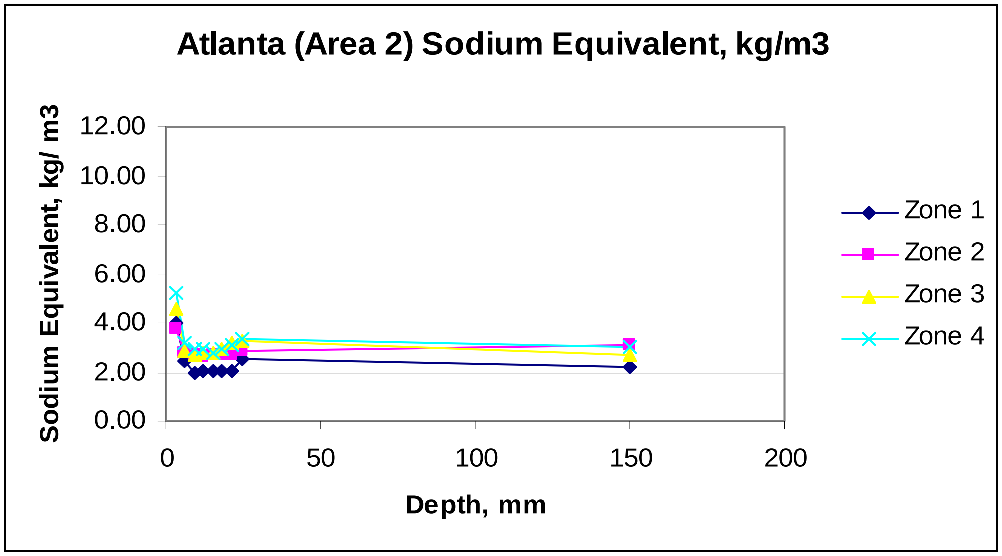

Figure 36: Graph Results of Alkali Sodium Equivalent of Area 2 at Hartsfield-Jackson Atlanta International Airport

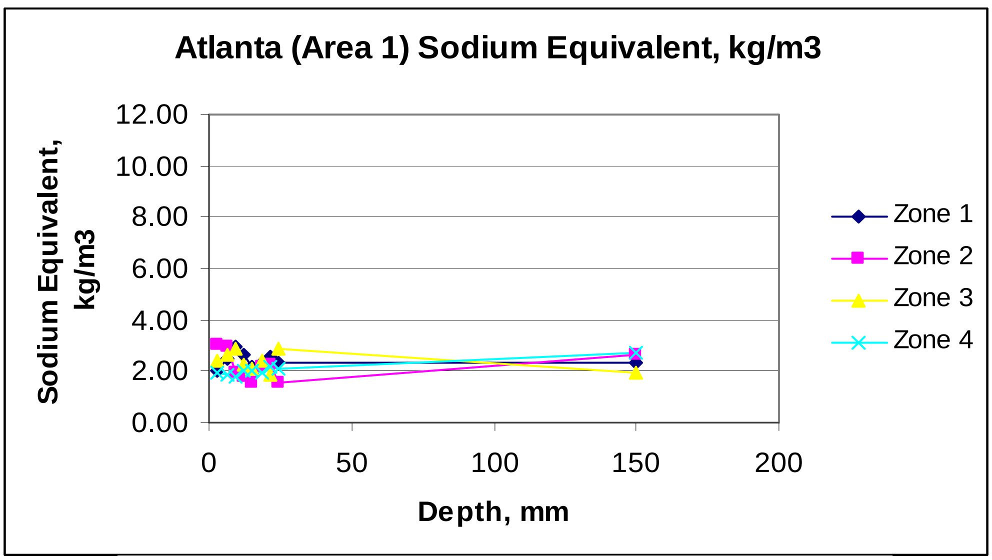

Figure 37: Graph Results of Alkali Sodium Equivalent of Area 1 at Hartsfield-Jackson Atlanta International Airport

Figures 36 and 37 show the sodium equivalent of alkalis in the concrete in all zones in Area 1 are lower than the Canadian Standards guideline stated threshold (3.0 kg/m^3) at nearly all depths tested on the cores. In Area 1 it can be concluded that there may not be potential for further reactivity in the concrete. However in Area 2 the sodium equivalent of alkalis in the concrete in all zones was near or above this threshold level in many of the locations and depths tested. In Area 2 it can be concluded that there is a potential for further reactivity in the concrete.

