8-2007

EVALUATION OF LITHIUM BASED DEICING CHEMICALS FOR MITIGATING ASR IN CONCRETE PAVEMENT

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Recommended Citation

Soundarapandian, Senthil, "EVALUATION OF LITHIUM BASED DEICING CHEMICALS FOR MITIGATING ASR IN CONCRETE PAVEMENT" (2007). *All Dissertations*. 130.
https://tigerprints.clemson.edu/all_dissertations/130

EVALUATION OF LITHIUM BASED DEICING CHEMICALS FOR MITIGATING ASR IN CONCRETE PAVEMENT

A Dissertation
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy
Civil Engineering

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by
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August 2007

Accepted by:
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ABSTRACT

Deicing and anti-icing chemicals such as alkali-acetate and alkali-formate based formulations are increasingly being used on airfield pavements. Among these new deicers, potassium acetate-based formulations are widely used due to their environmentally friendly nature and effectiveness in melting and undercutting ice at low temperatures. Recent research on premature deterioration of airfield pavements due to alkali-silica reaction (ASR) has indicated that alkali-acetate and alkali-formate deicers such as potassium acetate and sodium formate may have been responsible for the observed distress. In an effort to develop a deicing chemical that is benign to concrete from an ASR standpoint, a new deicing formulation based on lithium compounds is being explored.

This research study presents the findings from a laboratory-based investigation on developing a lithium-acetate based deicing chemical to specifically address ASR concern in concrete. In these studies, mortar bars and concrete prism specimens were prepared with aggregates of known reactivity and exposed to solutions of pure lithium acetate and pure potassium acetate at different concentrations. In addition, parallel tests were conducted on mortar bars and concrete prisms in which test specimens were exposed to solution blends of lithium acetate and potassium acetate at different Li/K molar ratios (Li/K molar ratios=0.2, 0.4, 0.6, 0.8). Also, in order to evaluate the effect of these deicing chemicals on scaling resistance of concrete, modified ASTM C 672 tests were conducted. In order to understand the extent of externally applied damage in concrete, the K^+ ion and Li^+ ion profiles were established using Inductively Coupled Plasma (ICP) and X-Ray

Fluorescence spectrometer (XRF) techniques. Also, tests were conducted to determine the effectiveness of lithium nitrate, when applied as a pre-treatment before exposing to potassium acetate to find its effect in mitigating ASR.

Results from this study showed that specimens containing reactive aggregates and soaked in blends of lithium acetate and potassium acetate showed little or no expansion due to alkali-silica reactivity. It is also observed that potassium acetate deicer at concentration levels of 3 and 6.4 plays a significant role in the expansion of mortar bars and concrete prisms. No scaling was observed in concrete slabs made with both reactive and non-reactive aggregate exposed to 3 and 6.4 molar KAc solutions. From the penetration test, the gradient from top to bottom showed the influence of K in concrete samples. Mortar bars which were pre-treated with $LiNO_3$ showed significantly lesser expansion compared to bars which were not treated, upon exposure to potassium acetate deicers. In general, specimens made with high-alkali cement expanded more, compared to specimen made with low-alkali cement. It is recommended that lithium blended deicers with at least Li/K ratio of 0.2 be used for mitigating ASR. Also, low-alkali cements should be preferred when exposure to deicers is anticipated.

DEDICATION

This dissertation is dedicated to my parents, brother, sister and their family and to my dear wife Ida. The continued support, encouragement and love from them helped me in producing this work. I also dedicate this dissertation to God for his love and grace who enabled me to achieve this work.

ACKNOWLEDGMENTS

I like to acknowledge my graduate advisor, Dr. Prasada Rao Rangaraju for his continuous guidance and support in research and in the development of this dissertation. I would also like to thank Dr. Serji Amirkhanian, Dr. Bradley Putman and Dr. Patrick Fortney for their advice and serving as committee members.

I would also like to thank Mr. Jeff Davis from NIST for his significant contribution, Dr. John Kaup and Ms. Joaudimir Castro for their support in conducting chemical analysis. I would also like to thank all the undergraduate assistants who helped me in this research and colleagues for their support.

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CHAPTER ONE

INTRODUCTION

1.1 General

Concrete deterioration due to alkali-silica reaction (ASR) is a serious problem throughout the world. ASR is a deleterious chemical reaction between hydroxide ions in concrete pore solutions and certain reactive siliceous aggregate components, resulting in the formation of gel. When the alkali-silica gel absorbs moisture, it swells and exerts an internal pressure on the concrete and if the internal pressure exceeds the tensile strength of concrete it eventually produces cracks in the concrete. The most common methods of minimizing the expansion due to ASR are using nonreactive aggregates, limiting the alkali content of concrete, using supplementary cementing materials and using lithium compounds. Lithium compounds have been found to be the most effective agents to mitigate expansion due to ASR in both new and old concrete structures, when used at adequate dosage levels.

One of the main components necessary for ASR to occur is the alkali content. The main source of alkali in concrete is Portland cement. It is now suggested that alkalis from external sources such as deicing salts and salt water spray in marine environments play a vital role in triggering ASR. In the airfield industry, new generation deicers like potassium acetate, sodium acetate and sodium formate are replacing the traditional deicers and are widely used due to their low environmental impact. Potassium acetate is being used by major airports and military bases worldwide. Recent premature deterioration of airfield concrete pavements has indicated that these airfield deicers may be responsible for triggering ASR in concrete.

It is well known that several of the lithium compounds like lithium fluoride, lithium chloride, lithium hydroxide, lithium carbonate, etc, when proportioned appropriately into the fresh concrete, have shown potential to mitigate expansions induced by ASR in concrete. Topical applications of solutions of lithium compounds like lithium nitrate have also shown promise in this regard to mitigate ASR in existing concrete structures. However, the use of lithium acetate as an ASR-mitigation measure has not been explored yet. As a new approach, this research investigates the effects of lithium acetate compounds as an alternative deicing chemical and also in combination with potassium acetate deicing chemicals in mitigating ASR.

1.2 Problem Statement

In recent years, potassium acetate-based deicers have gained popularity in airfield concrete pavement deicing operations. Potassium acetate-based deicers are not only effective in ice and snow removal at much lower temperatures than either sodium chloride or calcium chloride based deicers, but are also considered environmentally benign. However, investigations at selected airports have suggested that potassium acetate-based deicers may have lead to premature distress in certain concrete pavements. In support of this, a preliminary finding from the Innovative Pavements Research Foundation (IPRF) study indicates that the potassium acetate deicers have the potential to induce aggressive alkali-silica reactions in certain concretes. Since these deicers affect the durability of concrete pavements, it became necessary to explore the use of deicing chemicals that are based on lithium compounds as alternative deicing chemicals and also in combination with potassium acetate as mitigation measure as lithium compounds have shown potential to mitigate ASR.

1.3 Need for the Research

There has been a tremendous increase in the use of potassium acetate deicers in winter operations of airfield concrete pavements. Also, there has been premature deterioration of several airfield concrete pavements due to the use of this environmentally acceptable deicer. As a result of this, there was an urgent need to find alternative deicing chemicals and also to find mitigation measures to combat ASR induced by potassium acetate. Since there are no deicers based on lithium compounds to combat ASR, it has become necessary to determine the effectiveness of lithium acetate as an alternative deicer and also as a combination with potassium acetate in mitigating ASR.

1.4 Research Objectives

The principal objectives of this research study were:

1. To determine the effectiveness of lithium acetate as a deicer solution in mitigating ASR induced by Potassium acetate deicer.
2. To study the effectiveness of lithium acetate in combination with potassium acetate deicer soak solutions with different Li/K ratios and at different concentrations in mitigating ASR.

1.5 Scope of the Research

The scope of this research was to study the effects of:

1. Lithium acetate as deicer solution
2. Lithium acetate in combination with potassium acetate deicer.

In this study, five different reactive aggregates that are different in level of reactivity and two non-reactive aggregates were used.

Reactive Aggregates:

1. Rhyolite from New Mexico (Las Placitas Gravel Pit, Lafarge Aggregates, NM).
2. Siliceous limestone from Ontario, Canada (Spratt Quarry, Ontario, Canada).
3. Quartzite from South Dakota (L.G. Everist Quarry, Sioux Falls, SD).
4. Argillite from North Carolina (Gold Hill Quarry, NC).
5. Fused Silica

Non-Reactive Aggregates:

1. Ottawa sand from Illinois (ASTM C 778 Standard Sand).
2. Dolomite from Illinois (Material Service Corporation, Illinois).

Two types of cements were used to study the influence of the alkali content of cement.

1. High-alkali cement (0.83% Na_2Oeq).
2. Low-alkali cement (0.29% Na_2Oeq)

Modified ASTM test procedures were adopted when standard test methods were not available which is explained in the appropriate section of this dissertation.

The standard and modified ASTM C 1260 tests were conducted with different aggregate type to find the reactivity of aggregate for which 208 samples were tested. To determine the length change of concrete due to alkali silica reaction, a modified ASTM C 1293 test was conducted for which 120 samples were tested. Modified ASTM C 672 test were conducted to determine the resistance to scaling of a horizontal concrete surface when exposed to freezing and thawing cycles in the presence of deicing chemicals for which 18 samples were tested. Modified ASTM C 227 test were conducted to determine the effectiveness of lithium nitrate as a pre-treatment measure before exposing to regular deicers for which 15 samples were tested.

1.6 Research Approach

The research approach of this dissertation was as follows:

1. Evaluate lithium acetate by itself a deicer and with different combinations with potassium acetate by running a modified ASTM C 1260 test procedure.
2. From ASTM C 1260 test results the effective combination in mitigating ASR was selected to conduct modified ASTM C 1293 test.
3. Determine the physical deterioration caused by deicers on mortar bars and concrete prisms by measuring the loss in dynamic modulus of elasticity of the specimens.

4. Conduct pH measurements, scanning electron microscopy (SEM) and energy dissipative x-ray analysis (EDX) for mortar bars and concrete prisms at the end of the study.
5. Evaluate the influence of these deicer formulations on scaling resistance of concrete by running ASTM C 672 tests.
6. Measure the penetration depth of deicers on the concrete slabs by drilling cores of sample and using ion chromatography.
7. Conduct chemical analyses to understand the mechanism of these deicers in mitigating ASR.

1.7 Organization of the Dissertation

The dissertation is comprised of five chapters. Chapter I is the introductory chapter and states the problem statement, need for the research, research objectives, scope of the research, research approach, and organization of the dissertation. Chapter II presents a literature review on ASR and various mitigation measures. It provides the general information on ASR and different deicing chemicals based on their properties. Chapter II also discusses the deicers which are used on regular highway pavements and airfield pavements. As mitigation measures, various lithium compounds being used are also discussed in detail. Chapter III describes the materials used in the research and the test procedures. It also provides a layout of the experimental program along with the mixture designs used in all the tests. Chapter IV presents the results and discussions of the various tests. Chapter V presents the summary of the various tests and the principal findings of the research and the conclusions drawn from the findings. Based on the findings, recommendations are made for the use of lithium blended deicers and the future research work needed.

CHAPTER TWO

LITERATURE REVIEW

2.1 General

This chapter provides an overview of alkali-silica reaction (ASR) and also some general information on different types of deicing chemicals used for concrete pavements. It also discusses the mechanism involved in ASR and the various mitigation measures which are currently used to mitigate expansion due to ASR, and also a wide range of research performed using lithium to combat ASR. In addition, a review of literature is presented as the case of lithium admixture in mitigating ASR expansions.

2.2 Introduction to Alkali Silica Reaction

In the United States during late 1920s to the early 1940s there were reported failures of concrete structures due to the result of overall cracking throughout the structure manifested at the surface as extensive map cracking or pattern cracking, frequently accompanied by gel exuding from the cracks or surface popouts and spalling[1]. In the early 1940s, Stanton [2] first identified the cause in which he revealed that the deterioration is due to expansions caused by the chemical reaction between the alkalis from the cement and certain reactive forms of silica within the aggregate.

It has been found that various forms of silica have different reactivities, depending on the degree of crystallinity, internal porosity, crystallite size, and internal crystal strain. Due to this, different aggregates react at different rates and the damage due to ASR may not be apparent for many years after a structure is put into service.

Since this initial discovery, there have been reported cases throughout the world. ASR has been implicated in the deterioration of various types of concrete structures, including dams, pavements, bridges, and other structures.

2.2.1 Factors Affecting Expansion

Factors that control the ASR expansion are

1. Reactive silica
    - Nature of reactive silica.
    - Amount of reactive silica.
    - Particle size of reactive materials.
2. Amount of available alkali and
3. Amount of available moisture.

Reactive Silica

One of the essential components needed for ASR to occur is the reactive aggregate. Reactive aggregates are those that tend to breakdown under exposure to the highly alkaline pore solution in concrete and subsequently react with the alkali-hydroxides (sodium and potassium) to form ASR gel. It is important to note that not all siliceous aggregates are prone to ASR. The inherent reactivity of aggregates depends on several factors, including aggregate mineralogy, degree of crystallinity, and solubility of the silica in pore solution.

Sufficient Alkalis

The presence of sufficient alkalies is essential to trigger ASR. The source of alkalies can be from any of the following:

1. Portland cement.
2. Supplementary cementing materials (fly ash, slag, silica fume, etc.).
3. Aggregates.
4. Chemical admixtures.
5. External sources (seawater and deicing salts).
6. Wash water.

Of the above materials, Portland cement is the main contributor of alkalies. The alkalies present in Portland cement are in the form of potassium oxide (K_2O) and sodium oxide (Na_2O). The quantity of alkalies in Portland cement is typically expressed as follows:

$$Na_2O_e = Na_2O + 0.658K_2O$$

Where: Na_2O_e = Total sodium oxide equivalent (or equivalent soda), in percent by mass

Na_2O = sodium oxide content, in percent

K_2O = potassium oxide content, in percent

Although laboratory tests shows that keeping the total alkali content below 3.0 kg/m^3 Na_2O_e is an effective method of limiting expansion, field structures have exhibited damage with even lower alkali loadings, especially when alkalies have also been contributed by the aggregates in the mixture or by external sources, such as deicing salts. Thus, when considering imposing a limit on the alkali content for a given concrete mixture, consideration should be given to the aggregate type and reactivity, exposure conditions, and nature of the structure (i.e., design life or relative importance).

Sufficient Moisture

Available moisture is important when considering the potential for ASR-induced damage in field structures. Concrete mixtures comprised of highly reactive aggregates and high-alkali cements have shown little or no expansion in certain very dry environments. Likewise, local differences in moisture availability within the same structure have resulted in vastly different performance within that structure. Specifically, portions of the structure exposed to a constant or steady source of moisture (e.g., due to poor drainage or poor detailing) have exhibited significant ASR induced damage, while other portions of the structure that remain essentially dry have shown little or no damage. Therefore, in general, the exposure conditions, and the availability of moisture specifically, play an important role in the ASR induced damage in concrete structures.

2.2.2 Mechanism of ASR

Based on the synthesis a broad range of research by Helmuth and Stark [1] they observed ASR results in the production of two component gels – a nonswelling calcium-alkali-silicate-hydrate [C-N(K)-S-H] and a swelling alkali-silica-hydrate [N(K)-S-H].

Whenever ASR occurs in concrete, some nonswelling [C-N(K)-S-H] is always formed. The reaction will be safe if this is the only reaction product, but unsafe if both gels form.

The overall mechanism of ASR proceeds in the following way:

1. In the presence of various pore solution ions, the reactive silica in the aggregate undergoes depolymerization, dissolution and swelling.
2. The alkali and calcium ions diffuse into the swollen aggregate resulting in the formation of a nonswelling C-N(K)-S-H gel.
3. The pore solution diffuses through the porous layer of C-N(K)-S-H gel to the silica. If CaO constitutes 53% or more of the C-N(K)-S-H on an anhydrous (without water) weight basis of the gel, only a nonswelling gel will form. However, for high alkali concentrations, the solubility of CH is depressed resulting in the formation of some swelling N(K)-S-H gel that contains little or no calcium. Both nonswelling and swelling gel results in the formation of a composite gel with greatly increased viscosity and decreased porosity.
4. The N(K)-S-H gel attracts water due to osmosis, which results in an increase in volume, which ultimately leads to tensile stresses and cracking. The cracks fill with reaction product, which gradually flows under pressure from the point of its initial formation.

2.2.3 Mitigating ASR

Some of the common methods of mitigating or preventing ASR in new and existing concrete structures are:

1. Using nonreactive aggregates
2. Limiting the alkali content of the concrete
3. Using supplementary cementitious materials
4. Using lithium compounds
5. Avoiding future use of deicing salts that will increase alkali content within the structure.

Nonreactive Aggregates

Using nonreactive aggregates is the best method of preventing ASR induced damage. The aggregate reactivity is established based on their performance in standardized tests such as ASTM C 1260 and ASTM C 1293 test. Aggregates that were believed to be nonreactive have caused damages due to ASR expansion in field structures. In those cases, proper attention should be given to the prior field performance of structures built with the aggregates and where possible, additional precautionary measures should be taken, such as adding supplementary cementing materials, etc. The best solution, whenever it is practical, is to avoid susceptible aggregate based on aggregate reactivity tests and service records.

Limiting the Alkali Content of Concrete

Limiting the alkali content of concrete mixtures below some threshold value (3.0 kg/m^3) is generally effective in preventing ASR, but this approach is not always effective by itself. Since, aggregates that are durable at relatively low alkali contents may become more reactive when exposed to higher alkali contents under field conditions from exposure to deicing salts, alkali release from aggregates and other field effects. With respect to this, there are reported increases in soluble alkalis from 1.1 to 3.6 kg/m3 Na_2Oe close to the surface of some highway structures [3].

It is also now recognized that limiting the alkali content of portland cement is not an effective way of preventing ASR induced damage since this does not control the total alkali content of the concrete mixture. Therefore, limiting the maximum alkali content of concrete is the preferred approach when specifying alkali levels.

Lithium Compounds

Using lithium compounds is a viable approach in controlling ASR. Since the scope of this research performed on using lithium compounds based deicer to mitigate ASR, no additional discussion is provided in this section. Detailed review is discussed in section 2.4 of this chapter.

Supplementary Cementing Materials

Mineral admixtures like fly ash, ground-granulated blast furnace slag, and silica fume have been used to reduce the effects of ASR. The beneficial effects of these materials are due to:

1. Dilution of the cement due to partial replacement with the mineral admixture
2. Reduced pH of the pore solution
3. Increasing solubility of calcium, and
4. Subsequent formation of nonexpanding C-N(K)-S-H gel in place of swelling N(K)-S-H gel.

It has been found that a large quantity of pozzolan or slag is needed to successfully control ASR. Adequate protection is attained by replacing 15 to 20 percent of the cement by Class F fly ash. For Class C fly ash with high lime content, a replacement level of 35 to 40 percent is required. This higher level is due to the greater portion of silica in the fly ash that is tied up by the lime, lowering the amount of silica available to control the ASR.

Silica fume is highly effective in controlling the ASR due to its high silica content and high surface area, cement replacement values of 10 to 15 percent are typical. Slag is typically used at replacement levels of 35 percent or more, to mitigate ASR.

It is important to use enough pozzolan, since low quantities of added reactive silica may increase the severity of ASR rather than decreasing.

2.2.4. Test Methods to Evaluate Reactivity of Aggregates for ASR

Field performance is the best method for evaluating the potential reactivity of an aggregate. When long term data are not available, short term laboratory test should be used to indicate the potential reactivity of an aggregate, although the results often do not predict field behavior accurately.

There are several ASTM test procedures to find the reactivity of aggregates for ASR. ASTM C 289 is a quick chemical test that measures the solubility of silica when powdered aggregate is treated with sodium hydroxide. ASTM C 227 involves measuring the deleterious expansion in a mortar bar at 38ºC to 3 or 6 months. ASTM C 289 is a standard test method for potential ASR of aggregates, in which crushed aggregate is immersed in 1N NaOH solution for 24 hours, The NaOH solution is then analyzed for amount of dissolved silica and alkalinity (Chemical Method). ASTM C 295 involves petrographic examination of aggregates. ASTM C 441 is a mortar bar test, using pyrex glass as aggregate to evaluate the effectiveness of mineral admixtures in controlling ASR. ASTM C 1260 is a mortar bar test where bars are soaked in 1N NaOH solution for 14 days to assess aggregate reactivity. ASTM 1293 is a recommended test in which the alkali content of the cement is artificially increased to 1.25% by weight of cement and the test is conducted at high humidity (close to 100%) at 38°C. The expansion of the concrete prism is monitored up to a period of 1 year. This method is used to test the effectiveness of SCMs and lithium compounds, but the test typically runs for 2 years.

2.3 Introduction to Deicing Chemicals

One of the important factors for ASR to occur is the alkali in the concrete. Alkalies can be ingressed into the concrete by an external source like deicing chemicals, which are studied in this research.

Deicing chemicals or “deicers” are chemicals that are sprayed on pavements to melt ice or snow. The chemicals work by dissolving slowly on contact to create brine, with the heat of solvation helping to melt the ice or snow.

Anti-icing chemicals or “ant-icers” are applied on pavement surfaces or aircraft bodies before snowfall to prevent ice or snow from adhering to their surface. This prevents the formation of a bond between slippery snow and ice and the roadway, thereby facilitating mechanical removal. Anti-icing allows for a very high level of traffic safety at low cost and significantly reduces the amount of road salt used.

In this dissertation, both deicing chemicals and anti-icing chemicals will be termed as “deicing chemicals” or ‘deicers” for the sake of simplicity

2.3.1 Function of Deicing Chemicals

Salts are used as deicers for winter road maintenance because they lower the freezing point of water. Deicers are incapable of melting snow and ice in their dry (solid) state. When they first come into contact with moisture (ice and snow) they form brine chemical/water solution. Since the solution of deicers in water has a lower vapor pressure than the ice the ice changes its phase to liquid water. The brine then penetrates down through the ice and snow until it reaches the pavement. Once on the pavement surface, it spreads outwards melting and undercutting the ice and snow for mechanical removal, plowing or shoveling [4]. Pellets are highly effective at undercutting because they contact only a small area of ice and bore vertically downward, quickly reaching the ice/pavement interface.

2.3.2 Classification of Deicers

Based on the chemical composition deicers are classified as:

1. Chloride based deicers: These are most widely used deicers. They are easily available and at a low price. Sodium chloride and calcium chloride are some of the chloride based deicers.
2. Magnesium based deicers: These deicers are non-chloride based and therefore, do not pose any problem like corrosion due to chloride and they are more expensive. Calcium magnesium acetate (CMA) is a magnesium based deicer.
3. Acetate and formate based deicers: These deicers replaced glycol and urea based deicers and are generally selected for their low environmental impact, high performance and corrosion inhibitors. Examples of acetate based deicers are potassium acetate and sodium acetate and examples of formate based deicers are sodium formate and potassium formate. They are high in cost.
4. Glycol based deicers: These deicers were used at airports before the acetate and formate based deicers. They are non-chloride based. Propylene glycol is used as aircraft deicer and is the only aircraft deicer approved for purchase for Air Force activities [5].

5. Urea: Urea is used as an airfield deicer/anti-icer in the aviation industry to avoid aircraft corrosion. However its use is now discouraged by Environmental Protection Agency due to environmental concerns.

2.3.3 Highway Deicing Chemicals

Chloride based deicers like calcium chloride and sodium chloride (rock salt) are widely used deicers for winter operations for snow and ice removal on concrete pavements. They are the most cost effective and easily available deicers in USA. Considerable research has been done to understand the influence of these deicers in initiating ASR in concrete pavement [6-14]. One of the adverse effects of sodium chloride deicers is on the corrosion of highway structures, especially bridge decks.

It was estimated that the cost of corrosion damage caused by deicing and sea salt on highway bridges exceeded US$150 billion in the United States [15]. Of an estimated 80,000 bridges in Canada, 50% have an average age of between 30 and 45 years and require major rehabilitation or total replacement [16].

Chloride attack in concrete is not essentially only on the cement paste but the reinforcement present in the concrete. A passivity layer of ferrous oxide forms on the steel as soon as the hydration of cement begins. This passivity layer protects the steel from any reactions with water and oxygen to from rust. However, chloride present in the deicer destroys this passive steel layer and activates the steel to form an anode in these reactions. Chloride ions combine with ferrous ions to form ferrous chloride. The ferrous chloride, in turn, reacts with water to form ferrous hydroxide and hydrochloric acid.

Hydrochloric acid in water exists as H+ and Cl- ions. Therefore chloride ions are regenerated, which cause further corrosion of the steel in concrete.

Chloride based deicers also aggravate ASR in concrete. When concrete is exposed to chloride based deicers, they react with the hydration products of the concrete causing the liberation of OH- ions, which causes an increase in the pH of the pore solution of the concrete. This high alkaline environment, along with the presence of reactive silica from aggregate and moisture from the surrounding or the pore solution, triggers ASR in the concrete [17].

Calcium magnesium acetate (CMA) is used as an alternative deicer for chloride based deicers for concrete pavement because of its reduced potential to affect the environment and it is not as corrosive as salt. However, the use of these deicers as a general replacement for traditional deicers is restricted due to their high cost. From the various researches on CMA the results indicated that concrete was attacked by the CMA solutions through a de-lamination process of the cement matrix most likely associated with leaching of the calcium hydroxide. When the concrete is exposed to freezing and thawing in the presence of CMA deicing chemicals this leads to significant degradation of the concrete. The attack manifests itself through deterioration of the cement matrix and exposure of the aggregates which results in mass loss and decrease in the load capacity (as great as 50%) [18-20].

2.3.4 Airfield Deicing Chemicals

Deicers are used on airport runways for removal (deicing) and prevention (anti-icing) of frost, ice, or snow accumulation on aircraft, airfields, and other base areas. Deicing and anti-icing are vital to flight safety because even small amounts of ice on airframes and airfoils can degrade aircraft lifting properties and control. Since chloride salts (sodium chloride and calcium chloride) and CMA are the cause of environmental impacts like groundwater contamination, damage to vegetation and corrosion they are not preferred for winter operations for snow and ice removal on airfield pavements.

Grade B isopropyl alcohol has been in limited use for deicing and anti-icing due to its high volatility and vapors could be carried inside the aircraft creating a fire hazard. Ethylene glycol has a high biochemical oxygen demand (BOD), and is toxic to aquatic life and mammals. It is subject to various hazardous substance regulations under the Clean Air Act. BOD is defined as the rate at which microorganisms use the oxygen in water or wastewater while stabilizing decomposable organic matter under aerobic conditions. The effect of increased BOD is to deplete dissolved oxygen levels in the water and deprive aquatic life of oxygen. Because of this, propylene glycols and Type I glycol are the only glycol based deicing and anti-icing chemical agents approved for purchase by airfield activities [21]. Urea has been used in pellet form and has a high BOD, and is of limited effect at temperatures below 25ºF.

Due to the negative effects of the glycol based deicers and urea, the US Air Force advocates the use of three environmentally acceptable chemical agents such as potassium acetate, sodium acetate, and sodium formate.

Sodium acetate is a granulated product applied in the same manner as urea and is effective at temperatures as low as 10ºF, has a lower BOD and is less toxic than urea. Sodium formate is a granulated product similar to sodium acetate. It is effective at temperatures as low as 5ºF, has a low BOD, and has a neutral pH, which reduces corrosion problems. Potassium acetate is standardized with a minimum concentration of 50% potassium acetate in water, by weight. Potassium acetate runway deicers were introduced in Europe in 1988 [22]. Today, this deicer is being used by over 200 major airports and military bases worldwide. It is effective at temperatures as low as 20ºF. Potassium acetate may be used as a pre-wetting solution when applying granulated sodium formate.

At present, there are several airfield pavements experiencing premature deterioration due to the use of environmentally acceptable chemical agents like potassium acetate, sodium acetate, and sodium formate. Recent investigations on premature deterioration of airfield pavement have indicated deicing chemicals, such as potassium acetate and others, may be causing ASR distress in concrete. In studying the mechanism, it has been found that there is an apparent jump in pH (and presumably in OH^- ion activity) that occurs when potassium acetate solutions come in contact with Portland cement concrete, in particular calcium hydroxide present in concrete. The innocuous pH of the 50% potassium acetate solution itself (pH 11) jumped to a pH level of 15. The resulting solutions appear to be highly aggressive with respect to inducing ASR [23-24].

2.4 Lithium compounds

2.4.1 History and Background

The concept of using lithium salts to inhibit ASR expansion was first reported in 1951 by McCoy and Caldwell [25]. In this study, mortar bars were produced with Pyrex glass as the reactive aggregate, and the alkali content of the cement was raised to 1.15% Na_2O_{eq} by adding NaOH to the mixing water. Additional lithium compounds such as LiCl, Li_2CO_3, LiF, Li_2SiO_3, $LiNO_3$, and Li_2SO_4 were found to be the most effective agents to mitigate expansion due to ASR in mortars. From these studies, they recommended that a minimum lithium to alkali (potassium plus sodium) molar ratio (expressed as [Li]/[Na+K]) of 0.74 was needed to efficiently suppress expansion. Although initial findings were quite promising. it was not until the 1990s that interest in lithium as an admixture for concrete was renewed.

2.4.2 Effects of Lithium Salts on ASR

In 1989, Sakaguchi et al. [26] used Pyrex glass and known reactive sand as the reactive aggregates. LiOH H_2O, $LiNO_3$, and Li_2CO_3 were added to the mortar bars. All of the lithium compounds were effective in reducing expansion. The results also indicated that the effect of lithium salts varies with lithium to alkali molar ratios. The threshold lithium to alkali molar ratio to completely suppress ASR expansion was 0.9. He also found from expression of pore solutions from mortar bars made with $LiNO_2$ that the concentration of lithium ions decreased with time while that of sodium and potassium remained nearly constant. This was in contrast to tests without lithium where a decrease in both the sodium and potassium concentration was observed.

