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SUMMARY REPORT

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Performance of Concrete in the Presence of Airfield Pavement Deicers and Identification of Induced Distress Mechanisms

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EXECUTIVE SUMMARY

Premature deterioration of concrete due to materials-related distresses has been observed with increased frequency in airfield pavements across the United States in the past two decades. The use of a new breed of deicing chemicals based on alkali-acetates and alkali-formates, starting in the early 1990s, has been suspected to be one of the significant reasons for the increase in the observed deterioration. Previous laboratory-based studies have found that the early-age deterioration in concrete is associated with exposure to deicers causing acceleration of the Alkali Silica Reaction (ASR) deterioration mechanism and consequent failure. However, no systematic forensic studies on the impact of these deicers on field concrete were conducted to correlate the lab findings with the field performance.

The principal objective of this study was to conduct forensic investigation of airfield pavements that exhibit materials-related distress and establish if the use of alkali acetate-based deicers on airfield pavements have any role in initiating or accelerating the damage. While the fundamental objective was to establish the underlying mechanisms involved in the premature failure of concrete pavements and correlate to what is being observed in the lab conditions, it was evident from previous studies that alkali acetate deicers were indeed capable of causing ASR distress in lab concrete, and therefore have a potential to cause similar distress in the field. Therefore, it was considered important to have a secondary objective of developing a quick and conservative test method that can be implemented to identify aggregate materials that are potentially susceptible to ASR phenomenon in the presence of deicing chemicals, so that potential problems associated with incompatible materials is minimized. Considering that the predominant deicer used in the field is based on potassium acetate, this deicer was exclusively used in this study.

Following a comprehensive forensic investigation on concrete pavements from eight different airports the results of forensic study showed that majority of the pavements exhibited significant evidence of ASR distress; however other materials-related distresses were also observed, including alkali-carbonate reaction, freeze-thaw induced damage and shrinkage cracking. Also, a suite of defects related to poor construction practices were observed in some pavements. These defects were confirmed through petrographic analysis and macroscopic examinations. In general, the hardened air content, strength, and modulus of elasticity of concrete appeared to be adequate in the majority of the concrete investigated. Examination of concrete to determine the depth of deicer

penetration into concrete showed that in the majority of airfield pavements, the deicer penetration depth was limited to 10 – 15 mm from the pavement surface. However, where concrete exhibited some cracking slightly deeper penetration of deicer was observed, preferentially along the cracks. The correlation between deicer usage and ASR occurrence was not strong due to lack of adequate deicer penetration into the pavement.

Based on the results from petrographic examination, SEM-EDX examination, and depth of deicer penetration studies it appears that the source of the ASR distress in pavements is inherent to the concrete mixture. Examination of specifications and mixture proportions of materials suggests that majority of the pavements investigated in this study were constructed when the specifications had not required adequate screening of aggregates for their reactivity or promoted the use of low-alkali cement. In pavements that were more recently constructed (i.e. when existing P-501 specifications required evaluating aggregate reactivity and use of effective ASR mitigation measures) the use of reactive aggregates in combination with the ineffective ASR mitigation measures (i.e. using 15% Class C fly ash) was responsible for the observed deterioration. Even though the topical application of KAc deicer may not have yielded adequate level of alkalis needed for active ASR distress throughout the thickness of the pavement, it is quite likely that the on-going ASR distress in the pavements may have been exacerbated by other indirect mechanisms of deicers such as maintaining a high relative humidity in the pavement owing to the hygroscopic nature of the potassium acetate deicer. However, this mechanism was not explored in the present studies.

Another distress mechanism in which deicers can actively play a role is in the freeze-thaw damage of concrete. In this investigation, a deicer-modified ASTM C 666 testing regime was implemented to evaluate the impact of potassium acetate deicer on the premature deterioration of field concrete. The results from these tests showed that concrete subjected to periodic exposure of potassium acetate deicer can undergo significant deterioration, compared to control specimens that were subjected to plain water. The specimens used in both regimens of the modified ASTM C 666 test method were sectioned from the same core and therefore the air-void characteristics of concrete were very similar to each other. The precise mechanism by which potassium acetate deicer is enhancing the freeze-thaw damage in an air-entrained concrete is not yet known, and needs further fundamental investigation. Similar observations are being made when urea deicer is being used, although research on this subject is on-going and will be presented later.

Although the direct relation between KAc deicer and ASR distress in the field concrete could not be established the potential for their deleterious interactions cannot be ruled out, particularly if conditions permit excessive deicer penetration into concrete. Results from previous laboratory studies show that there is strong potential for acceleration of ASR if the deicer was readily available in a concrete specimen containing reactive aggregates. Based on these results, it was considered important to explore and develop a test method to assess the sensitivity of aggregates to deicer chemicals.

The secondary objective of this study was to develop a rapid and a conservative test method that can identify reactive aggregates sensitive to deicer solutions. This was achieved through revisions to the existing deicer-modified mortar bar test method (EB-70 test method). A fundamental investigation conducted as part of this research study showed that pH-jump in deicer solution associated with interaction between deicers and alkali hydroxide was central to the development of the new test method. The new test method, Revised EB-70, was based on using a soak solution with a composition of 3 Molar potassium acetate and 1 Normal sodium hydroxide. This soak solution captures the effects of pH jump associated with KAc deicers, while maintaining a high hydroxyl ion concentration. This revised test method produced conservative results when compared to the conventional test methods such as ASTM C 1260 test and EB-70 test method. It was also shown that the new test method can be used to select effective mitigation measures in helping to reduce deleterious ASR expansions. Overall, the results of this study show that it is important to select quality aggregate materials and maintain high quality construction methods to ensure that the pavement system will meet its design life.

In conclusion, it can be stated from the forensic examination of airfield pavements that while ASR was observed to be the predominant distress mechanism, other modes of distress were also evident. In particular, ACR, shrinkage cracking and freeze-thaw damage were observed. Poor construction practices also further worsened the quality of pavements in selected airfield pavements. The predominant reasons for the occurrence of ASR distress in the airfield pavements were: (i) lack of adequate specifications at the time of construction to screen aggregate materials and, (ii) the use of inadequate and inefficient ASR mitigation measures in concrete.

While lab studies have shown that KAc deicer is very capable of inducing and promoting ASR distress in concrete, such evidence in field conditions was not readily evident, and often made more difficult due to simultaneous presence of multiple distress mechanisms. Perhaps, the major reason for the lack of correlation between the ASR distress in the field and the KAc deicer usage on the affected pavements was due to lack of significant penetration of deicer into sound concrete. However, such a lack of correlation should not be construed as a reason to disregard the potential impact of deicers on ASR distress in concrete. Evidence has been found in this research study that when the integrity of concrete is compromised by other precursor mechanisms that cause cracking, deeper penetration of deicer was observed along the length of the crack.

Research on the development of the deicer-modified mortar bar test method to assess the deleterious effects of deicers has shown that certain aggregates are more susceptible to deicer-induced ASR distress than others, and care should be taken to avoid such aggregates or use effective ASR mitigation measure to address the potential incompatibility. It is quite likely that deicer can penetrate to a greater extent in concrete that is cracked or compromised due to other reasons and initiate the distress. The revised deicer-modified test method based on the use of soak solution with 3M KAc and 1N NaOH was found to be more reliable than previous test methods in detecting reactive aggregates that are sensitive to KAc deicers in this regard. Also, the revised test method can identify effective ASR mitigation measures that can mitigate the ASR distress in the presence of deicing chemicals.

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1. INTRODUCTION

Premature deterioration of concrete due to materials-related distresses has been observed with increased frequency in airfield pavements across the United States in recent years. The use of new generation of deicing chemicals based on alkali-acetates and alkali-formates starting in the early 1990s have been suspected to be one of the significant reasons for the increased occurrences in pavement deterioration, particularly alkali-silica reaction distress (ASR) in concrete. To investigate these concerns, preliminary laboratory-based research studies were conducted in which the effect of various airfield pavement deicing chemicals in causing and/or accelerating ASR distress in concrete was studied [1-5]. Results from these studies indicated that both alkali-acetate and alkali-formate deicers were capable of initiating and accelerating ASR distress in concrete test specimens when subjected to prolonged exposure to deicers. The deleterious effects of the deicers were observed regardless of the alkali content of the cement used in the concrete, and the distress was further amplified when deicer-exposure studies were conducted at elevated temperatures. In these studies, conventional ASR mitigation measures such as Class F fly ash and meta-kaolin were found to be effective in controlling expansions of test specimens with moderate to highly reactive aggregates when used at typical dosage levels. However, slag was found to be effective only when used in substantially higher dosage levels, often exceeding 40% by mass replacement of cement [2].

While much of this knowledge on the effects of alkali-acetate and alkali-formate deicers on concrete was based on laboratory based test methods, a comprehensive forensic investigation of affected airfield pavements had not been conducted. Knowledge gained from such forensic studies would be valuable in critically ascertaining the role of deicing chemicals in causing the distress in the field and in calibrating the findings from the laboratory studies. Furthermore, findings from such forensic investigation could be used in developing a new test method or refining an existing test method in capturing the potential influence of the deicer on the durability of concrete pavements.

2. BACKGROUND

Deicers such as urea, ethylene glycol (EG), propylene glycol (PG), and blends of PG and urea have been successfully used on airfield pavements as deicing and anti-icing agents in the past. However, concerns arising from the toxicity of these chemicals to aquatic life have led to regulations which strongly discouraged the use of these chemicals as deicers on airfield pavements, although the glycol-based formulations are routinely used to deice and anti-ice aircrafts in secure deicing pad areas, where the runoff is collected and processed [6, 7]. In response to the limitations on the use of glycols and urea as pavement deicers, a new generation of deicers had emerged in early 1990s which were based on alkali-acetate and alkali-formate formulations. Since that time deicers and anti-icers such as potassium acetate (KAc), sodium acetate (NaAc), potassium formate (KF) and sodium formate (NaF) have seen an enormous growth in their use as airfield pavements deicers and anti-icers. In particular, in the United States KAc based formulations were largely preferred and widely used in airports across the country.

In recent years, the number of airfield concrete pavements experiencing premature deterioration in the form of materials-related distress had increased substantially. In some of these airports, it has been suspected that the exposure of the concrete pavement to KAc deicer may have played a role in either triggering or accelerating the pavement distress. Figure 1 shows the typical distress patterns observed in these airfield concrete pavements. While much of the distress observed in the field manifests itself in the form of a map cracking pattern throughout the slab that is akin to what many consider to be associated with alkali-aggregate reaction (AAR) distress, other distress patterns are also observed. Typically, the intensity of the distress is accentuated near the joints, perhaps due to enhanced availability of moisture and deicer, and the proximity to free surfaces where the expansive pressures from the distress can be relieved through cracking. However, the cracking near joints can potentially be attributed to other mechanisms than AAR such as freeze-thaw damage in the paste or aggregates. Only comprehensive forensic investigation of affected pavements would reveal the nature of the distress. Furthermore, certain fundamental investigation would be necessary to ascertain whether the observed distress is induced by the presence of deicers in the concrete or not. For instance, fundamental investigations would be necessary to determine if and how KAc deicer would be able to promote conditions that initiate or accelerate alkali-silica reaction (ASR) distress in concrete. Also, it would be important to establish whether the use of deicers such as potassium acetate would be able to cause scaling or freeze-thaw deterioration in a well air-entrained concrete.

Figure 1 – Typical Patterns of Deterioration in Six Different Airfield Pavements Exposed to Deicing Chemicals

3. RESEARCH OBJECTIVES

The principal objectives of this research study are:

1. To conduct a comprehensive field-based forensic investigation of selected airfield pavements that have been exposed to typical airfield pavement deicing chemicals such as potassium acetate deicer, and have experienced some level of materials-related distress.

2. Based on the knowledge gained through studies under Objective 1, conduct comprehensive lab-based forensic investigation to identify the underlying mechanisms/reasons for the premature deterioration of airfield pavements and ascertain any relationship between the distress mechanisms and the deicers used on the pavements.

3. To conduct fundamental investigations on interactions between deicing chemicals and cement paste/aggregate materials, that would aid in resolving questions that may arise in the forensic investigations of airfield pavements.

4. To develop a rapid test method that allows for screening of aggregates materials that exhibit deleterious interactions with deicing chemicals in concrete.

4. ORGANIZATION OF THE REPORT

The research work conducted as part of this investigation is divided into 3 major tasks:

Task 1 – Field and Lab-Based Forensic Investigation of Pavements

Task 2 – Fundamental Investigations to Study Cement Paste/Deicer Interactions

Task 3 – Development of a Test Method to Screen Aggregate Materials that Deleteriously Interact with Deicers in Concrete

The primary focus of this summary report is to present the findings from Task 1 of this study, i.e. findings from the forensic investigation of 8 different airfield pavements that have experienced varying levels of materials-related distress, and study what if any role the deicers have in causing the distress.

Due to extensive nature of this study the volume of data gathered and results generated are quite voluminous in nature. In order to present the findings the results from this study in a distilled manner, much of the data and the results from investigation are presented in a series of appendices, A through F. Data shown in Appendices A through C and Appendix F was generated from research efforts at Clemson University. Information contained in Appendices D and E was developed from research activities at Purdue University.

Appendix A contains comprehensive information about the condition survey of the affected pavements from different airports, where available information about concrete mixture proportions, and specific information on locations from where cores have been retrieved, core catalogs from each of the 8 airports describing the visual condition of the cores and photographic evidence. In addition Appendix A contains information about the deicer usage at different airports investigated in this research study.

Appendix B contains results from tests conducted on cores including (i) Pulse Velocity (ii) Hardened Air Void Content and Air Void Characteristics (iii) Depth of Deicer Penetration using disc specimens from cores and drill dust samples from field (iv) Freeze-Thaw Test Results, and (v) Reactivity of Aggregates from Airfield Pavements.

Appendix C contains the petrographic reports from investigations conducted on cores from each of the 8 airfield pavements. This information was developed with help from outside Petrographers.

Appendix D contains data from SEM/EDX analysis of concrete from cores, along with results from tests conducted to determine the extent of deicer penetration into concrete using the profiling grinding method as per ASTM C 1556 test method. This study was conducted at Purdue University. Note that the data on deicer penetration into concrete presented in Appendix B was developed based on testing conducted on half-inch thick concrete discs cut from cores. This work was conducted at Clemson University.

Appendix E contains data from fundamental investigations exploring the interactions between deicing chemicals and constituent materials in concrete. These fundamental investigations are unrelated to the forensic studies on field concrete specimens. However, they are intended to fill gaps in knowledge that would enhance the analysis in forensic investigations.