The results of the lithium profile testing are shown below for Area 1 Zone 1 (one lithium application) and Zone 3 (multiple lithium applications) as well as Area 2 Zone 1 and Area 2 Zone 3 respectively. They are compared to the 2005 results in % by mass of concrete and are shown in Figures 38, 39 and 40, 41. The core surfaces were noted to be visibly cracked. The full testing report is found in Appendix 5. The pavement surfaces had transverse saw cut grooves. The surfaces of the cores were noted to be visibly cracked.

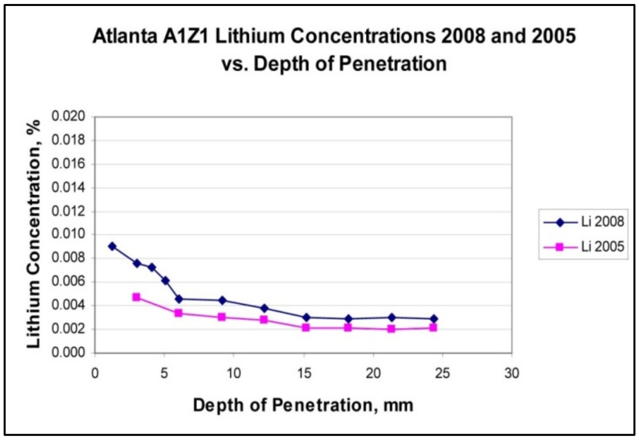

Figure 38: Graph Results Atlanta Area 1 Single Application - Lithium Concentration vs. Depth of Penetration 2005 & 2008

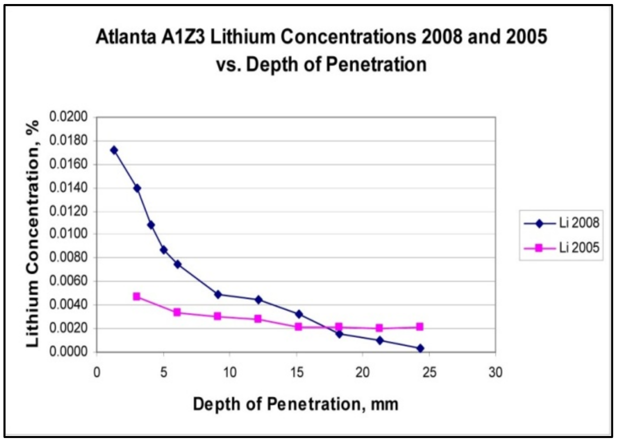

Figure 39: Graph Results Atlanta Area 1 Multiple Applications - Lithium Concentration vs. Depth of Penetration 2005 & 2008

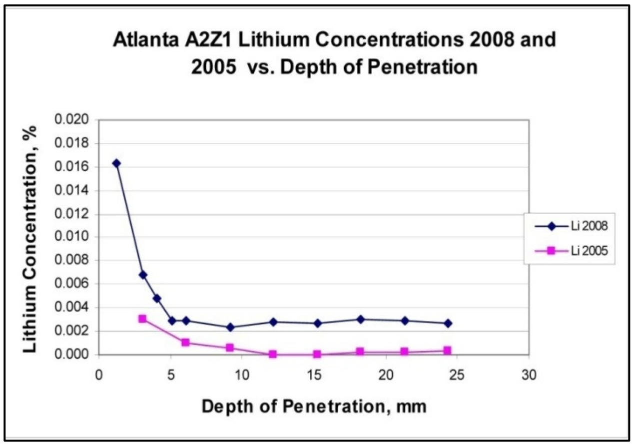

Figure 40: Graph Results Atlanta Area 2 Single Application - Lithium Concentration vs. Depth of Penetration 2005 & 2008

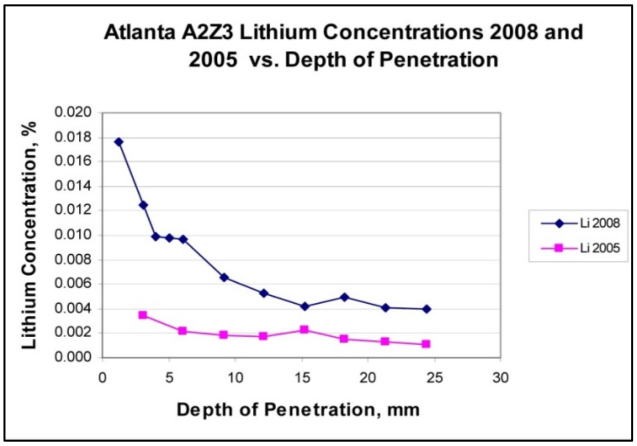

Figure 41: Graph Results Atlanta Area 2 Multiple Applications - Lithium Concentration vs. Depth of Penetration 2005 & 2008

From these results, it can be seen that multiple lithium treatments have increased the depth of penetration (Zones 3: 15-18 mm) over one application (Zone 1: 5-6 mm). When comparing this data to the amount of alkali loading in the cores we can determine the molar ratio of lithium per alkali equivalent ratio.