The suppressive effects of lithium fluoride, lithium carbonate and lithium hydroxide was also confirmed [27, 28]. Also, insufficient dosage of lithium actually resulted in an increase in expansion compared to the control mortar without lithium; this is known as the pessimum effect.

Pessimum effect may be caused due to an increase in the alkalinity (OH^-) of the pore solution caused by the addition of lithium, especially LiOH. Most other forms of lithium also increase the pH of the pore solution. $LiNO_{3,}$ however, is unique in that it does not tend to increase the pH, thereby eliminating the pessimum effect [29]. The suppressive effects of lithium compounds on ASR expansion depend strongly on the kind of lithium compounds used, the [Li]/[Na+K] molar ratio, and on the nature of the reactive aggregate [30].

It has also been found that there is a linear relationship between the effective dosage of $LiNO_3$ in terms of [Li]/[Na+K] molar ratio and the difference between the concrete alkali content and the threshold alkali level of the aggregate (alkali reactivity level) [32]. $LiNO_3$ was also effective regardless of whether the concrete prisms were stored in a moisture room at 38ºC or soaked in alkaline solutions.

Although both LiOH and $LiNO_3$ are good inhibitors for suppressing ASR induced expansion, $LiNO_3$ is a better choice compared to LiOH. LiOH raises the OH^- ion concentration of the pore solution, increasing the challenge for lithium. Furthermore, the caustic nature of LiOH poses some safety concerns. The findings on $LiNO_3$ indicate that it does not introduce more OH^- ions in the pore solution, it is fully soluble, and of neutral pH, making it convenient and safe to handle. $LiNO_3$ also has a benign effect on the concrete properties of strength, electrical resistance, drying shrinkage, and resistance to freezing and thawing, whereas LiOH can retard the strength development [32]. Studies also show that $LiNO_3$ is compatible with other chemical admixtures [33]. For these reasons, $LiNO_3$ has become the most promising lithium salt for suppressing ASR expansion [34].

2.4.3 Summary of Research Findings with Lithium Compounds

Some general facts regarding the effects of lithium in controlling ASR expansion:

1. All 11 types of lithium salts studied, including LiF, LiCl, LiBr, LiOH, LiOH H2O, $LiNO_3$, $LiNO_2$, Li_2CO_3, Li_2SO_4, Li_2HPO_4, and Li_2SiO_3, have shown some suppressive effects in controlling ASR induced expansion in fresh concrete, provided they are present at appropriate dosages.

2. The efficiency of lithium in suppressing expansion due to ASR strongly depends on the nature or reactivity of the aggregate, the form of the lithium, and the amount of alkalis present.

3. About half the amount of the lithium added to suppress ASR induced expansion is adsorbed by the hydrating cement, and the uptake of lithium by C–S–H is more than that of sodium and potassium. Hence, only half of the lithium added is available for the suppressive purpose.

4. The minimum lithium to alkali molar ratio to efficiently inhibit deleterious ASR expansion is generally in the range of 0.67-1.20 for most of the lithium salts studied and 0.72-0.93 for $LiNO_3$.

5. Both LiOH and $LiNO_3$ are more effective in preventing the expansion of highly reactive aggregates than that of slowly reactive aggregate.

6. The benefit of using $LiNO_3$ to inhibit ASR expansion over other lithium salts is that $LiNO_3$ does not increase the OH^- ion concentration of the pore solution, therefore, there is no pessimum effect. Its benign effect on concrete properties, its neutrality, and high solubility all provide it with a unique response in controlling ASR expansion.

7. Although autoclaving offers a method for accelerating ASR and decreasing the duration of testing, the results from autoclave expansion tests involving lithium are not directly comparable to those from studies at lower temperatures and pressures.

2.4.4 Mechanism of lithium salts on ASR

Even though lithium-bearing admixtures have shown to be an effective method to mitigate expansion due to ASR, the mechanisms by which lithium salts inhibit expansion has not been unequivocally established.

The widely recognized mechanisms by which lithium compounds provide effectiveness include:

1. Effects of lithium on the nature of alkali silica reaction products
2. Effects of lithium on silica dissolution
3. Repolymerization of ASR gel.
4. Colloid and surface chemistry effects

Effects of Lithium on Alkali Silica Reaction Products

The ability of lithium to change the nature of the reaction products was first proposed by Lawrence and Vivian [35] and is now the most commonly recognized mechanism regarding the suppressive effect of lithium compounds. They studied the reactions of different alkali solutions, including NaOH, KOH, LiOH, and a mixture of those three alkalis, with finely divided, precipitated silica. A gelatinous product was observed in all of the reaction systems, but the gel product in the presence of lithium ion was different when only sodium or potassium was present. This suggests that the lithium–silica complex is less soluble and more stable and, therefore, is capable of protecting silica from further attack by other alkalis. A similar ASR reaction product was found by Sakaguchi et al. [28] by observing the interface between Pyrex glass and hardened cement paste by means of energy dispersive X-ray spectrometry. No visible ASR gel at the interface was found; instead, a form of lithium silicate, which hardly swells and dissolves, was produced at the surface of aggregates. This lithium–alkali (and possibly calcium)-silicate must contain a minimum proportion of lithium to be non-expansive because of the pessimum effect of lithium dosages on controlling ASR expansion as observed by Stark [27].

Chatterji [36] argued that when lithium is present with sodium and potassium, the alkalis would compete for adsorption at negatively charged sites on the silicate surface. Since adsorption affinity increases with ionic radius, the sodium adsorption will be preferential to lithium adsorption. But Iler [37] has already postulated that, of the alkali metal cations, lithium is unique because it stabilizes colloids and prevents gelling, so the highly hydrated lithium ions are not adsorbed as near to the silicate surface as a cation with smaller hydrated radius, such as sodium or potassium.

Effects of Lithium on Silica Dissolution

In examining the effect of various alkali-hydroxides on silica dissolution rate, it has been found that the dissolution rate increased in this order [35]

$$\text{LiOH} < \text{NaOH} < \text{KOH}$$

That is, among LiOH, NaOH, and KOH, the rate of silica dissolution is the slowest for LiOH and fastest for KOH [35, 38]. The rate of silica dissolution decreased in a similar order and this rate decreases with increasing hydrated ion radius of the alkali metal cations in solution surrounding a silicate surface [38].

Chatterji et al. (1987) [36] proposed that the size of the hydrated ion radius was important in determining the extent of chemical reaction during ASR, supporting research findings that degree of chemical reaction increased from lithium to sodium to potassium.

Recently, research was conducted to examine the reaction of silica gel in simulated pore solutions with and without lithium salts in which Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) was used to quantitively measure the ion concentrations of silicon, calcium, lithium, and sodium in the filtrates obtained from the slurry samples. In the slurries prepared with LiCl and $LiNO_3$, the dissolved Si concentration decreased with increasing lithium dosages, again suggesting that lithium could suppress silica dissolution. However, in the same work with LiOH, in contrast to the slurries with LiCl and $LiNO_3$, the slurry with LiOH showed an increase in silica dissolution with increasing lithium dosage, implying that LiOH actually accelerates silica dissolution [39-41].

Different lithium salts yield different influences on silica dissolution, thus it is hard to say that decreasing silica dissolution is the only reason for the suppressive effects of all lithium salts on ASR expansion.

ASR Gel Repolymerization

Based upon microscopy, elemental analysis, and surface chemistry principles, it has been suggested that in addition to decreasing the rate of silica dissolution, lithium may limit repolymerization of dissolved silica species into a gel, effectively reducing the potential for expansion [40, 41]. Based on the work on LiNO3, LiCl, and LiOH, it was suggested that the suppressive effect of lithium on ASR expansion should not largely depend on the quantity of dissolved silica, but should be attributed to the limitation of ASR gel repolymerization which is supported from the investigations of ASR gel in simulated pore solutions with and without lithium salts, in which transmission soft X-ray microscopy was employed to image the changes in gel microstructure. The ASR gel obtained from an ASR affected structure was exposed to NaOH alone and NaOH with LiCl solutions. In the presence of NaOH solution alone, the ASR gel was partially dissolved and repolymerized as a potentially expansive gel. While in the presence of LiCl, a significant dissolution of the original gel particles was observed, but the repolymerization into an expansive gel was decreased as compared to the reaction of the

ASR gel in NaOH solution alone. It was then proposed that lithium might limit the repolymerization of ASR gel, which can effectively reduce the potential for expansion.

It is noticeable that, in this theory, before adding lithium salts, the ASR has already occurred, and substantial ASR gel exists. It may be difficult to apply this theory to new concrete because according to previous findings [42], no ASR gel is formed when the lithium dosage is above a certain level. It should also be noted that these observations are based on one particular lithium salt. The situation may be different for other lithium salts. However, this theory may offer an explanation regarding the suppressive effect of lithium on existing concrete structures damaged by ASR expansion.

Colloid and Surface Chemistry Effects

Electrical double layer (EDL) theory was used to explain the suppressive effect of lithium on ASR [43, 44]. Exchange of electrical charges occurs whenever two dissimilar materials are brought in contact. The ASR gel is assumed to be negatively charged and surrounded by positively charged electrical double layers. These double layers not only determine the type and concentration of the positive ions in them, but also affect the ion transport to the ASR gel. The thickness of these double layers can be calculated from the ionic strength and hydrated radius of the cations. Theoretically, cations with larger valence and smaller hydrated ionic radii will result in a thinner double layer, consequently causing a smaller gel expansion. As shown in Table 2.1, at the same valence level, the hydrated ionic radius of Li^+ ion is larger than those of Na^+ and a K+ ion, which means that lithium should produce greater expansion as compared to sodium and potassium. This is contradictory to the results generally observed in expansion testing. Hence, the EDL theory cannot satisfactorily explain the suppressive effect of lithium in ASR expansion.

Table 2.1 Chemical information for Li^+, Na^+, and K^+ ions

Ions	**Valence**	**Ionic radius (nm)**	**Hydrated ionic radius (nm)**
Li	1	0.060	0.340
Na	1	0.095	0.276
K	1	0.133	0.232

It was then proposed that the suppressive effectiveness of cations depends on the ionic surface charge density (r) [45]. The larger the value of r of a cation, the greater its electron affinity and thus the stronger the bonding between the cation and anions in the gels, resulting in a more contracted and densified structure, which exhibits less tendency to expand. Therefore, from the information in Table 2.1, the effectiveness of cations in inhibiting ASR expansion followed the order: Li>K>Na, which coincides with the expansion testing results. It is also reasoned that the suppressive effect of lithium on ASR expansion is attributed to the reduction in surface charge density of the ASR gel, which may occur in the presence of lithium [40, 41].

It has been suggested to pay attention to the role of calcium in the suppressive effects of lithium on ASR expansion [46]. In a recent study, on mortars containing reactive flint sand and lithium ([Li]/[Na+K]=0.74), the reaction product was observed to contain K, Na, and Si but with little or no calcium. It was hypothesized that lithium might form a nonswelling lithium–alkali–silica complex instead of the typical swelling ASR gel composed of calcium–alkali–silica complex. Since this is contrary to the EDL theory, which predicts that an ASR gel containing larger concentrations of cations with larger valences will exhibit less expansion. That is, a gel with higher ratio of calcium to monovalent cations (Na+, K+, and Li+) should result in less expansion. Further study is necessary to elucidate the role of calcium.

2.4.5 Discussion on Lithium Compounds in Mitigating ASR

Even though all the mechanisms are reasonable under certain conditions, there are some findings from previous work on the influences of lithium on ASR that no mechanism completely explains such as: Why are lithium salts more effective with highly reactive aggregates than with slowly reactive aggregates and what is the role of calcium in affecting expansions? However, there are some general agreements as follows:

1. Lithium salts do react with silica to form lithium containing gel product in the absence of other alkalis, but this gel does not produce any expansion in mortar bar or concrete prism tests;

2. When the lithium is present with other alkalis, the form of reaction product, whether crystalline or gelatinous, significantly depends on the lithium dosage and may also vary with the location and time.

2.5 Summary

Based on the above review on lithium compounds, it is well understood that several lithium compounds, when proportioned appropriately into the fresh concrete, have shown potential to mitigate expansions induced by ASR. Topical applications of lithium compound solutions like $LiNO_3$ have also shown promising results to mitigate ASR in existing structures. However, the use of lithium acetate ($LiC_2H_3O_2$) as ASR mitigation in the existing concrete has not been explored yet.

In the midst of concrete deterioration caused by new formulated deicers such as potassium acetate, sodium acetates and formates, it is important to evaluate the effectiveness of deicing chemicals that are based on lithium acetate by itself, or by combination with potassium acetate, which is widely used as airfield deicing solution. Considering the properties of other alkali-acetates like potassium acetate and sodium acetate, lithium acetate may have a significant potential as a deicing chemical.

CHAPTER THREE

MATERIALS AND TEST PROCEDURES

3.1 Materials

In this study, test specimens comprising of mortar bars, concrete prisms and concrete slabs were subjected to deicer solution and evaluated for their potential to undergo ASR and scaling resistance of concrete.

As part of this study, seven aggregates were selected that differ in their mineralogy and degree of alkali silica reactivity. Depending on the specific test method, different sets of aggregates were employed. Low-alkali and high-alkali Type I Portland cements were used in this research.

In this study, four different soak solutions were employed to condition the concrete prisms, mortar bar specimens and the concrete slabs. These were potassium acetate deicer, potassium acetate with varying amounts of lithium acetate, lithium acetate solution, and sodium hydroxide solution.

3.1.1. Aggregates

In this research, four natural reactive aggregates and two natural non reactive aggregates with established history with respect to ASR, were selected. Fused silica was used as a control reactive aggregate in specific tests. The properties of these aggregates are listed in Table 3.1. The reactive aggregates used in this study were:

1. NM Rhyolite – This reactive gravel was obtained from the Las Placitas Gravel Pit from

the Bernalillo County in New Mexico. This aggregate primarily consists of rhyolite and has shown very high levels of reactivity [48].

2. Spratt Limestone – This aggregate was obtained from the Spratt quarry in Ontario, Canada. It consists primarily of calcite with minor amounts of dolomite, which are not alkali-reactive, plus about 10% acid insoluble residue. The latter contains the reactive component, which is reported to consist of 3% to 4% of microscopic chalcedony and black chert, which is finely dispersed in the matrix [49]. This aggregate has an established history of being alkali-silica reactive in field structures and has been used as a reference aggregate in many ASR studies.

3. NC Argillite – This aggregate is a quarried material from the slate belt of North Carolina from the Gold Hill Quarry in North Carolina. This aggregate primarily consists of reactive metatuff/argillite. This aggregate has an established history of poor field performance in several bridge structures in North Carolina [50].

4. SD Quartzite – This aggregate is obtained from crushing quarried rock from the Sioux Falls quarry, located in the southeastern South Dakota. This aggregate consists of strained quartz grains that are cemented with interstitial secondary quartz cement. The interstitial matrix also contains microcrystalline quartz, hematite and kaolinite. This aggregate has an established history of being reactive in concrete pavements in Minnesota and South Dakota [51].

5. Fused Silica – Graded fused silica obtained from C-E Minerala, Greenville, TN was used as a control reactive aggregate in specific tests. This aggregate is a commercially produced material that is of high purity silica, and has been established in previous lab

studies to be a highly reactive aggregate. This aggregate was used as a component of a blended aggregate with non-reactive Ottawa sand at 5% by mass.

The non-reactive aggregates used in this study were:

1. Graded Ottawa sand: A non-reactive silica sand from Ottawa, Illinois. This graded Ottawa sand conforms to the ASTM C 778 specification. The sand is mainly made of silicon dioxide (approximately 99.7%) and the main mineral of this aggregate is Quartz. The sand was procured by the US Silica Company.

2. Illinois, Dolomite: A quarried rock containing dolomite, from Material Service Corporation, Illinois.

Table 3.1 Properties of aggregates (X- No data)

Aggregate Property	**NM, Rhyolite**	**Spratt, Limestone**	**NC, Argillite**	**SD, Quartzite**	**IL, Dolomite**	**IL, Ottawa**
Water absorption, %	1.09	0.46	0.34	0.42	2.12	0.0
Bulk specific Gravity (OD)	2.60	2.69	2.75	2.51	2.66	2.65
Bulk specific gravity (SSD)	2.63	2.71	2.76	2.52	2.71	2.65
Dry rodded Unit weight, Kg/m^3	1585	1568	1566	1557	1563	X

3.1.2. Cement

Two different cements having different alkali contents were used in this research (Table 3.2):

1. High-alkali cement: A Type I cement having an alkali content of 0.83% (Na_2O_{eq}) was used. This cement was obtained from Lehigh, Evansville, P.A.

2. Low-alkali cement: A Type I cement having an alkali content of 0.29% (Na_2O_{eq}) was used. This cement was obtained from Lafarge, Holly Hill, SC.

Table 3.2 Chemical composition of cements

Oxide, %	**Low alkali cement (LA)**	**High alkali cement (HA)**
SiO_2	20.23	20.34
Al_2O_3	4.80	5.09
Fe_2O_3	3.26	2.67
CaO	64.45	61.60
MgO	1.17	2.16
SO_3	2.79	4.25
Na_2O	0.07	0.27
K_2O	0.34	0.85
Equivalent alkali	0.29	0.83
Loss on ignition	3.30	2.03
Insoluble residue	0.20	0.25
C_3A	7.20	8.97
C_3S	63.76	46.06
C_2S	9.90	23.57
C_4AF	9.92	8.12

3.1.3. Deicing Chemicals

Concrete and mortar specimens were exposed to the following solutions:

1. Potassium Acetate: It is a 50% by weight deicer solution, available commercially. This deicer was used in its available form in this study; it had molarity of 6.4 and a specific gravity of 1.265. To find the effectiveness of potassium acetate with a lower dosage level, a molar concentration of 3.0 was used.

2. Lithium Acetate: The effectiveness of lithium acetate as a deicer solution was studied in this research. It's a small crystal like substance with a density of 1.3 g/cc at 25ºC with the molecular weight of 102.1. A molar concentration of 3.04 was used.

3. Potassium Acetate–Lithium Acetate: Lithium acetate in different molar ratios with potassium acetate (Li/K) was used.

4. Sodium Hydroxide: Reagent grade sodium hydroxide pellets were used in this study to prepare the soak solution for conducting the standard ASTM C 1260 and ASTM C 1293 tests.

5. Lithium Nitrate: It is a 30% solution of $LiNO_{3,}$ produced by FMC chemicals and was used to understand the pre-treatment effect before exposing to deicers. It is a odorless white to yellow colored solution. The pH of 5% solution @ 25ºC is in between 7 and 9.5. The specific gravity is 1.2 to 1.3 at 25ºC. The molecular weight of $LiNO_3$ is 68.95. The density of $LiNO_3$ is 1.2 g/cm^3.

3.2 Sample Notation

In this dissertation, the aggregate sources and the deicer solutions with different combination were identified as listed in Table 3.3.

Table 3.3 Notation Table

Aggregates	
NM	Rhyolite from New Mexico
SP	Spratt Limestone from Ontario, Canada
NC	Argillite from North Carolina
SD	Quartzite from South Dakota
Soak Solutions	
6.4K	6.4 molar KAc
6.4K-0.2	6.4 molar KAc-LiAc blended deicer with Li/K ratio of 0.2
3K	3 molar KAc
3K-0.2	3 molar KAc-LiAc blended deicer with Li/K ratio of 0.2
3K-0.4	3 molar KAc-LiAc blended deicer with Li/K ratio of 0.4
3K-0.6	3 molar KAc-LiAc blended deicer with Li/K ratio of 0.6
3K-0.8	3 molar KAc-LiAc blended deicer with Li/K ratio of 0.8
1N	1N NaOH
3L	3 molar LiAc

3.3 Test Procedures

3.3.1 Standard and Modified ASTM C 1260 Test

The standard ASTM C 1260 test known as the “Accelerated Mortar Bar Test” is a method to assess the reactivity of aggregates. In this test, mortar bars (25 mm x 25 mm x 285 mm) with gage studs at the ends are prepared at a water-to-cement ratio of 0.47. The aggregate-to-cement ratio, by mass, is maintained at 2.25. After 24 hours of curing in a moist cabinet, the mortar bars are demolded. The mortar bars are then transferred to a storage container with sufficient water to immerse all the samples. The sealed container is placed in an oven at 80ºC for 24 hours. After 24 hours, the mortar bars are removed from the oven and a zero reading in the length change comparator is taken. The mortar bars are subsequently transferred to a 1N sodium hydroxide solution, which is preheated to 80ºC. Length change readings are taken thereafter at periodic intervals to determine the percent expansion. In this research, the length-change measurements were taken up to 28 days.

Generally, an expansion of 0.1% or less at 14 days of immersion in the sodium hydroxide solution is considered to indicate the innocuous nature of the aggregate. Expansion greater than 0.2% at 14 days is considered to indicate the potentially reactive nature of aggregate. Expansions between 0.1% and 0.2% require additional confirmation by either conducting petrographic examination (ASTM C 295), concrete prism tests (ASTM C 1293), or by evaluating the field performance to ascertain the reactivity of the aggregates.

Modifications to the standard ASTM C 1260 test were adopted in this research study to evaluate the ASR mitigation potential of lithium acetate and combination of LiAc with KAc. The principal modification to the standard procedure was to use potassium acetate deicer as a soak solution for mortar bars, instead of a 1N NaOH solution. Also, combination of KAc with LiAc at different Li/K molar ratios of 0.2, 0.4, 0.6, and 0.8 were used as soak solutions. In addition, saturated solutions of lithium acetate solutions were employed as soak solutions in some specific tests.

The procedure to prepare mortar bar specimens and their subsequent storage regime was identical to the procedure described in standard ASTM C 1260 test. In this research, the mortar bars were stored for 28 days in the soak solution, instead of typical 14 days as required in the standard ASTM C 1260 test procedure. The extended testing was conducted to assess the effectiveness of mitigation measures in suppressing the effects of ASR at later ages. During the course of 28 days, length-change measurements were taken at 0, 3, 7, 11, 14, 21 and 28 days. The results of all the standard and the modified ASTM C 1260 tests discussed in this research study are based on an average of readings obtained from 4 mortar bars.

3.3.2 Modified ASTM C 1293 Test

The standard ASTM C 1293 test known as the "Concrete Prism Test" is a method to determine the length change of concrete due to alkali silica reaction. This test was used to detect the potential for aggregate reactivity by measuring the length change in the concrete prism. In this test, a concrete prism of 75 mm x 75 mm x 285 mm with gage studs at the ends are prepared using a concrete having a cement content of 420 ± 10kg/m^3 and 70 ± 2% of the total volume of the concrete comprised of coarse aggregates. The water-to-cement ratio was maintained at 0.43 and high-alkali cement was used in this test procedure. In this test, including the cement alkalis, the total alkali content of the concrete was increased to 1.25% by mass of cement. The fine aggregate used was non-reactive graded Ottawa sand conforming to ASTM C 778.

Modification to the standard ASTM C 1293 test was made to evaluate the performance of deicing chemicals. The prisms were made in a similar way as described in the standard ASTM C 1293 test procedure, but after de-molding, the prisms were soaked in potassium acetate solution with different MC of 6.4 and 3.0. To study the mitigation effect of lithium acetate, it was added to potassium acetate with different MR of Li/K 0.2, 0.4, 0.6, and 0.8. Four prisms were cast in each test in which one prism was exclusively used for slicing and studying concrete specimens for SEM-EDX analysis. In these modified tests, apart from prisms made with boosted alkali levels using the high-alkali cement, prisms were also made without boosting the alkalis and made using low-alkali cement.

3.3.3 Modified ASTM C 672 Tests

This test was used to determine the resistance to scaling of a horizontal concrete surface exposed to freezing and thawing cycles in the presence of deicing chemicals. In this test, concrete slabs having a surface area of 0.045m^2 with 75mm in depth were prepared using a concrete having a cement content of 420 ± 10kg/m^3, with air content of

6 ± 1%. The water-to-cement ratio was maintained at 0.43 and low-alkali cement was used in this test procedure. The fine aggregate used was non-reactive graded Ottawa sand conforming to ASTM C 778. After the concrete stopped bleeding, a mortar dike (25mm wide and 20mm high along the perimeter) was placed on the top along the edges. The specimens were then immediately covered with a polyethylene sheet. After 24 hours of curing, the specimens were de-molded and placed in moist storage as prescribed in ASTM C 511. After the air and moist curing, the flat top surface of the concrete slab was covered with 6mm of soak solution.

The specimens were placed in a freezing environment at -18 ± 3ºC for 16 to 18 hours and then removed from the freezer and kept in the lab environment for 6 to 8 hours at 23 ± 2ºC, which is one cycle of the experiment. The test was continued for 100 cycles. After every 5 cycles, the solutions were flushed thoroughly and filtered for residue to determine the weight loss and visual examination was conducted. Visual rating of the surface was made after 5, 10, 15, 25 and every 25 cycles with the following scale: 0 for no scaling, 1 for very slight scaling, 2 slight for moderate scaling, 3 for moderate scaling, 4 moderate to severe scaling and 5 for severe scaling. After the visual examination, the solutions were replaced and the test was continued. Three slabs were cast in each test and 6.4 molar KAc and plain lithium acetate were used as deicers to determine there effects on the concrete surface.

3.3.4 Penetration Depth of Deicer Solution in Concrete Slab Tests

A new methodology was developed to determine the penetration of deicer solution into a concrete specimen. For this, the specimens used in the modified ASTM C

672 tests were reused. Samples were kept in a 38ºC room and the top surface of the concrete slabs were covered with 6mm of soak solution. Expansion readings were noted each month. After exposing the concrete slabs to deicer solution for six months, a core of concrete 1.5” in diameter and 3” in deep was taken from each test sample. After the core was dried, the concrete core was sliced into six pieces of 0.5” in height each. They were then crushed into fine powder and the potassium content was determined using Inductively Coupled Plasma (ICP) to establish a profile of potassium along the depth from the top. The cross section of core sample was also used for mapping using an X-Ray Fluorescence spectrometer (XRF) to establish the depth of penetration of potassium.

3.3.5 Modified ASTM C 227 Test Method to Evaluate Effectiveness of $LiNO_3$ Pre-treatment

The main objective of this test was to determine the effectiveness of lithium nitrate when applied as pre-treatment before exposing to regular deicers like potassium acetate. In this test, mortar bars (25 mm x 25 mm x 285 mm) with gage studs at the ends were prepared at a water-to-cement ratio of 0.47. The aggregate-to-cement ratio, by mass, was maintained at 2.25. Fused silica was used at five percent by mass of the blended aggregate with Ottawa sand. A low-alkali cement was used in preparing the mortar specimens.

After 24 hours of curing in a moist cabinet, the mortar bars were de-molded. The mortar bars were then dried at ambient temperature and a zero expansion reading was taken. Lithium nitrate was applied on the surface of the mortar bars by brushing 1 coat, 3 coats and 5 coats using a paint brush. The mass of the sample was recorded before and after application of $LiNO_3$ to ascertain the dosage. Once the lithium nitrate was totally absorbed, the mortar bars were brushed with 3 coats potassium acetate coats for each test. The samples were stored in the container as mentioned in the ASTM C 227 and maintained at 38°C (100°F). The bars were coated periodically with potassium acetate at 1, 7, 14, 28, and 56 days after measuring the length change and dynamic modulus of elasticity.

3.3.6 Dynamic Modulus of Elasticity

The dynamic modulus of elasticity (DME) of the mortar bars was measured at periodic intervals to quantify the physical distress occurring in the mortar bars and concrete prisms subjected to all ASTM C 1260 and ASTM C 1293 tests. The DME values were determined using the resonant frequency method based on impulse excitation technique based on ASTM E 1876-01. A GrindoSonic^{TM} instrument was used to determine the resonant frequencies of the samples.

In this test, the mass and the resonant frequency of the bar/prism specimen were determined soon after taking the expansion readings. The samples were supported on two rubber strips at a distance of 0.224L from the ends of the bar (as per ASTM C 2215, where L is the length of the bar). The detecting transducer was then placed at the center of the vertical face of the sample and the sample was struck by an exciter on the top surface of the bar. The resonant frequencies were recorded. Using this frequency, mass and the dimensions of the specimens, the DME values were calculated.

$E=CMn^2$

Where

M = mass of specimen, kg,

n = fundamental transverse frequency, Hz,

C = 0.9464 ($L3T/bt^3$), $N\cdot s^2$ ($kg\cdot m^2$) for a prism,

L = length of specimen.

t = dimensions of cross section of prism.

T = a correction factor which depends on the ratio of the radius of gyration.

3.3.7 pH Measurements

One of the main components necessary for ASR to occur is a high pH environment (high concentration of hydroxyl ions). In the standard ASTM C 1260 test, 1N NaOH solution provides a highly alkaline environment. In order to determine the changes in the hydroxyl ion concentration due to potential interaction between deicer soak solutions and hydration products of cement, the pH of the soak solution were measured at the 3 days, 14 days and 28 days for all ASTM C 1260 tests. In modified ASTM C 1293 tests, the pH was measured at 3 months, 6 months and 12 months. The pH of all the soak solutions was determined using an Oakton pH 110 meter with a low sodium error electrode, calibrated to buffer solutions with pH 4, 7, 10 and 12.45.

3.3.8 Scanning Electron Microscopy and Energy Dispersive X-Ray Analysis

Scanning electron microscopy (SEM), in back-scattered mode, and EDX analyses were conducted on polished sections of mortar bars from selected standard and modified ASTM C 1260 tests and selected prisms from modified ASTM C 1293 tests, using a Hitachi S3500N electron microscope. The instrument was operated at an accelerating voltage of 20KeV, in a variable pressure mode. The samples for the investigation were prepared by slicing the bars in a slow-speed diamond saw. The specimens were then impregnated with epoxy, vacuumed and cured until they were set. The specimens were then polished on a series of diamond embedded discs (No. 60, No. 140, No. 600 and No. 1200 grit), with a final polish using 3 micron and 0.5 micron diamond suspension on a cloth.