Appendix F pertains to the development of deicer-modified mortar bar test method to evaluate potential for alkali-silica reactivity of aggregates in presence of deicing chemicals. This Appendix essentially contains two technical papers that delve into the development of the test method. The first paper is "Assessing Potential Reactivity of Aggregates in the Presence of Potassium Acetate Deicer – Revised EB-70 Method" and the second paper is "Evaluating ASR Mitigation Potential of Supplementary Cementing Materials and Lithium Admixture in the Presence of Potassium Acetate Deicer – Revised EB-70 Test Method".

Findings from Tasks 2 and 3 are not discussed at length within the main report, but are presented in Appendices D through F, and interested readers can consult the appropriate appendices to learn more about those findings.

At the present time, Appendices D and E are not included in this report, as they have not yet been finalized. This information will be appended to the report as it becomes available.

5. EXPERIMENTAL PROGRAM

Due to the breadth of the topics addressed under this research study, the investigation was conducted in four distinct Tasks. Each of these Tasks is briefly described below. However, a more elaborate report of the experimental program including materials, test methods and detailed results from the research investigations is presented in Appendices A through E of this report.

5.1 Task I – Forensic Investigation of Affected Airfield Pavements

Under Part 1of this study, forensic investigation of airfield pavements was conducted to ascertain the cause of premature deterioration and determine if the deicers played a role in causing the failure. For this purpose 16 different airfield pavements from eight different airports were investigated. The airports were investigated in three phases. In Phases I and II, three airports each were studied and the remaining two airports were studied in Phase III. The intent of conducting the forensic investigations in three phases was to corroborate findings from one phase to the next phase, and determine if a common theme emerges that relates the pavement deterioration to the deicer usage or any other factors. Also, conducting these studies in three phases provided an opportunity to alter the scope of the project depending on the findings from the investigations during the course of the project.

The airfield pavements investigated as part of this research study were selected by steering committee comprised of members from FAA and IPRF, based on the condition of the existing pavements and the deicer usage at the airport as reported by the airport authorities.

In Phase I studies, three airfields (Airport I, II and III) were selected for forensic investigation based on the level of distress that the pavements exhibited at these facilities. In this study, the distress in the airfield pavements was categorized as being severe, moderate or mild/none depending on the extent of cracking that was observed on the pavement surface. The age of the pavement at which cracking was sufficiently evident was also considered in selecting these airports. Also, it was ensured that all the airfield pavements selected in this phase were subjected to potassium acetate- deicer (KAc) as the primary deicer and anti-icer.

In Phase II studies, three additional airfields (Airport IV, V and VI) were selected for forensic investigation. Of these three airfields, two were selected based on the evidence that the pavements were undergoing severe distress and employed KAc as the primary deicing and anti-icing agent. The third airfield in this phase was selected to represent a situation where the pavement was experiencing moderate level of materials-related distress, but was not exposed to KAc deicer. The purpose of selecting the third airfield pavement with no prior KAc deicer exposure was to investigate if the nature of the distress observed in the pavement was any different or similar compared to those pavements that had experienced significant KAc exposure.

In Phase III studies, two additional airfields (Airports VII and VIII) were investigated. Although the initial intent of selecting the two airfields for the Phase III of the forensic investigation was to confirm the findings from earlier phases, due to the nature of the findings from Phases I and II airports, the criteria for selecting airfields in Phase III were altered. Airport VII was selected based on the fact that the pavements experienced moderate level of materials-related distress, however only sodium acetate (NaAc) was employed as the deicing agent at this facility. Airport VIII was selected based on the information provided by the airport authorities that the concrete pavements in question had been in service for over 50 years with little to no materials-related distress, even though significant quantities of KAc deicer was used.

The forensic investigations at each of the eight airfield pavements included a field component and a lab component. The following information- and sample-gathering efforts in the field were conducted followed by a comprehensive laboratory testing program of the core specimens retrieved from the field:

5.1.1. Field Investigation

The following information- and sample-gathering efforts in the field were conducted:

a. *Collection of Background Information on Pavements and Deicing Chemicals.*
Information pertaining to pavement design, construction methodology of pavement, concrete mixture proportions, aggregate and cementitious material source information and their properties from construction records, where available, were collected by interviewing the key personnel. Also, a history of deicer usage on the airfield pavements

including types of deicers employed as well as the frequency and rate of their usage was obtained, where such information was readily available.

b. Survey and Documentation of Distressed and Non-Distressed Sections of Airfield Pavements and In-Situ Testing Plan.

Based on the guidance provided by the airport personnel on the extent of deicer usage on different pavements at the airport, visual inspection of selected pavements was conducted to ascertain the degree of damage in pavements. Based on these findings, specific locations were identified as suitable for sample collection. Photographic evidence of the distress in the pavements and the core locations was documented.

c. Core Removal and Lab Testing Plan.

Cores from affected pavements were retrieved from the locations previously identified. The core removal operations were sub-contracted to local coring companies, with specific guidelines on how to retrieve, handle, pack and ship the cores. Once the cores were retrieved, they were carefully labeled, photographed and packaged for shipment to lab for further investigation.

5.1.2. Lab Investigation

The following comprehensive laboratory testing program of the core specimens retrieved from the field were conducted:

a. Documentation of Condition of Cores

A detailed cataloging protocol of cores was followed, wherein the physical dimensions of the cores were measured and the condition of the cores was documented by capturing photographic evidence of cracks, stains, presence of ASR gel and/or excessive voids resulting from poor compaction of concrete in the field.

b. Pulse Velocity along Transverse and Longitudinal Directions in Cores

The physical properties of concrete measured included unit weight and pulse velocity of the cores in the longitudinal and transverse directions as per ASTM C 597 test method. Due to the scarcity of adequate number of cores from each airfield pavements, no destructive testing of concrete was conducted for determining the mechanical properties of concrete. After evaluating the condition of the cores using non-destructive tests, some of the cores were eventually used in conducting a deicer-modified ASTM C 666 test method to investigate the freeze-thaw durability of concrete in the presence of KAc deicer solution.

c. Petrographic Examination

Petrographic examination of concrete cores was conducted in accordance with ASTM C 856 test procedure. In these investigations specific attention was given to the type and extent of the distress as a function of distance from the pavement surface, where the deicers would have been applied. Numerous fresh fracture surfaces were studied to detect secondary materials such as ASR gel. Air content of hardened concrete was determined according to ASTM C 457 test method. Petrographic examination of Airports I through III were conducted by Campbell Petrographic Services, Inc. and that of Airports IV through VIII was conducted by Schmitt Technical Services, Inc.

d. SEM-EDX Examination.

Scanning electron microscopy and energy dispersive X-ray analysis (SEM-EDX) were conducted on polished and fractured core specimens to characterize the microstructure of the concrete. Emphasis was placed on identifying the presence of any ASR gel and determining its composition along with any distinctive features of the typical hydration products. The results from these investigations were analyzed in the context of findings from petrographic analysis. The cores were cut in half (lengthwise) and sections of approximately 15 mm were removed from 3 to 4 different locations along the core center to span across the depth of the core. The samples were prepared for SEM-EDX examination and analyzed. The analysis of the concrete along the depth of the core provided means to ascertain the influence of deicer on the observed distress.

e. Air-Void Parameters of Hardened Concrete

Air-void characteristics of hardened concrete define its ability to effectively resist the effects of repeated cycles of freezing and thawing. These characteristics include total air void content, spacing factor of air-voids and specific surface area of the void structure, and are determined using the standard ASTM C 457 test method. Depending on the maximum size of coarse aggregate used in the concrete, the sample area to be examined in the microscope was established as per the guidance provided in ASTM C 457 test method. To determine if any significant differences exist between the air void characteristics of concrete as a function of distance from the pavement surface, two sections of concrete – sections A and B, from each core were investigated. Section A consisted of concrete from the top 4 inches of the core, and section B consisted of concrete from 4 inches to 8 inches in the core.

In this investigation, the cores were sawn lengthwise using a masonry saw and subsequently sliced into sections A and B as described earlier. The sawn surfaces of each section were lapped using progressively decreasing sizes of silicon carbide grits, starting from a grit size of 60 and ending with a grit size of 1200. After ensuring the lapped samples were devoid of any ridges and scratches, the polished specimens were prepared for microscopic examination using a stereo microscope at a 40X magnification. In determining the hardened air-void parameters, the modified point-count method was employed.

f. Profile of Deicer Penetration into the Concrete Pavement

A two- step procedure was followed to achieve the objectives of determining the deicer penetration into the core as well as to estimate the pH of the pore solution. The deicer concentration profile with depth was determined by profile grinding the concrete core and analyzing the powdered samples for alkalis, sulfate and acetate phases. Prior to analysis, the powder was shaken with water (water : powder ratio of 2 to 1) and the pH of the suspension was determined. The profile grinding of the core was conducted in depth intervals specified in ASTM C 1556 - using a drilling machine with 2 inch drill bit. The concrete powder obtained was sieved to pass 125μm sieve, and a suspension was prepared with a water to powder ratio of 2:1. The suspension was allowed to sit for 6 hours at room temperature in a sealed container after which the pH of the suspension was measured. The suspension was then filtered under vacuum and the solution retrieved was used for analysis of potassium, sodium and calcium ions using atomic absorption spectroscopy, and sulfate and acetate ions using ion chromatography. The OH^- ion concentrations are determined by titration with standardized hydrochloric acid.

g. Freeze-Thaw Durability of Concrete Exposed to Deicer Solutions

The purpose of this investigation was to assess the freeze-thaw durability of concrete subjected to KAc deicer and compare the performance of the same concrete exposed to deionized water. In these investigations, a modified ASTM C 666 test procedure was employed, where in the core specimens were cyclically exposed to KAc deicer or deionized water before subjecting to repeated cycles of freeze-thaw. The six-step modified ASTM C 666 procedure is shown in Figure 2.

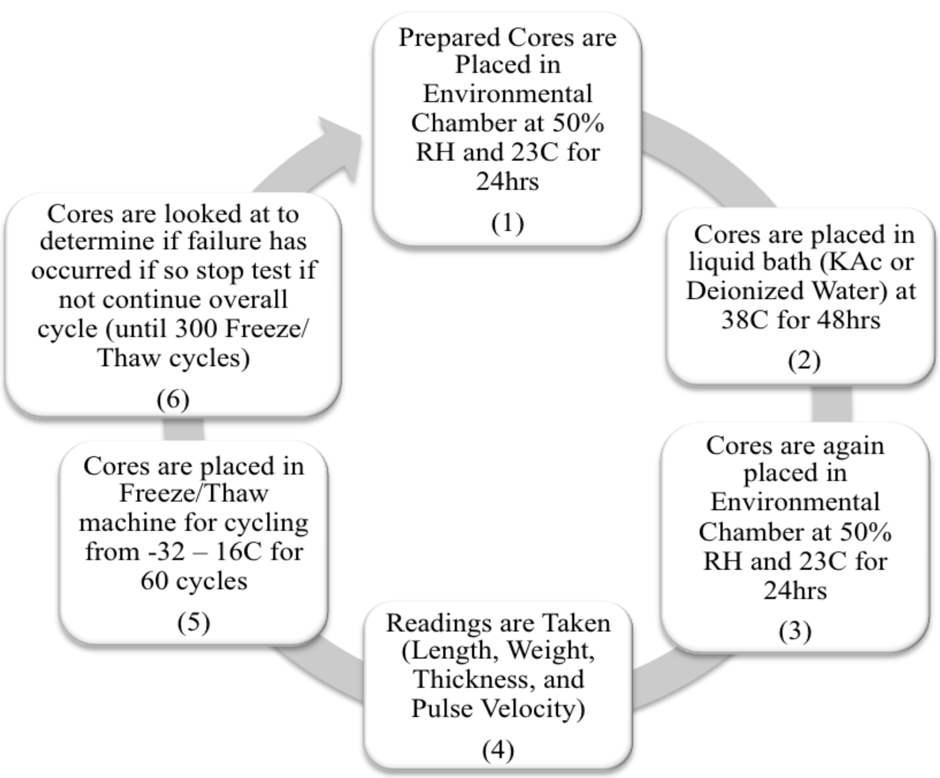


Figure 2 –Modified ASTM C 666 procedure to evaluate effect of KAc deicer exposure on freeze-thaw durability of concrete

The cores used in this test were cut to a thickness of about 2.9 inches and a height of 4 inches and fitted with metal studs on both ends for length measurements. The reason for the modification of the minimum thickness (Less than 3") was due to size restraints of the sample holders in the freeze-thaw apparatus.

The principal modification in the test method was the periodic exposure of specimens to deicer solution or deionized water prior to subjecting them to freeze-thaw cycling. This six-step process was repeated after every 60 cycles in the freeze-thaw chamber. Core samples were kept in a protective wrapping prior to the test to ensure that the moisture content remained the same as when first arrived to Clemson. At the beginning of the test and after every 60 cycles of freeze-thaw, measurements on test specimens were taken. These measurements included weight, pulse velocity and length-change in test specimens. The procedure was repeated until 300 cycles of freeze-thaw exposure were completed. Photographs of a prepared sample and the freeze-thaw testing machine can be seen in Figure 4.