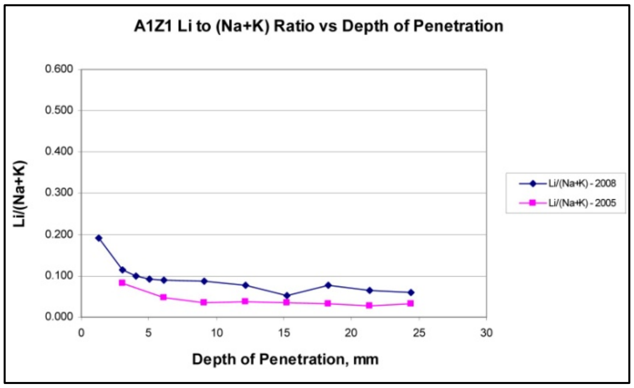

Figure 42: Graph Results Atlanta Area 1 Single Application - Lithium to Alkali Equivalent Ratio vs. Depth of Penetration 2005 & 2008

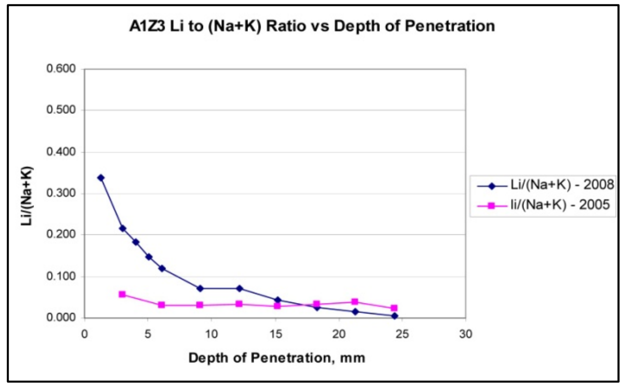

Figure 43: Graph Results Atlanta Area 1 Multiple Applications - Lithium to Alkali Equivalent Ratio vs. Depth of Penetration 2005 & 2008

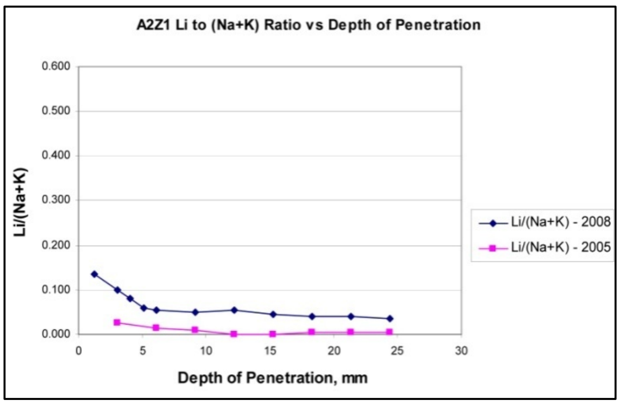

Figure 44: Graph Results Atlanta Area 2 Single Application - Lithium to Alkali Equivalent Ratio vs. Depth of Penetration 2005 & 2008

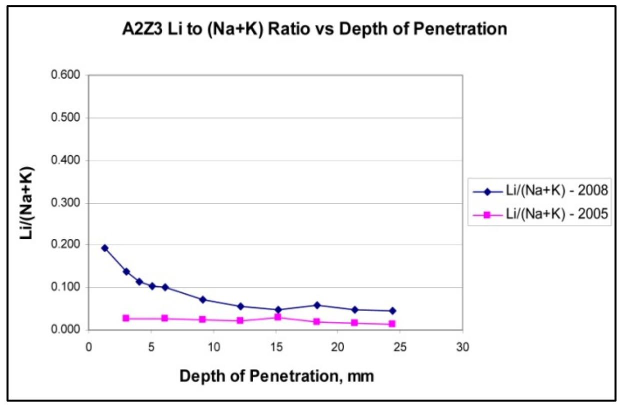

Figure 45: Graph Results Atlanta Area 2 Multiple Applications - Lithium to Alkali Equivalent Ratio vs. Depth of Penetration 2005 & 2008

Comparing the resultant ratio of lithium per alkali equivalent of the treated zones we can see that the Multiple Application Zone has a higher ratio. However only in Area 1 Zone 3 does the ratio surpass the theorized level, likely due to the lower level of alkali loading.