3.3.9 ICP to Determine the Depth of K and Li Penetration

An Ultima 2 ICP optical emission spectrometer (Horiba Jobin Yvon, Longjumeau, France) was used for sample analysis to determine the concentration of K and Li of the core samples from the slabs exposed to potassium acetate and lithium acetate. The 3” cores were sliced into 6 pieces of 0.5” each. Each piece was then crushed into a homogeneous fine powder. Approximately 0.1 gram of powder was accurately weighed on an analytical balance to 4 decimal places and placed into the bottom of 30 mL Teflon microwave digestion vessel and topped with a solution made of 10% nitric acid to dissolve the powder. The vessels were placed in the microwave system with the caps not fully torqued down. The samples were heated at 80°C for 10 minutes then cooled and vented. They were filtered and transferred to 50 mL volumetric flasks and diluted to 50ml with plasma grade water. Digested samples were transferred to 2 ounce (60 mL) amber Nalgene bottles that had been rinsed with plasma grade water and dried.

Calibration solutions were routinely prepared from aqueous multielement standards. Standards of 20ppm (High Purity Standards, Charleston, SC) were used to make stock solutions of 10ppm, 1ppm, 0.10ppm and 0.01ppm. Calibration standards were run in 3 replicates and plotted as a linear function for each element. After running the test, the results were compared with the XRF data for correlation to understand the penetration and the reaction mechanism with depth.

3.3.10 XRF to Determine the Depth of Penetration

To evaluate the penetration depth of deicers into concrete, X-Ray Fluorescence (XRF) techniques were adopted for mapping the concrete specimen using an Eagle 3 XRF with a 30 mm^2 EDAX energy dispersive spectrometer (EDS). The test was conducted at the National Institute of Standards and Technology (NIST). Mapping provides a simple method for visually organizing the chemical data collected with an EDS detector. A confocal X-Ray beam is addressed to every point in a visual field. The chemical data is stored in a multi-dimensional matrix where the Z-axis is the X-Ray energy for a specified energy window, which was set to 20keV, and the X and Y axes are simply coordinates of pixels whose relative brightness indicate the concentration of a particular element. Using a graphics processing tool developed at the NIST known as Lispix, the data are then organized to form element maps. These maps are images whose pixels represent the relative concentration of a particular element as defined by integrating the counts in the characteristic X-Ray peak for said element. In addition, because the entire X-ray spectrum is recorded at each pixel, unanticipated chemical features can be recovered [52].

Cores were taken from the concrete slabs that were exposed to deicers and they were cut with a diamond saw. The specimens were then impregnated with epoxy, vacuumed and cured until they were set. The specimens were then polished on a series of diamond embedded discs (No. 60, No. 140, No. 600 and No. 1200 grit), with a final polish using 3 micron and 0.5 micron diamond suspension on a cloth. Specimens were then examined using the XRF method.

3.3.11 Fresh Properties of Concrete

Properties of the fresh concrete were measured for all the batches evaluated in this study. The slump of the concrete was determined according to ASTM C 143. The unit weight and yield were determined in accordance with ASTM C 138. The amount of cement in kilograms was calculated from the actual density of the concrete for 1 m^3 volume of concrete to make sure the cement content was within 420 ± 10 Kg/m^3.

3.3.12 Dry Rodded Unit Weight

Coarse aggregates were sieved and mixed as per the gradation requirements of the standard ASTM C 1293 test procedure. Dry rodded unit weights of the graded aggregates were determined according to ASTM C 29.

3.4 Experimental Program and Mixture Designs

This section presents the experimental programs and mixture designs of the standard ASTM C 1260 test and modified ASTM C 1260, ASTM C 1293, ASTM C 672, and ASTM C 227 tests. The experimental program for penetration depth of deicer solution is also presented.

3.4.1 Standard and Modified ASTM C 1260 Tests

The test matrix of the standard and modified ASTM C 1260 tests is shown in Table 3.4

Table 3.4 Test program for the standard and modified ASTM C 1260 tests

Test Method	**Molar Concentration of KAc**	**Soak Solution**	**Cement Alkali Type**	**Aggregates**			
				NM	**SP**	**NC**	**SD**
Standard	--	1N NaOH	HA	X	X	X	X
Standard	--	1N NaOH	LA	X	X	X	X
Modified	3.0	Li/K = 0.0	HA	X	X	X	X
Modified		Li/K = 0.2	HA	X	X	X	X
Modified		Li/K = 0.4	HA	X	X	X	X
Modified		Li/K = 0.6	HA	X	X	X	X
Modified		Li/K = 0.8	HA	X	X	X	X
Modified	6.4	Li/K = 0.0	HA	X	X	X	X
Modified		Li/K = 0.2	HA	X	X	X	X
Modified	3.0	Li/K = 0.0	LA	X	X	--	--
Modified		Li/K = 0.2	LA	X	X	--	--
Modified		Li/K = 0.8	LA	X	X	--	--
Modified	6.4	Li/K = 0.0	LA	X	X	--	--
Modified		Li/K = 0.2	LA	X	X	--	--
Modified	--	LiA	HA	X	X	--	--
Modified	--	LiA	LA	X	X	--	--

Table 3.5 shows the mixture design used for the standard and modified ASTM C 1260 tests in this study. The mortar mix was proportioned as per ASTM C 1260 standard.

Table 3.5 Mixture design for ASTM C 1260 tests

Material	**Quantity for 4 mortar bars**
Cement	500 grams
Graded fine aggregates	1125 grams
Water	235 grams
W/C ratio*	0.47
A/C ratio*	2.25
Soak solution	3.312 liters

Note *: W/C means water to cement ratio and A/C means aggregate to cement ratio

3.4.2 Modified ASTM C 1293 Tests

The test matrix of the modified ASTM C 1293 tests is shown in Table 3.6

Table 3.6 Test program for the standard and modified ASTM C 1293 tests

Test Method	**Molar Concentration of KAc**	**Soak Solution**	**Cement Alkali Type**	**Aggregates**			
				NM	**SP**	**NC**	**SD**
Modified	--	1N NaOH	HA*	X	X	--	--
Modified	--	1N NaOH	LA	X	X	--	--
Modified	3.0	Li/K = 0.0	HA*	X	X	X	X
Modified		Li/K = 0.2	HA*	X	X	X	X
Modified		Li/K = 0.8	HA*	X	--	--	--
Modified	6.4	Li/K = 0.0	HA*	X	X	X	X
Modified		Li/K = 0.2	HA*	X	X	X	X
Modified	3.0	Li/K = 0.0	LA	X	X	--	--
Modified		Li/K = 0.2	LA	X	X	--	--
Modified		Li/K = 0.8	LA	X	--	--	--
Modified	6.4	Li/K = 0.0	LA	X	X	--	--
Modified		Li/K = 0.2	LA	X	X	--	--

*Note: Alkali content of the HA cement was increased to 1.25% by weight of the cement.

Tables 3.7 and 3.8 show the mix designs used for the modified ASTM C 1293 tests using different aggregates and high and low-alkali cements, respectively. The mixtures were designed as per the requirements of ASTM C 1293 specifications. The yield for all the mixes was found and the actual cement content in the concrete mix was calculated based on the actual densities of the concrete.

Table 3.7 Mixture design for ASTM C 1293 tests made with high-alkali cement per cubic meter

Materials	**Aggregates**			
	NM	**Spratt**	**NC**	**SD**
Cement, kg	420	420	420	420
Fine agg, kg	630	678	703	608
Coarse agg, kg	1121	1102	1099	1094
Water, kg	182.7	182.7	182.7	182.7
W/C	0.435	0.435	0.435	0.435
A/C	4.17	4.24	4.29	4.06
Density, kg/m^3	2499	2385	2408	2308
Actual density, kg/m^3	2440	2441	2459	2360
Actual cement, kg/m^3	410	429	428	429
Slump, mm	114	69	60	69

Note: 2.33 kg/m^3 of reagent grade sodium hydroxide was added in the mixes made using high-alkali cement to raise the total alkali content of the cement to 1.25%.

Table 3.8 Mixture designs for ASTM C 1293 tests made with low-alkali cements per cubic meter.

Materials	**NM**	**Spratt**
Cement, kg	420	420
Fine agg, kg	630	678
Coarse agg, kg	1121	1102
Water, kg	182.7	182.7
W/C	0.435	0.435
A/C	4.17	4.24
Density, kg/m^3	2499	2385
Actual density, kg/m^3	2470	2343
Actual cement, kg/m^3	415	412
Slump, mm	150	75

3.4.3 Modified ASTM C 672 Tests

The test matrix of the modified ASTM C 672 tests is shown in Table 3.9

Table 3.9 Test program for the modified ASTM C 672 tests

Test Method	**Solution**	**Cement Alkali Type**	**NM**	**SP**	**IL**
Modified	KAc	LA	X	X	X
Modified	LiAc	LA	X	X	X

Table 3.10 shows the mix designs used for the modified ASTM C 672 tests using different aggregates with low-alkali cement. The mixtures were designed as per the requirements of ASTM C 672 standards. The yield for all the mixes was found and the actual cement content in the concrete mix was calculated based on the actual densities of the concrete.

Table 3.10 Mixture design for modified ASTM C 672 tests made with low alkali cement per cubic meter.

Materials	**NM**	**Spratt**	**IL**
Cement, kg	420	420	420
Fine agg, kg	630	678	669
Coarse agg, kg	1121	1102	1117
Water, kg	182.7	182.7	182.7
W/C	0.435	0.435	0.435
A/C	4.17	4.24	4.25
Density, kg/m^3	2499	2385	2389
Actual density, kg/m^3	2440	2441	2429
Actual cement, Kg/m^3	410	429	426
Slump, mm	114	69	60

3.4.4 Modified ASTM C 227 Tests

The test matrix of the modified ASTM C 227 tests is shown in Table 3.11

Table 3.11 Test program for the modified ASTM C 227 tests

Test Method	**Solution**	**Cement Alkali Type**	**Ottawa Sand**
Modified	Water	LA	X
Modified	KAc- 6.4	LA	X
Modified	6.4 (Lithium Nitrate – 1 coating)	LA	X
Modified	6.4 (Lithium Nitrate – 3 coating)	LA	X
Modified	6.4 (Lithium Nitrate – 5 coating)	LA	X

Note: Fused Silica was added at 5 percent to study the reactivity.

Table 3.12 shows the mixture design used for the modified ASTM C 227 tests.

Table 3.12 Mixture design for modified ASTM C 227 tests

Material	**Quantity for 4 mortar bars**
Cement	500 grams
Graded fine aggregates (Ottawa sand)	1068 grams
Fused silica	56 grams
Water	235 grams
W/C ratio*	0.47
A/C ratio*	2.25
Soak solution	3.31 liters

Note *: W/C means water to cement ratio and A/C means aggregate to cement ratio.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 General

This chapter presents the results and discussion of all tests conducted in this research. Results from the standard and the modified ASTM C 1260 tests, modified ASTM C 1293 tests, modified ASTM C 672 tests, modified ASTM C 227 tests, dynamic modulus of elasticity, pH measurements, SEM-EDX studies, ICP and XRF tests to evaluate penetration depth of deicers are presented in this chapter.

4.2 Test Results from ASTM C 1260 Tests for New Mexico Aggregate

Expansion behavior of mortar bars prepared with NM aggregate in the standard and modified ASTM C 1260 tests are presented in this section. In addition, changes in the DME of mortar bars subjected to standard and modified ASTM C 1260 tests are presented.

4.2.1 Length-Change Behavior

Figure 4.1 shows the expansion behavior of mortar bars made with NM aggregate and high-alkali cement, exposed to 1N NaOH solution, 6.4 molar and 3 molar KAc solution and 3 molar LiAc solution. Figure 4.2 shows the results of mortar bars prepared with low-alkali cement, containing the same aggregate and deicers as in Figure 4.1.

From these figures, it can be seen that NM aggregate is highly reactive when it is exposed to all deicers other than LiAc solution, with expansions of more than 1.4% at 14 days. For both cement types, mortar bars prepared with NM aggregate, showed more expansion when exposed to 3 molar KAc solution than 6.4 molar KAc solution or 1N NaOH solution, at 28 days. Bars exposed to LiAc did not show noticeable expansion even with the highly reactive NM aggregate. Also, alkali content of the cement showed a significant influence in the expansion of the mortar bars as bars made with high-alkali cement expanded more compared to bars made with low-alkali cement.

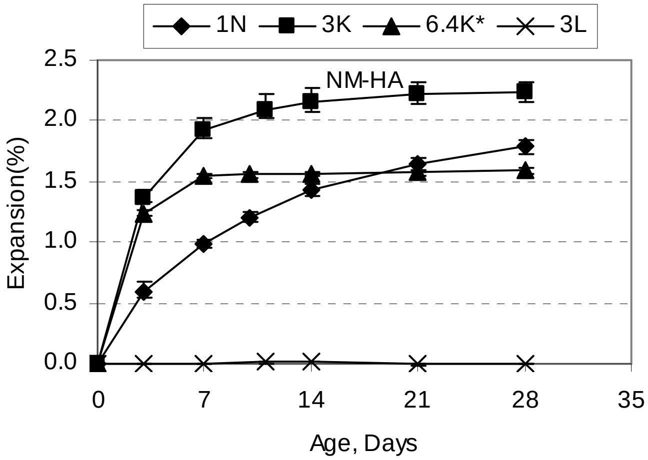


Figure 4.1 Expansion of Mortar Bars in Standard and Modified ASTM C 1260 Test with NM Aggregate and High-Alkali Cement (See Chapter 3.2 for Notation, *Sompura, 2006)

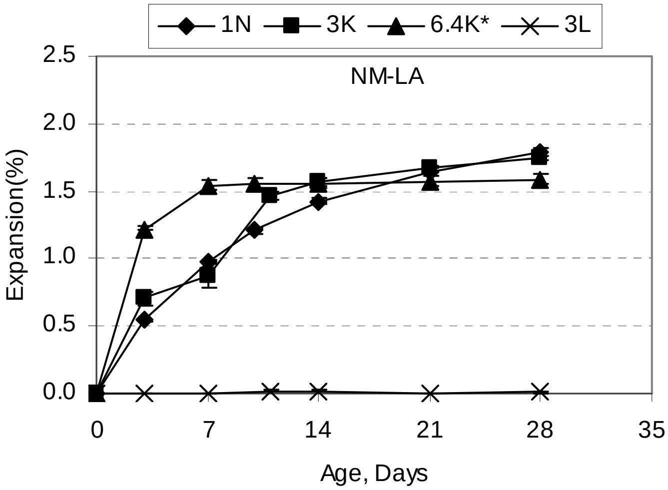


Figure 4.2 Expansion of Mortar Bars in Standard and Modified ASTM C 1260 Test with NM Aggregate and Low-Alkali Cement (See Chapter 3.2 for Notation, * Sompura, 2006)

Figures 4.3 and 4.4 show the expansion results of modified ASTM C 1260 tests. Figure 4.3 shows the expansion behavior of bars made with NM aggregate exposed to 6.4 molar KAc solution and 6.4 molar KAc-LiAc blended deicer with Li/K ratio of 0.2 (6.4-0.2) using high-alkali cement. Figure 4.4 shows the results for mortar bars prepared with the same aggregate and exposed to the same deicer combinations as in Figure 4.3 using low-alkali cement. From these figures, it can be seen that NM aggregate is highly reactive when exposed to 6.4 molar KAc solution, with expansions of more than 1.5% at 28 days. At 28 days, mortar bars with NM aggregate, showed a significant reduction (0.65%) in expansion, when exposed to blended deicer with Li/K of 0.2 (6.4-0.2). The alkali content of cement did not have any influence in the expansion of mortar bars when exposed to 6.4 molar KAc solution. However, there was significant effect of alkali content when the bars exposed to 6.4 molar KAc solution with Li/K ratio of 0.2 as bars with high-alkali cement showed higher expansions than bars with low-alkali cement.

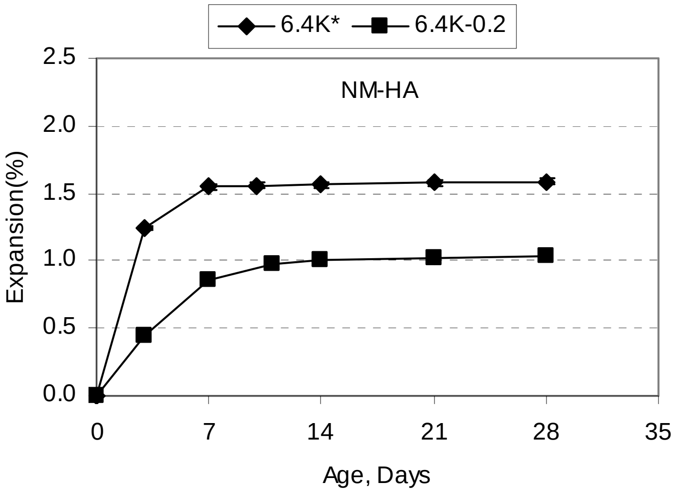


Figure 4.3 Expansion of Mortar Bars in Modified ASTM C 1260 Test with 6.4 Molar KAc Solution and Blended Deicers with NM Aggregate and High-Alkali Cement (See Chapter 3.2 for Notation, * Sompura, 2006)

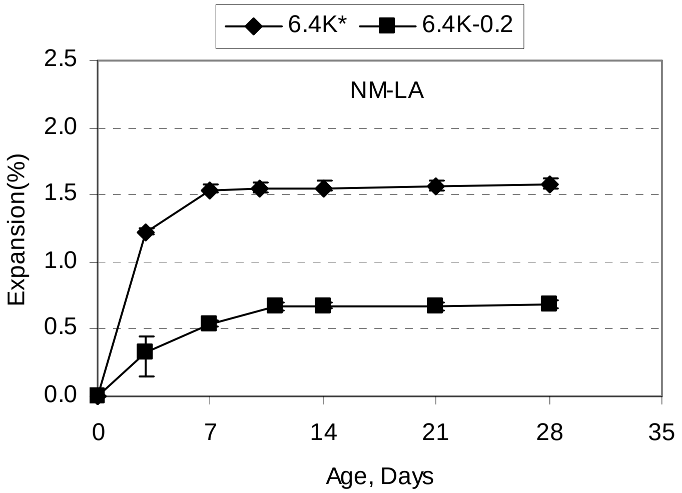


Figure 4.4 Expansion of Mortar Bars in Modified ASTM C 1260 Test with 6.4 Molar KAc Solution and Blended Deicers with NM Aggregate and Low-Alkali Cement (See Chapter 3.2 for Notation, * Sompura, 2006)

Figures 4.5 and 4.6 show the expansion results of the modified ASTM C 1260 tests. Figure 4.5 shows the expansions of bars made with NM aggregate exposed to 3 molar KAc solution and 3 molar KAc-LiAc blended deicer with Li/K ratio of 0.2, 0.4, 0.6, and 0.8 using high-alkali cement. Figure 4.6 shows the results of mortar bars prepared with the same aggregate exposed to 3 molar KAc solution and 3 molar KAc-LiAc blended deicer with Li/K ratio of 0.2 and 0.8 using low-alkali cement. From these results, it is evident that the aggregate is highly reactive when exposed to 3 molar KAc solution with expansions of more than 2.1% for high-alkali cement and 1.8% for low-alkali cement at 28 days. When the bars were soaked with different Li/K ratios there was a significant reduction in expansion and LiAc mitigates ASR expansion with increase in Li/K ratio. A Li/K ratio of 0.8 was found to be very effective in mitigating the expansion due to ASR to less than 0.1% in both high-alkali and low-alkali cement. Statistically, bars made with high-alkali cement, soaked in the Li/K ratios of 0.6 and 0.8 showed no significant difference. Also, bars made with high-alkali cement showed more expansion compared to bars made with low-alkali cement.

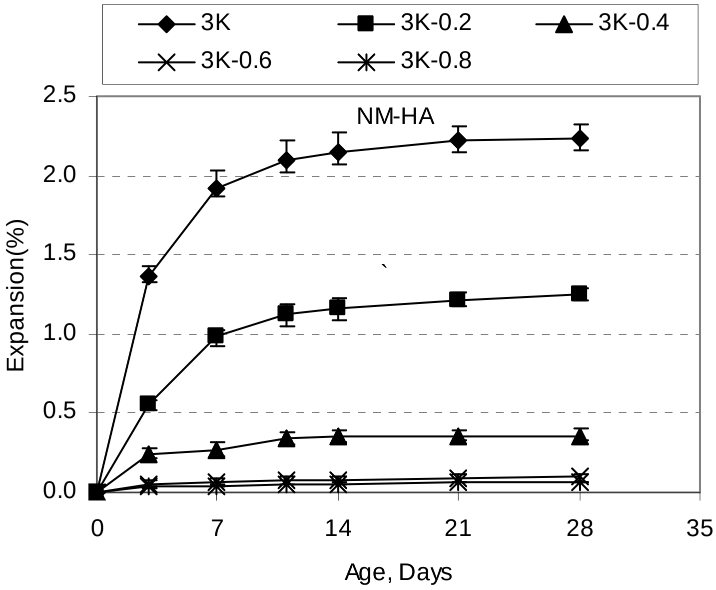


Figure 4.5 Expansion of Mortar Bars in Modified ASTM C 1260 Test with 3 Molar KAc Solution and Blended Deicers with NM Aggregate and High-Alkali Cement (See Chapter 3.2 for Notation)

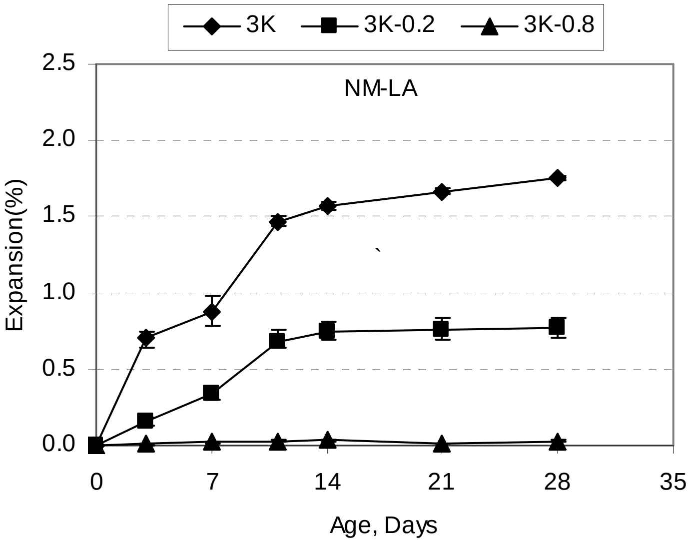


Figure 4.6 Expansion of Mortar Bars in Modified ASTM C 1260 Test with 3 Molar KAc Solution and Blended Deicers with NM Aggregate and Low-Alkali Cement (See Chapter 3.2 for Notation)

4.2.2 Dynamic Modulus of Elasticity

Figure 4.7 shows changes in dynamic modulus of elasticity of NM aggregate mortar bar specimens exposed to 1N NaOH, 3 molar and 6.4 molar KAc solution and 3 molar LiAc solution, and blended deicer solutions. The resonant frequency method was used to measure the DME of the mortar bars. From the results, it can be seen that whenever there is drop in DME, a corresponding increase in the linear expansion of the mortar bars was observed in the ASTM C 1260 test. It is also evident that the loss in DME was dependent on the concentration of KAc. Also, the addition of LiAc to the KAc helped in mitigating loss in DME as observed in the ASTM C 1260 tests. The cement alkalinity does not have much influence in the loss in DME. Bars which were exposed to 3 molar KAc-LiAc blended deicer with Li/K ratio of 0.6 and 0.8 showed no significant difference in loss of DME.

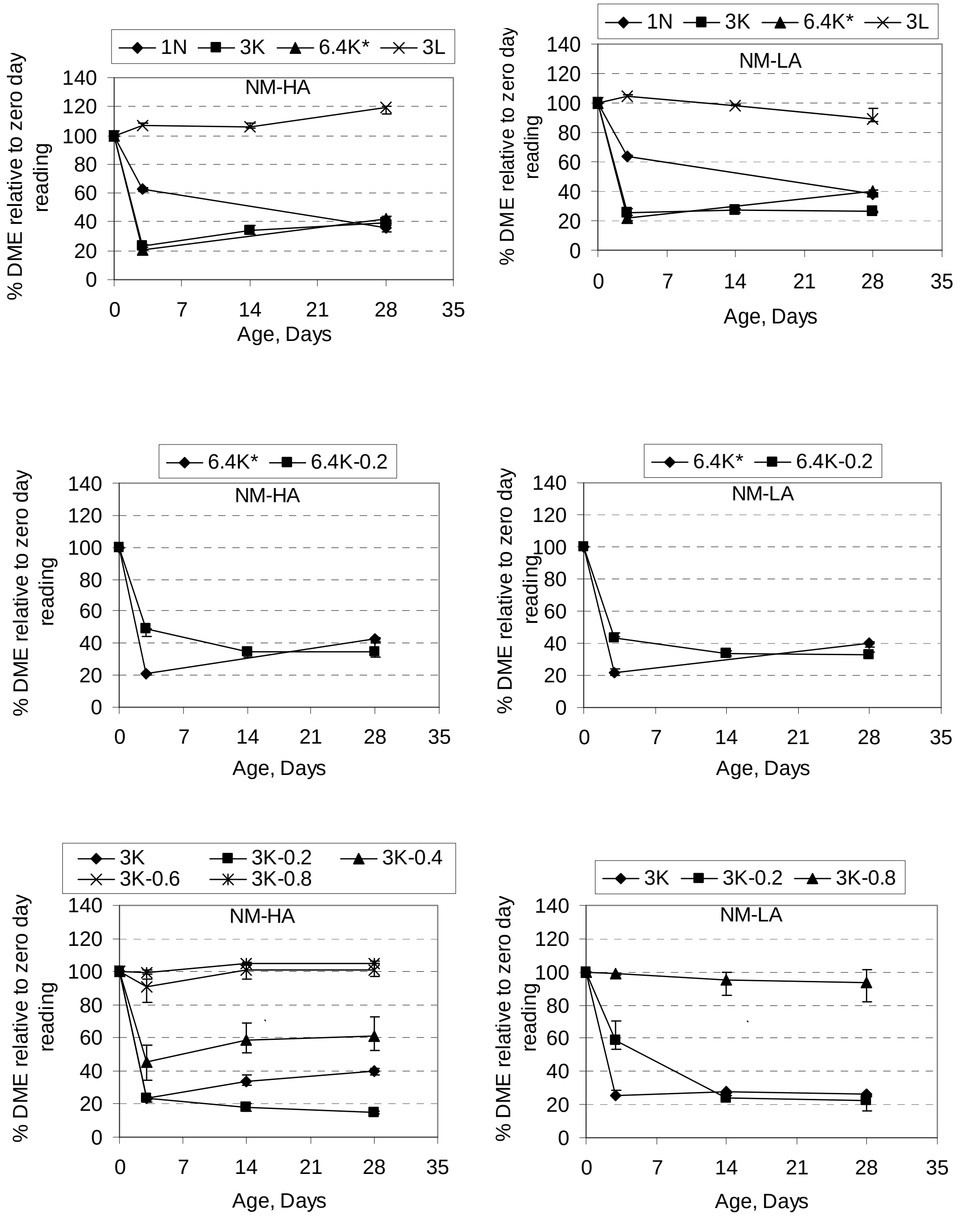


Figure 4.7 Change in Dynamic Modulus of Mortar Bars made with NM Aggregate in Standard and Modified ASTM C 1260 Test
(See Chapter 3.2 for Notation, * Sompura, 2006)

4.3 Test Results from ASTM C 1260 Tests for Spratt Aggregate

Expansion behavior of mortar bars prepared with SP aggregate in the standard and modified ASTM C 1260 tests are presented in this section. In addition, changes in the DME of mortar bars subjected to standard and modified ASTM C 1260 tests are presented.

4.3.1 Length-Change Behavior

Figures 4.8 and 4.9 show the expansion results of the standard and modified ASTM C 1260 tests. Figure 4.8 shows the expansions of bars made with SP aggregate and high-alkali cements and exposed to 1N NaOH, 6.4 molar and 3 molar KAc solution and 3 molar LiAc solution. Figure 4.9 shows the results of mortar bars prepared with the same aggregate and exposed to same deicers using low-alkali cement.

From the figures, it can be seen that SP aggregate is highly reactive when exposed to the deicers other than LiAc. With both high-alkali and low-alkali cements at 28 days, mortar bars with SP aggregate, when exposed to 6.4 molar KAc solution, showed more expansion followed by 1N NaOH. Bars made with both high-alkali and low-alkali cement and exposed to 3 molar LiAc solution did not show significant expansion as their expansion was less than the expansion limit of 0.1% at 28 days. Statistically, the alkali content of the cement did have a significant influence on expansions of mortar bars. Bars made with high-alkali cement expanded more compared to bars made with low-alkali cement.