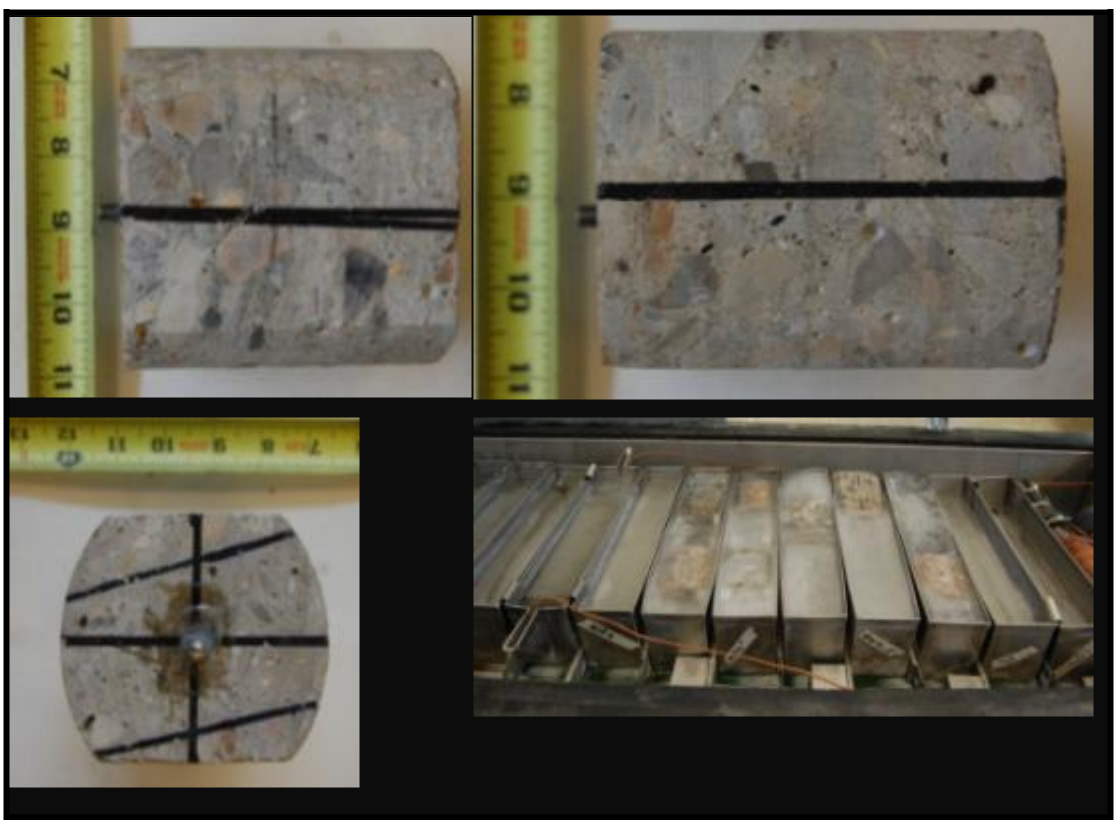


Figure 4 – Prepared Freeze Thaw Samples and Test Setup

5.2 Task 2 - Fundamental Investigation on Interactions between Deicing Chemicals and Concrete Materials

The intent of these investigations was to better understand the chemical interactions that occur between the KAc deicer solution and the constituent materials present in concrete, so that a meaningful interpretation of evidence from field investigations and prior lab investigations can be made. A detailed description of the experimental program, test methods employed and the results from each of the investigations will be presented in Appendix D. However, a brief description of the research need is presented below and a summary of principal findings is presented in Section 5. The following are the primary fundamental investigations carried out in this study:

a. pH Jump Effect of Deicer Solutions

Earlier investigations conducted as part of IPRF 03-9 studies revealed that the pH of the 50% wt. solution of KAc (i.e. typical KAc deicer solution) exhibited significant jump in pH when even a small amount of hydroxides such as $Ca(OH)_2$ were dissolved in it [1, 4]. The increase in pH was disproportionate to the amount of hydroxyl ions contributed by the dissolved $Ca(OH)_2$. Considering that the concentration of hydroxyl ions and the accompanied pH of the solutions are vital in understanding the potential of the deicer to initiate or accelerate ASR distress in concrete, it was considered important to conduct fundamental investigations to understand the underlying mechanisms for the increase in the pH. In this investigation, different amount of $Ca(OH)_2$ and NaOH were dissolved in KAc deicer solution and the resulting changes in the pH and hydroxyl ion concentrations were monitored. Also, the activity coefficient of the hydroxyl ions in these solutions was monitored.

b. Stability of Hydrated Cement Paste in Presence of KAc Deicer Solutions

In order to understand if the KAc deicer solution has any deleterious effect on hydrated cement paste itself, a fundamental investigation was conducted wherein hydrated cement paste specimens were exposed to KAc deicer solutions of different concentrations. Both the paste and the surrounding soak solution were periodically analyzed to study any negative interactions between the two. This knowledge is essential to understand if the deterioration being observed in the concrete pavements is one related to cement paste deterioration or negative aggregate interactions such as alkali-aggregate reactions.

c. Stability of Siliceous Aggregates in Deicer Solutions

As indicated in section 4.2.1 deicer solutions in the presence of hydrated cement paste exhibits a pH level that is significantly higher than its native pH value. Considering that the stability of siliceous aggregates is highly dependent on the pH of the surrounding environment, and consequently its impact on ASR distress, it is important to understand how siliceous aggregates behaved in the presence of deicer solutions with a high pH. Test methods and the experimental program associated with this study are described in detail under section 5.

d. Stability of Sulfo-Aluminate Phases in Deicer-Affected Concrete

In IPRF 03-9 studies, microstructural investigations conducted on mortar and concrete specimens exposed to KAc deicer revealed while ASR was that on alkali-silica reactivity in concrete, it was observed that The stability of the sulfo-aluminate phases in hydrated cement paste in concretes exposed to KAc deicer solutions was in question from some preliminary investigations [1, 4]. Fundamental studies to understand these behaviors were necessary to explain any causes for premature deterioration in concrete. In Part 2 studies, such fundamental investigations were

e. Penetration of KAc Deicer into Concrete

Deicing and anti-icing chemicals are applied on concrete pavements by spraying-equipment mounted on trucks. Understanding the manner in which the deicers penetrate into concrete surface and the depth to which they penetrate into the matrix of concrete under field conditions is important in studying their influence on durability of concrete. Among the parameters that influence the sorption and the subsequent diffusion of the deicer in to the concrete, the ambient conditions prevailing at the pavement surface is likely to be one of the most important factors. In order to better understand how ambient conditions influence the depth of penetration of deicer into concrete a fundamental study was conducted wherein concrete test specimens were exposed to KAc deicer under a series of different exposure conditions for a period of 3 months. The depth of penetration of KAc deicer in the concrete specimens was subsequently determined by profile-grinding the specimens and subsequently extracting and analyzing the water-soluble potassium and acetate content of the ground powder. The ambient conditions considered in the study include: (a) continuous exposure of concrete to KAc deicer at standard room temperature (b) periodic exposure of concrete to KAc deicer wherein the concrete goes cyclic wetting and drying conditions, and the drying cycle is executed at 23˚C, (c) periodic exposure of concrete to KAc deicer wherein the concrete goes cyclic wetting and drying conditions, and the drying cycle is executed at 80˚C temperature, (d) continuous exposure of concrete to KAc deicer under freeze-thaw conditions wherein the specimens were subjected to alternate cycles of freezing at -20˚C and thawing at 23˚C, for a period of 24 hours each. The details of this study are further elaborated in the test methods section of this report.

5.3 Task 3 - Development of Test Method to Assess Deleterious Interactions Between Deicing Chemicals and Concrete Materials

A deicer-modified mortar bar test method was developed in IPRF 03-9 and IPRF 04-8 studies to investigate the influence of KAc deicer on ASR distress in mortar and concrete specimens. Findings from these studies, based on limited number of aggregates used in the study, clearly indicated that KAc deicer was capable of initiating and accelerating ASR distress in concrete, regardless of the alkali content of the cement used in the mix. This test method was adopted by Federal Aviation Administration to screen aggregate materials that were susceptible to deleterious effects of KAc deicer, and guidelines for its proper use in screening aggregate materials were formalized through issuance of FAA Engineering Brief-70. This test method came to be known as "deicer-modified ASTM C 1260 test method" or sometimes EB-70 protocol. Soon after the deployment of this test method for screening aggregate against deicer-induced ASR distress in concrete, it became apparent that the results from the EB-70 protocol were not always in agreement with the results from the standard ASTM C 1260 test method. Lack of agreement between the results from these two test methods prompted a need for conducting a though investigation of the interactions between the deicers and concrete materials, and develop a refined test method that effectively identifies aggregate materials that are incompatible with KAc deicer solution. Research conducted under Task 3 studies focused on applying the fundamental knowledge gained from studies on interactions between hydrated cement and KAc deicer solution in Task 2 studies, and refining the deicer-modified ASTM C 1260 test method. More detailed description of the test method development is presented in Appendix F.

6. RESULTS AND DISCUSSION

Considering the large volume of data gathered in this research study from the forensic investigation of eight different airports, fundamental investigations carried out on deicer-concrete interactions, studies on development of a refined aggregate screening protocol, and the investigations on the influence of urea deicer on concrete, a summary of principal findings that address the main objectives of this research study are presented in this summary report. A more elaborate treatment of these topics can be found in Appendices A through F to this document. In this section, principal results from the field and the lab forensic investigations are presented.

6.1 Task I – Forensic Investigation of Affected Airfield Pavements

6.1.1. Field Investigation

a. Background Information on Airfield Pavements and Deicing Chemical Usage on Airfields

Information about Airfield Pavements

In this study 16 airfield pavements from 8 different airports were considered. These pavements were selected based on the degree of materials-related distress they experienced and their level of exposure to deicing chemicals. Of the 16 pavements, 5 pavements were runways and the remaining 11 pavements were taxiways or aprons. Information about pavement characteristics and deicer usage was obtained by interviewing key personnel at the airport who were familiar with the condition of the pavements and deicing operations at the airports. Where available, information such as pavement design characteristics, concrete mixture proportions, source information for aggregates and their potential for alkali-silica reactivity, source and composition of cementitious material, age of pavements, and age at which first signs of deterioration were observed was solicited. Detailed information about different airfield pavements is provided in Appendix A. However, a summary of the information is presented below:

i. The age of the 16 airfield pavements investigated in this research study ranged from 5 years to 50 years at the time of this investigation. Considering that the use of KAc and NaAc deicers had begun only in early 1990s in the United States, airfield pavements at Airports I, IV, V were subjected to KAc and NaAc deicers throughout their life span. However, airfield pavements at Airports II, III, and VIII had accumulated significant service life even before they were subjected to their first KAc and NaAc deicer exposure. Airport VI was subjected to Urea deicer alone, and airport VII was subjected to NaF deicer alone from the time it was constructed.

   The age at which first signs of material-related distress were observed in these pavements ranged from as early as 4 years from the time of construction to over 15 years from the time of construction. This information is based on visual evidence of distress in the form of surface cracks and spalls as observed by the maintenance personnel and is subjective in nature. Based on these findings, it can be concluded that pavements at Airports I, IV, V and VII exhibited early-age distress (less than 10 years from the time of construction), while pavements at Airports II, III, VI and VIII exhibited signs of distress that were evident at later ages in the life of the pavement.

   Taxiways Echo at Airport I and Airport IV had deteriorated at such a significant rate that they were replaced at 10 years and 14 years, respectively, from the time they were constructed. Other pavements studied in this investigation had undergone significant repairs to address the materials-related distresses during the life of the pavements, however at the conclusion of this research study these pavements were still in service.

   The primary materials-related distress observed in these airports was alkali-silica reaction (ASR) distress; although certain other modes of deterioration were also observed in the pavements. These included alkali-carbonate reaction (ACR), D-cracking, drying-shrinkage, plastic shrinkage, and construction-related defects.

ii. Of the 8 airports, only two airports (Airports I and III) were able to provide meaningful information related to pavement construction, concrete mixture proportions and source information of aggregate materials used in the construction. Table 1 provides typical mixtures proportions employed in pavements at Airport I. In the case of 6 other airports (Airport II, IV, V, VI, VII and VIII), only qualitative information about the concrete mixture proportions such as the rock type of the aggregates, nature of the materials used (i.e. potential source of aggregate, cement and fly ash used) or other unique construction-related issues that arose at the time of construction were made available.

Table 1 – Mixture Proportions of Concrete Used in Pavements at Airport I

Taxiway	**Cement Content (lbs/cy) /Alkali Content (%)**	**SCM Content (lbs/cy, Replacement %)**	**Water to Cement Ratio**	**Air Content (%)**	**Coarse Aggregate Content (lbs/cy)**	**Fine Aggregate Content (lbs/cy)**
Echo	540 (Type I) (0.50% $Na_2O_{eq.}$)	90, 14 (Fly ash) (17.44% CaO)	0.33	5.6	1960	1200
Tango	549 (Type I) (0.57% $Na_2O_{eq.}$)	99, 15 (Fly ash) (27.22% CaO)	0.41	Not Available	1840	1153
Victor	381 (Type I) (0.61% $Na_2O_{eq.}$)	254, 40 (Slag)	0.42	Not Available	1840	1118

iii. Interviews with the airport personnel revealed that during the span of last 50 years (covering the ages of the pavements investigated in this study) specification requirements pertaining to the assessment of alkali-silica reactivity potential of aggregates and use of low-alkali cement or other ASR mitigation measures when reactive aggregates are used were non-existent in P-501 specifications until before mid-1990s. Therefore, in some of the pavements investigated in this study potential for significant ASR distress exists regardless of the exposure of the pavement to KAc deicing chemicals.

iv. In the case of airfield pavements where information about aggregate reactivity was required through specification and where such information was available before the pavement construction began, (i.e. 3 airfield pavements - Taxiways Echo, Tango and Victor at Airport I), it was found that fine aggregates used in the pavements were highly reactive (with a 14-day ASTM C 1260 expansion in the range of ~ 0.30%) and the ASR mitigation measures employed were ineffective. For instance, Class C fly ash was used as a supplementary cementitious material at a cement replacement level of ~15% in Taxiways Echo and Tango. Considering the reactive nature of the fine aggregate in these pavements, neither the quality of the Class C fly ash nor its dosage level was adequate to mitigate the threat of ASR. In these situations, the role of deicers in affecting the deterioration may be difficult to discern.

v. For the remainder of the airports that exhibited ASR distress (i.e. Airports III, IV, V, VI), they were built before any specifications were in place requiring the assessment of aggregate reactivity or the use of low-alkali cement. Also, no requirement to use ASR mitigation was existent. Even though documented evidence of concrete mixture proportions was not available for these airfield pavements (in Airports III, IV, V and VI) petrographic examination of cores revealed that premature deterioration in concrete was due to ASR distress in all cases where high-lime fly ash was used at a low dosage level.

<u>Deicer Usage Information</u>

Information pertaining to deicers usage on the airfield pavements including types of deicers employed as well as the frequency and dosage rate was solicited by interviewing the Maintenance personnel at the airport. Appendix A contains comprehensive information about deicer usage at different airports, however a summary is provided below:

i. KAc based liquid formulations (typically 50% wt. solution) were the most widely used deicing and anti-icing chemicals for pavements, followed by solids pellets of NaAc (sodium acetate) and NaF (sodium formate) and Urea deicers.

ii. In the present investigation all airports except Airport VI and VII reported using KAc as the primary deicing agent with NaAc as the secondary deicing agent. Airport VI reported using Urea as the primary deicing agent, while Airport VII indicated NaF as the primary deicing agent.

iii. KAc usage as deicer and anti-icer varied anywhere from a few tens of thousands of gallons per year to a few hundreds of thousands of gallons per year, depending on the location of the airfield pavement in the country and the severity of the winter weather conditions in any given year at a particular location. Typical volumes of deicers used at Airport I are shown in Table 2.