4.2 VISUAL SURVEY

In an attempt to track the effect of lithium treatment two types of visual surveys have been completed three times over the course of 4 years. These surveys were performed in accordance with FAA Advisory Circular AC 150/5380-8 "Handbook for Identification of Alkali-Silica Reactivity in Airfield Pavements" and ASTM D5340-03 "Standard Test Method for Airport Pavement Condition Index Surveys". Calculation of Pavement Condition Indexes (PCI) from ASTM D5340-03 can be found in Appendix 7 as well as year to year photos in Appendix 8.

4.2.1 Cheyenne Regional Airport (CYS)

Table 7: PCI Assessments from ASTM D5340-03 of Cheyenne Regional Airport

Location	Date	PCI	Rating	Percent Change
Zone 1 Control	July 2005	62.5	Good	-
	September 2006	59	Good	-5.6%
	August 2008	54	Fair	-13.6%
Zone 2 Single Application	July 2005	51	Fair	-
	September 2006	50.5	Fair	-1.0%
	August 2008	49	Fair	-3.9%
Zone 3 Multiple Application	July 2005	42	Fair	-
	September 2006	38	Poor	-9.5%
	August 2008	36	Poor	-14.3%

From the surveys at CYS, changes have been noted in the individual distress levels from the initial survey to the subsequent surveys. These changes observed, including the apparition of new distresses as well as the increase in severity of old ones, show a constant reduction in PCI with the most reduction being 14%. The Control Zone underwent the same level of change in its PCI as did the Multiple Application Zone, with the Single Application Zone undergoing the least amount of change. When looking at the PCI results it just as important to examine the changes in the individual distresses (Appendix 7). The Control Zone showed an increase in slabs with longitudinal cracks and durability cracking. Single Application Zone showed an increase in slabs with map cracking, longitudinal cracks and corner spalling. The Multiple Application Zone increased in the number of slabs with longitudinal cracks and joint spalling.

Table 8: ASR Features Score from Visual Inspection from FAA Advisory Circular AC 150/5380-8 Cheyenne Regional Airport

Location	Date	Score	Score Change
Zone 1 Control	July 2005	11	-
	September 2006	12	+1
	August 2008	14	+3
Zone 2 Single Application	July 2005	17	-
	September 2006	19	+2
	August 2008	21	+4
Zone 3 Multiple Application	July 2005	18	-
	September 2006	19	+1
	August 2008	26	+8

From the totals obtained in the FAA scores, the Control and Single Application Zones have only degraded somewhat with the Multiple Application Zone showing the most change. The FAA scores are for more specific ASR-related deterioration, and coincide with the degradation of the PCI scores because this was due to distresses associated with ASR (map cracking, joint spalling, etc.) The distresses found initially in Zone 3 did not seem to be slowed or halted. This may be that the already low PCI rating of the section has prevented it from receiving the full benefit of the treatment and is already “too far gone”.

4.2.2 Phoenix Sky Harbor International Airport (PHX)

Table 9: PCI Assessments from ASTM D5340-03 of Phoenix Sky Harbor Airport

Location	Date	PCI	Rating	Percent Change
Zone 1 Control	September 2005	77.5	Very Good	-
	September 2006	78	Very Good	0.6%
	November 2008	77	Very Good	-0.6%
Zone 2 Single Application	September 2005	74	Very Good	-
	September 2006	69	Very Good	-8.0%
	November 2008	64	Very Good	-13.5%
Zone 3 Multiple Application	September 2005	74	Very Good	-
	September 2006	67	Very Good	-9.5%
	November 2008	62	Very Good	-16.2%

From the surveys at PHX, changes have been noted in the individual distress levels from the initial survey to the subsequent surveys. The Control Zone underwent the least amount of change out of the three. When looking at the PCI results it just as important to examine the changes in the individual distresses (Appendix 7). Control Zone showed an increase in slabs showing map cracking and joint spalling. Single Application Zone showed an increase in slabs with map cracking as well as a deterioration of the utility cut patching. And the Multiple Application Zone deteriorated in the same way, an increase in the number of slabs showing map cracking and deterioration of the utility cut patching.