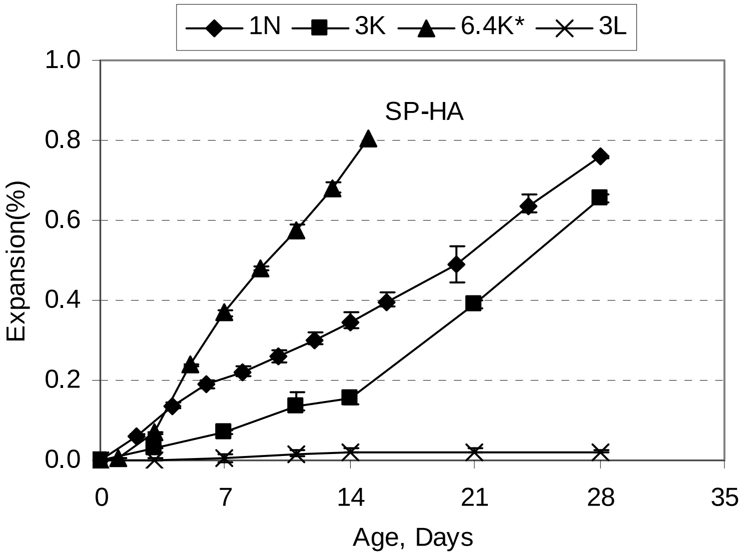


Figure 4.8 Expansion of Mortar Bars in Standard and Modified ASTM C 1260 Test with SP Aggregate and High-Alkali Cement (See Chapter 3.2 for Notation, * Sompura, 2006)

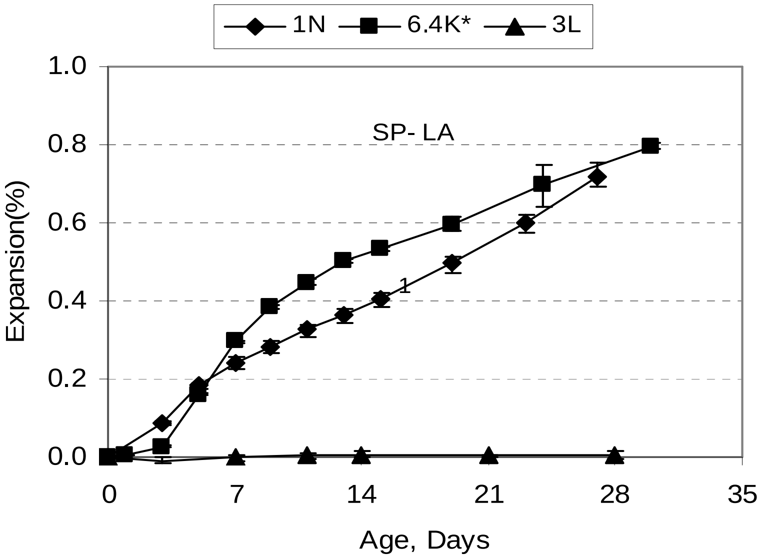


Figure 4.9 Expansion of Mortar Bars in Standard and Modified ASTM C 1260 Test with SP Aggregate and Low-Alkali Cement (See Chapter 3.2 for Notation, * Sompura, 2006)

Figures 4.10 and 4.11 show the expansion results from modified ASTM C 1260 tests. Figure 4.10 shows the expansions of bars made with SP aggregate exposed to 6.4 molar KAc solution and 6.4 molar KAc-LiAc blended deicer with Li/K ratio of 0.2 (6.4-0.2) using high-alkali cement. Figure 4.11 shows the results of mortar bars prepared with the same aggregate exposed to the same deicer combinations using low-alkali cement. From these figures, it can be seen that SP aggregate is highly reactive when exposed to 6.4 molar KAc solution with an expansion of more than 0.8% at 14 days. At 28 days, mortar bars with SP aggregate exposed to blended deicer of 6.4 molar KAc with Li/K of 0.2 completely mitigated the expansion due to ASR with an expansion of 0.06% with high-alkali cement and about 0.08% with low-alkali cement which is below the expansion limit of 0.1%.

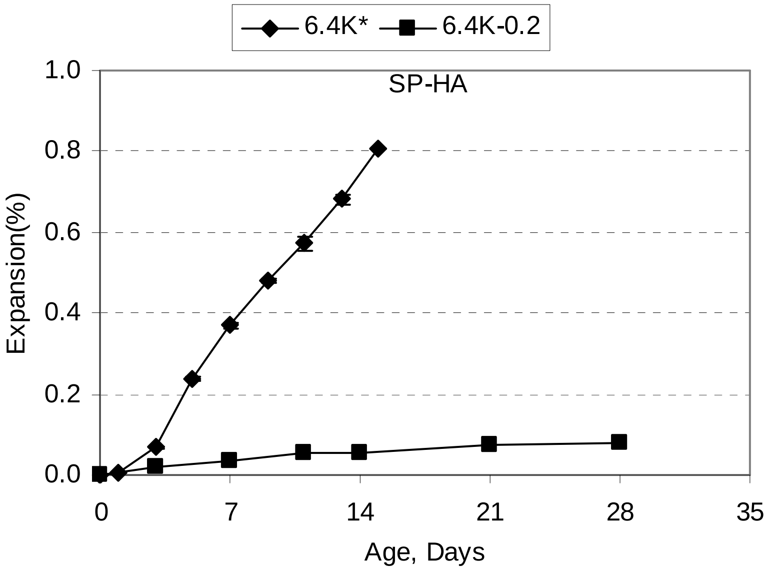


Figure 4.10 Expansion of Mortar Bars in Modified ASTM C 1260 Test with 6.4 Molar KAc Solution and Blended Deicers with SP Aggregate and High-Alkali Cement (See Chapter 3.2 for Notation, * Sompura, 2006)

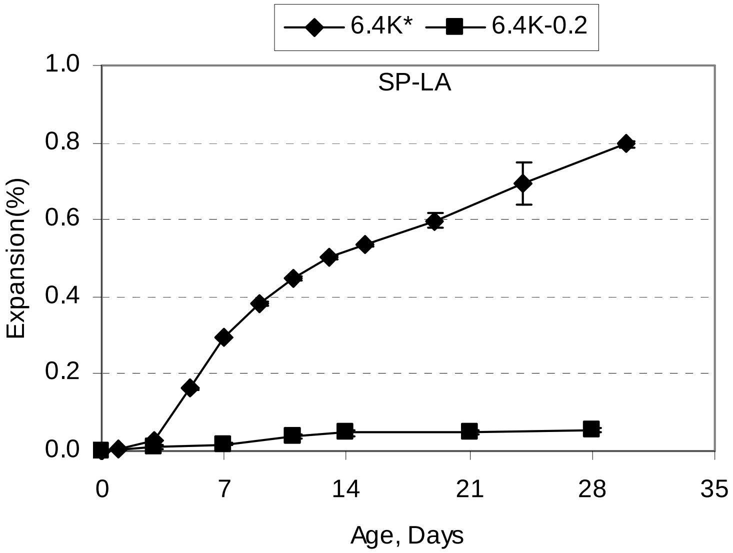


Figure 4.11 Expansion of Mortar Bars in Modified ASTM C 1260 Test with 6.4 Molar KAc Solution and Blended Deicers with SP Aggregate and Low-Alkali Cement (See Chapter 3.2 for Notation, * Sompura, 2006)

Figures 4.12 and 4.13 show the expansion results of the modified ASTM C 1260 tests. Figure 4.12 shows the expansions of bars made with SP aggregate exposed to 3 molar KAc solution and 3 molar KAc-LiAc blended deicer with Li/K ratio of 0.2, 0.4, 0.6, and 0.8 using high-alkali cement. Figure 4.13 shows the results of mortar bars prepared with same aggregate exposed to 3 molar KAc solution and 3 molar KAc-LiAc blended deicer with Li/K ratio of 0.2 and 0.8 using low-alkali cement. SP aggregate is reactive when exposed to 3 molar KAc solution with an expansion of more than 0.6% for high-alkali cement at 28 days. LiAc was found to be effective in mitigating ASR with all Li/K ratios as the expansion for Li/K of 0.2 through 0.8 is less than 0.1% in both high-alkali and low-alkali cement. Statistically, bars made with HA cement, soaked in the Li/K ratios of 0.4, 0.6 and 0.8 showed no significant difference in its effect in mitigating the expansion.

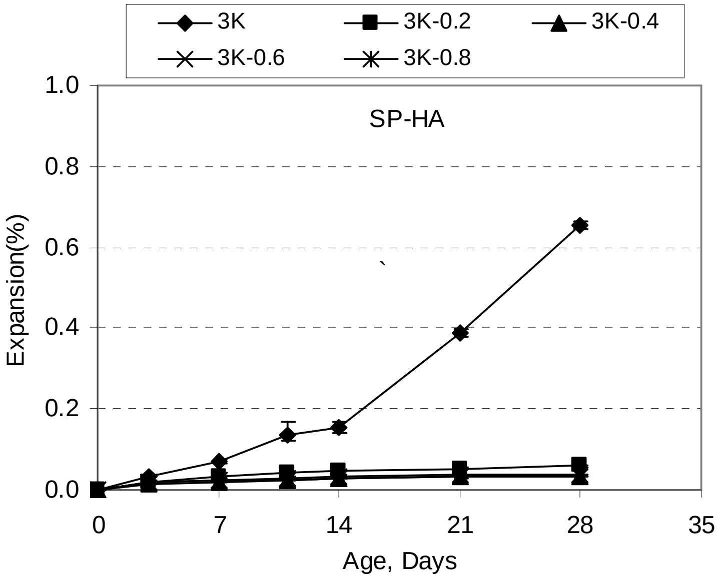


Figure 4.12 Expansion of Mortar Bars in Modified ASTM C 1260 Test with 3 Molar KAc Solution and Blended Deicers with SP Aggregate and High-Alkali Cement (See Chapter 3.2 for Notation)

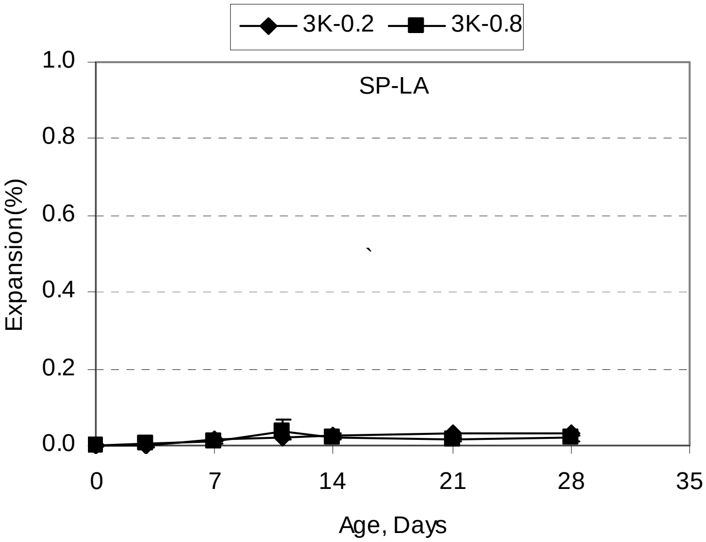


Figure 4.13 Expansion of Mortar Bars in Modified ASTM C 1260 Test with 3 Molar KAc Solution and Blended Deicers with SP Aggregate and Low-Alkali Cement (See Chapter 3.2 for Notation)

4.3.2 Dynamic Modulus of Elasticity

Figure 4.14 shows the changes in dynamic modulus of elasticity of mortar bar specimens made with SP aggregate and exposed to 1N NaOH, 3 and 6.4 molar KAc solution and 3 molar LiAc solution, and blended deicer solutions. There was not noticeable loss in DME when bars were soaked in 3 molar LiAc solution as there was no much expansion observed in expansion tests. From the results, it can be seen that whenever there was drop in DME, a corresponding increase in the linear expansion of the mortar bars was observed in ASTM C 1260 test. Bars made with high-alkali cement, soaked in the blended deicer of with 3 molar KAc with Li/K ratios of 0.4, 0.6 and 0.8 showed no significant drop in DME. Concentration of KAc also influences the drop in DME as bars exposed to 6.4 molar KAc solution dropped more in DME compare to bars exposed to 3 molar KAc solution.

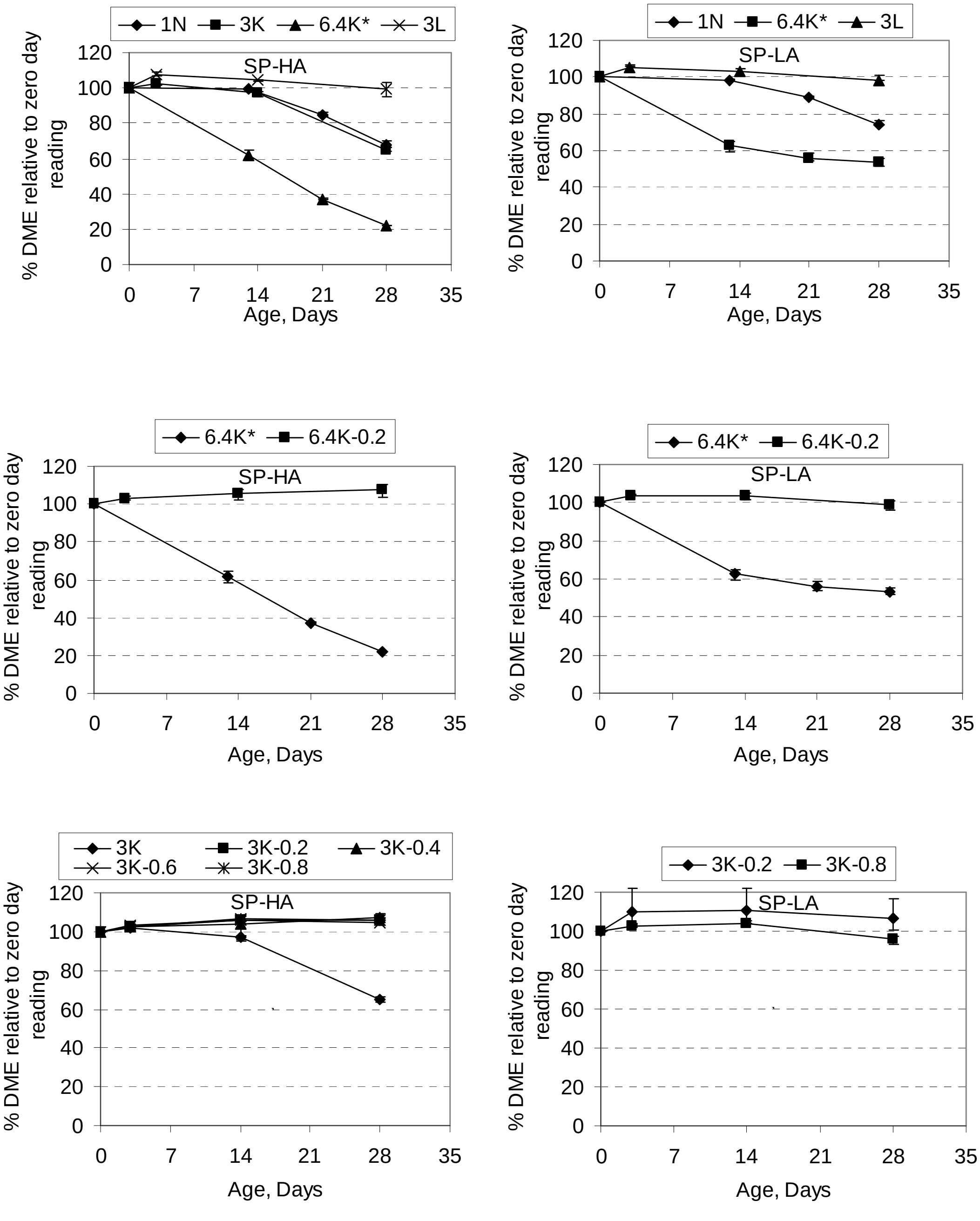


Figure 4.14 Change in Dynamic Modulus of Mortar Bars made with SP Aggregate in Standard and Modified ASTM C 1260 Test
(See Chapter 3.2 for Notation, * Sompura, 2006)

4.4 Test Results from ASTM C 1260 Tests for North Carolina Aggregate

Expansion behavior of mortar bars prepared with NC aggregate in the standard and modified ASTM C 1260 tests are presented in this section. In addition, changes in the DME of mortar bars subjected to standard and modified ASTM C 1260 tests are presented.

4.4.1 Length-Change Behavior

Figure 4.15 shows the expansion results of the standard and modified ASTM C 1260 tests made with NC aggregate and high-alkali cement, exposed to 1N NaOH solution, 6.4 molar and 3 molar KAc solution. From the figure, it can be seen that NC aggregate is reactive with an expansion of more than 0.24% at 14 days for 1N NaOH solution. Mortar bars prepared with NC aggregate, showed more expansion (1.0%), when exposed to 3 molar KAc solution compared to mortar bars exposed to 6.4 molar KAc solutions (0.6%), at 28 days. As compared to other deicers, bars which were soaked in 3 molar KAc solution showed low expansion until 14 days, after which there was a sudden increase in expansion more than bars soaked in 1N NaOH solution and 6.4 molar KAc solutions.

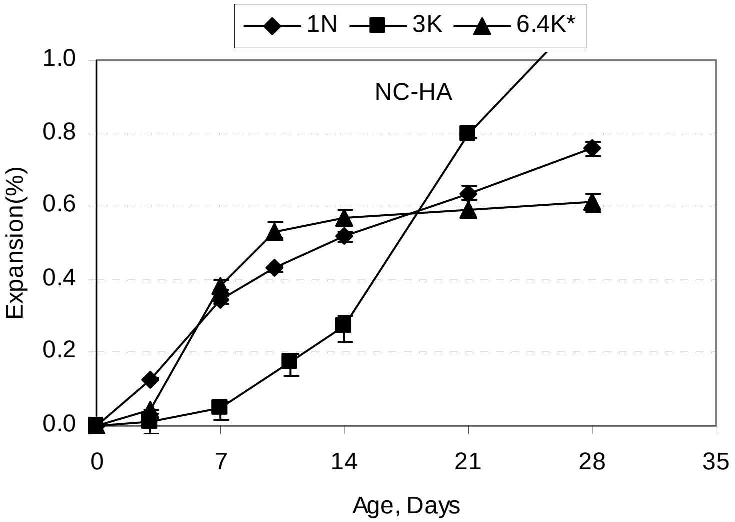


Figure 4.15 Expansion of Mortar Bars in Standard and Modified ASTM C 1260 Test with NC Aggregate and High-Alkali Cement (See Chapter 3.2 for Notation, * Sompura, 2006)

Figure 4.16 shows the expansion behavior of bars made with NC aggregate exposed to 6.4 molar KAc solution and 6.4 molar KAc-LiAc blended deicer with Li/K ratio of 0.2 (6.4-0.2) using high-alkali cement. From the figure, it can be seen that the NC aggregate is highly reactive when exposed to 6.4 molar KAc with an expansion of more than 0.6% at 28 days. At 28 days, bars made with NC aggregate, when exposed to 6.4 molar KAc-LiAc blended deicer with Li/K ratio of 0.2 (6.4-0.2), showed to be non reactive with expansion of less than 0.1% with high-alkali cement showing the effectiveness of LiAc in mitigating the expansion due to ASR.

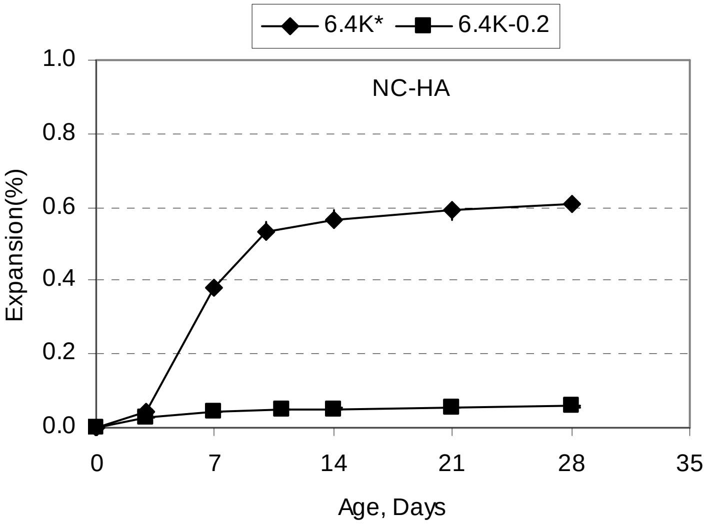


Figure 4.16 Expansion of Mortar Bars in Modified ASTM C 1260 Test with 6.4 Molar KAc Solution and Blended Deicers with NC Aggregate and High-Alkali Cement (See Chapter 3.2 for Notation, * Sompura, 2006)

Figure 4.17 shows the expansion results of the modified ASTM C 1260 tests. Figure 4.17 shows the expansions of bars made with NC aggregate exposed to 3 molar KAc solution and 3 molar KAc-LiAc blended deicer with Li/K ratio of 0.2, 0.4, 0.6, and 0.8 using high-alkali cement. NC aggregate is highly reactive when exposed to 3 molar KAc solution with an expansion of more than 1.01% for high-alkali cement at 28 days. When the bars were soaked with different Li/K ratios of 0.2, 0.4, 0.6, and 0.8 there was a total mitigation in expansion of less than 0.1% in both high-alkali and low-alkali cement. Statistically, bars made with high-alkali cement, soaked in the Li/K ratios of 0.2, 0.4, 0.6 and 0.8 showed no significant difference in its effect in mitigating the expansion due to ASR.

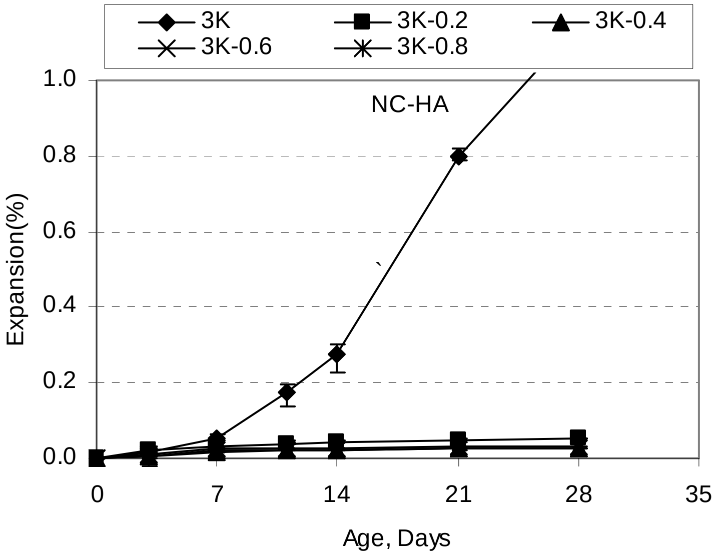


Figure 4.17 Expansion of Mortar Bars in Modified ASTM C 1260 Test 3 Molar KAc Solution and Blended Deicers with NC Aggregate and High-Alkali Cement (See Chapter 3.2 for Notation)

4.4.2 Dynamic Modulus of Elasticity

Figure 4.18 shows the changes in dynamic modulus of elasticity of mortar bar specimens made with NC aggregate and exposed to 1N NaOH, 3 molar and 6.4 molar KAc solution and 3 molar LiAc solution, and blended deicer solutions. From the results, it can be seen that whenever there is drop in DME, a corresponding increase in the linear expansion of the mortar bars was observed in the ASTM C 1260 test. It is also evident that the loss in DME was dependent on the concentration of KAc. Bars made with high-alkali cement, soaked in the blended deicer of with 3 molar KAc with Li/K ratios of 0.2, 0.4, 0.6 and 0.8 showed no significant drop in DME.

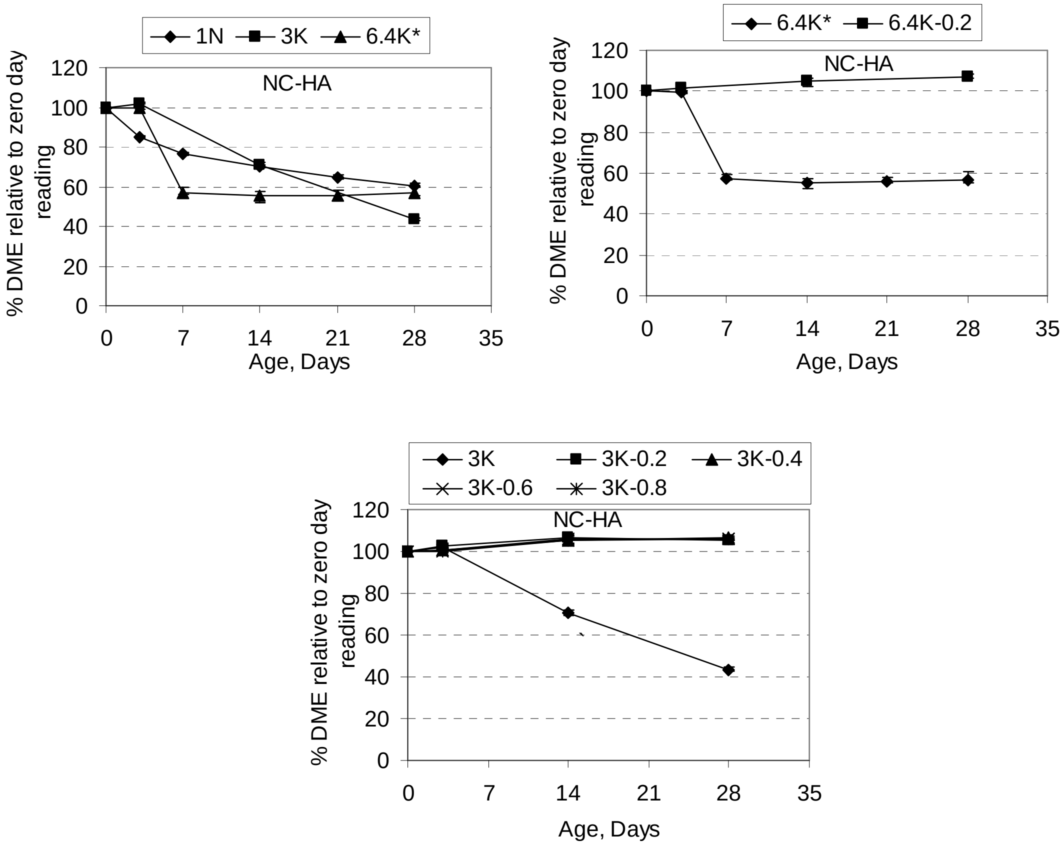


Figure 4.18 Change in Dynamic Modulus of Mortar Bars made with NC Aggregate in Standard and Modified ASTM C 1260 Test
(See Chapter 3.2 for Notation, * Sompura, 2006)

4.5 Test Results from ASTM C 1260 Tests for South Dakota Aggregate

Expansion behavior of mortar bars prepared with SD aggregate in the standard and modified ASTM C 1260 tests are presented in this section. In addition, changes in the DME of mortar bars subjected to standard and modified ASTM C 1260 tests are presented.

4.5.1 Length-Change Behavior

Figure 4.19 shows the expansion results of the standard and modified ASTM C 1260 tests made with SD aggregate and high-alkali cement, exposed to 1N NaOH solution, 6.4 molar and 3 molar KAc solution. From the figure, it can be seen that SD aggregate is reactive when exposed to all deicers. At 28 days, SD aggregate, when exposed to 3 molar KAc solution, showed less expansion compared to 1N NaOH and 6.4 molar KAc solution.

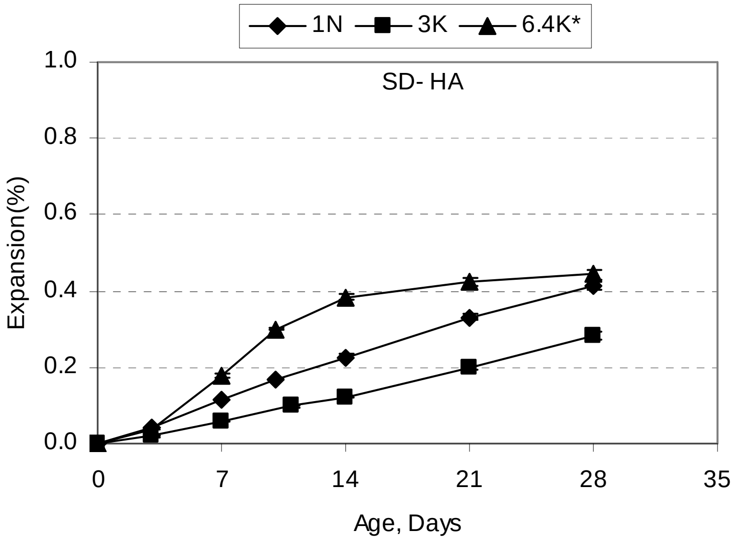


Figure 4.19 Expansion of Mortar Bars in Standard and Modified ASTM C 1260 Test with SD Aggregate and High-Alkali Cement (See Chapter 3.2 for Notation, * Sompura, 2006)

Figure 4.20 shows the expansion behavior of bars made with SD aggregate exposed to 6.4 molar KAc solution and 6.4 molar KAc-LiAc blended deicer with Li/K ratio of 0.2 (6.4-0.2) using high-alkali cement. At 28 days, bars made with SD aggregate, when exposed to 6.4 molar KAc-LiAc blended deicer with Li/K ratio of 0.2 (6.4-0.2), showed to be non-reactive with expansion of less than 0.1% with high-alkali cement, compared to bars exposed to 6.4 molar KAc solution with an expansion of more than 0.4% showing the effectiveness of LiAc in mitigating the expansion due to ASR.