Table 2 – Deicer Usage at Airport I from 1991 – 2006

Deicing Season	Type of Deicer			
	Urea (Tons)	Potassium Acetate (Gallons)	Sodium Acetate (Tons)	Sodium Formate (Tons)
1991-92	500	N/A	N/A	N/A
1992-93	857	N/A	N/A	N/A
1993-94	816	N/A	N/A	N/A
1994-95	204	2,175	N/A	N/A
1995-96	696	58,950	N/A	N/A
1996-97	37	41,211	N/A	N/A
1997-98	19	50,000	N/A	40
1998-99	208	122,987	157	0
1999-2000	0	117,000	100	20
2000-01	0	403,224	226	305
2001-02	0	106,880	0	179
2002-03	0	204,000	20	100
2003-04	0	253,000	0	35
2004-05	0	91,800	0	2
2005-06	0	130,800	113	0

N/A – Not available

iv. Under typical winter weather conditions, the dosage rate of KAc applied on airfield pavement was reportedly between 0.5 gallons to 3 gallons per 1000 sq. ft. However, if certain adverse winter weather conditions were faced with fairly rapid accumulations of snow and ice, much higher dosage rates (as much as 5 gallons per 1000 sq. ft.) were reportedly used.

v. No meaningful information could be obtained on frequency of application of KAc deicer. However, it has come to attention that deicer can be applied at different dosage rates on the airfield pavement depending on the weather conditions, volume of aircraft traffic and locations on runway where higher levels of traction are needed. These situations typically arise at the beginning and end of runways where the aircrafts make sudden and steep turns, or in the mid-section of the runway where high-speed parallel taxiways are connected.

vi. In certain unique instances sections of the airfield pavements were exposed to much higher levels of KAc deicer. For instance, excessive deicer exposures occurred due to leaking KAc deicer tanks or holding patterns of the deicer trucks waiting for runway closure, etc. It has been reported that these locations where excessive deicer exposure occurred preferentially caused more severe deterioration in concrete.

b. Survey and Documentation of Distressed and Non-Distressed Sections of Airfield Pavements and In-Situ Testing Plan.

Each of the airfield pavement investigated in this study was visually surveyed and photographed. Locations with varying intensity of materials-related distress were identified. Typically, the distress in the pavements manifested itself in the form of cracks and spalls on the surface of the pavement. In some instances, significant misalignment of the joints in the pavements, excessive cracking in the pavement adjacent to light canisters on the ground, and misalignment of the light canisters themselves was observed due to differential expansion in the pavement slabs. These pavements were further inspected to identify coring locations which were representative of the condition of the pavement across large sections. Figures 2A, 2B and 2C show distress in different pavements investigated in this research study.

The nature and the orientation of the cracks in each of the pavements were different from one pavement to another as seen in these figures. In majority of the pavements, the predominant crack pattern was the "map cracking" pattern, while in others the cracks were preferentially oriented in a direction that was parallel or sub-parallel to the joints. In some other pavements, a single dominant crack in the middle of the slab (typically orienting in longitudinal direction) was surrounded by tributaries of map-cracks.

Also, in majority of the pavements, the crack density was more intense near the joints and were much more visually evident (in terms of ease of identification), particularly at the intersection of transverse and longitudinal joints compared to other locations within the slab. However, in some pavements the crack density was more uniform across the entire surface of the pavement with no preferential orientation.

Figure 3 shows a typical layout of pavements at an airfield and coring locations in those pavements. Figure 4 shows photographs of typical locations in pavements from where cores were obtained. Where possible, multiple cores representing concrete from the same pavement with varying degree of distress were obtained. The typical core size used in this investigation was 4 inch in diameter and full depth of the pavement, although in a few pavements the core diameter ranged from 3.75 inches to 5.75 inches.

Figure 2A - Typical Deterioration in Different Airfield Pavements

Figure 2B – Typical Deterioration in Airfield Pavements

Taxiway Alpha, Airport III

Taxiway Tango, Airport I

Misalignment and Damage to Light Canisters on Taxiway Echo at Airport IV

Blowout of Pavement in Airport VII

Figure 2C – Typical Deterioration in Airfield Pavements

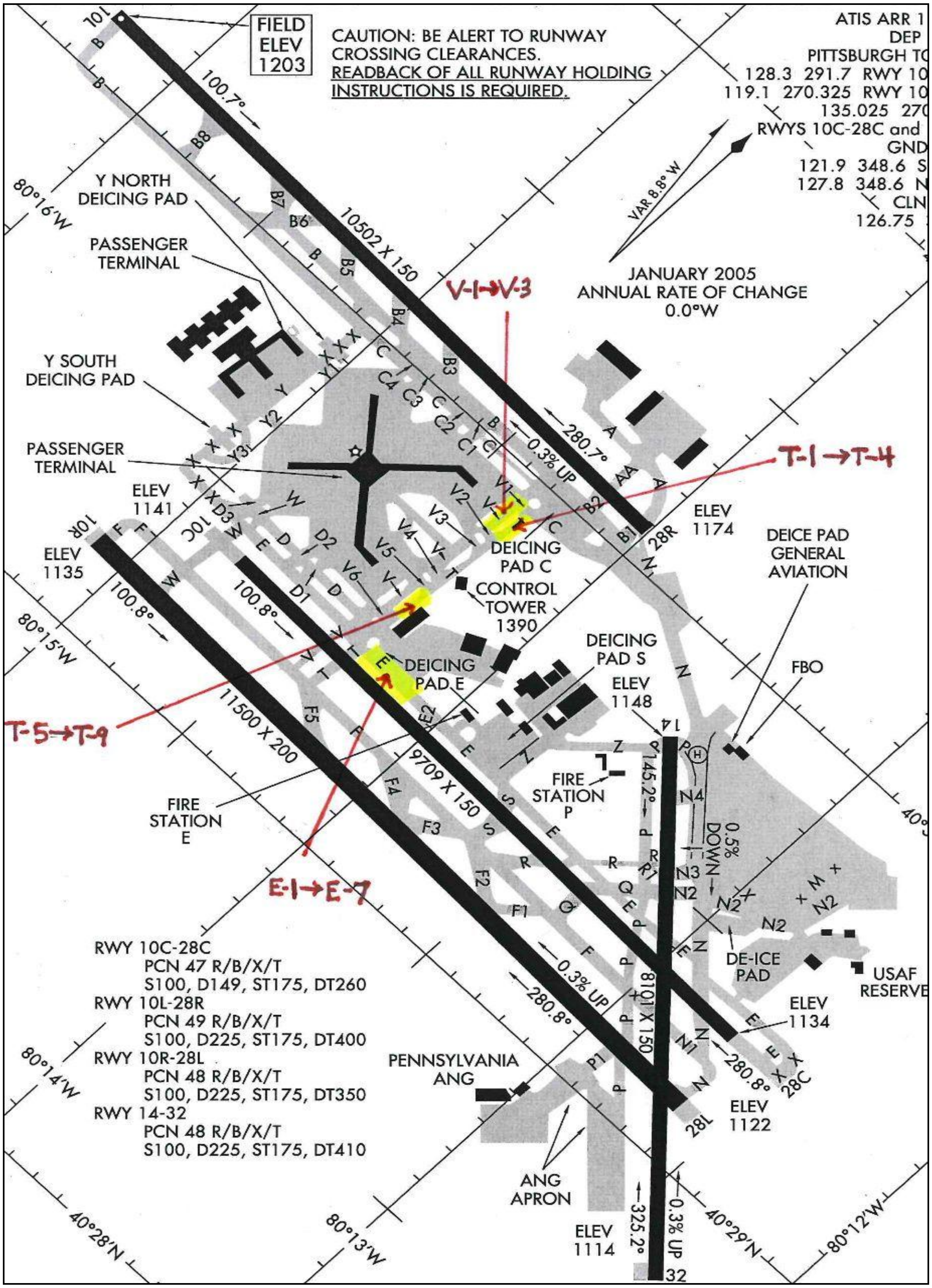


Figure 3 – Locations of distressed pavements and coring sites at Airport I.

Figure 4 – Typical coring locations in airfield pavements to capture distress of different intensity

c. Core Removal and Lab Testing Plan.

The cores were retrieved from the pavements using a truck-mounted core drilling machine with water as the core drilling fluid. The diameter of the cores from different airfield pavements ranged from 3.75 inches to 5.75 inches. The cores were drilled to a depth equal to full thickness of the pavement, typically ranging between 13 inches to 18 inches. In some cases, intact cores could not be retrieved due to internal fractures in the pavement. After retrieving the cores were labeled to clearly identify the pavement from which they were obtained. The condition of the cores was documented by photographing the exterior surface of the core and any internal fractured surfaces to capture the evidence of distress, such as reaction rims around exposed aggregate particles or reaction products in cracks and voids (see Figures 5A, 5B and 5C). The cores were then wrapped in a moist towel and packed in a plastic bag and sealed, to prevent any moisture loss, until they were processed in the laboratory.

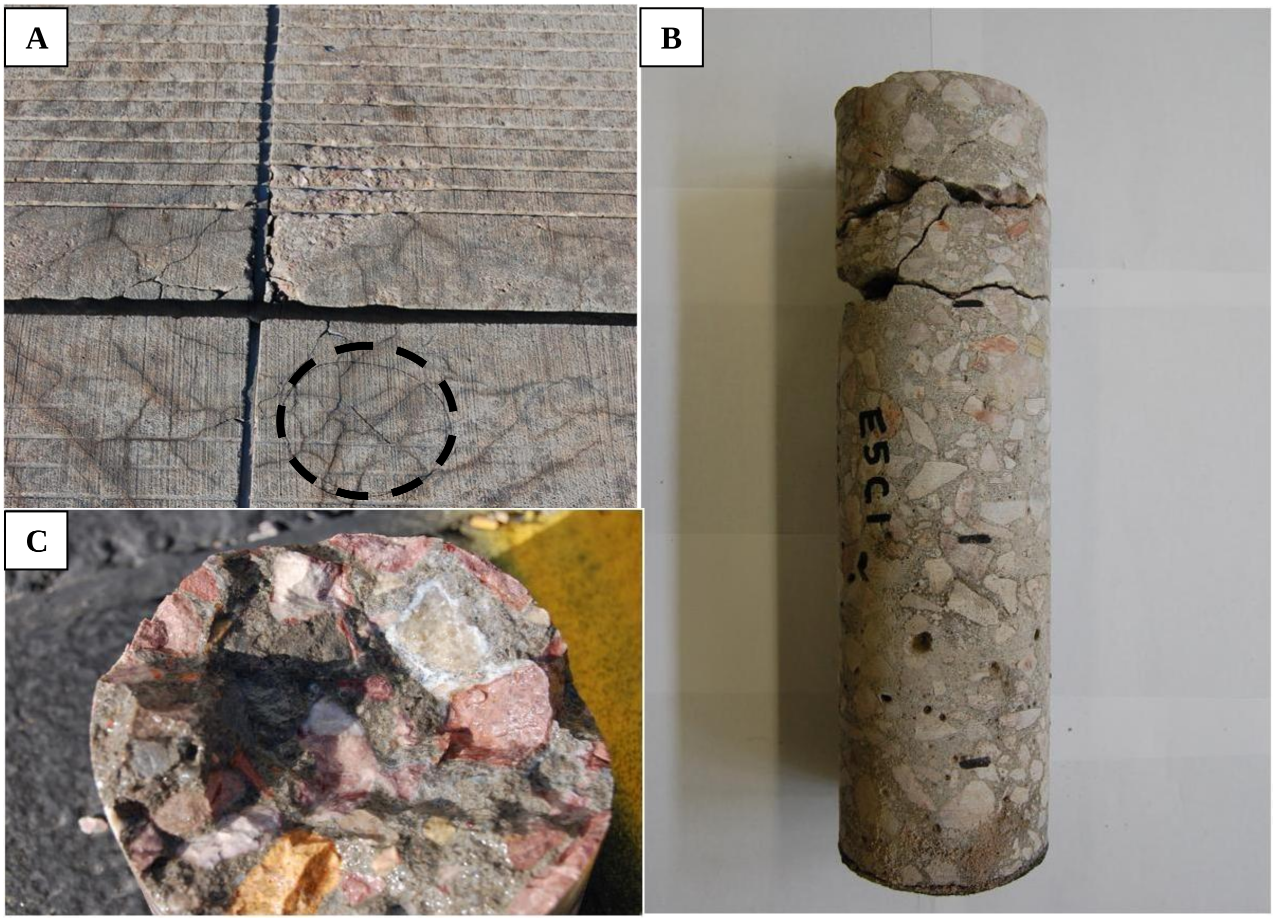


Figure 5A – (A) Typical location for coring in a distressed pavement (Taxiway Echo Connector 5 at Airport IV) (B) – Physical condition of the core showing cracks running down from the pavement surface (C) Fractured surface showing reactions rims and white reaction product surrounding coarse aggregate particles. The 3.75 in. diameter core is 15.50 inches long with multiple fractures in the core in the top 5 inches.

Figure 5B – (A) Typical location for coring in a distressed pavement (Runway at Airport VI) (B) – Physical condition of the core (C) The 5.75 in. diameter core was 16.38 inches long with a single crack running down from the pavement surface to about a depth of 2.5 inches.

Figure 5C – (A) Typical location for coring in a distressed pavement (Taxiway Foxtrot at Airport VI) (B) – Physical condition of the core with significant honeycombing in the top 4 inches and from 7 - 12 inches below the pavement surface. The core was retrieved in two pieces, with 5.75 in. in diameter and a total length of 16.13 inches.

6.1.2 Lab Investigation

Prior to initiating comprehensive testing, the cores were cataloged by documenting the condition of the cores. The documentation included measuring the physical dimensions of the core, digital imaging and rating the severity of distress in the concrete based on the number of cracks observed in the core. Once all the cores from a particular pavement were cataloged, specific cores that adequately represented the distress in the concrete were selected for petrographic examination and SEM/EDX examination. The remaining cores were subjected to other physical and chemical tests. The comprehensive testing program on cores included the following:

i. Pulse-velocity along longitudinal and transverse directions to assess the physical condition of the core and presence of cracks
ii. Petrographic examination of concrete to determine the cause of failure in concrete
iii. Scanning electron microscopy and energy-dispersive X-ray analysis to determine the microstructure and composition of the reaction products in deteriorated concrete
iv. Microscopic examination of concrete to determine the hardened air content
v. Freeze-thaw cyclic testing of cores in the presence of water and deicer solutions.
vi. Penetration profile of deicers into concrete

Appendices B, C and D present the results from each of the tests conducted on the cores, however, in this section a summary of important results are presented which form the basis of principal conclusions drawn from this investigation.

a. *Documentation of Condition of Cores*

The first step in the lab investigation of the cores was to catalog the cores by recording their physical dimensions and documenting the nature of distress by photographing and providing a qualitative rating of crack intensity (or severity) from 0 through 3, depending on the number of cracks observed on the top surface of the core. In rating the condition of cores, the pavement condition from where the cores were obtained was also considered. Table 1 shows typical core catalog information from Airport I. Appendix A provides detailed core catalogs for each of the cores retrieved from all the airfield pavements in this investigation.