Table 10: ASR Features from Visual Inspection from FAA Advisory Circular AC 150/5380-8 of Phoenix Sky Harbor Airport

Location	Date	Score	Score Change
Zone 1 Control	September 2005	10	-
	September 2006	15	+5
	November 2008	17	+7
Zone 2 Single Application	September 2005	5	-
	September 2006	5	0
	November 2008	8	+3
Zone 3 Multiple Application	September 2005	2	-
	September 2006	4	+2
	November 2008	6	+4

The largest change in the FAA survey score is found in the Control Zone. This is contrast to the PCI survey where the Control Zone showed the least change in PCI rating. Airport personnel did not report any FOD creation or maintenance issues in the testing area or differences in the Control Zone or the Application Zones. In can likely be concluded that the higher changes in

PCI in application zones can be attributed to distresses not associated with ASR specific deterioration. This is supported by the field observations which from year-to-year showed increased deterioration in the areas where surface markings were removed by mechanical means, which led to further deterioration of the joint material and some level of edge spalling as well as deterioration of utility patch deterioration.

4.2.3 Hartsfield-Jackson Atlanta International Airport (ATL)

Table 11: PCI Assessments from ASTM D5340-03 of Area 1 Hartsfield-Jackson Atlanta International Airport

Location	Date	PCI	Rating	Percent Change
Zone 1 Control	November 2005	87	Excellent	-
	December 2006	83	Very Good	-4.6%
	October 2008	78	Very Good	-10.3%
Zone 2 Single Application	November 2005	81	Very Good	-
	December 2006	78	Very Good	-3.7%
	October 2008	76	Very Good	-6.2%
Zone 3 Control	November 2005	80	Very Good	-
	December 2006	80	Very Good	0.0%
	October 2008	79.5	Very Good	-0.6%
Zone 4 Multiple Application	November 2005	78	Very Good	-
	December 2006	76	Very Good	-2.6%
	October 2008	71	Very Good	-9.0%

Table 12: PCI Assessments from ASTM D5340-03 of Area 2 Hartsfield-Jackson Atlanta International Airport

Location	Date	PCI	Rating	Percent Change
Zone 1 Control	November 2005	73	Very Good	-
	December 2006	72	Very Good	-1.4%
	October 2008	74	Very Good	1.4%
Zone 2 Single Application	November 2005	76	Very Good	-
	December 2006	76	Very Good	0.0%
	October 2008	76	Very Good	0.0%
Zone 3 Control	November 2005	79	Very Good	-
	December 2006	79	Very Good	0.0%
	October 2008	79	Very Good	0.0%
Zone 4 Multiple Application	November 2005	81	Very Good	-
	December 2006	79	Very Good	-2.7%
	October 2008	81	Very Good	0.0%

From the surveys at the two locations in ATL, changes have been noted in the slab distresses from the initial survey to the subsequent surveys however these essentially made no change to the PCI rating. In Area 1, the Control Zone (Zone 1) for the Single Application Zone (Zone 2) experienced a higher change in PCI score, however only slightly. Control Zone showed an increase in individual deterioration types, including joint deterioration, which subsequently increased in severity. The only change in the Single Application Zone was of the apparent appearance of map cracking in a few slabs over the course of testing. The Control Zone (Zone 3) for the Multiple Application Zone (Zone 4) experience relatively no change in PCI score, whereas the Multiple Application Zone experienced a nearly 10% decrease in score. Control Zone showed an increase in the number of slabs that were showing shrinkage cracking. Multiple Application Zone showed a slight increase in the number of slabs that were showing shrinkage cracking and patching but the greatest deterioration from the appearance of a longitudinal crack.

Area 2 showed few to no changes in all zones. This area was in worse condition than Area 1 and it was assumed that it would continue to deteriorate at the same rate as Area 1. This assumption was supported by the petrographic analysis which suggested Area 2 had a higher percentage of expansion and sodium equivalent testing showed levels over threshold.

Table 13: ASR Features from Visual Inspection from FAA Advisory Circular AC 150/5380-8 of Area 1 Hartsfield-Jackson Atlanta International Airport

Location	Date	Score	Score Change
Zone 1 Control	November 2005	3	-
	December 2006	3	0
	October 2008	3	0
Zone 2 Single Application	November 2005	4	-
	December 2006	6	+2
	October 2008	5	+1
Zone 3 Control	November 2005	4	-
	December 2006	4	0
	October 2008	5	+1
Zone 4 Multiple Application	November 2005	1	-
	December 2006	1	0
	October 2008	1	0

Table 14: ASR Features from Visual Inspection from FAA Advisory Circular AC 150/5380-8 of Area 2 Hartsfield-Jackson Atlanta International Airport