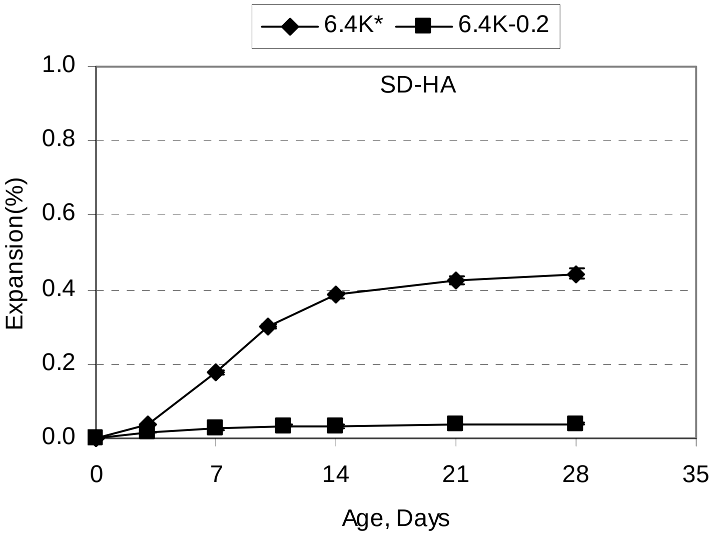


Figure 4.20 Expansion of Mortar Bars in Modified ASTM C 1260 Test 6.4 Molar KAc Solution and Blended Deicers with SD Aggregate and High-Alkali Cement (See Chapter 3.2 for Notation, * Sompura, 2006)

Figure 4.21 shows the expansions of bars made with SD aggregate exposed to 3 molar KAc solution and 3 molar KAc-LiAc blended deicer with Li/K ratio of 0.2, 0.4, 0.6, and 0.8 using high-alkali cement. SD aggregate was reactive when exposed to 3 molar KAc solution with expansion of more than 0.2% for high-alkali cement at 28 days. When the bars were soaked with different Li/K ratios of 0.2, 0.4, 0.6, and 0.8, they were non-reactive as the expansions were less than 0.1% with high-alkali cement. From statistical analysis, bars made with high-alkali cement, soaked in the Li/K ratios of 0.2, 0.4, 0.6 and 0.8 showed significant difference in its effect in mitigating the expansion due to ASR.

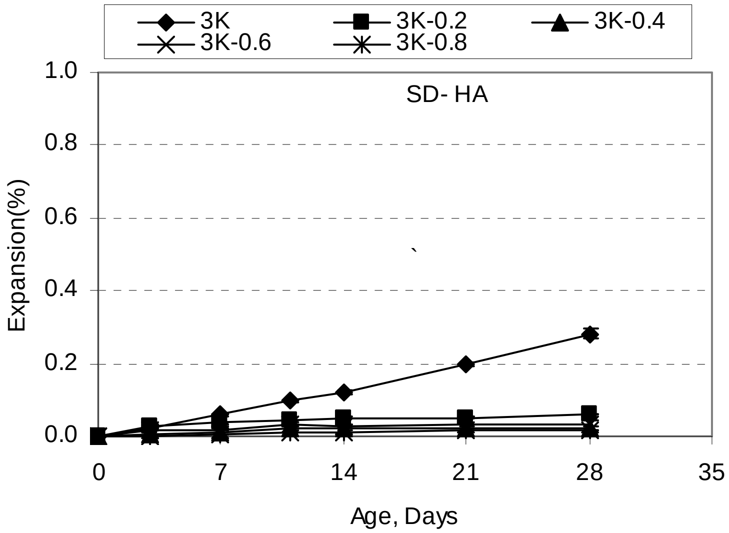


Figure 4.21 Expansion of Mortar Bars in Modified ASTM C 1260 Test with 3 Molar KAc Solution and Blended Deicers with SD Aggregate and High-Alkali Cement (See Chapter 3.2 for Notation)

4.5.2 Dynamic Modulus of Elasticity

Figure 4.22 shows the changes in dynamic modulus of elasticity of mortar bar specimens made with SD aggregate and exposed to 1N NaOH, 3 molar and 6.4 molar KAc solution, and blended deicer solutions. From the results, it can be seen that whenever there was drop in DME, a corresponding increase in the linear expansion of the mortar bars was observed in the ASTM C 1260 test. Bars made with high-alkali cement, soaked in the blended deicer with Li/K ratios of 0.2, 0.4, 0.6 and 0.8 with 3 molar KAc solution showed no noticeable drop in DME.

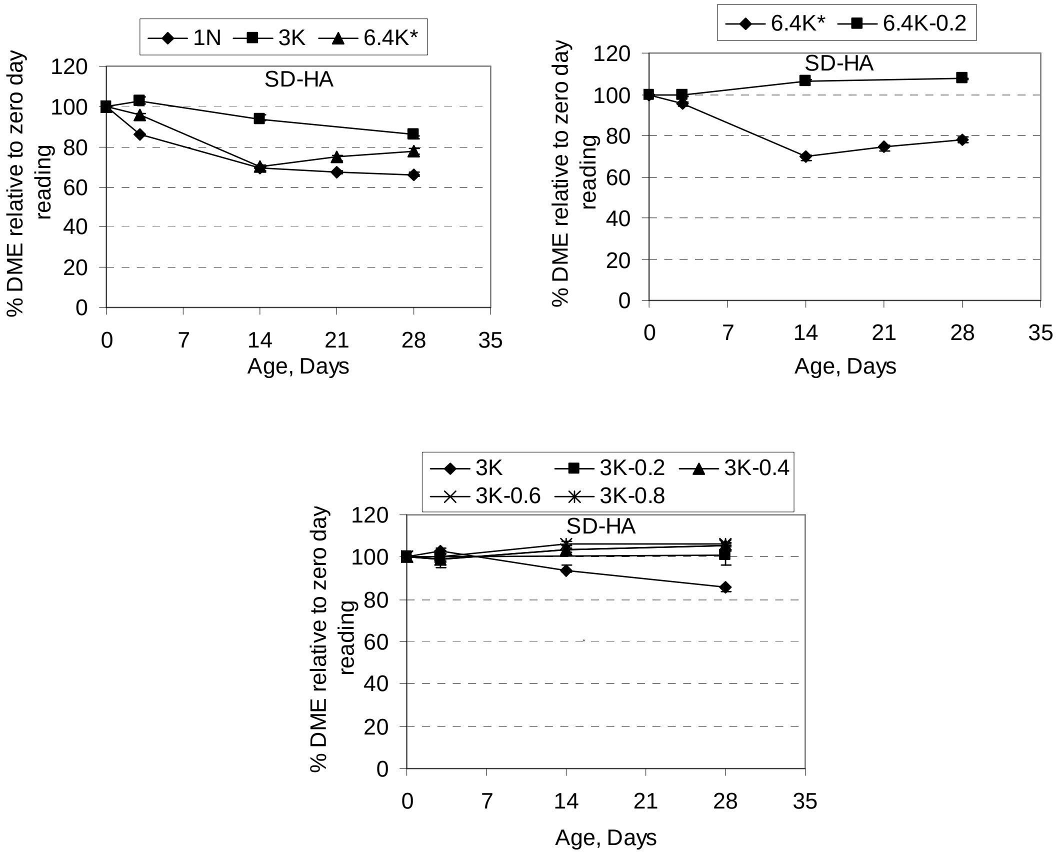


Figure 4.22 Change in Dynamic Modulus of Mortar Bars made with SD Aggregate in Standard and Modified ASTM C 1260 Test
(See Chapter 3.2 for Notation, * Sompura, 2006)

4.6 Results and Discussion from ASTM C 1260 and DME Tests

From the expansion and DME test results from ASTM C 1260 tests on mortar bars made with different aggregate, it was found that the level of distress observed in any mortar bars was dependent on the aggregate reactivity and deicer used. Mortar bars made with reactive aggregate exposed to plain potassium acetate with both 6.4 molar KAc solution and 3 molar KAc solution showed significant potential to cause distress. NM and NC bars expanded more when exposed to 3 molar KAc solution compared to bars exposed to 6.4 molar KAc solution. Whereas, mortar bars made with SP and SD aggregate showed more expansion when exposed to 6.4 molar KAc solution compared to bars exposed to 3 molar KAc solution. Mortar bars made with NM and NC aggregate and high-alkali cement when exposed to 3 molar KAc solution expanded more compared to bars exposed to 1N NaOH solution. Whereas, NM and NC bars exposed to 1N NaOH solution expanded more than bars exposed to 6.4 molar KAc solution. Bars made with NM aggregate and low-alkali cement when exposed to 1N NaOH solution expanded more than when they were exposed to 3 and 6.4 molar KAc solution. Bars made with SP and SD aggregate and high-alkali cement expanded more when exposed to 1N NaOH solution, compared to 3 molar KAc solution. Bars with SP, NC and SD aggregate and low-alkali cement expanded more when exposed to 6.4 molar KAc solution, compared to bars exposed to 1N NaOH solution.

Mortar bars made with SP, NC and SD aggregate exposed to blended deicer of 3 molar KAc solution with Li/K ratio of 0.2, 0.4, 0.6 and 0.8, proved to be effective as LiAc totally mitigated the expansion due to ASR. Bars made with NM aggregate was mitigated when exposed to blended deicer of 3 molar KAc solution with Li/K of 0.6 and 0.8. Also, mortar bars made with SP, NC and SD aggregate exposed to blended deicer of 6.4 molar KAc solution with Li/K ratio of 0.2 with proven to be effective in mitigating expansion. Whereas, expansion in mortar bars made with NM aggregate was not mitigated with Li/K ratio of 0.2 with 6.4 molar KAc solution. For both cement types, bars made with NM aggregate showed the highest expansions compared to other aggregate type. In general, the alkali content of the cement did have a significant influence on the expansions of mortar bars as bars made with high-alkali cement expanded more compared to bars made with low-alkali cement.

From the DME test results, it can be seen that whenever there was drop in DME, a corresponding increase in the linear expansion of the mortar bars was observed in ASTM C 1260 tests. It was also evident that loss in DME was dependent on the concentration of KAc solution. As bars made with NM and NC aggregate reacted more with 3 molar KAc solution compared to bars exposed to 6.4 molar KAc solution. Whereas, bars made with SP and SD aggregate reacted more with 6.4 molar KAc solution compared to bars exposed to 3 molar KAc solution, this suggest that reactivity of aggregate is very important for the distress of the bars. Also, LiAc addition to the KAc helped in mitigating loss in DME as observed in ASTM C 1260 tests. For both cement types, bars made with NM aggregate showed more loss in DME compared to other aggregate type as observed in the expansion results.

Figure 4.23 shows graphs of % DME relative to zero day reading compared to the % expansion in 1260 tests at similar ages of mortar bars made with different aggregates, high-alkali cement when exposed to 3 molar KAc solution and different blended deicer of 3.0 molar KAc with Li/K ratios of 0.2, 0.3, 0.4, 0.6 and 0.8. It can be observed that whenever there is change in DME, a corresponding change in the linear expansion of the mortar bars was observed in ASTM C 1260 tests.

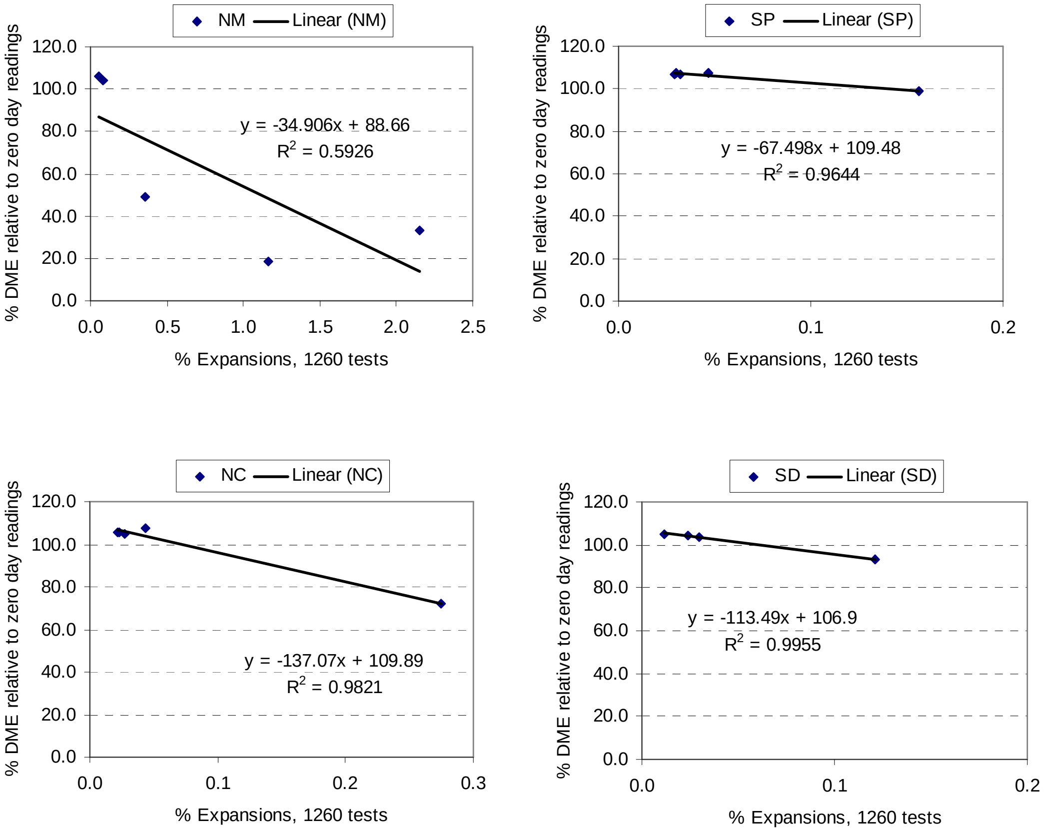


Figure 4.23 Percentage DME Relative to Zero Day Reading and Expansions in C 1260 Tests

4.7 Results and Discussions from pH Measurements on Soak Solution in the Modified ASTM C 1260 Test

Figure 4.24 shows the pH of soak solutions exposed to mortar bars at 80ºC measured at 28 days in the modified ASTM C 1260 tests for NM, SP, NC and SD made with HA cement. The pH was also measured before the mortar bars were exposed to soak solution (0 day). From the figure, it can be observed that in all the cases the pH of the soak solution value increased from 10 to approximately 13 after being exposed to mortar bars. Also, it was noticed that the increase in pH was greater with solutions containing higher K concentration. Although, increase in pH of soak solution was observed even in presence of LiAc, significant reduction in mortar bars expansions were observed. This suggests that the ASR gel found in presence of LiAc was not expansive. This mechanism was observed with all Li/K ratios of 0.2, 0.4. 0.6 and 0.8. The same trend was observed in all the aggregate types.

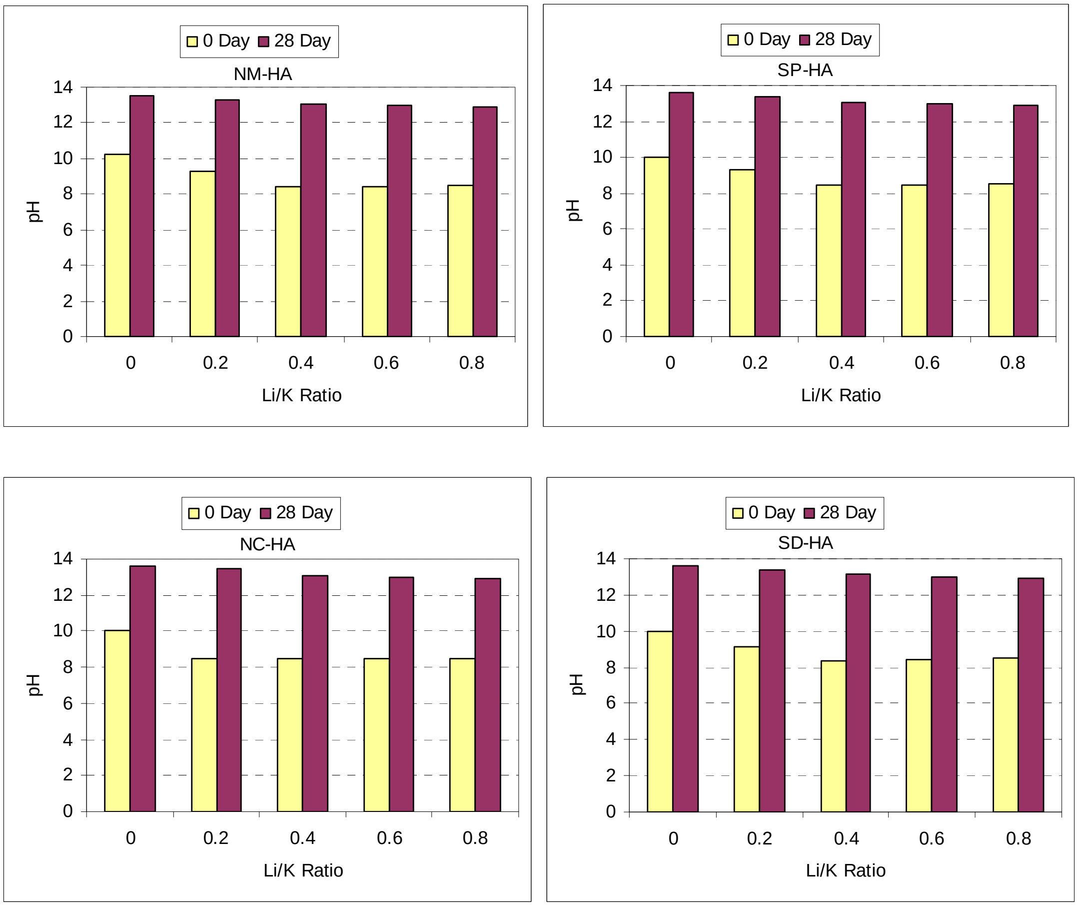


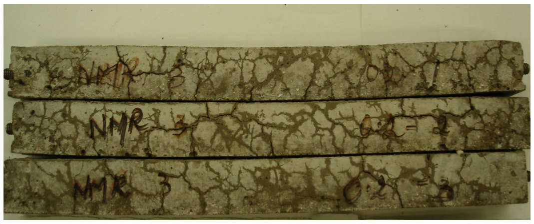
Figure 4.24 pH Values of Soak Solution from Modified ASTM C 1260 Tests for all Aggregate made with High-Alkali Cement

4.8 Results and Discussion from Visual and SEM-EDX Analysis on Mortar Bars

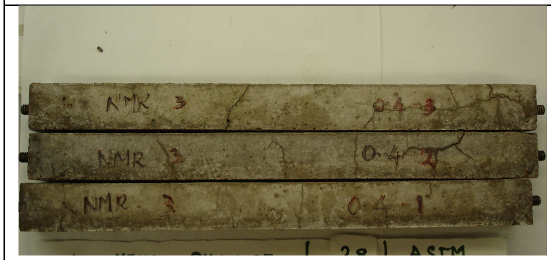
Visual and SEM-EDX analyses were conducted on mortar bars exposed to deicer solutions to study the reaction products formed due to interactions between the soak solutions and mortar bars. SEM-EDX analyses were conducted on mortar bars at the end of 28 days. SEM and EDX analyses of mortar bars made with NM and SP aggregate are discussed in detail as the influence of soak solution with aggregate was well observed.

Figure 4.25 shows the visual images of NM-HA soaked in 3 molar KAc solution with different Li/K ratios. From the visual image, the influence of LiAc in mitigating expansion due to ASR is clearly observed as the higher the Li/K ratio, the higher the mitigation.

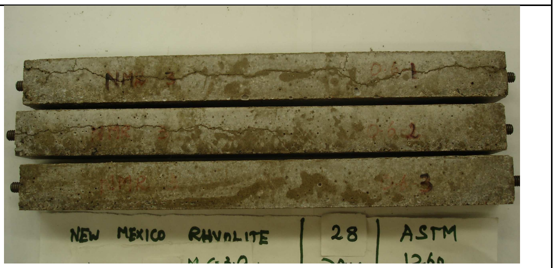
Soaked in 3 Molar KAc Solution



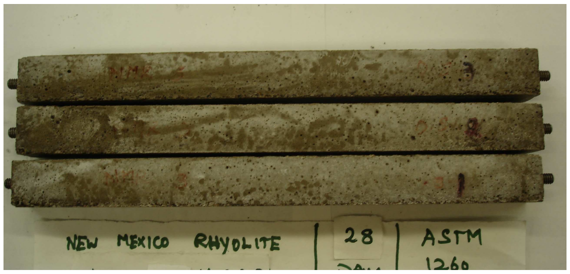
Soaked in 3 Molar KAc Solution and Blended Deicers with Li/K 0.2



Soaked in 3 Molar KAc Solution and Blended Deicers with Li/K 0.4



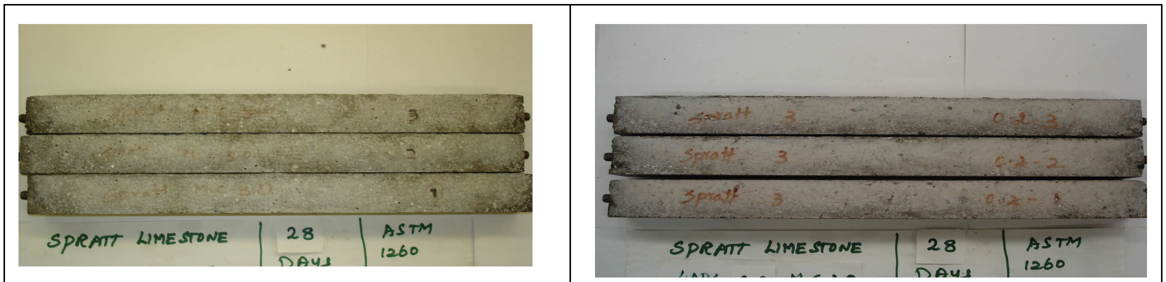
Soaked in 3 Molar KAc Solution and Blended Deicers with Li/K 0.6



Soaked in 3 Molar KAc Solution and Blended Deicers with Li/K 0.8

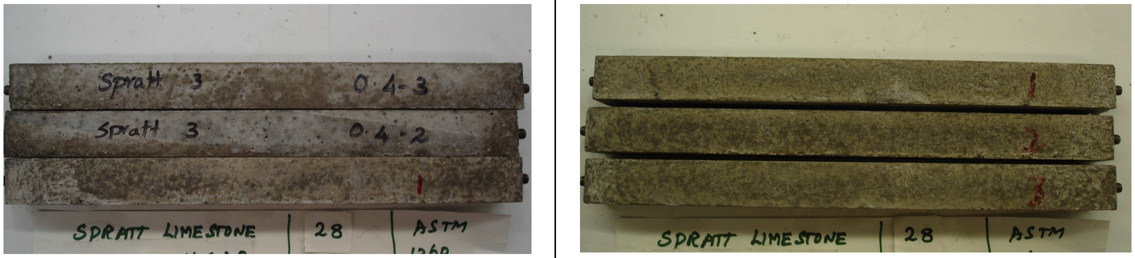
Figure 4.25 Figures shows the visual images of NM-HA exposed to different Li/K ratio in Modified ASTM C 1260 Test.

Figure 4.26 shows the visual images of SP-HA soaked in 3 molar KAc solution with different Li/K ratios. From the visual images, the influence of LiAc in mitigating expansion due to ASR is clearly observed as the Li/K ratio increases the higher mitigation.



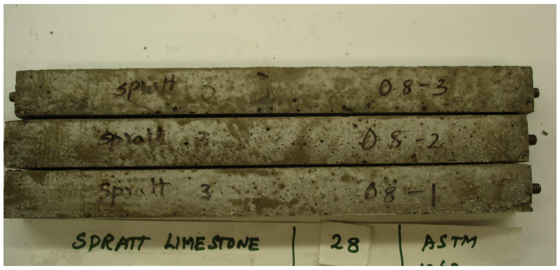
Soaked in 3 Molar KAc Solution

Soaked in 3 Molar KAc Solution and Blended Deicers with Li/K 0.2



Soaked in 3 Molar KAc Solution and Blended Deicers with Li/K 0.4

Soaked in 3 Molar KAc Solution and Blended Deicers with Li/K 0.6



Soaked in 3 Molar KAc Solution and Blended Deicers with Li/K 0.8

Figure 4.26 Figures shows the visual images of SP-HA exposed to different Li/K ratio in Modified ASTM C 1260 Test.

Figures 4.27 through 4.29 show the SEM-EDX images of NM-LA-3, NM-LA-3-0.2 and NM-LA-6.4-0.2, respectively. From the figures it is evident that bars exposed to KAc show the deterioration of cement paste with significant cracking and some cracking through the aggregate. The EDX spectrum of the gel surrounding the aggregate and through the cement paste shows the presence of potassium in the gel and the formation of ASR gel.

Figures 4.30 through 4.32 show the SEM-EDX images of SP-HA-3, SP-HA-3-0.2 and SP-HA-3.0-0.8, respectively. From the SEM images, it is clear that the deterioration of the bar is influenced by the potassium concentration. Lithium acetate was proven to be effective in mitigating the cracking, and the EDX spectra of the gel shows the presence of less potassium level in higher Li/K ratios. Similar results were observed in the expansion and DME results as higher the Li/K concentration the higher the mitigation.

Figures 4.33 and 4.34 show the SEM-EDX images of SP-HA-6.4 and SP-HA-6.4-0.2, respectively. In figure 4.33 it can be seen that there is a significant amount of cracking throughout the bar. Most of the wide cracks are empty, which may be the reason for the loss in DME. The cracks are found largely in the cement paste rather than in the aggregate. The EDX spectrum of the gel shows the presence of ASR gel made of potassium, silica and calcium. Figure 4.34 shows the effects of LiAc in mitigating ASR as there were not many cracks and even the EDX spectrum of the gel shows mitigation of expansion due to ASR.