Table 3 – Core Catalog for Airport I

Core Label	Broken (Y/N)	Tining (Y/N)	Surface Cracking (0,1,2,3)	Visual ASR Gel (Y/N)	Length (in)	Broken At (in)	Notes
Airport I-Echo Taxiway-Core 1	N	N	1	N	7.25	NA	
Airport I-Echo Taxiway-Core 2	N	N	1	N	13.50	NA	Reaction Rims on Aggregate
Airport I-Echo Taxiway-Core 3	Y	N	1	N	15.50	?	Reaction Rims on Aggregate
Airport I-Echo Taxiway-Core 3A	N	N	2	N	15.50	NA	
Airport I-Echo Taxiway-Core 4	N	N	0	N	13.75	NA	
Airport I-Echo Taxiway-Core 5	N	N	1	N	15.50	NA	Crack terminates in Air Void
Airport I-Echo Taxiway-Core 6	N	N	1	N	6.50	NA	Steel Strand at Bottom of Core
Airport I-Echo Taxiway-Core 7	N	N	3	N	5.75	NA	
Airport I-Tango Taxiway-Core 1	N	N	3	N	8.25	NA	Top Separated from Core
Airport I-Tango Taxiway-Core 2	Y	N	3	N	8.50	?	Top in Pieces and Separated from Core,
Airport I-Tango Taxiway-Core 3	N	N	3	N	8.75	NA	Top Separated from Core
Airport I-Tango Taxiway-Core 4	N	N	0	N	8.75	NA	
Airport I-Tango Taxiway-Core 5	Y	N	0	N	8.50	7.875	
Airport I-Tango Taxiway-Core 6	N	N	0	N	10.50	NA	
Airport I-Tango Taxiway-Core 7	N	N	0	N	10.25	NA	
Airport I-Tango Taxiway-Core 8	N	N	0	N	8.75	NA	
Airport I-Tango Taxiway-Core 9	N	N	1	N	11.25	NA	Large Air Voids on Sides
Airport I-Victor Taxiway-Core 1	N	N	2	N	8.00	NA	Top Separated from Core
Airport I-Victor Taxiway-Core 2	N	N	1	N	8.25	NA	
Airport I-Victor Taxiway-Core 3	N	N	0	N	13.25	NA	Lots of Air Voids on Sides
Diameter for All Airport I Cores is 3.75" (92.25mm)			0=None 1=Slight 2=Moderate 3=Severe				

b. Pulse Velocity Along Transverse and Longitudinal Directions in the Cores

Pulse velocity tests provide a means to assess the physical condition of the cores and determine the dynamic modulus of elasticity (DME) of concrete. In these studies, only cores that appeared intact and represented entire thickness of the pavement were selected so that the base line characteristics of concrete unaffected by distress can be established. This information was also helpful in establishing that the original concrete was not of an inferior quality due to poor construction practices or for other reasons, and the principal reason for the observed distress was one of a gradual deterioration during the service life of the pavement. The pulse velocity was determined along transverse and longitudinal directions of cores to ascertain if the concrete exhibited any differential properties relative to the pavement surface owing to any preferred orientation of cracking. The transverse pulse velocity measurements were determined at 2 inch (~ 50 mm) increments from the pavement surface, using a pulse transit distance equal to the diameter of the core. The longitudinal pulse velocity measurements were calculated based on pulse transit times determined across the length of the core.

Figure 6 shows typical results from pulse velocity tests conducted on cores taken from the three pavements at Airport I: Taxiways Echo, Victor and Tango. Results from tests on cores from all the other airports are included in Appendix B. From the data it is evident that the variability in pulse velocity in concrete cores from each of the pavements was very minimal. In general, the pulse velocities for all the cores ranged between 4000 m/sec and 5000 m/sec. Also, no significant differences in pulse velocity between longitudinal and transverse direction were observed in cores. No clear trend in pulse velocities could be established as a function of depth from the top surface of the pavement in any of the cores. These results indicate that the cores considered for this investigation were sound and the original concrete was not inferior and not have any inherent defects that were pervasive. The DME of cores from all airfield pavements are shown in Table 4 and the results suggest that in all the pavements investigated the original concrete was sound before being affected by the materials-related distress.

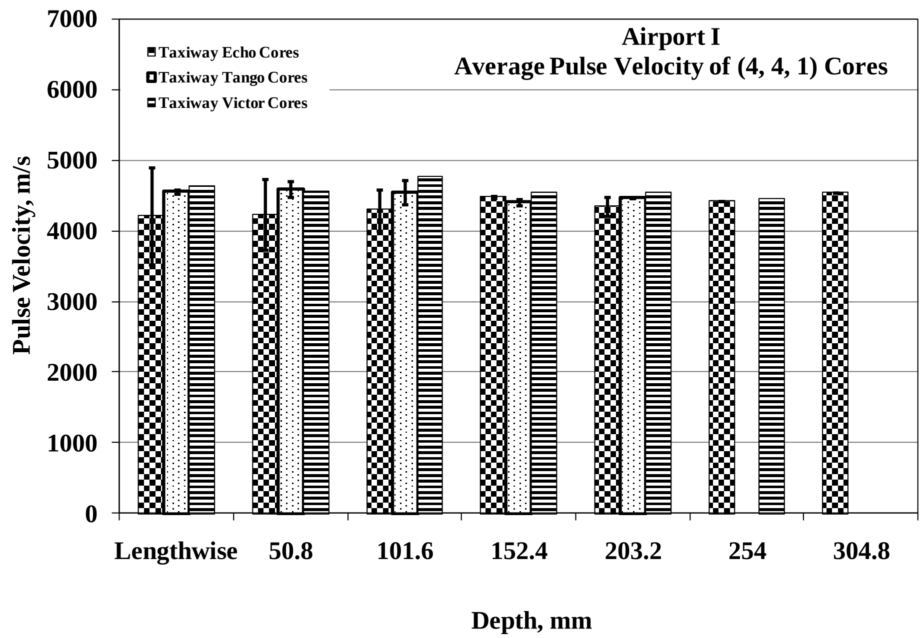


Figure 6 – Pulse velocity results from Airport I cores. The depth represents the distance from the surface of the pavement at which readings were taken on the cores.

Table 4 – Dynamic Modulus of Elasticity of Concrete from Different Airports

Pavement	Longitudinal Modulus of Elasticity (psi)	Transverse Avg. Modulus of Elasticity (psi)
Airport I-Echo	5.76E+06	6.25E+06
Airport I-Tango	6.53E+06	6.38E+06
Airport I-Victor	6.82E+06	6.62E+06
Airport II – Runway	7.60E+06	7.42E+06
Airport III – Runway	5.35E+06	6.08E+06
Airport IV-Golf	NA	6.39E+06
Airport IV-Charlie 7	NA	7.05E+06
Airport IV-Echo 5	NA	6.79E+06
Airport IV-Echo 4	NA	6.54E+06
Airport IV-Deicing Pad	NA	5.44E+06
Airport V - Runway	NA	6.20E+06
Airport VI-Bravo	5.13E+06	6.19E+06
Airport VI-Foxtrot	NA	6.31E+06
Airport VI-Runway	NA	6.44E+06

c. Petrographic Examination of Concrete Cores

Petrographic examination of concrete was conducted to determine the nature of the distress observed in the pavements and to examine the possible role of deicing chemicals in causing the distress. Cores for petrographic examination were retrieved from locations in the pavement where visible distress is evident on the surface and such distress is suggestive of a materials-related distress, for instance, based on crack pattern or presence of gel in cracks on the surface of the pavement. Microscopic examination was conducted on both fractured and polished specimens from the core, as well as on powder mounts when necessary to identify an unknown product based on its characteristics. Detailed reports of petrographic examination of concrete from different airports are included in Appendix C. However, a summary of principal findings from all the petrographic investigations is presented here. Findings from Airport I will be used as illustrative examples in this section.

The following are the overarching principal findings from petrographic examination of cores from 8 different airports:

i. ASR was found to be the dominant distress mechanism in majority of the pavements investigated in this research study. Pavements most influenced by ASR distress include: Taxiway Echo from Airport I, Runway and Taxiway Alpha in Airport III, Runway and Taxiway Alpha in Airport V, Runway in Airport VI, Apron in Airport VII and Runway in Airport VIII. The most common types of reactive aggregates encountered in this investigation include siliceous limestone, siltstone, greywacke, metaquartzites and chert. Although both coarse and fine aggregates were found to be reactive in majority of the pavements, simultaneous presence of reactive coarse and reactive fine aggregates in pavement is not an essential requirement for the ASR distress to manifest itself in the pavement. For instance, the only reactive aggregate in pavements at Airport V was the fine aggregate, however, severe ASR distress was observed in a short span of 10 years.

On the contrary, the only reactive aggregate in the runway at Airport VI was coarse aggregate and yet the pavement exhibited significant ASR distress.

ii. Although ASR was the dominant distress mechanisms observed in most pavements, other mechanisms such as alkali-carbonate reaction (ACR), drying shrinkage, and freeze-thaw failure due to marginal air void content and D-cracking susceptible aggregates were also observed. In particular, Taxiway Victor at Airport I and all pavements in Airport IV exhibited significant ACR distress. In these pavements ASR distress was also observed but to a lesser extent.

iii. In pavements where ASR and ACR distress was observed, micro-cracking and presence of reaction products such as ASR gel in aggregates and paste were observed throughout the thickness of the pavement, albeit the cracking was more intense and the cracks were somewhat wider near the pavement surface. There was no visible indication to suggest that deicer had preferentially caused any additional damage in the concrete near surface or the nature of the reaction products observed near surface were any different than those observed at deeper locations in the pavements.

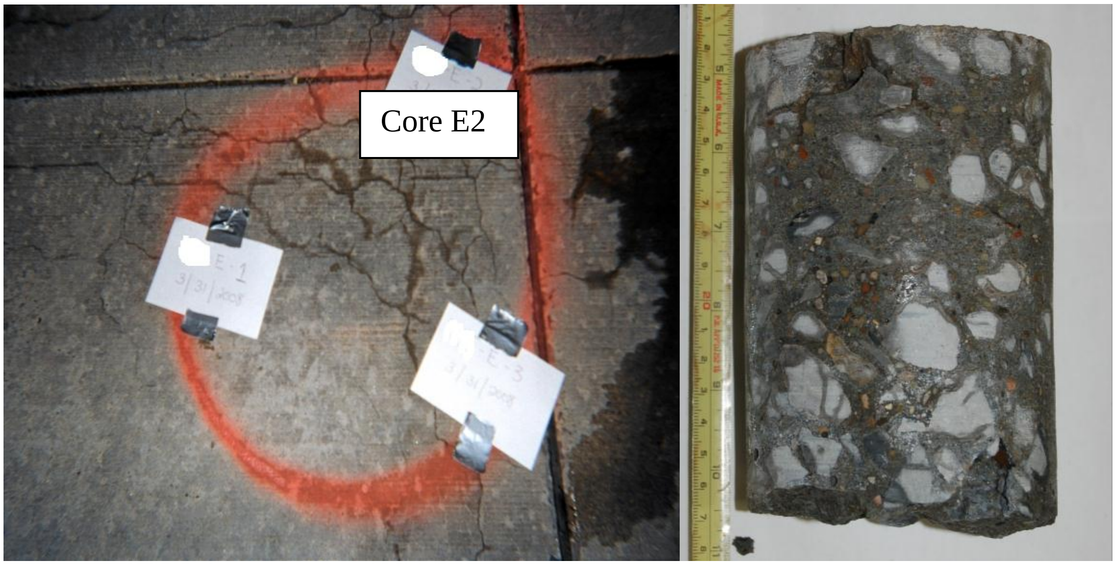
For instance, Figure 7 shows the photographs of core E2 and the location from where the core was retrieved. Also, a polished section of core E5 that was obtained in the same vicinity as core E2 is shown. It can be observed from these figures that cracking in concrete is extensive and extends to a significant depth below the surface of the pavement. Figures 8A and 8B shows evidence from stereo microscope examination of fractured and polished specimens at substantial depth from the pavement surface (i.e. 65 mm and 140 mm) showing evidence of ASR distress in the form of cracks in aggregates and presence of ASR gel deposits around the rim of the aggregate. Figure 8C and 8D show evidence from examination of thin sections under transmitted polarized light with simultaneous reflected UV light. The presence of cracks in aggregates along with deposits of

ASR gel in adjacent voids at depths of 140 mm clearly indicates that the ASR distress has occurred well below the immediate vicinity of the pavement surface, where the deicer influence would be the most significant. Similar observations were made in pavements where ACR distress was observed (see Figure 9.)