Location	Date	Score	Score Change
Zone 1 Control	November 2005	8	-
	December 2006	8	0
	October 2008	9	+1
Zone 2 Single Application	November 2005	7	-
	December 2006	8	+1
	October 2008	10	+3
Zone 3 Control	November 2005	4	-
	December 2006	4	0
	October 2008	6	+2
Zone 4 Multiple Application	November 2005	8	-
	December 2006	8	0

	October 2008	8	0

Much like PCI ratings, the FAA numbers did not experience much change over the course of the survey, with many zones experiencing no change whatsoever. Airport personnel did not report any differences in the Control Zone or the Application Zones. This is supported by the types of deterioration seen in the PCI survey's where little if any change was observed in ASR specific types of deterioration. Few changes have been noted in the individual distresses from the initial survey to the anniversary surveys. The initial survey showed distresses and in the time that elapsed between surveys, any observed changes were minimal.

4.3 EXPANSION AND MOVEMENT

The extensometer measurements were corrected as to accommodate thermal expansion of the concrete using the average coefficient of lineal thermal expansion of the cores removed from each zone during the initial characterization testing. The numbers presented in Tables 15 to 18 are average percent change of the same direction of measurement (either longitudinal or transverse) during the different measurement period.

4.3.1 Cheyenne Regional Airport (CYS)

Table 15: Percent Change in Extensometer Measurements – Cheyenne Regional Airport

Average % Change	2005-2006		2006-2008		2005-2008	
	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse
Zone 1 Control	0.004%	0.025%	-0.005%	0.060%	-0.003%	0.076%
Zone 2 Single Application	0.022%	0.059%	-0.023%	0.114%	0.025%	0.167%
Zone 3 Multiple Application	0.019%	0.054%	0.023%	0.066%	0.042%	0.112%

The changes in size at CHY show expected trends. It would stand to reason if the concrete is undergoing continued expansion due to ASR then the likely direction for expansion would be in the transverse direction. In the longitudinal direction, the concrete is confined by the entire length of taxiway which would prevent any size change, however in the width or transverse direction the concrete is bordered by soil only. Expansion has occurred and most notably in the Zones 2 and 3. This expansion would serve to account for the increase in deterioration in these two zones over the course of the testing. With a larger expansion in the transverse direction as well as some expansion in the longitudinal direction despite confinement, cracking of increasing severity is likely to occur.

4.3.2 Phoenix Sky Harbor International Airport (PHX)

Table 16: Percent Change in Extensometer Measurements – Phoenix Sky Harbor International Airport

Average % Change	2005-2006		2006-2008		2005-2008	
	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse
Zone 1 Control	-0.041%	-0.021%	-0.023%	-0.020%	-0.050%	-0.049%
Zone 2 Single Application	-0.003%	-0.011%	-0.011%	0.029%	-0.008%	0.008%
Zone 3 Multiple Application	-0.012%	-0.011%	0.038%	0.035%	0.017%	0.034%

The test section in PHX is a terminal apron area and does not have easily defined longitudinal and transverse directions. It is therefore assumed that these designations should correspond to the direction of aircraft travel: longitudinal direction was defined as perpendicular to the terminal building S3 and in the direction of aircraft parking at the jet way and transverse was assumed parallel to the terminal building and perpendicular to the aircraft when parked. However, the expansion measurements from PHX are difficult to interpret. Because the testing area is not a taxiway or runway, there is no specific direction where expansion is expected to manifest. Therefore there are many average percent changes that are negative. However the resistance to movement would induce compression stress in the concrete to varying degrees that may mask the true expansion of the pavement. While testing for compressive strains was outside the indeed scope of the project, the expansion observed in the transverse direction at the other sites supports this theory. Some expansion was measured in Zone 3 which is the furthest from the terminal building and nearest to the edge of the apron. With less adjacent panels to resist the expansion due to ASR, this zone has shown to have expanded the most.

4.3.3 Hartsfield-Jackson Atlanta International Airport (ATL)

Table 17: Percent Change in Extensometer Measurements – Hartsfield-Jackson Atlanta International Airport Area 1

Area 1 Average % Change	2005-2006		2006-2008		2005-2008	
	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse
Zone 1 Control	0.006%	0.023%	0.018%	0.003%	0.020%	0.039%
Zone 2 Single Application	-0.017%	-0.014%	0.031%	0.037%	0.014%	0.026%
Zone 3 Control	0.007%	0.000%	0.014%	0.034%	0.021%	0.032%
Zone 4 Multiple Application	0.001%	0.000%	0.035%	-0.007%	0.033%	0.003%

Table 18: Percent Change in Extensometer Measurements – Hartsfield-Jackson Atlanta International Airport Area 2