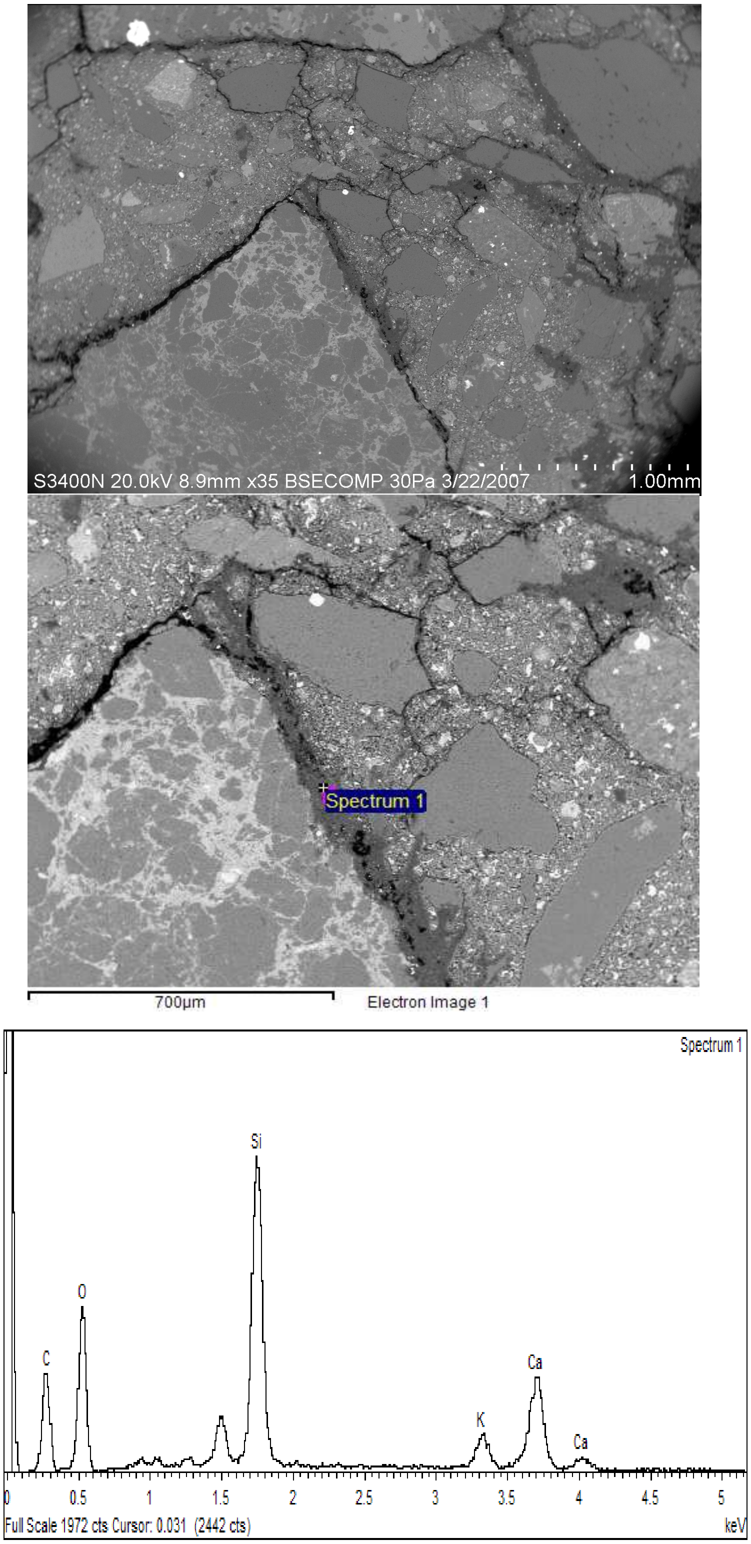


Figure 4.27 Figures showing SEM-EDX images of NM-LA-3.0 mortar bars

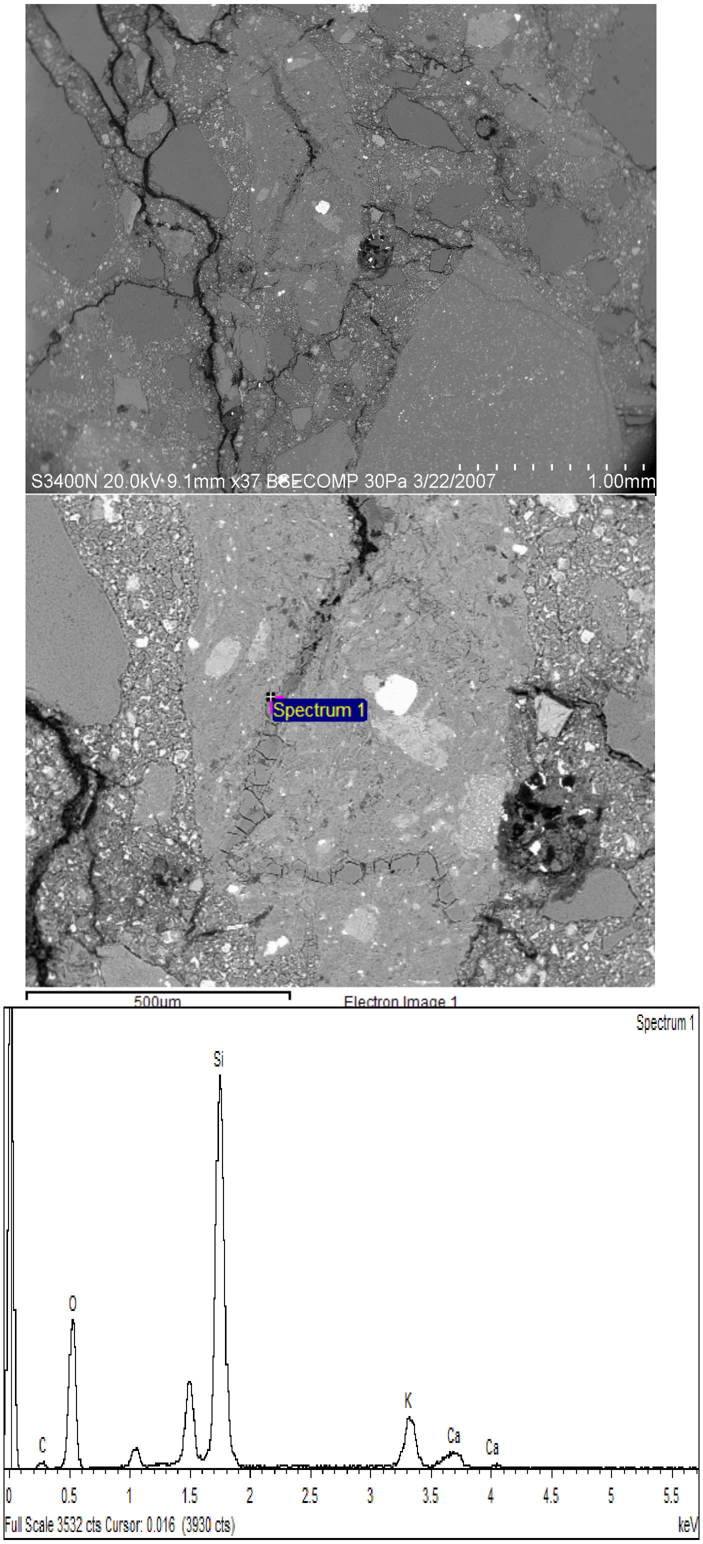


Figure 4.28 Figures showing SEM-EDX images of NM-LA-3-0.2 mortar bars

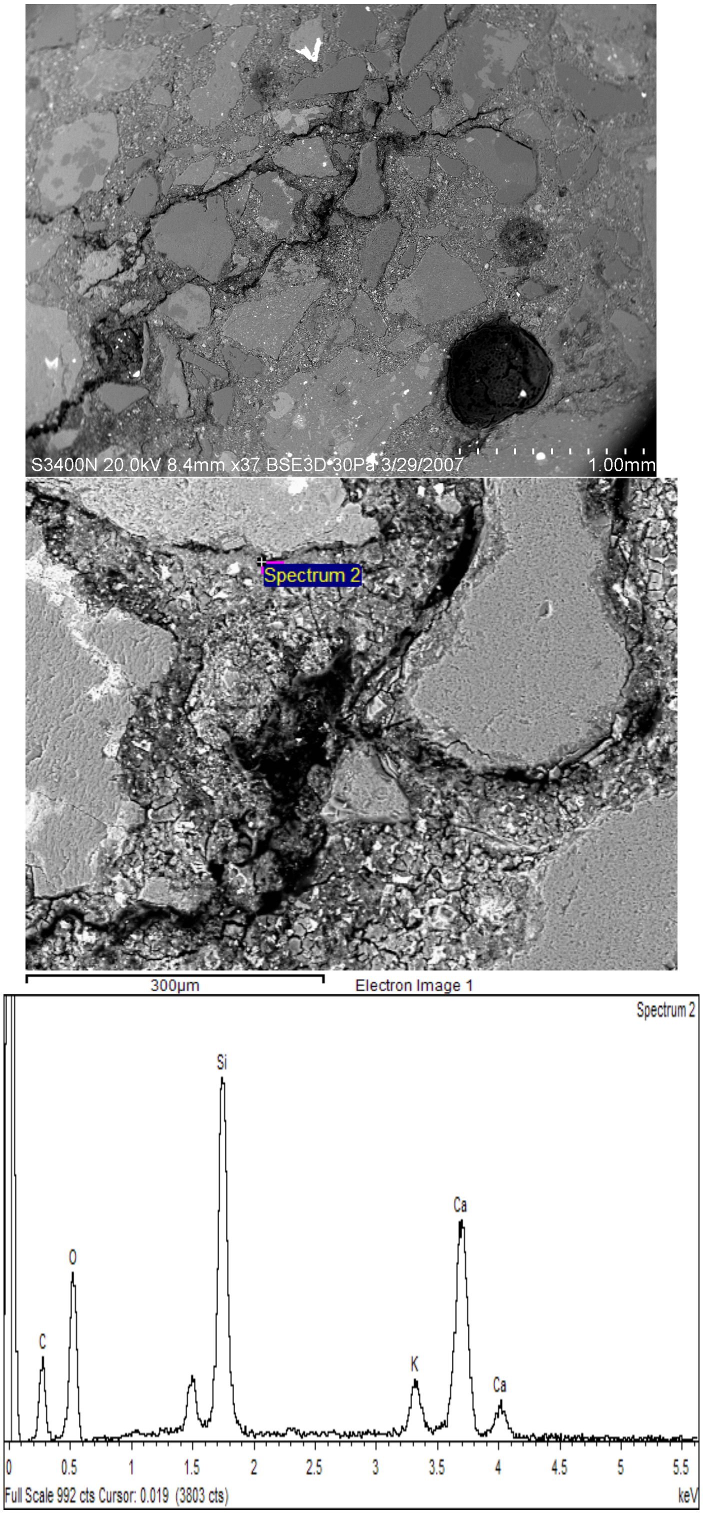


Figure 4.29 Figures showing SEM-EDX images of NM-LA-6.4-0.2 mortar bars

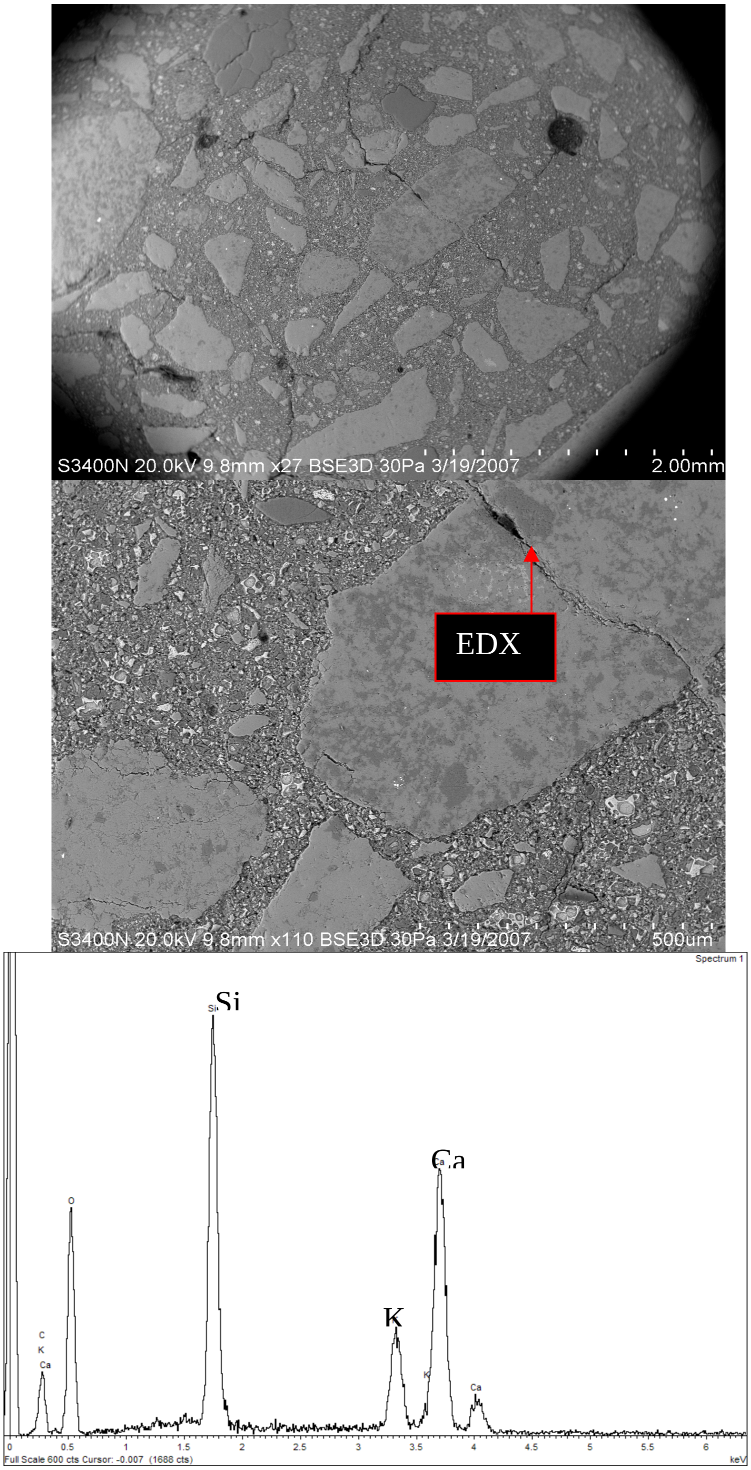


Figure 4.30 Figures showing SEM-EDX images of SP-HA-3.0 mortar bars

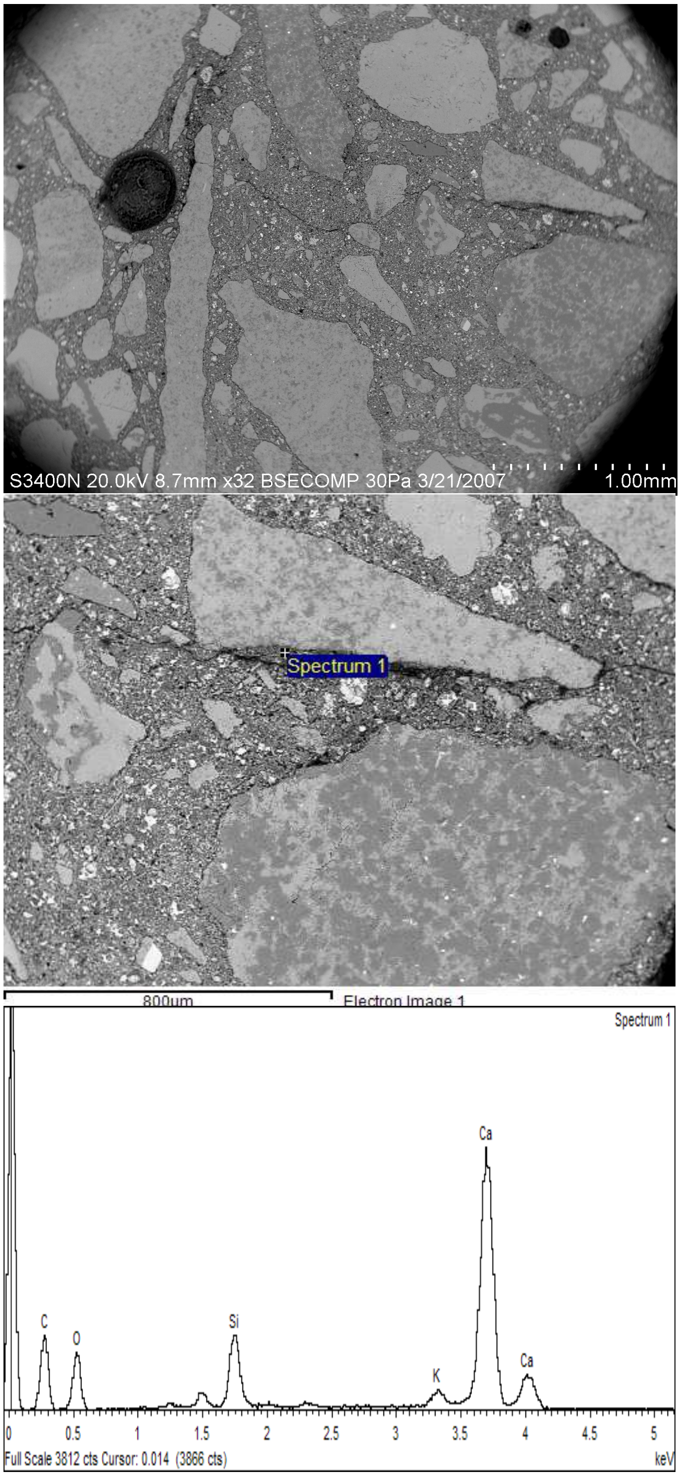


Figure 4.31 Figures showing SEM-EDX images of SP-HA-3-0.2 mortar bars

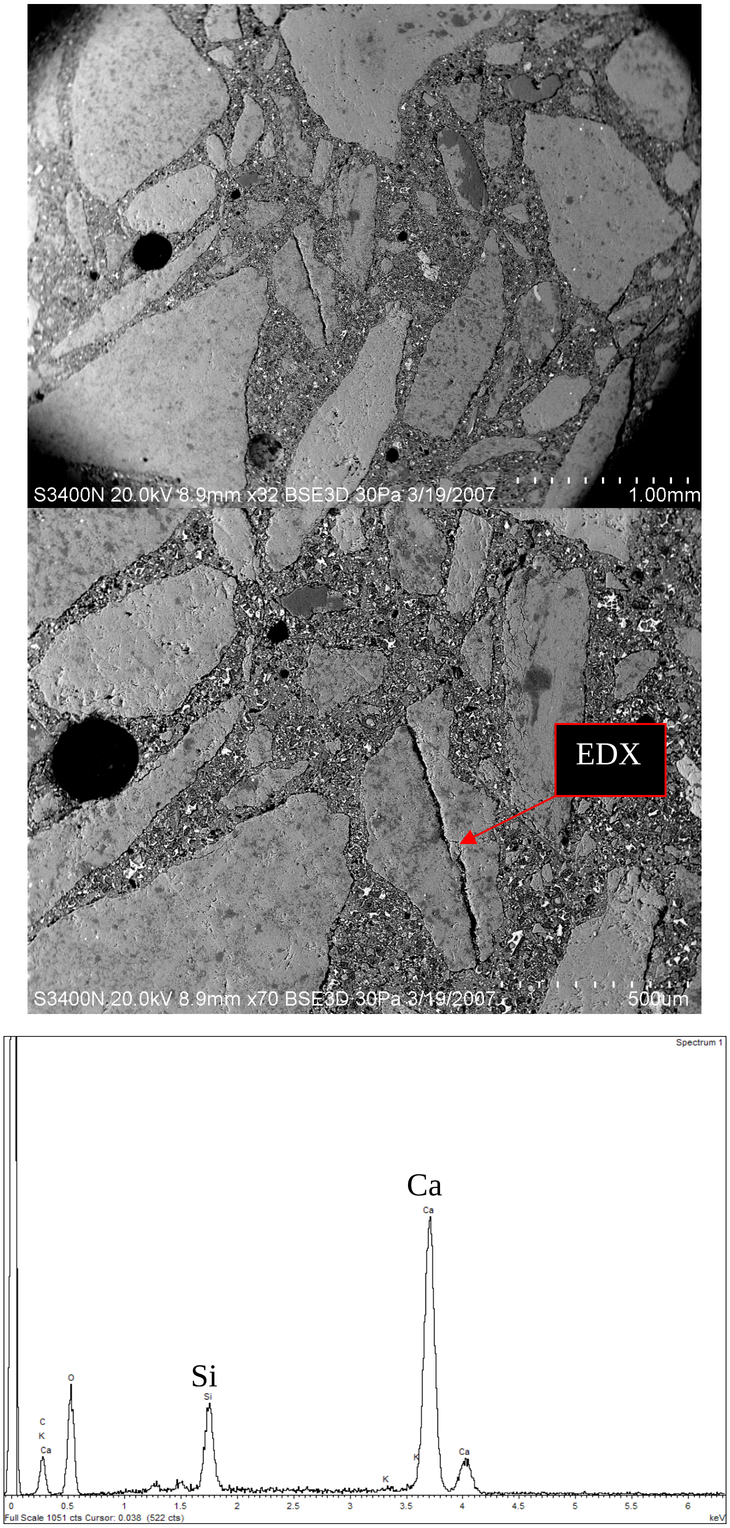


Figure 4.32 Figures showing SEM-EDX images of SP-HA-3-0.8 mortar bars

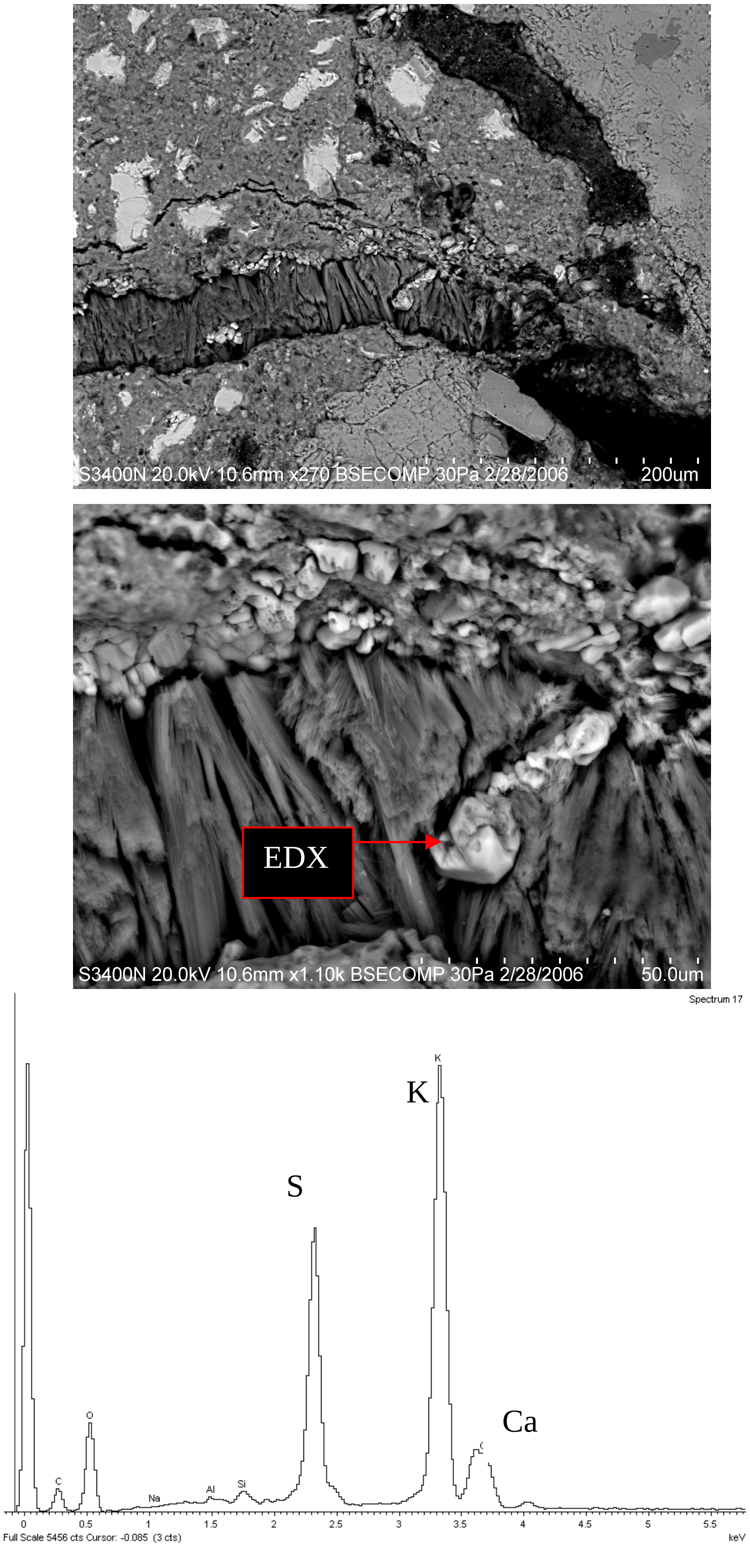


Figure 4.33 Figures showing SEM-EDX images of SP-HA-6.4 mortar bars

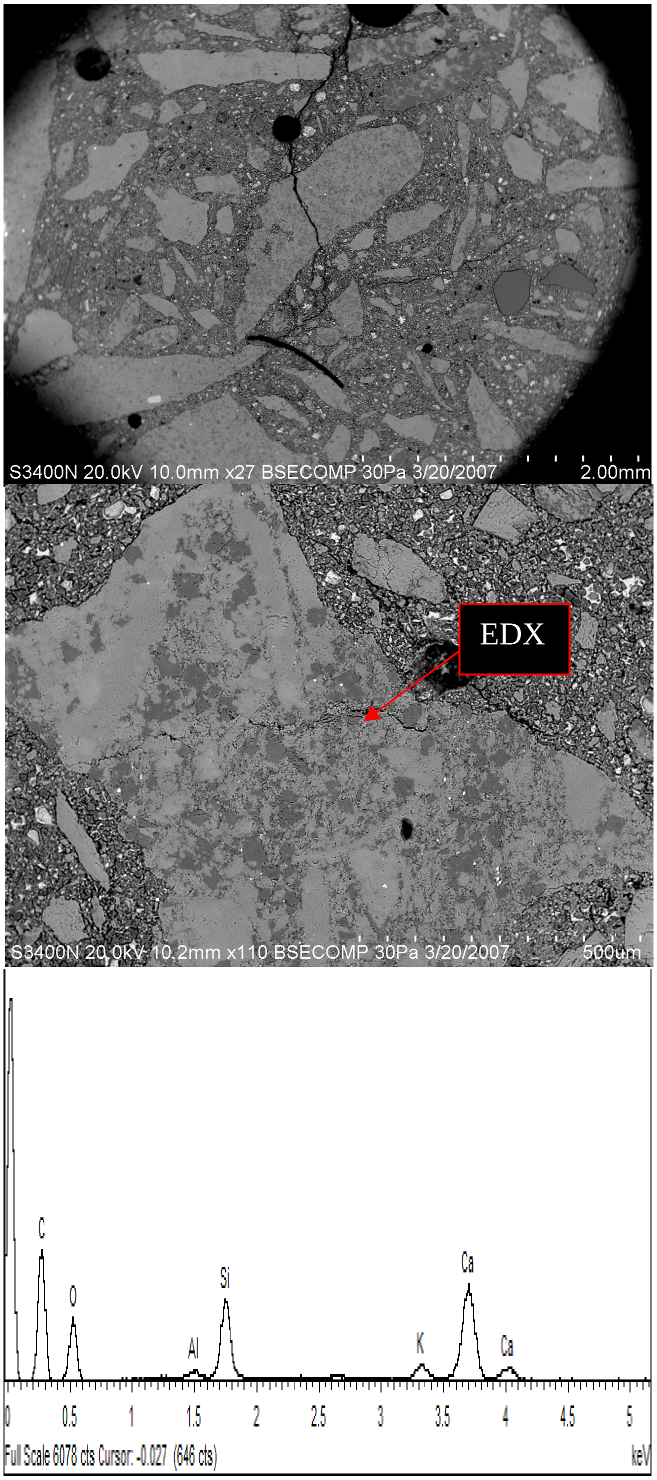


Figure 4.34 Figures showing SEM-EDX images of SP-HA-6.4-0.2 mortar bars

4.9 Statistical Analyses for Modified ASTM C 1260 Test

Statistical analyses were conducted on the data obtained from the modified ASTM C 1260 tests. The objectives of these analyses were:

1. To study if there was any significant difference between Li/K ratio and expansion of mortar bars in modified ASTM C 1260 tests.
2. To study if the expansions of mortar bars made with HA cement were higher than expansions of the corresponding specimens made with LA cement.
3. To determine the nature of the relationship between lithium content of the soak solution and the expansion in modified ASTM C 1260 tests.

Results from Statistical Analysis

Hypothesis testing for two or more population means was conducted using SAS program, to determine if there was any significant difference between various Li/K ratios in mitigating expansion in modified ASTM C 1260 test. Least Significant Difference (LSD) was used to find if there was any significant difference between different Li/K ratios with respect to expansion. The level of significance used for the entire hypothesis test was 0.05. The null hypothesis (Ho) assumed that all expansions of mortar bars in different soak solutions with different Li/K ratios were the same. The alternative hypothesis (H_A) was that not all dosage levels were equal in mitigating expansion. If the p-value from the test was less than the level of significance, the null hypothesis statement was rejected and if the value was greater, the null hypothesis statement was not rejected.

The tests were conducted for mortar bars made with NM, SP, NC and SD aggregate with HA cement exposed to different Li/K ratios. The test results of the LSD procedure are presented in Table 4.1. For a given aggregate, same letter for different Li/K ratios indicate that there is no significant difference in effectiveness of the different dosage of lithium. If not, there is a significant difference. From the results, it is seen that when mortar bars made with NM aggregate, exposed to blended deicer of 3.0 molar KAc with Li/K ratios of 0.6 and 0.8 are similar as there were no significant difference in its effect in mitigating expansion. In SP aggregate, Li/K of 0.4, 0.6, and 0.8 are similar. In NC aggregate, Li/K of 0.2, 0.4, 0.6, and 0.8 are similar. In SD aggregate, each Li/K ratio had a significantly different effect on expansion.

Table 4.1 Comparison of effect of soak solution with different Li/K ratio in mitigating expansion for mortar bars within aggregate source at modified ASTM C 1260 tests, at 14 days.

Soak Solution Li/K ratio	NM	SP	NC	SD
0	A	A	A	A
0.2	B	B	B	B
0.4	C	C	C	C
0.6	D	C	C	D
0.8	D	C	C	E

Statistical analyses were conducted on all aggregate types with different soak solution combinations to find relative levels of mitigation offered for different aggregates, and if a significant difference exists between the different levels of mitigation. From the LSD procedure, the test results are presented in Table 4.2. The treatments with same letters means that there is no significant difference between those soak solution ratios and the effect of aggregate type. From Table 4.2 it is found that Li/K ratio of 0.8 seems to produce similar results, regardless of aggregate reactivity.

Table 4.2 Comparison of effect of soak solution with different Li/K ratio in mitigating expansion for mortar bars between aggregate sources at modified ASTM C 1260 tests, at 14 days.

Soak Solution Li/K ratio	NM	SP	NC	SD
0	A	E	D	E
0.2	B	G	G	G
0.4	C	G	G	G
0.6	F	G	G	G
0.8	G	G	G	H

Expansions of Low and High Alkali Mortar Bars

Hypothesis testing for two population means was conducted using SAS program, to determine whether expansions of mortar bars were influenced by alkali content of cement.

From the hypothesis testing, it was seen that mortar bars made with HA cement showed more expansion than bars made with LA cement. Only one combination showed an insignificant difference between expansions made with these cement types.

The results from the tests are presented in Table 4.3. In the table, for any aggregate-soak solution combination, HA>LA means for that particular aggregate-soak solution combination expansions of HA bars were higher than LA bars. HA<LA means expansions of LA bars were higher than HA bars. HA=LA means expansions were not significantly different in expansion between bars made with HA cement and bars made with LA cement.

Table 4.3 Comparison of expansions in modified ASTM C 1260 tests for mortar bars made with high-alkali and low-alkali cement at 14 days (X- No Data)

Soak Solution Li/K ratio	NM	SP
0	HA>LA	X
0.2	HA>LA	HA>LA
0.8	HA>LA	HA>LA

Regression Analysis

To study the relationship between lithium acetate additions in mitigating expansion in modified ASTM C 1260 tests regression analysis were conducted. In this research, mortar bars were prepared with different aggregate soaked in different Li/K ratios prepared with both high and low-alkali cement. To establish the relationship, regression analysis was carried out by plotting expansion of C1260 test on Y-axis and the Li/K ratio in X-axis on a graph.

Comparing the relationship between increase in Li/K ratio and expansion of mortar bars it can be said that there is good exponential relationship in NM aggregate with both HA and LA cements, when soaked with different Li/K ratio. Whereas in SP, NC and SD aggregate the exponential relationship does not fit as well compared to bars with NM aggregate with both cement types.