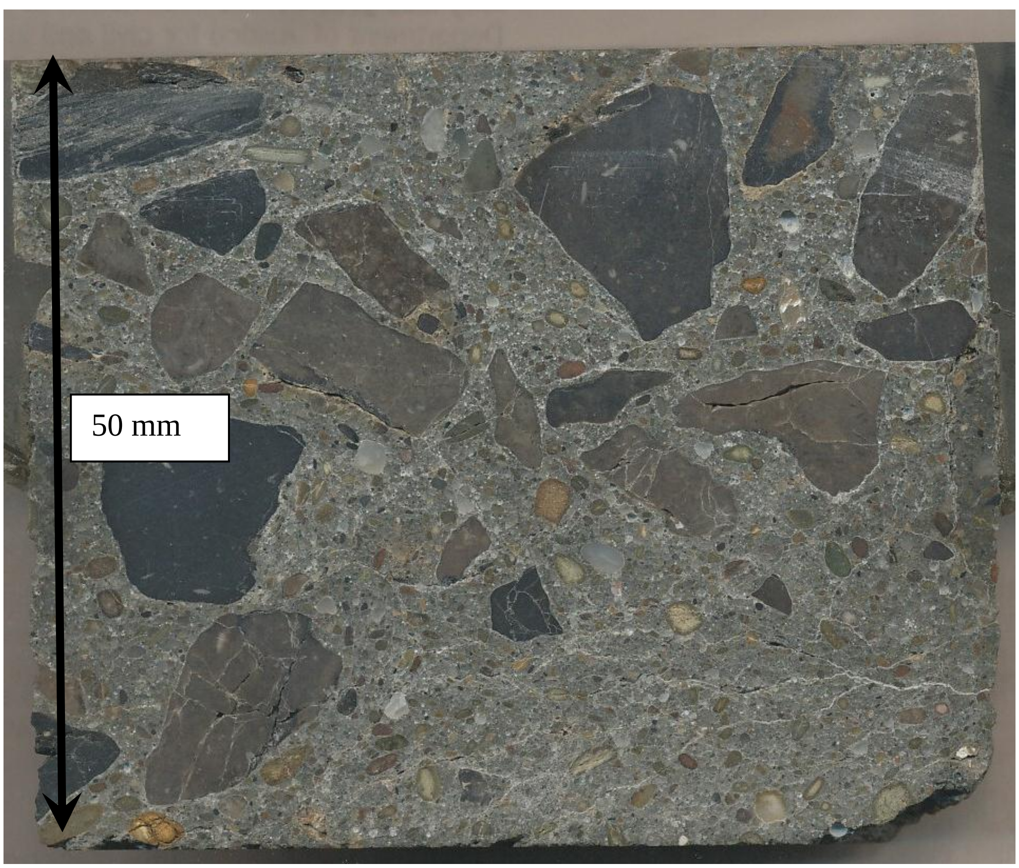
iv. In majority of the pavements that exhibited alkali-aggregate reactions, the concrete either did not contain pozzolans or contained a small amount of ineffective pozzolan such as a high-lime Class C fly ash. For instance, in majority of the pavements that exhibited ASR distress in this investigation, a Class C fly ash was employed as a cement replacement material at a dosage of about 15%. This level of fly ash dosage is generally inadequate to control any deleterious expansions induced by ASR distress. Also, in pavements affected by ACR distress the use of pozzolans such as Class C fly ash or slag does not mitigate the deleterious effects. For instance, Taxiway Victor in Airport 1 contains 40% slag as cement replacement material, however due to the presence of ACR prone aggregates the pavement is beginning to exhibit incipient stages of failure.

v. Drying shrinkage was found to be a significant cause for distress in runway at Airport II, while poor construction practices such as inadequate mixing and consolidation of concrete have led to failure in Taxiway Foxtrot at Airport VI. (see Figure 5C).

In summary, the evidence from petrographic examination of the cores suggests that the pavements that are exhibiting significant ASR distress at the present time were constructed with marginal materials and little to no effective ASR mitigation in the concrete. Based on these findings, it appears that the ASR distress in these pavements was imminent regardless of the use of deicers on the pavement surface.



(A) Photograph of core and its location (Echo-2) showing cracks near the surface



(B) Photograph of polished section from core Echo-5 from nearby location. The width of this specimen is 50 mm.

Figure 7 – Core Echo-2 from Airport I

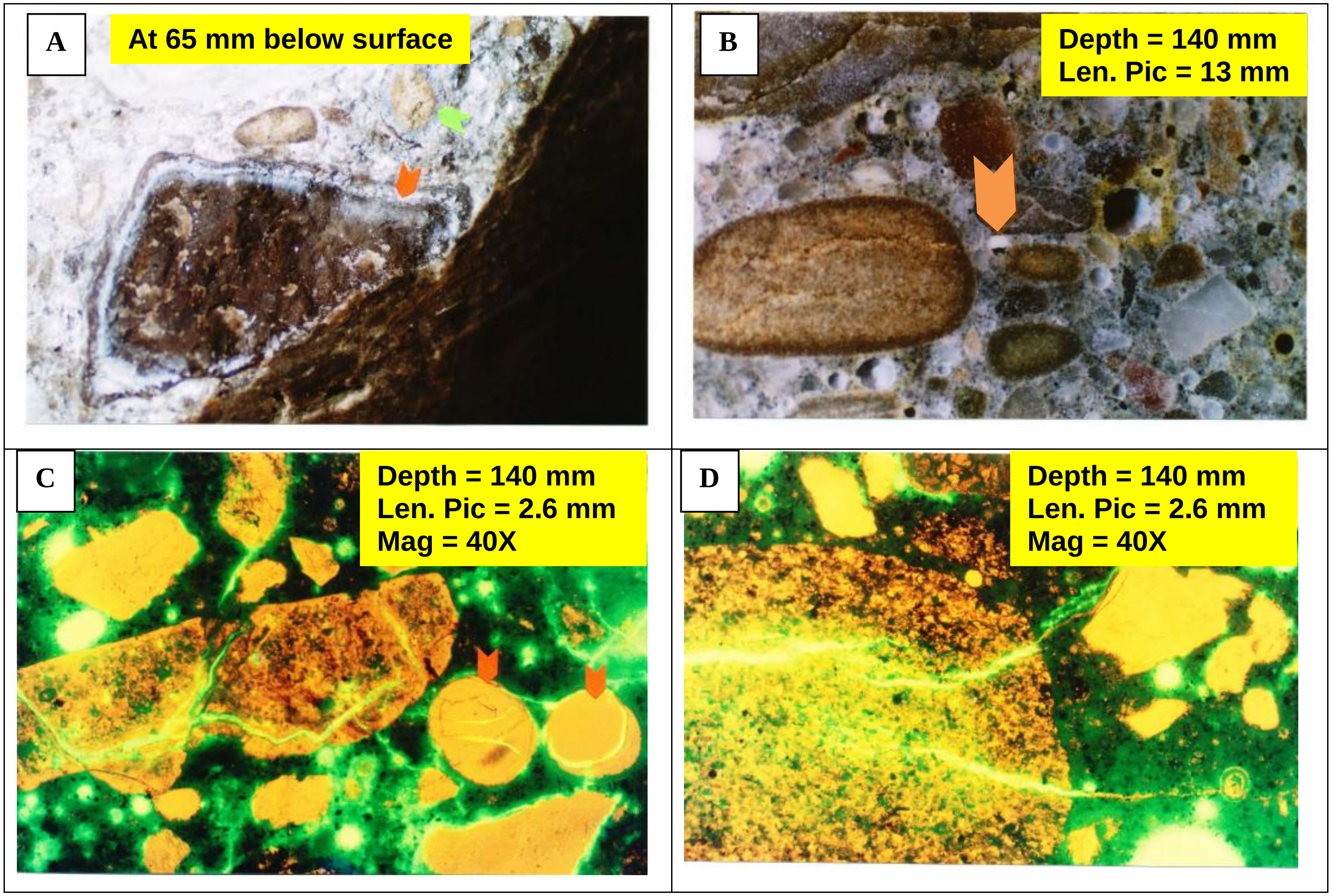


Figure 8 – Evidence of reacted aggregates and ASR gel at different depths in the core. Images A and B were taken using a stereo microscope on fractured and lapped specimens, respectively. Images C and D show thin sections subjected to transmitted polarized light and simultaneous reflected UV light. The orange arrows indicate ASR gel deposits.

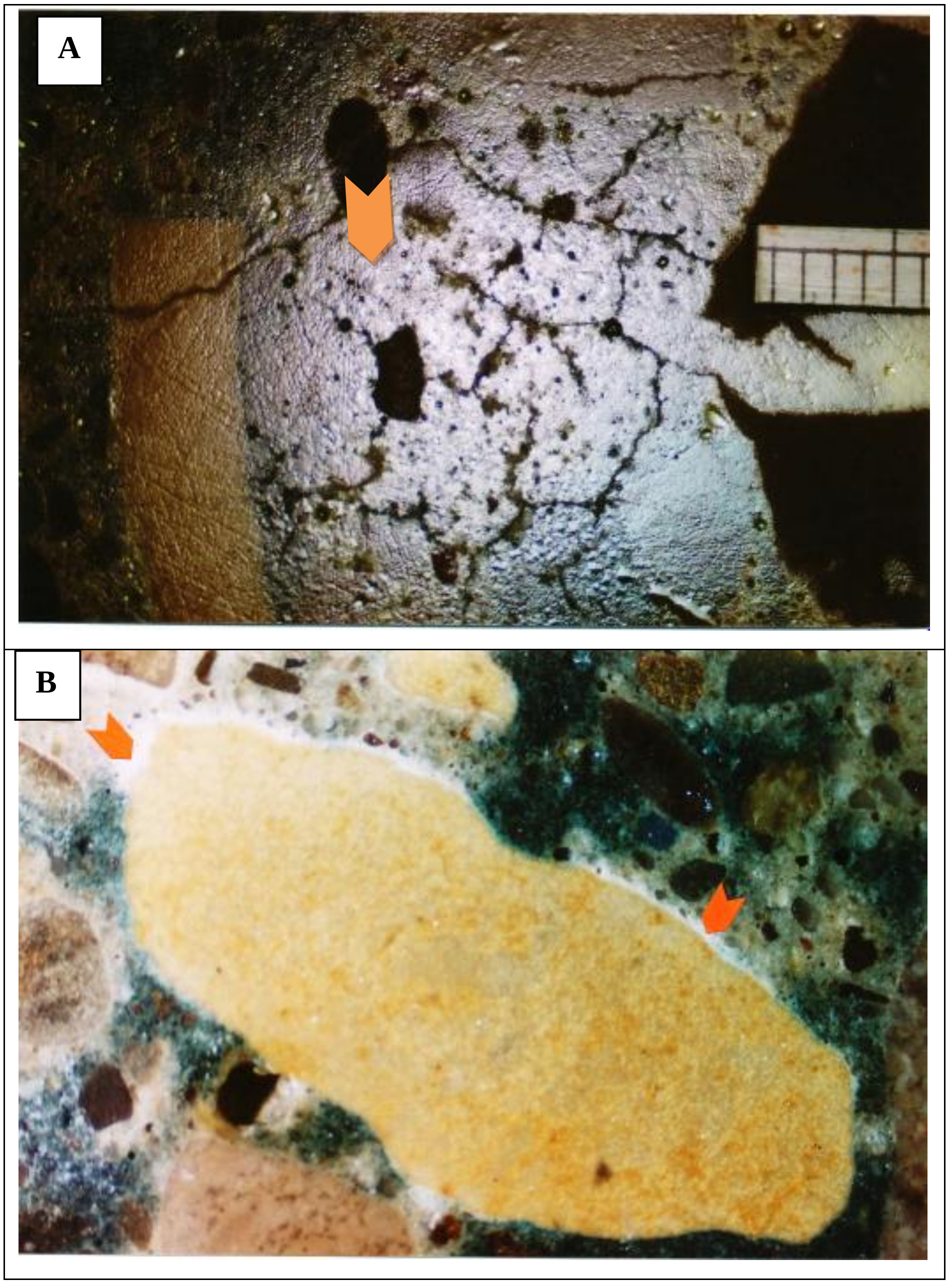


Figure 9 – (A) Typical ACR macrocracking and microcracking in core from Taxiway Victor at a depth of 90 mm in an epoxy-impregnated surface under the stereo-microscope. Similar cracking was observed throughout the entire length of the core. Millimeter scale divisions. (B) Tan dolomitic coarse-aggregate limestone under the stereo-microscope in core from Taxiway Victor at a depth of approximately 140 mm, partially surrounded by a thin discontinuous band of white carbonated paste (arrows), the carbonation believed to result from an alkali carbonate reaction. Width = 16 mm.

d. SEM/EDX Examination of Concrete Cores

SEM and EDX examination of polished and epoxy-impregnated specimens of concrete from different depths within a given core for a pavement were conducted to ascertain the nature of the distress, establish the extent of distress and any variations in chemical composition of the reaction product formed as a function of the distance from the deicer exposed surface. Detailed results from these investigations will be presented in Appendix D. However, a summary of the key findings is presented below.

As observed in petrographic examination, SEM-EDX examination of concrete cores from majority of the pavements investigated in this research study showed that ASR distress was widely present in these pavements. Also, the distress was not limited to near surface portion of the pavement, but was observed at different depths within the core. For instance, SEM-EDX examination of concrete core from Taxiway Echo at Airport I showed presence of micro-cracking in both paste and aggregate, and layer of ASR gel was observed lining some of the cracks in the aggregate (see Figures 10A and 10B). As determined by EDX analysis, the ASR gel contained only traces of alkalis: sodium and in some cases sodium and potassium. No significant evidence was found in this investigation to suggest that deicers were initiating the distress or altering the composition of the ASR gel formed.