Area 2 Average % Change	2005-2006		2006-2008		2005-2008	
	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse
Zone 1 Control	0.001%	0.011%	-0.001%	0.006%	0.000%	0.006%
Zone 2 Single Application	-0.016%	-0.016%	-0.004%	0.014%	-0.020%	0.002%
Zone 3 Control	-0.005%	-0.022%	-0.006%	0.018%	-0.011%	-0.009%
Zone 4 Multiple Application	-0.010%	-0.025%	0.005%	0.038%	-0.005%	0.003%

The immediate trend when comparing the measurement changes in both areas is the difference in change between Area 1 and 2. Area 1 had shown more changes in dimension than Area 2. In addition, with the exception of Zone 4, all zones showed larger expansion in the transverse direction, which is expected, however they also showed somewhat significant expansion in the longitudinal direction as well. This is different than Area 2 which shows very little expansion in either direction except for between 2006 and 2008 which seems to be an expansion after an apparent contraction in 2005 to 2006. However, when looking at the overall change from 2005 to 2008 very little change is seen in Area 2. These results are consistent with the results of the visual survey; the more expansion in Area 1 has led to more visible signs of deterioration, and Area 2 which has shown very little dimensional change also showed little visual deterioration.

5. DISCUSSION

Full scale application of the lithium treatment was performed with a pull behind spray unit. In a larger application, a longer boom width would better serve applicators to prevent long applications times and minimize disruption to airport facilities. The use of a pre-wetting phase seemed not to show any added benefit, in either daylight (Cheyenne Regional) or in nighttime application (Phoenix Sky Harbor). However there was a large benefit to the post-wetting phase. After application of the lithium product, there was a large amount of lithium salt crystallization on the surface of the concrete due to evaporation of the solution liquid. The crystallized surface was found to be slightly slick and “greasy”. This effect was more prominent in application during daylight, and higher temperatures, likely due to higher rates of evaporation. A post-wetting cycle following the application helped re-dissolve the crystallization and allow it to penetrate into the concrete and minimize any “greasy” effects. Also to prevent this effect, the application of 4.5 gallons per 1000ft^2 was also done in two applications of 2.25 gallons per 1000ft^2 done on subsequent days. In order to work in conjunction with airport authorities, it is important to not minimize any interruption in their operations. Longer boom lengths, minimization of surface changes are import considerations when dealing with this type of treatment of concrete airport pavements.

Alkali testing has shown that in most cases the alkali content of the near-surface concrete tested above the threshold required for further reactivity at the surface. At greater depths however, the samples from CYS and Area 1 in ATL showed alkali levels lower than threshold, whereas samples from PHX and Area 2 in ATL showed alkali levels above or near threshold. Petrographic analysis of cores taken at the airports also showed that the initial deterioration observed was likely due the alkali-silica reactivity and therefore all areas should continue to show deterioration due to ASR.

In CHY and PHX the control zones showed less expansion in the transverse direction than the treated zones, however this unexpected result can be explained. The treated areas in CHY were more deteriorated in the beginning of the testing and the initial petrographic testing showed more reactive concrete. In PHX the treated zones were closer to the unconfined areas in the apron which may have allowed for addition expansion. This is despite the seemingly more highly reactive concrete found in the petrographic testing in Zone 1, which may be attributed to sampling outlier. In ATL we see similar, if not slightly larger amounts of expansion in the control zones versus the treated zones. The difference between the zones in ATL is however no more than 0.01%.

The two types of visual surveys have given an insight into the level of deterioration of the concrete surface during the testing period. Where Cheyenne showed an ever increasing level of deterioration, and a subsequent deterioration of serviceability, Atlanta and Phoenix's serviceability did not deteriorate quite as much. This is likely due to the initial state of the taxiway in Cheyenne. More cracking and joint deterioration in this location simply continued to deteriorate and was seemingly not kept in check by the topical application of lithium salts and was perhaps too far gone to receive any benefit. In Cheyenne the initial characterization testing determined that this location was showing the most susceptibility for ASR and visually the highest level of deterioration, with PCI rating in the "Good" to "Fair" range. While the other two locations began the testing with PCI ratings in the "Excellent" to "Very Good" range and during the testing changed very little. It may be concluded from this observation that whatever benefit is received from the application of lithium salts may best be served by airport pavements that are in the initial stages of deterioration.