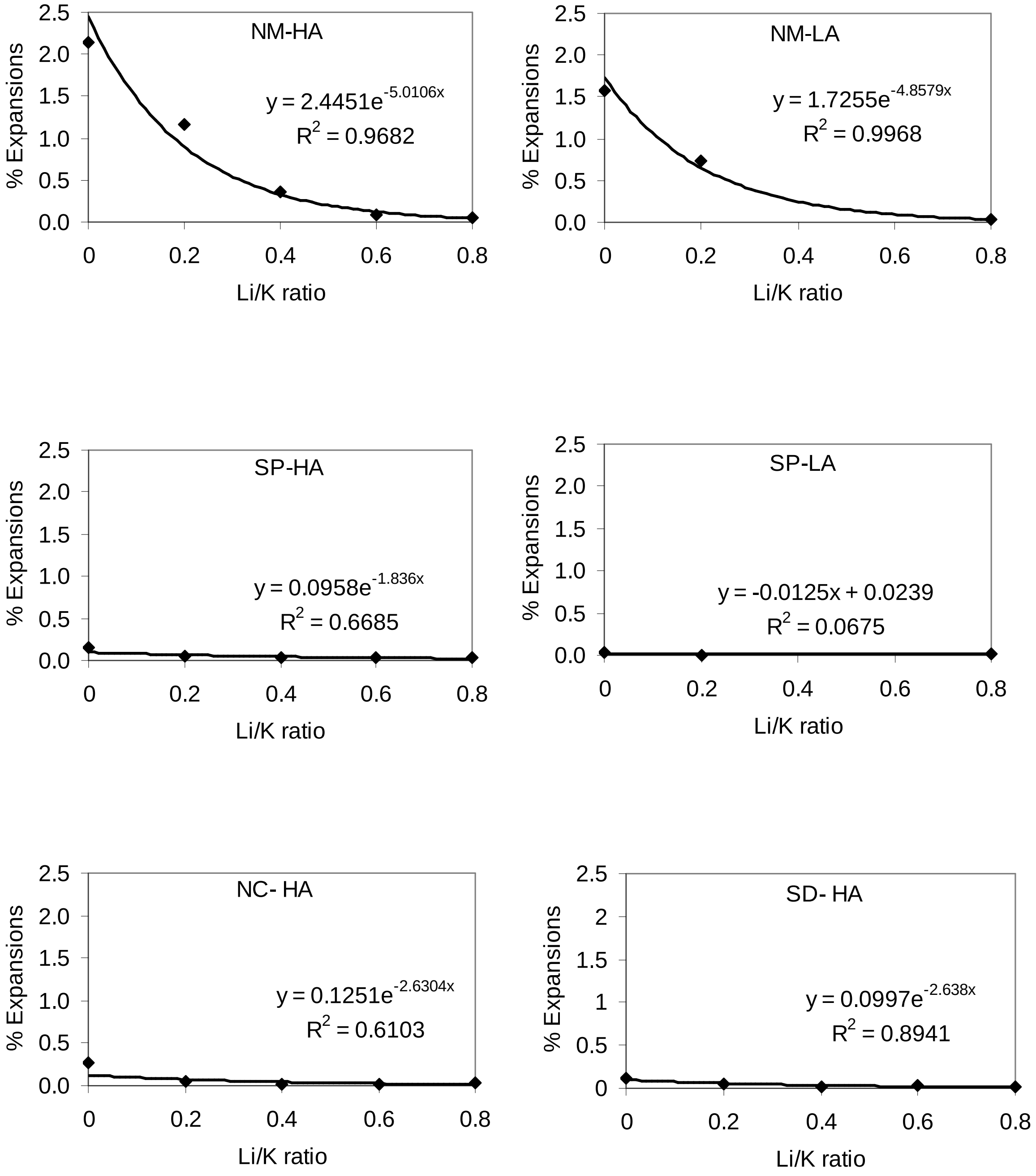


Figure 4.35 Expansions in Modified C 1260 tests at 14 days made with high-alkali and low-alkali cement for Li/K ratio of 0, 0.2, 0.4, 0.6, 0.8 solutions.

4.10 Results from Modified ASTM C 1293 Tests for New Mexico Aggregate

Expansion behavior of concrete prisms prepared with NM aggregate in the modified ASTM C 1293 tests are presented in this section. In addition, changes in the DME of concrete prisms subjected to modified ASTM C 1293 tests are presented.

4.10.1 Length-Change Behavior

Figure 4.36 shows the expansion behavior of concrete prisms made with NM aggregate and high-alkali cement, exposed to 1N NaOH solution, 6.4 molar and 3 molar KAc solution. Figure 4.37 shows the results of concrete prisms prepared with low-alkali cement, containing same aggregate and containing same deicers as in Figure 4.36.

From these figures, it can be seen that NM aggregate is highly reactive when it is exposed to NaOH and KAc deicer solutions as the prisms expanded more than 0.04% after 30 days when exposed to NaOH solution and after 7 days when exposed to 3 and 6.4 molar KAc solution. In the presence of 6.4 molar KAc solution, the NM concrete prisms prepared with both high-alkali and low-alkali cements showed severe distress (cracking) in less than 180 days. In presence of 3 molar KAc solution, the distress was more gradual.

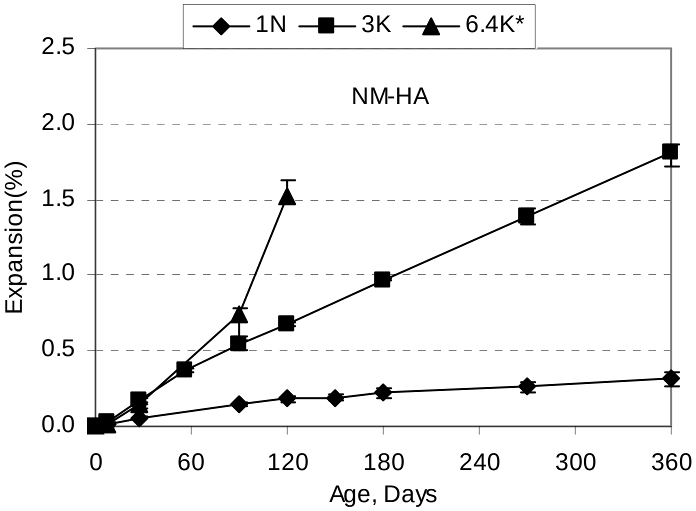


Figure 4.36 Expansion of Concrete Prisms in Modified ASTM C 1293 Test with NM Aggregate and High-Alkali Cement
See Chapter 3.2 for Notation, * Sompura, 2006)

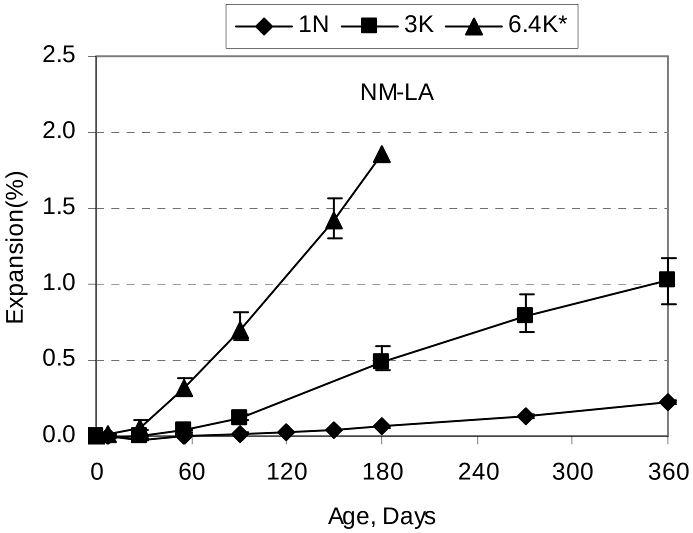


Figure 4.37 Expansion of Concrete Prisms in Modified ASTM C 1293 Test with NM Aggregate and Low-Alkali Cement
(See Chapter 3.2 for Notation, * Sompura, 2006)

Figure 4.38 shows the expansion behavior of prisms made with NM aggregate exposed to 6.4 molar KAc solution and 6.4 molar KAc-LiAc blended deicer with Li/K ratio of 0.2 (6.4-0.2) using high-alkali cement. Figure 4.39 shows the results for concrete prisms prepared with same aggregate and exposed to same deicer combinations as in Figure 4.38 using low-alkali cement.

From these figures, it can be seen that NM aggregate is highly reactive when exposed to these deicers. Concrete prisms exposed to blended deicer of 6.4 molar KAc with Li/K ratio of 0.2 expanded to 0.8% at 1 year with low-alkali cement and 2.5% at 270 days with high-alkali cement. Statistically, prisms made with high-alkali cement showed more expansion compared to prisms made with low-alkali cement.

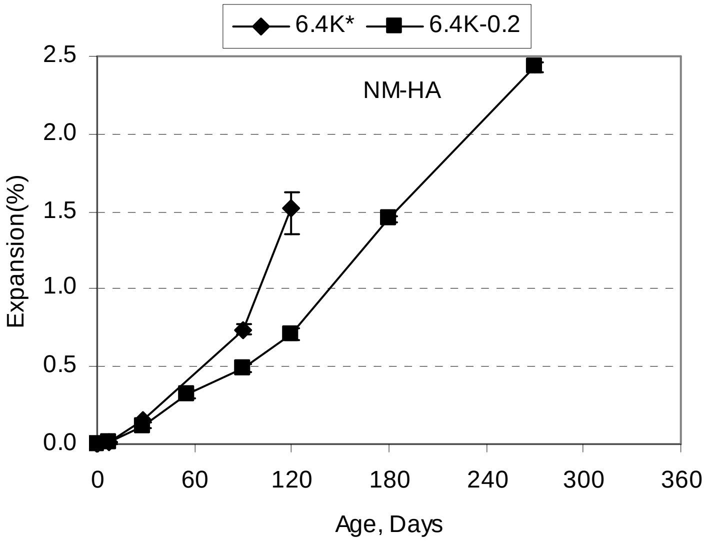


Figure 4.38 Expansion of Concrete Prisms in Modified ASTM C 1293 Test with 6.4 Molar KAc Solution and Blended Deicers with NM Aggregate and High-Alkali Cement (See Chapter 3.2 for Notation, * Sompura, 2006)

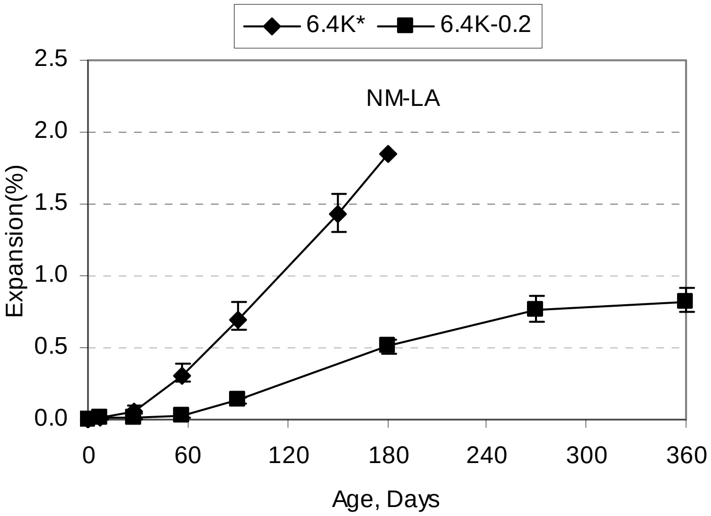


Figure 4.39 Expansion of Concrete Prisms in Modified ASTM C 1293 Test with 6.4 Molar KAc Solution and Blended Deicers with NM Aggregate and Low-Alkali Cement (See Chapter 3.2 for Notation, * Sompura, 2006)

Figures 4.40 and 4.41 show the expansion results of the modified ASTM C 1293 tests. Figure 4.40 shows the expansions of high-alkali prisms made with NM aggregate and exposed to 3 molar KAc solution and 3 molar KAc-LiAc blended deicer with Li/K ratio of 0.2 and 0.8 using high-alkali cement. Figure 4.41 shows the results of mortar bars prepared with the same aggregate exposed to the same deicer solution using low-alkali cement.

From these results, it is evident that the NM aggregate is highly reactive when exposed to 3 molar KAc solution. When the prisms were soaked in blended deicer of 3 molar KAc solution with Li/K of 0.8, there was a significant reduction in expansion with both high-alkali and low-alkali cements. Statistically, prisms made with low-alkali cement, showed no significant difference when soaked in blended deicer of 3 molar KAc solution with Li/K of 0.2 compared to 3 molar KAc solution. However, prisms made with high-alkali cement showed a significant expansion when soaked in blended deicer of 3 molar KAc solution with Li/K of 0.2 when compared with 3 molar KAc solution.

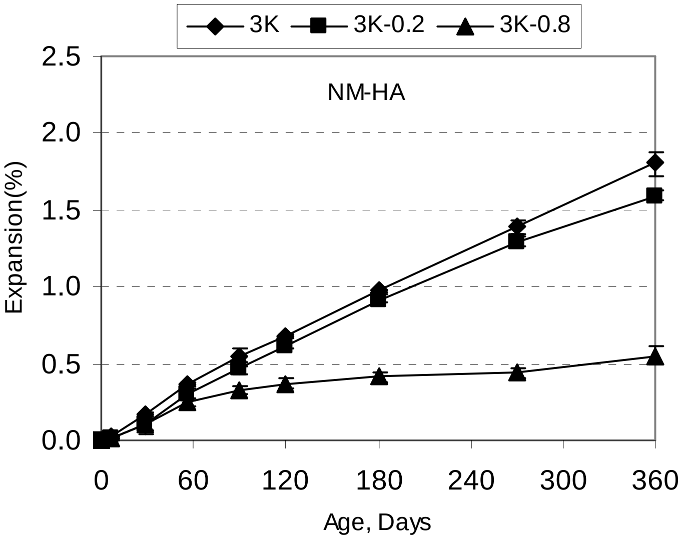


Figure 4.40 Expansion of Concrete Prisms in Modified ASTM C 1293 Test with 3 Molar KAc Solution and Blended Deicers with NM Aggregate and High-Alkali Cement (See Chapter 3.2 for Notation)

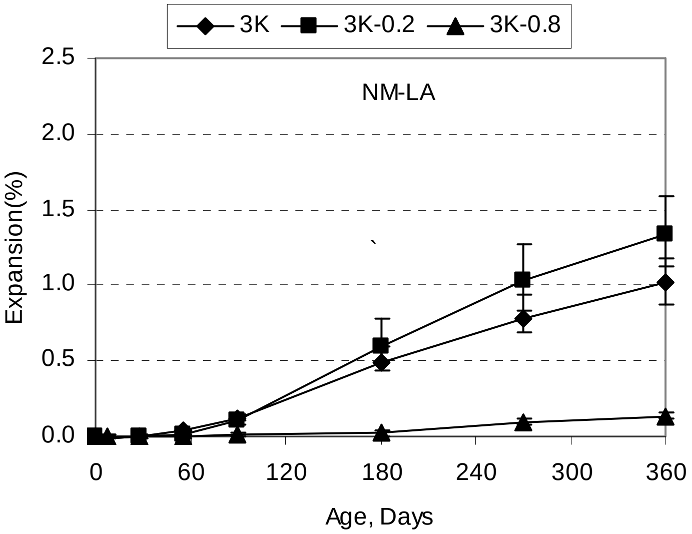


Figure 4.41 Expansion of Concrete Prisms in Modified ASTM C 1260 Test with 3 Molar KAc Solution and Blended Deicers with NM Aggregate and Low-Alkali Cement (See Chapter 3.2 for Notation)

4.10.2 Dynamic Modulus of Elasticity

Figure 4.42 shows changes in dynamic modulus of elasticity of NM aggregate concrete prisms specimens and exposed to 1N NaOH, 3 molar and 6.4 molar KAc solution, and KAc-LiAc blended deicer solutions. From the results, it can be seen that whenever there was drop in DME, a corresponding increase in the linear expansion of the concrete prisms was observed in the ASTM C 1293 test. It is also evident that the loss in DME was dependent on the concentration of KAc. Also, the addition of LiAc to the KAc helped in mitigating loss in DME as observed in the ASTM C 1293 tests. In these test results, concrete prisms showed an increase in DME for the first two months after which there was a drop. This initial increase in the DME is due to the increase in the strength of the concrete prisms due to continued hydration. Thereafter, the deterioration weakens the matrix and the DME decreases. At the conclusion of the test at one year, there does not appear to be a noticeable effect of alkali content of cement on decrease in DME. Prisms made with high-alkali cement showed more rapid deterioration than those made with low-alkali cement.

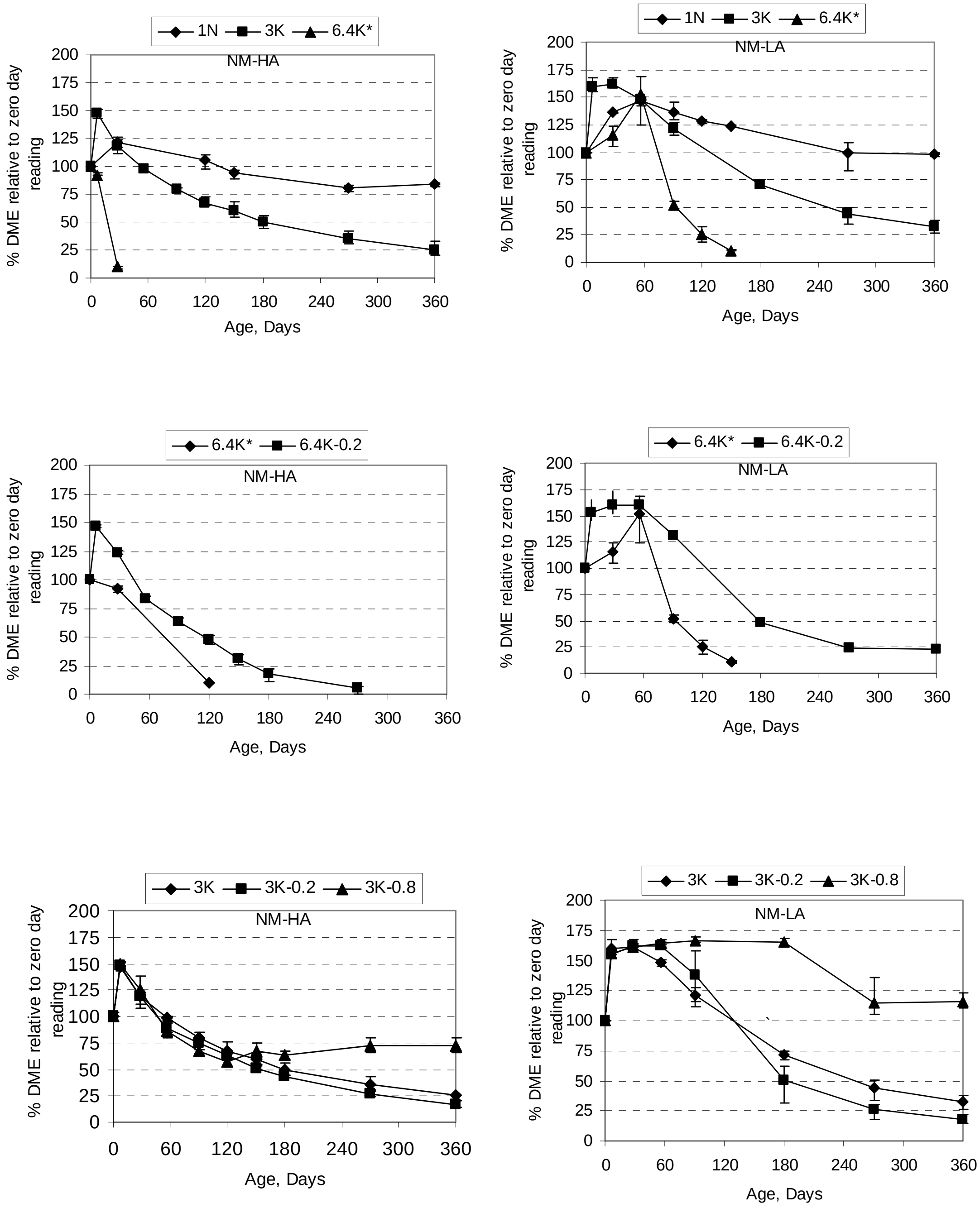


Figure 4.42 Change in Dynamic Modulus of Concrete Prism made with NM Aggregate in the Modified ASTM C 1293 Test (See Chapter 3.2 for Notation, * Sompura, 2006)

4.11 Results from Modified ASTM C 1293 Tests for Spratt Aggregate

Expansion behavior of concrete prisms prepared with SP aggregate in the modified ASTM C 1293 tests are presented in this section. In addition, changes in the DME of concrete prisms subjected to modified ASTM C 1293 tests are presented.

4.11.1 Length-Change Behavior

Figure 4.43 shows the expansion behavior of mortar bars made with SP aggregate and high-alkali cement, exposed to 1N NaOH solution, 6.4 molar and 3 molar KAc solution. Figure 4.44 shows the results of concrete prisms prepared with low-alkali cement, containing the same aggregate and containing same deicers as in Figure 4.43.

From the figures, it can be seen that SP aggregate was reactive when exposed to these deicers. There is a significant effect of alkali content of the cement and on the level of concentration of soak solution, as prisms exposed to 6.4 molar KAc solution expanded more compared to prisms exposed to 3 molar KAc solution. Prisms made with low-alkali cement expanded more than 0.04% after 90 days with all soak solution. Whereas, prisms made with high-alkali cement expanded after 30 days. Statistically, prisms made with high-alkali cement showed more expansion compared to bars made with low-alkali cement when they were exposed to KAc solution.

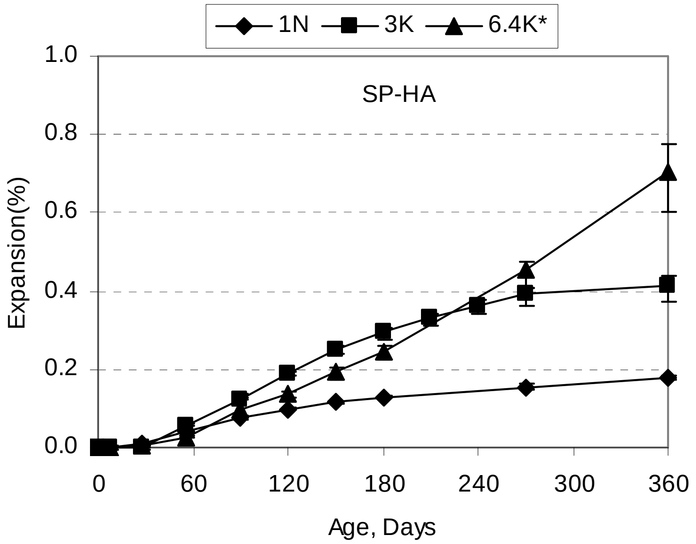


Figure 4.43 Expansion of Concrete Prisms in Modified ASTM C 1293 Test with SP Aggregate and High-Alkali Cement (See Chapter 3.2 for Notation, * Sompura, 2006)

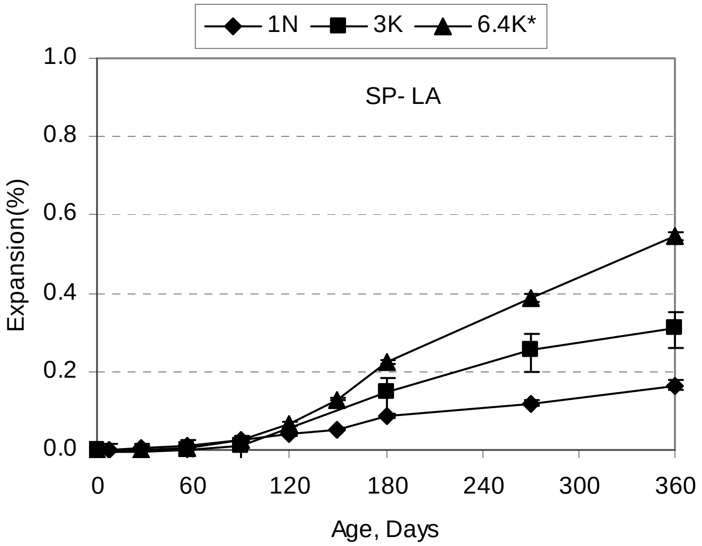


Figure 4.44 Expansion of Concrete Prisms in Modified ASTM C 1293 Test with SP Aggregate and Low-Alkali Cement (See Chapter 3.2 for Notation, * Sompura, 2006)

Figures 4.45 and 4.46 show the expansion results of modified ASTM C 1293 tests. Figure 4.45 shows the expansions of prisms made with SP aggregate exposed to 6.4 molar KAc solution and 6.4 molar KAc-LiAc blended deicer with Li/K ratio of 0.2 (6.4-0.2) using high-alkali cement. Figure 4.46 shows the results of mortar bars prepared with the same aggregate exposed to same deicer combinations using low-alkali cement. From these figures, it can be seen that SP aggregate is reactive when exposed to 6.4 molar KAc solution with an expansion of more than 0.7% for high-alkali cement and 0.5% for low-alkali prisms at 360 days. Statistically, prisms made with high-alkali cement showed more expansion compared to bars made with low-alkali cement. Concrete prisms with SP aggregate, showed significant reduction in expansion when exposed to blended deicer of 6.4 molar KAc with Li/K of 0.2 compared to 6.4 molar KAc solution. However, the level of mitigation was not adequate for this blended deicer to be effective (i.e., < 0.04% expansion at one year).

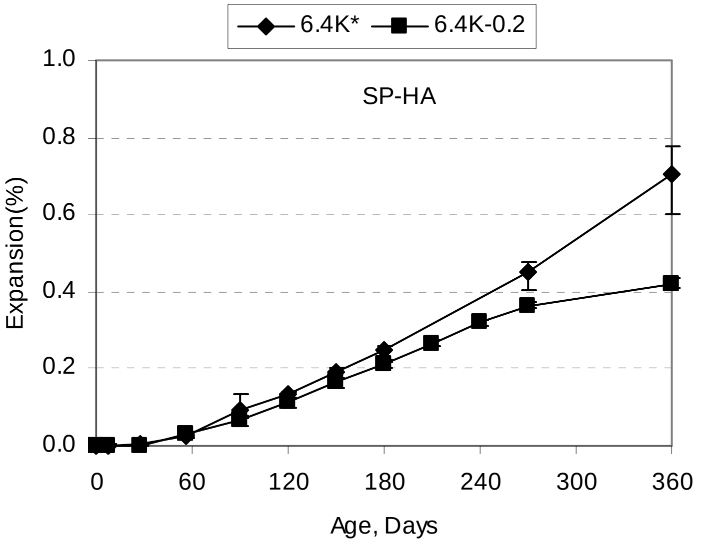


Figure 4.45 Expansion of Concrete Prisms in Modified ASTM C 1293 Test with 6.4 Molar KAc Solution and Blended Deicers with SP Aggregate and High-Alkali Cement (See Chapter 3.2 for Notation, * Sompura, 2006)

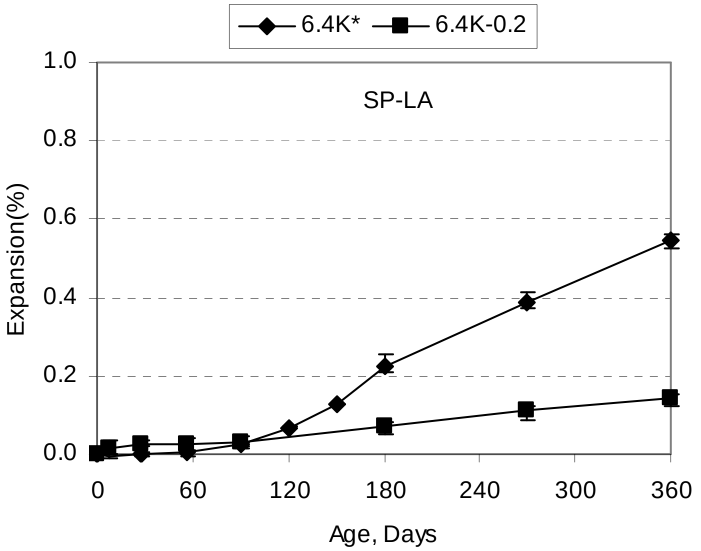


Figure 4.46 Expansion of Concrete Prisms in Modified ASTM C 1293 Test with 6.4 Molar KAc Solution and Blended Deicers with SP Aggregate and Low-Alkali Cement (See Chapter 3.2 for Notation, * Sompura, 2006)

Figures 4.47 and 4.48 show the expansion results of the modified ASTM C 1293 tests. Figure 4.47 shows the expansions of prisms made with SP aggregate exposed to 3 molar KAc solution and 3 molar KAc-LiAc blended deicer with Li/K ratio of 0.2 using high-alkali cement. Figure 4.48 shows the results of mortar bars prepared with the same aggregate exposed to the same deicer using low-alkali cement. Statistically, prisms made with high-alkali cement, soaked in blended deicer blended deicer of 3 molar KAc with Li/K of 0.2 showed no significant difference in its effect in mitigating the expansion, when compared to 3 molar KAc solution. However, prisms made with low-alkali cement showed a significant reduction in expansion when exposed to blended deicer of 3 molar KAc with Li/K of 0.2, when compared to 3 molar KAc solution. Prisms made with low-alkali cement were within the expansion limit of 0.04% until 90 days when exposed to both solutions. After which, there was an gradual increase in expansion. SP aggregate, when made with high-alkali cement, was within the expansion limit until 30 days after which there was sudden increase in expansion with both solutions.