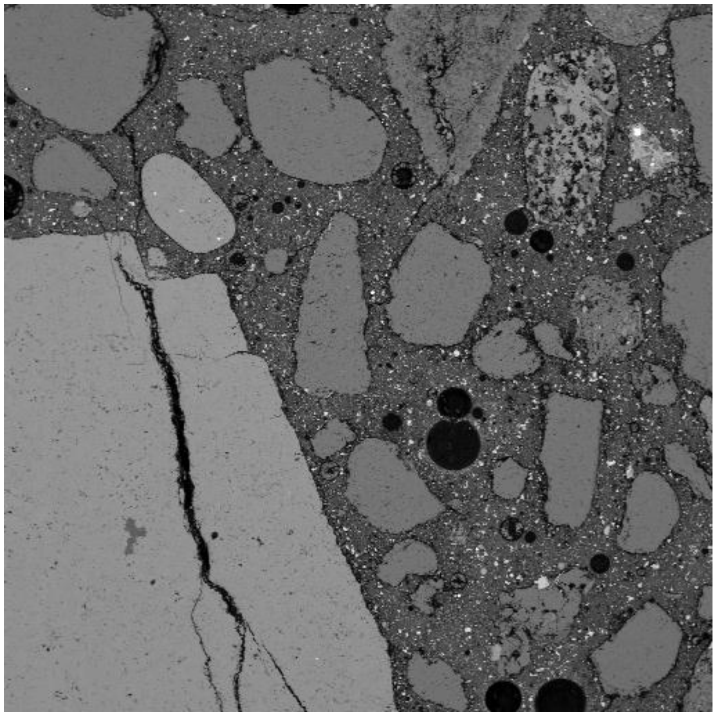


Figure 10A – Cracking in carbonate aggregate (at 30x magnification)

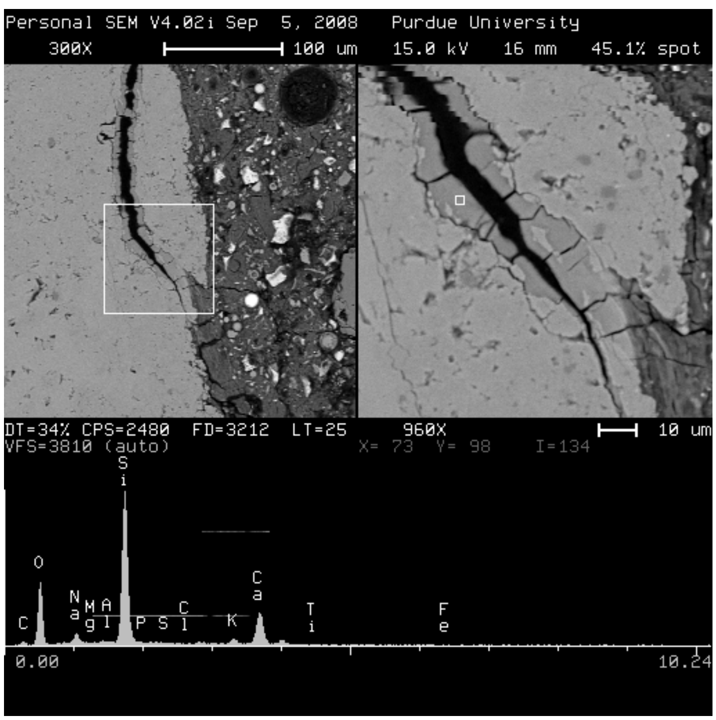


Figure 10B – Crack in aggregate filled with gel (with smaller cracks oriented perpendicular to the larger crack). Textural differences in matrix close to crack opening (right picture, bottom right corner).

e. Air-Void Parameters in Hardened Concrete

Appendix B shows detailed results from the air-void analysis of hardened concrete from all airfield pavements; however a summary of principal findings from this investigation is provided. Based on all the results from this investigation, the hardened air content of concrete from all the pavements ranged between 3.8% and 7.7% with spacing factors ranging from 0.112 mm to 0.255 mm. The spacing factors in some of these cores are considered marginal in nature. Generally, concrete with an air-void spacing factor of 0.200 mm or less is considered to possess a good air-void system that is capable of resisting the effects of freeze-thaw cycling. Overall 89% of the samples investigated in this study had spacing factors less than 0.200 mm and 81% had air contents greater than 5% showing that vast majority of the pavements studied in this investigation had acceptable air-void systems to protect concrete against cyclic effects of freezing and thawing. Also, in majority of the pavements no significant differences could be observed in the air content of concrete as a function of distance from the pavement surface. Where some differences were observed, the air content of concrete was still within what is considered to be acceptable. For instance, Table 5 shows air-void characteristics of concrete from Taxiway Echo at Airport 1. Sections E5A and E5B represent concrete from 0 to 4 inches from the pavement surface and 4 to 8 inches from pavement surface respectively. These results suggest that even though the total air void content and spacing factor of concrete in section E5A are somewhat less optimal than that observed in section E5B, the values are still within the range of values that are considered as acceptable.

Table 5 – Air void characteristics of concrete from Taxiway Echo in Airport I

Air Void Parameters	E-5A	E-5B
Air Content (%)	4.55	6.96
Void Frequency (mm^{-1})	0.287	0.422
Paste Content (%)	27.82	26.15
Paste to Air Ratio	6.11	3.76
Average Chord Length (mm)	0.159	0.165
Specific Surface (mm^2/mm^3)	25.20	24.23
Spacing Factor (mm)	0.201	0.155
Raw Data		
Total Voids Intercepted (N)	651	1002
Total Number of Stops (St)	1384	1350
Total Number of Stops on Air Voids (Sa)	63	94
Total Number of Stops on Paste (Sp)	385	353
Distance Between Stops (I) (mm)	1.64	1.76
Total Traversed Distance (Tt) (mm)	2269.76	2376.00
Total Area (cm^2)	82.0	81.0

f. Profile of Deicer Penetration Into Concrete

Detailed results from this investigation are included in Appendix D. However, some typical results (from Taxiway Echo at Airport I) showing the profile of various anions and cations in three different cores (E3, E3A and E7 from Airport 1) are shown in Figures 11 through 16, to illustrate the principal findings from this investigation. Figures 11 through 16 show profiles of K^{+}, Na^{+}, Ca^{+2}, SO_4^{-2}, OH^{-}, and CH_3COO^{-} ions, respectively. Based on these results it can be observed that the penetration of K^{+} ions into concrete is very minimal and restricted to less than 5 mm from the pavement surface. The concentration profile of acetate ions (CH_3COO^{-}) is very similar to that of K^{+} ions. Similar profiles of potassium and acetate ions were observed in investigations conducted on cores from other pavements. The principal anions and cations present in the extracted solutions were found to be Na^{+} and OH^{-} ions. On a relative scale the concentration of Ca^{+2} and SO_4^{-2} was minimal at all depths investigated. Overall, it appears that the penetration of KAc deicer into concrete is no more than 10 – 15 mm.

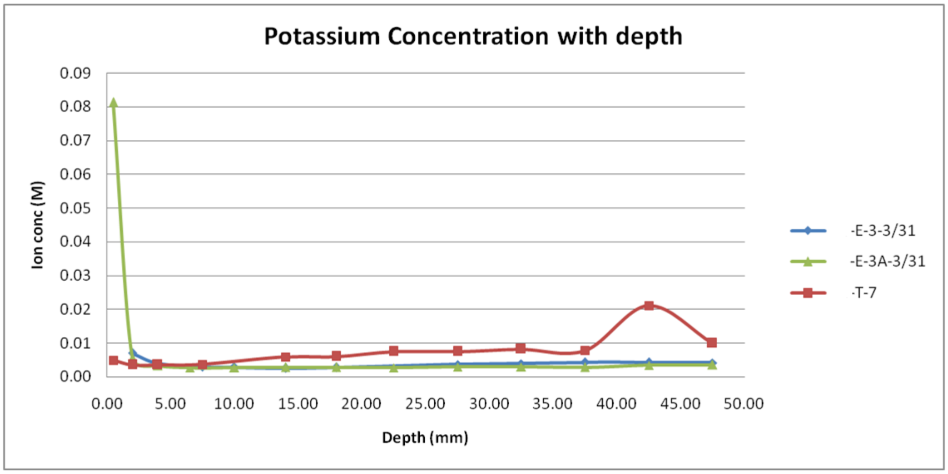


Figure 11 – Profile of potassium ions in Taxiway Echo cores.

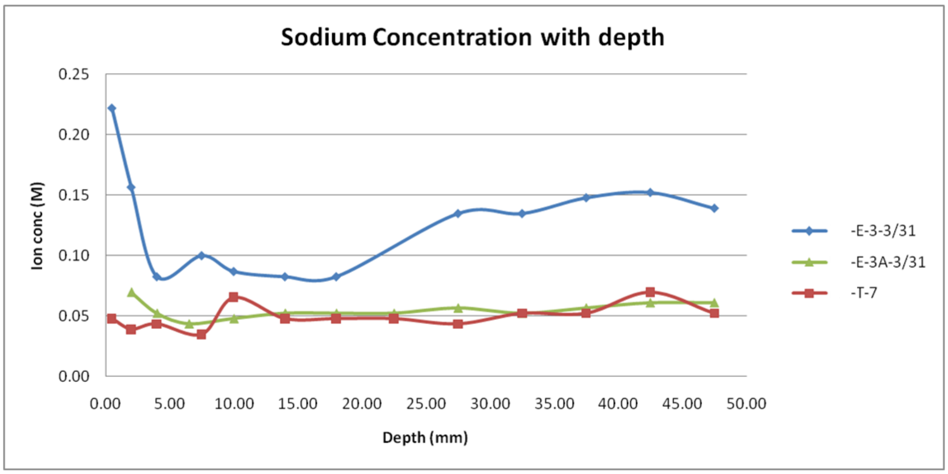


Figure 12 – Profile of sodium ions in Taxiway Echo cores.

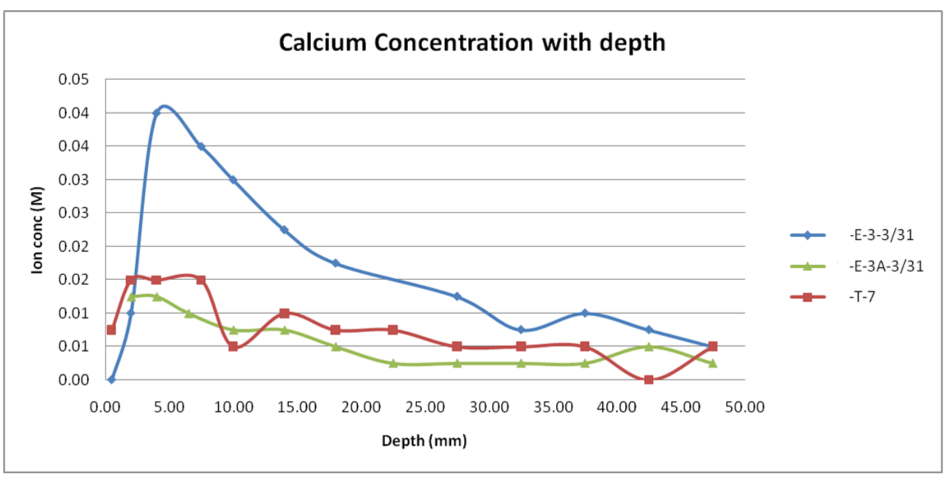


Figure 13 – Profile of calcium ions in Taxiway Echo cores. Note that the Y-axis scale is not the same in all the graphs

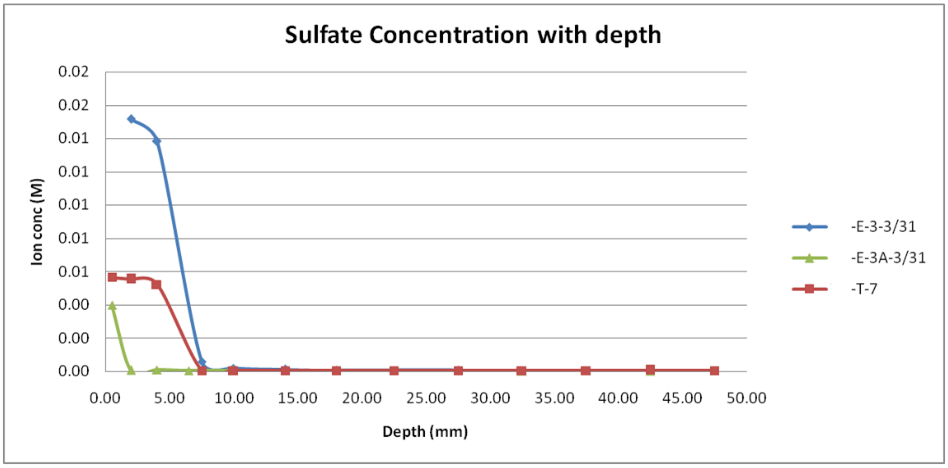


Figure 14 – Profile of sulfate ions in Taxiway Echo cores.

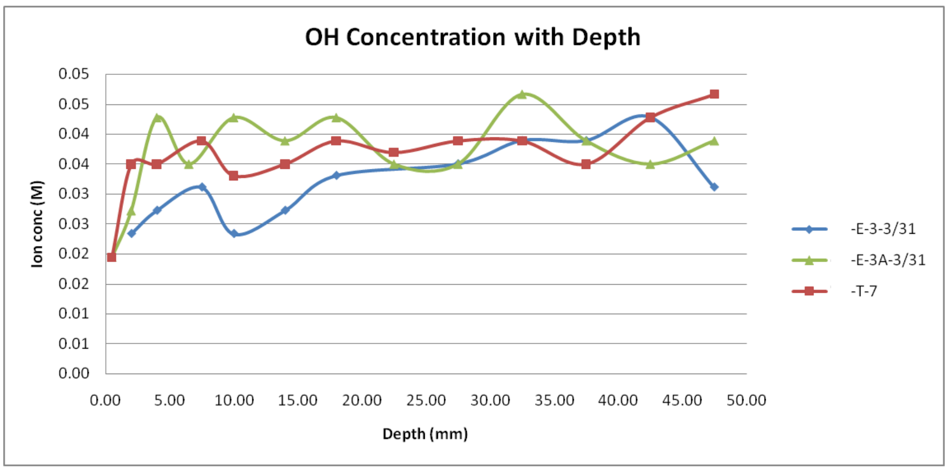


Figure 15 – Profile of hydroxyl ions in Taxiway Echo cores.

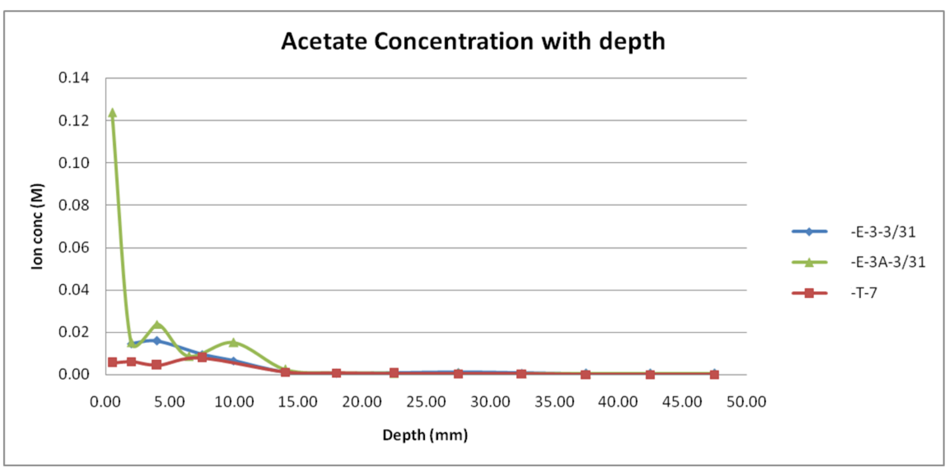


Figure 16 – Profile of acetate ions in Taxiway Echo cores. Note that the Y-axis scale is not the same in all the graphs

g. Freeze-Thaw Durability of Concrete Exposed to Deicer Solutions

A detailed summary of results from these tests is provided in Appendix B. However, a summary of important trends in the results is given below and the implications of KAc exposure on freeze-thaw durability of concrete are explained.

The freeze thaw testing of field cores using the modified ASTM C 666 procedure showed a general trend of increased deterioration when exposed to potassium acetate deicer. However, when companion test specimens were subjected to deionized-water in the modified ASTM C 666 procedure, the extent of deterioration was minimal to none. Figures 17 and 18 show the changes in pulse velocity readings of a few test specimens from different airfield pavements subjected to periodic exposure of deionized water and 6.4 M KAc deicer solution, respectively, over the course of 300 freeze-thaw cycles in the modified ASTM C 666 test method. The visual condition of companion test specimens (from Airport IV Taxiway Echo) subjected to deionized water and 6.4M KAc deicer solution, respectively, are shown in Figures 19 and 20.