These visual surveys did however have their limitations. The surveyor's bias can be affected year to year when looking at the same area, either looking for difference in the concrete or perhaps seeing distressed that existed previously but were missed and subsequently assumed to be new. The FAA advisory's limitation lies in the nature of the document. It is inherently a tool for the identification of ASR in airfield pavements, and may be ill-suited for the tracking of the deterioration over a period of time. This visual survey which looks for specific ASR-related deteriorations with the added modifiers may be better served with more detail similar to the ASTM survey in order to properly score the different modifiers in order to track the changes over time. Rather than simply providing a score based on the degree of severity, it may consider detailing these levels of severity for the modifiers. Another method of indicator of surface changes, the ROSAN measuring device may be used in order to compare results with the initial data taken before the start of treatment. With the measurement of the surface profile, it is theorized that if there are changes over time, that the ROSAN measurement device would be able to determine it. At this time however, the visual surveys remain somewhat inconclusive.

No change in deterioration or creation of foreign object debris was observed. Other than re-painting, the tested areas received little to no maintenance over the course of the study, with the exception of Hartsfield-Jackson which in Area 2 received rubber removal by mechanical means. Conversations with airport personnel did not reveal any difference in opinion, observation or maintenance issues between control and treated areas. This type of observation may only be seen after more years of service. If the treatment was effective in these cases, then after several more years it would be assumed that the deterioration would be more deleterious in the control zone. In the case of Cheyenne Regional, the multiple treatment zone (Zone 3) will likely require repair work in the near future. This may seem like a failure of the Lithium application however it is possible that due to the high level of deterioration present at the time of the application, the concrete deterioration was too far along to receive the benefit of the treatment.

At all sites, the penetration of the lithium salts into the concrete was measured. Lithium penetrated only the top layer of the concrete. At no site did it penetrate any further than 18mm and this was only observed in a multiple application zone. Penetration was measured deeper into the concrete in multiple application zones as compared to single application zones with the exception of the CYS test location. While this is the value that ASR expansion would be prevented it is unknown to what effect lesser ratios have on ASR, and is outside the scope of this study. In a few test locations this ratio was reached in the shallowest depths. With further applications and/or higher application rates this ratio may be achieved.

Despite similar absorption percentages and permeable voids the test areas in CYS showed far shallower penetration of the lithium than at in PHX. In ATL, where the penetration was the deepest for the multiple application zones, it has even lower absorption percentages and permeable voids. This may be a function of the environmental exposure of the sites. ATL is easily the most humid and receives the most precipitation, which would provide a mode of diffusion for the lithium salts to penetrate further into the concrete. While it is true PHX is the driest of the sites, the test location is at the terminal ramp areas where the airplanes are serviced on a daily basis which, at times, includes washing as well as filling with water. The final difference in the sites, which may affect the amount of penetration, would be that the application at CYS was done during the day, in summertime conditions. This may have caused loss of product and prevented it from penetrating well.

6. CONCLUSION

This study evaluated the effect of surface applied lithium salts to prevent the deterioration of concrete pavements suffering from ASR. These salts have shown potential to prevent further growth of ASR gel. The principal foci of this work was to evaluate the ability of lithium salt solutions to extend the functional service life of existing airfield pavement and reduce the generation of foreign object debris (FOD).

It is difficult to conclude if the topical application of lithium was successful at mitigating ASR in the tested airport pavements. Penetration rates were shallow, and therefore this treatment cannot be expected to provide mitigation to the entire thickness of the concrete pavement. In some of the test zones, the lithium/alkali ratio was over a theoretical threshold of 0.37 near the surface. In other test zones the lithium/alkali ratio did not reach 0.37. Higher lithium/alkali ratios may be achieved with additional applications and/or higher application rates.

No FOD generation was observed. Additional time is required to determine whether the treated areas will fare better than the control areas. In some cases the treated areas deteriorated less than the control areas when compared using the PCI rating system. In other cases the treated areas deteriorated more than the control areas when compared using the PCI rating system. Generally, significant change of major deterioration indicators such as crack expansion, joint raveling and further cracking were not observed during the study period. With a longer timeframe for observation it could be determined if there is a difference in performance between the control and treated areas. Additional evaluation, at a later date would be likely to provide a clearer picture as to the long term performance of the topical application.

Areas with PCI ratings of “Fair” and below may be too deteriorated to receive benefit from treatment.

Growth and expansion was measured in all treated and untreated zones at all sites. Based on this study, topical application will not prevent excessive growth of thick airport pavements.

Additional monitoring of the field sites at a later date is recommended. Long term monitoring may provide a more definite conclusion regarding the effect of topical lithium treatment on reducing surface deterioration. Any benefit of the treatment will become measureable and apparent with time.

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