It is evident from both visual evidence and pulse velocity results that periodic exposure of test specimens to 6.4 M KAc can cause significant damage in concrete specimens when subjected to repeated cycles of freezing and thawing. For instance, out of the five test specimens shown in Figure 18, four of them completely failed at the conclusion of the test. It should be noted that while the hardened air content of companion specimens shown in Figures 19 and 20 was marginal at 3.89% with a spacing factor of 0.220 mm, other test specimens with better air-void characteristics also showed significant damage in the freeze-thaw test when subjected to 6.4M KAc deicer.

Based on these results, it appears that the KAc deicer may have a significant impact on freeze-thaw durability of concrete compared to other materials-related distresses such as ASR. However, more detailed investigations are necessary to ascertain how and why a functional air-void system is being compromised in the presence of KAc deicer solution.

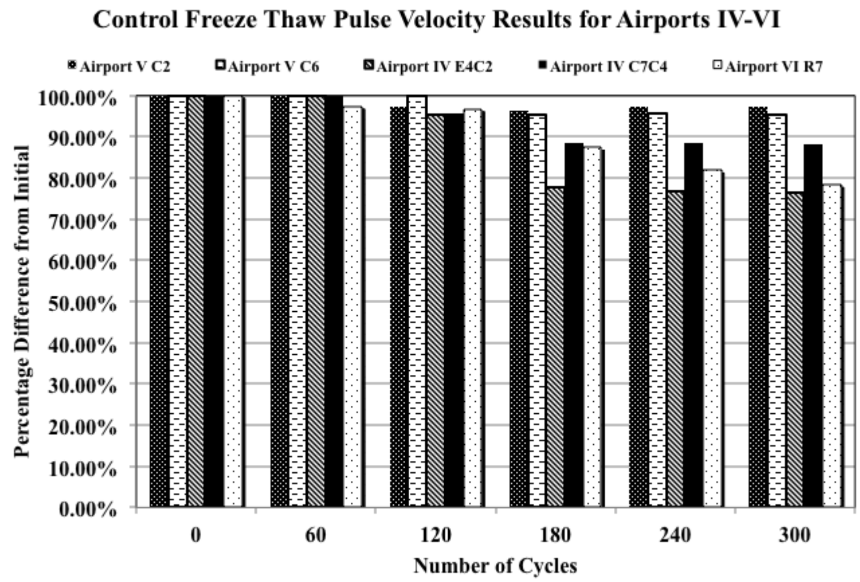


Figure 17 – Control Freeze Thaw Pulse Velocity Results for Airports IV-VI

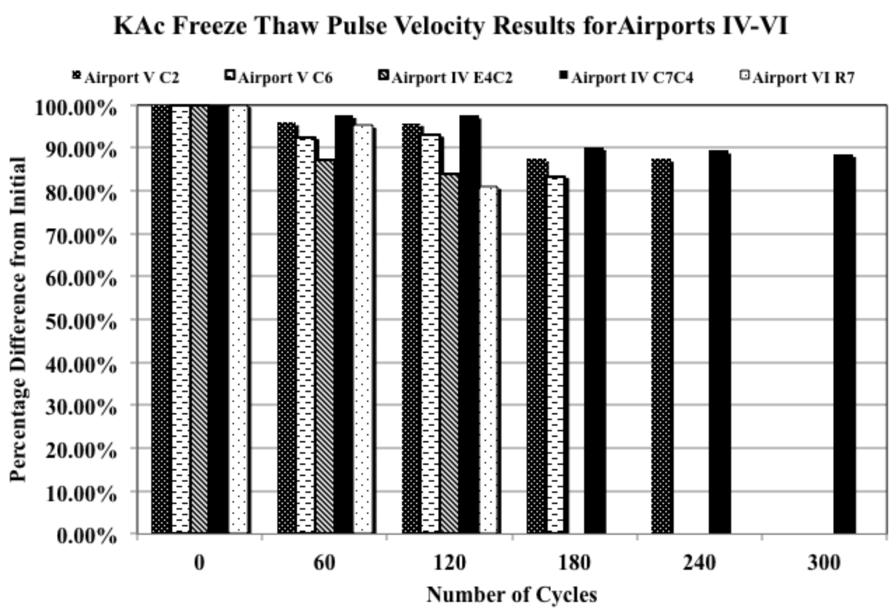


Figure 18 – 6.4M KAc Freeze Thaw Pulse Velocity Results for Airports IV-VI

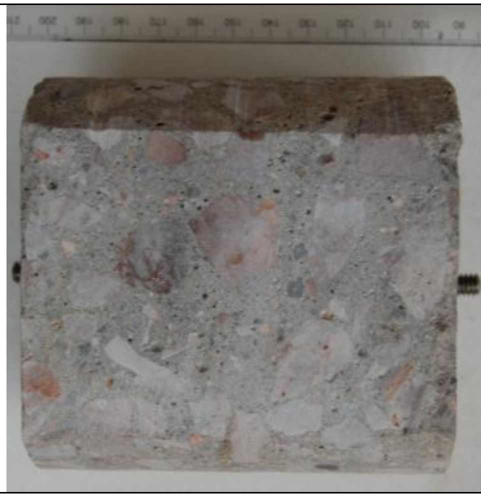
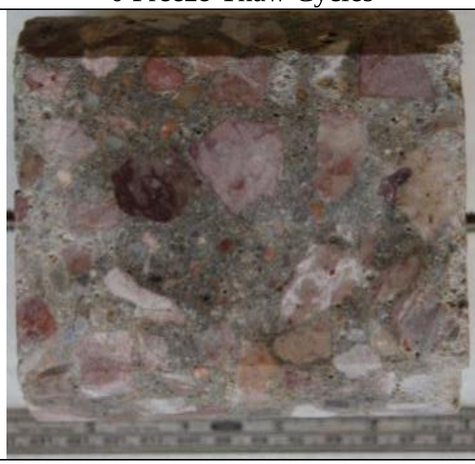
		
0 Freeze-Thaw Cycles	60 Freeze-Thaw Cycles	120 Freeze-Thaw Cycles
		
180 Freeze-Thaw Cycles	240 Freeze-Thaw Cycles	300 Freeze-Thaw Cycles

Figure 19 – Visual Condition of Airport IV Taxiway Echo 4 Core 2 (exposed to deionized water) During the Freeze Thaw Testing

		
0 Freeze-Thaw Cycles	60 Freeze-Thaw Cycles	120 Freeze-Thaw Cycles
	Sample Failed	Sample Failed
180 Freeze-Thaw Cycles	240 Freeze-Thaw Cycles	300 Freeze-Thaw Cycles

Figure 20 – Visual Condition of Airport IV Taxiway Echo 4 Core 2 (exposed to 6.4 M KAc deicer) During the Freeze Thaw Testing

6.2 Task 2 - Fundamental Investigation on Interactions between Deicing Chemicals and Concrete Materials

In this segment of the investigation fundamental chemical interactions between KAc deicer solution and constituents of concrete were studied, so that any evidence of distress from examination of field concrete can be better understood. While the results from this study are very important, they do not bear a direct relation to the forensic investigation of airfield pavements, which is the principal objective of this research study. Hence the findings from these studies are entirely presented in Appendix E.

6.3 Task 3 - Development of Test Method to Assess Deleterious Interactions Between Deicing Chemicals and Concrete Materials

Appendix F presents a comprehensive report that discusses the development of a rational test method to assess the aggregate reactivity in the presence of deicing chemicals and evaluate effectiveness of various ASR mitigation measures in the presence of deicing chemicals. However, a summary of the findings is provided in this section that highlights the advantages of the proposed test method.

Based on investigations conducted to study the fundamental interactions between deicing chemicals and cement paste constituents, it was determined that the pH jump phenomenon was an important mechanism by which the KAc was able to initiate and accelerate ASR. Interactions between KAc deicer solution and granular calcium hydroxide resulted in substantial jump in pH, however this phenomenon was not accompanied by a corresponding increase in hydroxyl ion content of the solution. The low hydroxyl ion concentration in the solution is to be expected as calcium hydroxide is not highly soluble in water at ordinary temperatures and therefore its contribution to hydroxyl ion content of the solution is minimal.

Based on fundamental studies conducted in this investigation, it has been postulated and proven that when KAc deicer solution and calcium hydroxide interact the increase in the pH of the solution was due to an increase in the activity coefficient of hydroxyl ions and not due to increase in the concentration of hydroxyl ions. The shortcoming of using a straight 6.4 M KAc deicer solution in the mortar bar test is that, to the extent that the activity coefficient of the hydroxyl ions in high the small concentration of hydroxyl ions will actively react with aggregates and when the hydroxyl ion concentration decreases the alkali-silica reaction ceases. This is the reason why different reactive aggregates behaved very differently in the EB-70 test method compared to the standard ASTM C 1260 test method.

Considering these findings, it was proposed that the new test method should employ a soak solution that has a concentration of 3M KAc and 1N NaOH. This combination ensures that soak solution not only has a high hydroxyl ion concentration (due to 1N NaOH), the activity coefficient of the hydroxyl ions is also high (due to a high concentration of KAc) in the solution. With the increase in both concentration and activity coefficient of hydroxyl ions, the ASR reaction induced by the deicing chemicals will be sustained as well as aggressive.

Based on a series of ASTM C 1260 tests, EB-70 tests and revised EB-70 tests conducted on over 30 aggregates in this research study, it has been shown that the proposed test method will effectively screen aggregates that are susceptible to KAc deicers. A detailed description of the development of the revised test method is provided in Appendix F, along with the application of this test method to evaluate supplementary cementing materials.

7. CONCLUSIONS

Based on the comprehensive forensic investigations conducted in this research study on pavements at eight different airports, the following conclusions are drawn:

1. Alkali-silica reaction distress was the most significant type of materials-related distress observed in majority of the airfield pavements investigated in this research study, followed by alkali-carbonate reaction to a lesser extent.
2. Distress due to other mechanisms such as drying shrinkage and freeze-thaw cycles were also observed in most pavements, although to a much lesser extent compared to the ASR distress.
3. Defects in pavements due to poor construction practices were observed in some pavements.
4. In all the pavements affected by ASR distress, characteristic features of ASR damage in concrete such as the micro-cracking in paste/aggregate interface regions and presence of ASR gel in cracks and voids surrounding aggregates were observed through the thickness of the pavement.
5. Studies on the profile of potassium and acetate levels in the concrete showed that the penetration of KAc deicer into sound concrete was minimal. Based on the results from all the pavements the penetration of KAc deicer into concrete was restricted to less than 15 mm from the pavement surface.
6. In all the pavements that exhibited significant premature distress due to ASR, either Class C fly ash at a nominal dosage of 15% was used in the concrete or no supplementary cementing materials were employed.
7. In majority of the pavements investigated in this research study, no specifications were available at the time of construction to address ASR distress in concrete. Consequently, neither the aggregates were required to be evaluated for their alkali-silica reactivity nor the use of low-alkali cements or effective ASR mitigation measures was required.
8. ASR distress was also observed in pavements that were built more recently (i.e. < 10 years old). In these pavements the existing specifications were not strictly enforced, particularly in allowing the use of Class C fly ash at a minimal dosage of 15%.

9. The hardened air content of concrete in majority of the pavements was found to be adequate in its quantity and quality (i.e. spacing factor) to resist freeze-thaw cycles. However, evaluation of concrete cores in the modified ASTM C 666 test in the presence of KAc deicer showed poor performance in some cases. Precise reasons for the failure are not evident yet.
10. Fundamental studies on deicer-calcium hydroxide interactions have shown that the pH jump observed in the solution is due to increase in activity coefficient of hydroxyl ions, and not due to increase in concentration of the hydroxyl ions. However, when KAc deicer interacts with NaOH solution, the observed pH jump is a function of both increased activity coefficient of hydroxyl ions as well as increase in the concentration of hydroxyl ions.
11. The deicer-modified mortar bar test method developed in this research study to assess aggregate reactivity in the presence of KAc deicer has been shown to be effective in screening a wide range of aggregates. The use of a soak solution with a composition of 3 M KAc and 1N NaOH has adequately captured the interactions of KAc deicer with constituents of hydrated cement paste. This method is also effective in assessing the effectiveness of ASR mitigation measures against the effects of KAc deicer.

Based on the overall findings from this research study, it appears that KAc deicer does not penetrate sound concrete adequately to trigger deleterious levels of ASR distress. Considering the evidence that the distress was observed throughout the thickness of the pavement, the source of the ASR distress is inbuilt into the pavement, for instance the use of reactive aggregate with no suitable ASR mitigation measures or the use of high-alkali cement. It appears that lack of adequate specifications at the time of construction of pavements to restrict use of reactive aggregates and/or encourage the use of effective ASR mitigation measures such as Class F fly ash or slag is the main reason for the observed distress.

While ASR distress in field concrete may not be driven by KAc deicer, results from freeze-thaw tests in lab suggest that concrete exposed to KAc deicer is more susceptible to freeze-thaw failure. Additional research is needed to investigate this phenomenon.

8. RECOMMENDATIONS

Based on the findings from this study, the following recommendations are offered:

1. Proper screening of aggregate and cementitious materials is necessary to avoid ASR distress in future. It is recommended that specifications be strictly enforced to avoid using marginal aggregate and cementitious materials.
2. Even though the deicer usage has not been found to be a major cause in triggering ASR distress, the test method proposed in this research study should be used as an interim screening tool along with the standard ASTM C 1260 and ASTM C 1567 test methods to avoid selecting aggregates that may be susceptible to KAc deicer. A final decision on whether or not to consider the deicer-modified test method to evaluate aggregate reactivity should be taken after accumulating more field evidence and confirming the benign nature of the deicers. It should be acknowledged that majority of the pavements have multiple distresses and it is difficult to discern which of the distresses occurred initially and could perhaps have triggered other distress modes. The data gathered in the present research suggests that the observed ASR distress in the pavements was caused primarily due to use of substandard materials and improper ASR mitigation strategies. Although the deicers may have contributed to increasing the alkali burden in the concrete in near surface, it is difficult to isolate and discern the effects of deicers alone. The lack of adequate deicers in deeper section of the airfield pavements suggests that deicers may not have participated in causing the ASR distress at those levels.
3. It is recommended that a comprehensive investigation be carried out to study the susceptibility of KAc deicer exposed concrete to freeze-thaw damage.

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