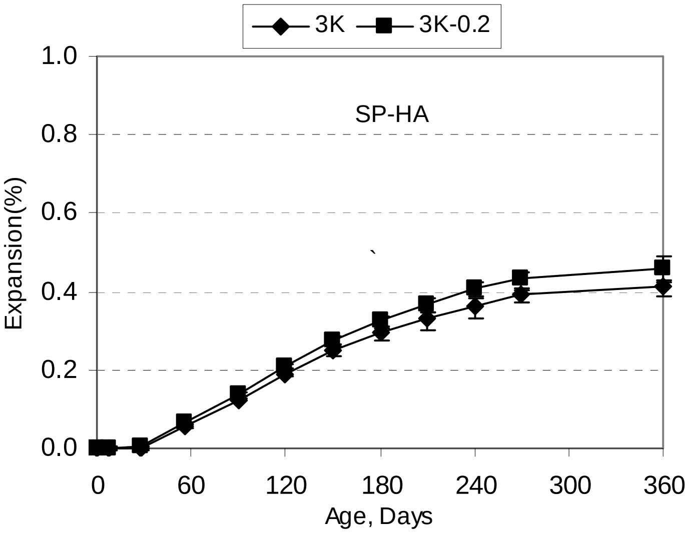


Figure 4.47 Expansion of Concrete Prisms in Modified ASTM C 1293 Test with 3 Molar KAc Solution and Blended Deicers with SP Aggregate and High-Alkali Cement (See Chapter 3.2 for Notation)

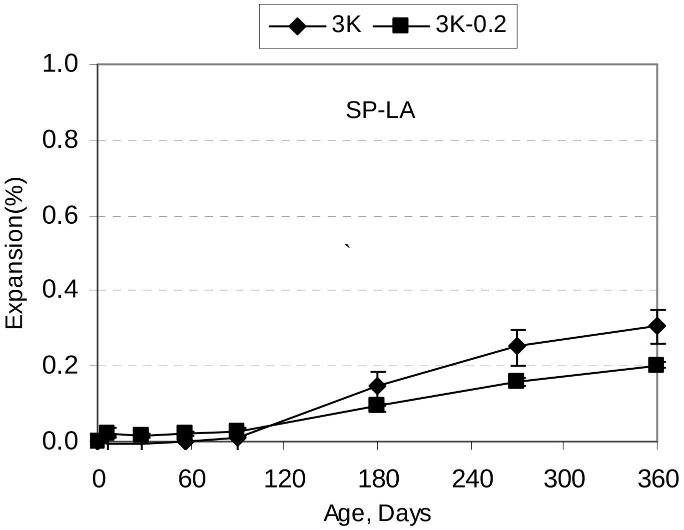


Figure 4.48 Expansion of Concrete Prisms in Modified ASTM C 1293 Test with 3 Molar KAc Solution and Blended Deicers with SP Aggregate and Low-Alkali Cement (See Chapter 3.2 for Notation)

4.11.2 Dynamic Modulus of Elasticity

Figure 4.49 shows the changes in dynamic modulus of elasticity of SP aggregate concrete prisms specimens exposed to 1N NaOH, 3 molar and 6.4 molar KAc solution, and blended deicer solutions. From the results, it is evident that whenever there was drop in DME, a corresponding increase in the linear expansion of the concrete prisms was observed in the ASTM C 1293 test. During the first 60 days concrete prisms made with low-alkali cement showed a much higher increase in DME when compared to prisms made with high-alkali cement. However, the drop in DME was similar after 1 year for concrete prisms exposed to 6.4 molar KAc solution which indicates that the concentration of soak solution influences the changes in DME as it influences the expansion.

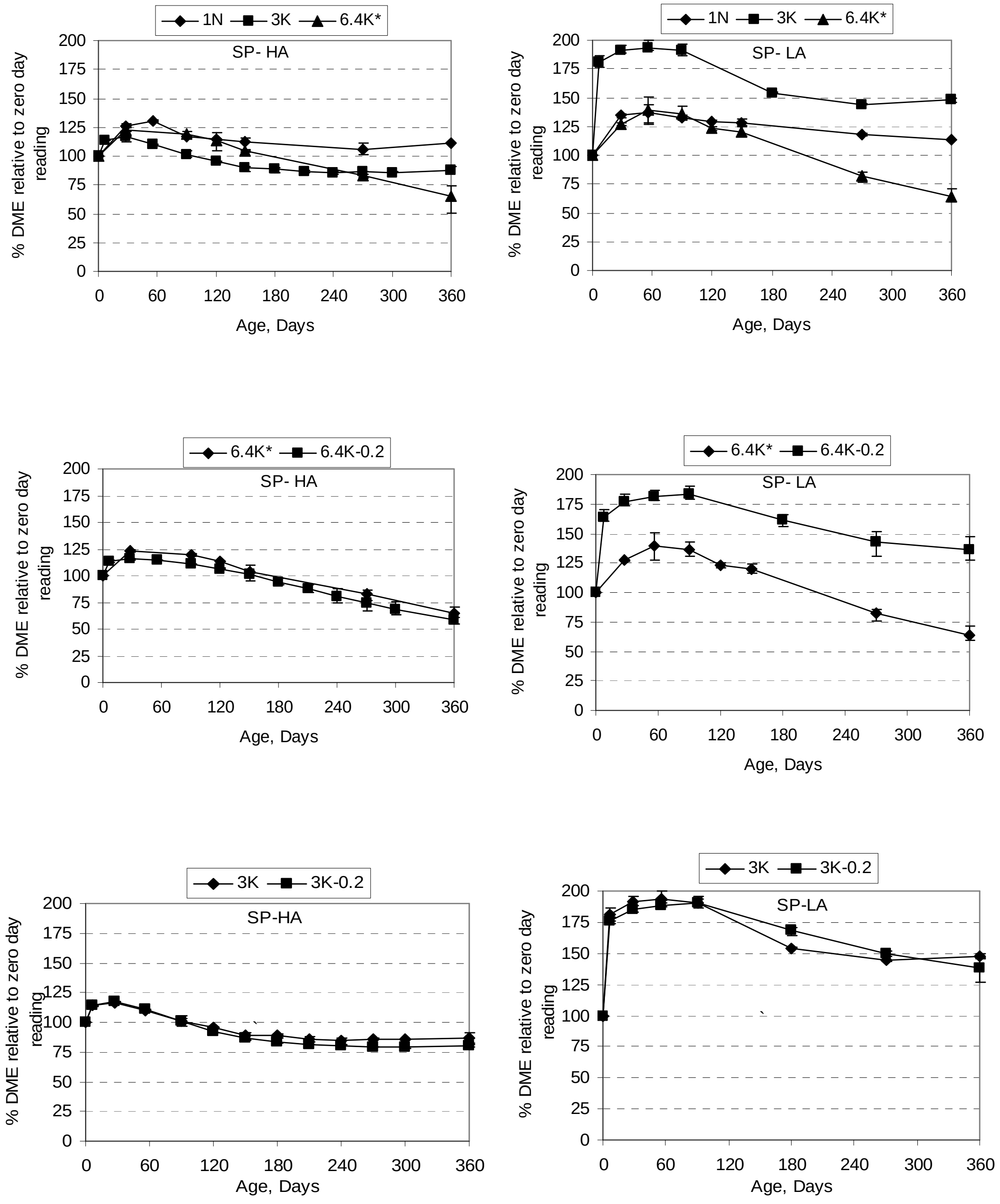


Figure 4.49 Change in Dynamic Modulus of Concrete Prism made with SP Aggregate in Modified ASTM C 1293 Test (See Chapter 3.2 for Notation, * Sompura, 2006)

4.12 Results from Modified ASTM C 1293 Tests for North Carolina Aggregate

Expansion behavior of concrete prisms prepared with NC aggregate in the modified ASTM C 1293 tests are presented in this section. Also, changes in the DME of concrete prisms subjected to modified ASTM C 1293 tests are presented.

4.12.1 Length-Change Behavior

Figure 4.50 shows the expansion behavior of concrete prisms made with NC aggregate and high-alkali cement, exposed to 1N NaOH solution, 6.4 molar and 3 molar KAc solution. From this figure, it can be seen that NC aggregate is highly reactive when it is exposed to the soak solutions, KAc deicer. Prisms started expanding after 60 days when exposed to all soak solutions. At 360 days, concrete prisms exposed to 6.4 molar KAc solution showed an expansion above 1% and those exposed to 3 molar KAc solution, showed an expansion of 0.65%.

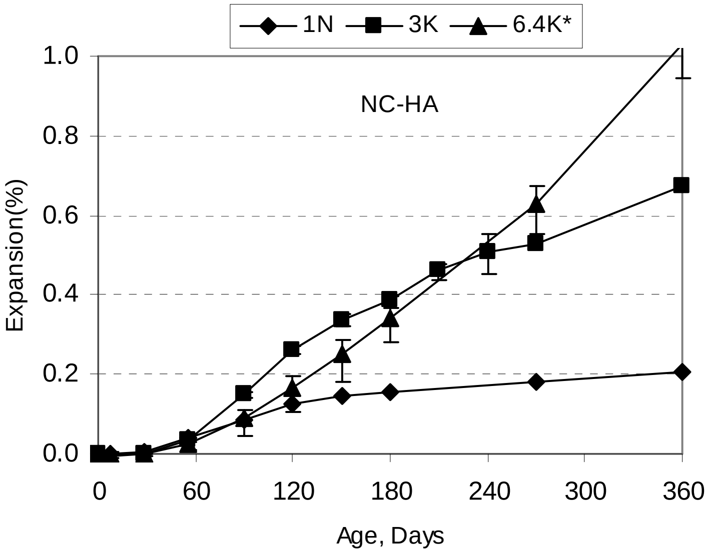


Figure 4.50 Expansion of Concrete Prisms in Standard and Modified ASTM C 1260 Test with NC Aggregate and High-Alkali Cement

(See Chapter 3.2 for Notation, * Sompura, 2006)

Figure 4.51 shows the expansion behavior of prisms made with NC aggregate exposed to 6.4 molar KAc solution and 6.4 molar KAc-LiAc blended deicer with Li/K ratio of 0.2 (6.4-0.2) using high-alkali cement. NC aggregate is highly reactive when exposed to these deicers, since the expansion exceeded 0.04% after 60 days. From this figure, it can be seen that there was a sudden increase in expansion of prisms exposed to 6.4 molar KAc solution after 270 days. Statistically, prisms soaked in blended deicer with Li/K ratio of 0.2 with 6.4 molar KAc-LiAc showed significant difference in its effect in mitigating the expansion compared to prisms soaked in 6.4 molar KAc.

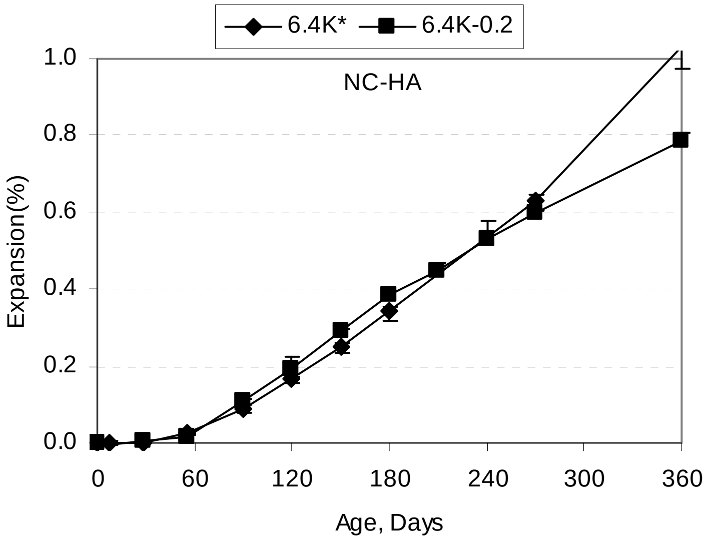


Figure 4.51 Expansion of Concrete Prisms in Modified ASTM C 1293 Test with 6.4 Molar KAc Solution and Blended Deicers with NC Aggregate and High-Alkali Cement (See Chapter 3.2 for Notation, * Sompura, 2006)

Figure 4.52 shows the expansion behavior of prisms made with NC aggregate exposed to 3 molar KAc solution and 3 molar KAc-LiAc blended deicer with Li/K ratio of 0.2 (3-0.2) using high-alkali cement. NC aggregate is highly reactive when exposed to these deicers as the expansion of concrete prisms exceeds the expansion limit of 0.04% after 60 days. After which, there was a sudden increase in the level of expansion till the end of the test period. Prisms exposed to both deicers showed same level of expansion. Statistically, prisms soaked in blended deicer with Li/K ratio of 0.2 with 3 molar KAc-LiAc showed no significant difference in its effect in mitigating the expansion compared to prisms soaked in 3 molar KAc.

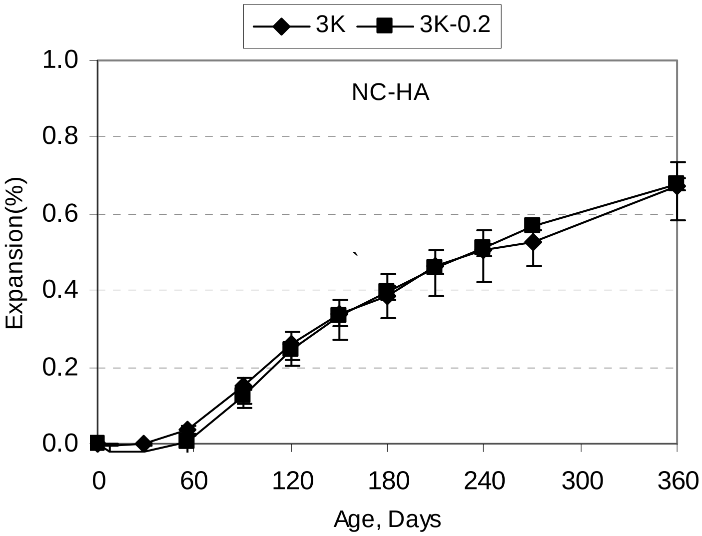


Figure 4.52 Expansion of Concrete Prisms in Modified ASTM C 1260 Test with 3 Molar KAc Solution and Blended Deicers with NC Aggregate and High-Alkali Cement (See Chapter 3.2 for Notation)

4.12.2 Dynamic Modulus of Elasticity

Figure 4.53 shows changes in dynamic modulus of elasticity of NC aggregate concrete prisms specimens exposed to 1N NaOH, 3 molar and 6.4 molar KAc solution, and blended soak solution. From the results, it can be seen that whenever there was drop in DME, a corresponding increase in the linear expansion of the concrete prisms was observed in the ASTM C 1293 test. It is also evident that the loss in DME was dependent on the concentration of KAc. Prisms exposed to 6.4 molar KAc solution showed greater loss when compared to prisms exposed to 3 molar KAc solution. Also, the addition of LiAc to the KAc did not help in mitigating loss in DME as observed in the ASTM C 1293 tests, with high-alkali cement.

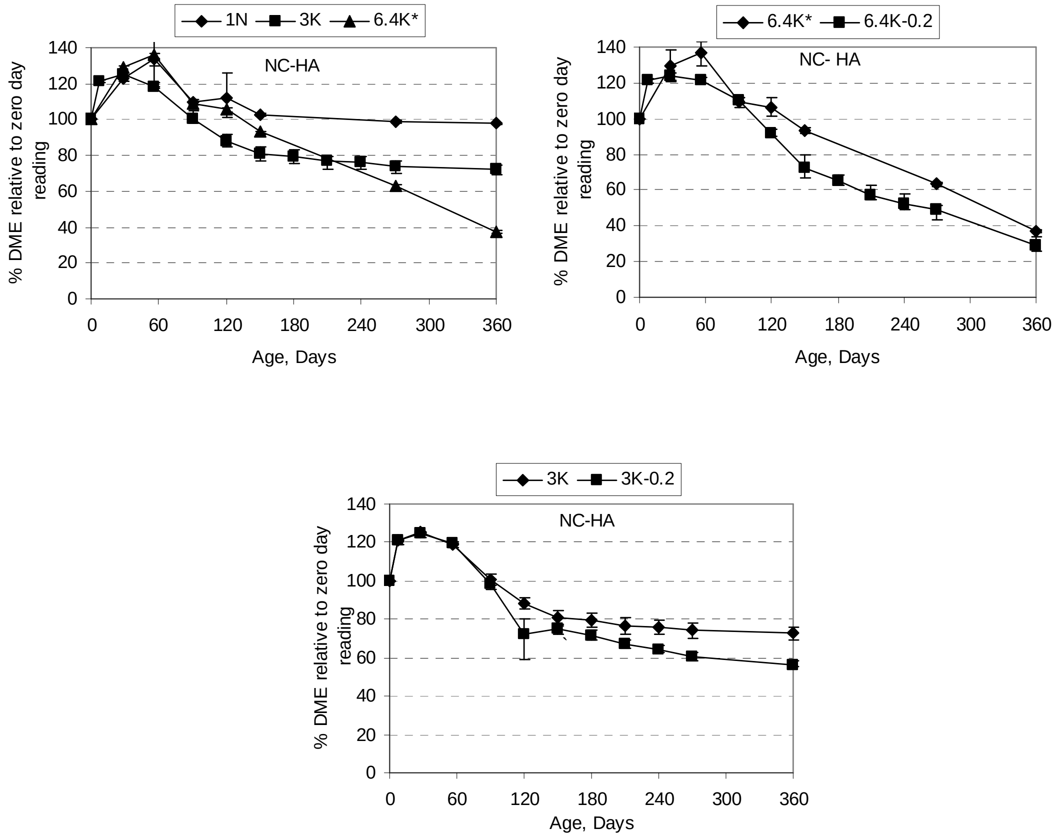


Figure 4.53 Change in Dynamic Modulus of Concrete Prism made with NC Aggregate in Modified ASTM C 1293 Test (See Chapter 3.2 for Notation, * Sompura, 2006)

4.13 Results from Modified ASTM C 1293 Tests for South Dakota Aggregate

Expansion behavior of concrete prisms prepared with SD aggregate in the modified ASTM C 1293 tests are presented in this section. In addition, changes in the DME of concrete prisms subjected to modified ASTM C 1293 tests are presented.

4.13.1 Length-Change Behavior

Figure 4.54 shows the expansion behavior of concrete prisms made with SD aggregate and high-alkali cement, exposed to 1N NaOH solution, 6.4 molar and 3 molar

KAc solution. From this figure, it can be seen that SD aggregate is reactive when exposed to all soak solutions. Prisms were within the expansion limit of 0.04 till 120 days, after which, there was a gradual increase in expansion. However, compared to other aggregate evaluated in this study, SD aggregate was less reactive. At 360 days, the expansion of concrete prisms exposed to these deicers expanded less than 0.17%. The concentration of KAc solution does not have much effect and the prisms expanded to the same level as prisms exposed to 1N NaOH.

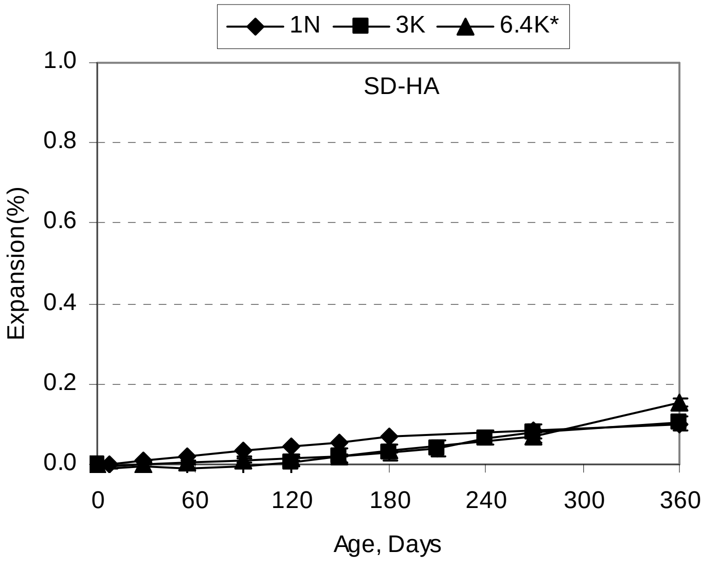


Figure 4.54 Expansion of Concrete Prisms in Modified ASTM C 1293 Test with SD Aggregate and High-Alkali Cement (See Chapter 3.2 for Notation, * Sompura, 2006)

Figure 4.55 shows the expansion behavior of prisms made with SD aggregate exposed to 6.4 molar KAc solution and 6.4 molar KAc-LiAc blended deicer with Li/K ratio of 0.2 (6.4-0.2) using high-alkali cement. From this figure, it can be seen that SD aggregate is reactive when exposed to these deicers. Prisms were within the expansion limit of 0.04% till 180 days, after which, there was a gradual increase in expansion. However, compared to other aggregate evaluated in this study, SD aggregate was less reactive. Statistically, prisms soaked in blended deicer with Li/K ratio of 0.2 with 6.4 molar KAc-LiAc showed no significant difference in its effect in mitigating the expansion compared to prisms soaked in 6.4 molar KAc.

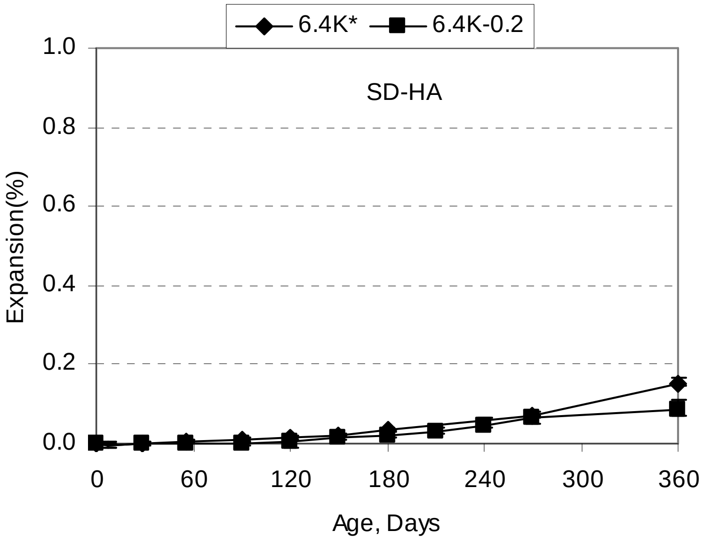


Figure 4.55 Expansion of Concrete Prisms in Modified ASTM C 1293 Test with 6.4 Molar KAc Solution and Blended Deicers with SD Aggregate and High-Alkali Cement (See Chapter 3.2 for Notation, * Sompura, 2006)

Figure 4.56 shows the expansion behavior of prisms made with SD aggregate exposed to 3 molar KAc solution and 3 molar KAc-LiAc blended deicer with Li/K ratio of 0.2 using high-alkali cement. At 120 days, prisms exposed to these soak solution expanded within the expansion limit of 0.04%, after which, there was a gradual increase in expansion. Statistically, prisms soaked in blended deicer with Li/K ratio of 0.2 with 3 molar KAc-LiAc showed no significant difference in its effect in mitigating the expansion compared to prisms soaked in 3 molar KAc.

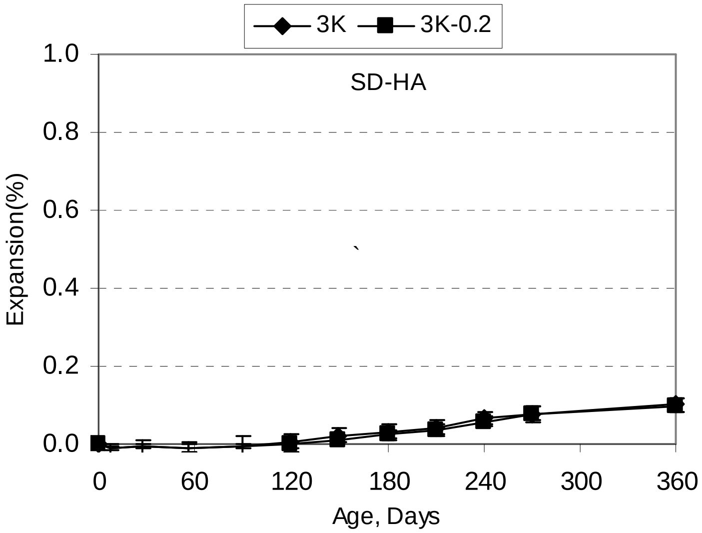


Figure 4.56 Expansion of Concrete Prisms in Modified ASTM C 1293 Test with 3 Molar KAc Solution and Blended Deicers with SD Aggregate and High-Alkali Cement (See Chapter 3.2 for Notation)

4.13.2 Dynamic Modulus of Elasticity

Figure 4.57 shows changes in dynamic modulus of elasticity of SD aggregate concrete prisms specimens exposed to 1N NaOH, 3 molar and 6.4 molar KAc solution, and blended deicer solutions. From the results, it can be seen that whenever there was drop in DME, a corresponding increase in the linear expansion of the concrete prisms was observed in the ASTM C 1293 test. While expansions of prisms exposed 3 molar KAc solution showed slightly higher loss in DME, compared to 6.4 molar KAc solution.

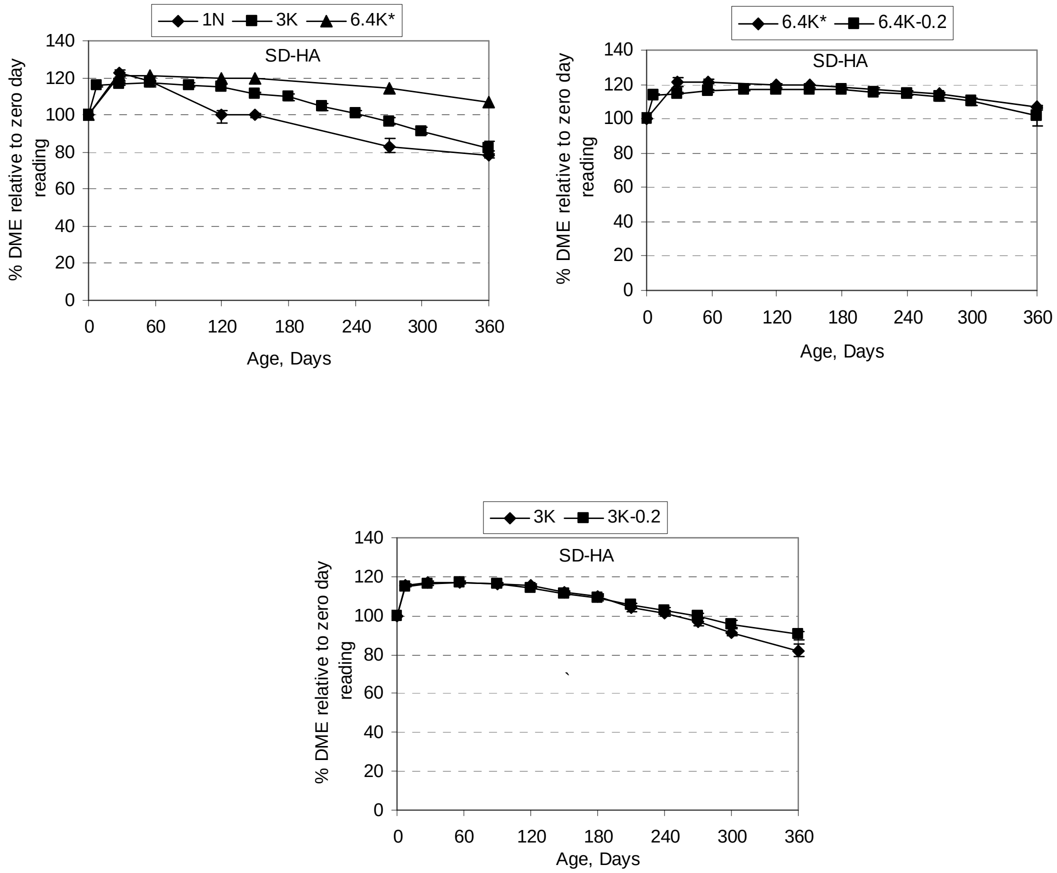


Figure 4.57 Change in Dynamic Modulus of Concrete Prism made with SD Aggregate in Modified ASTM C 1293 Test (See Chapter 3.2 for Notation, * Sompura, 2006)

4.14 Discussion and Results from ASTM C 1293 and DME Tests

From the expansion and DME test results from the ASTM C 1293 tests on concrete prisms made with different aggregate, it was found that the level of distress observed in any prisms was dependent on the aggregate reactivity and deicer used. Prisms made with NM, SP and NC aggregate expanded more when exposed to 6.4 molar KAc solution compared to bars exposed to 3 molar KAc solution. Whereas, concrete prisms made with SD aggregate showed no significant difference in expansion when exposed to

6.4 molar KAc solution and 3 molar KAc solution. Concrete prisms made with NM, SP, NC and SD aggregate expanded more when exposed to 3 molar and 6.4 molar KAc solution, compared to prisms exposed to 1N NaOH solution.

Concrete prisms made with NM, SP, NC and SD aggregate when exposed to blended deicer of 3 molar KAc with different Li/K ratios of 0.2, 0.4, 0.6, and 0.8 were not effective in mitigating the expansion due to ASR. This may be due to specimen size as the penetration of LiAc solution is less in concrete prisms when compared to penetration of LiAc in mortar bars. This aspect will be further discussed in ICP test. Also, prisms made with NM, SP, NC and SD aggregate when exposed to blended deicer with Li/K ratio of 0.2 with 6.4 molar KAc solution, were not effective in mitigating the expansion due to ASR. However, prisms made with SD aggregate expanded less compared to other aggregate type. For both cement types, prisms made with NM aggregate showed the highest expansions compared to other aggregate types. This finding indicate that perhaps higher Li/K molar ratios should be considered for further investigation.

From the DME test results, it can be seen that whenever there was drop in DME, a corresponding increase in the linear expansion of the concrete prisms was observed in ASTM C 1293 tests. In general, the alkali content of the cement did have a significant influence on expansions and loss in DME of concrete prisms, as prisms made with high-alkali cement showed more loss in DME compared to samples made with low-alkali cement. Upon exposure to any given deicer, prisms made with NM aggregate showed more loss in DME compared to prisms made with SP, NC and SD aggregate.

Figure 4.58 shows graphs of % DME relative to zero day reading compared to the expansion in ASTM C1293 tests at similar ages of mortar bars made with different aggregates and high-alkali cement when exposed to 3 molar KAc solution and different blended deicer of 3.0 molar KAc with Li/K ratios. It can be observed that whenever there was change in DME, a corresponding change in the linear expansion of the mortar bars was observed in ASTM C 1293 tests.

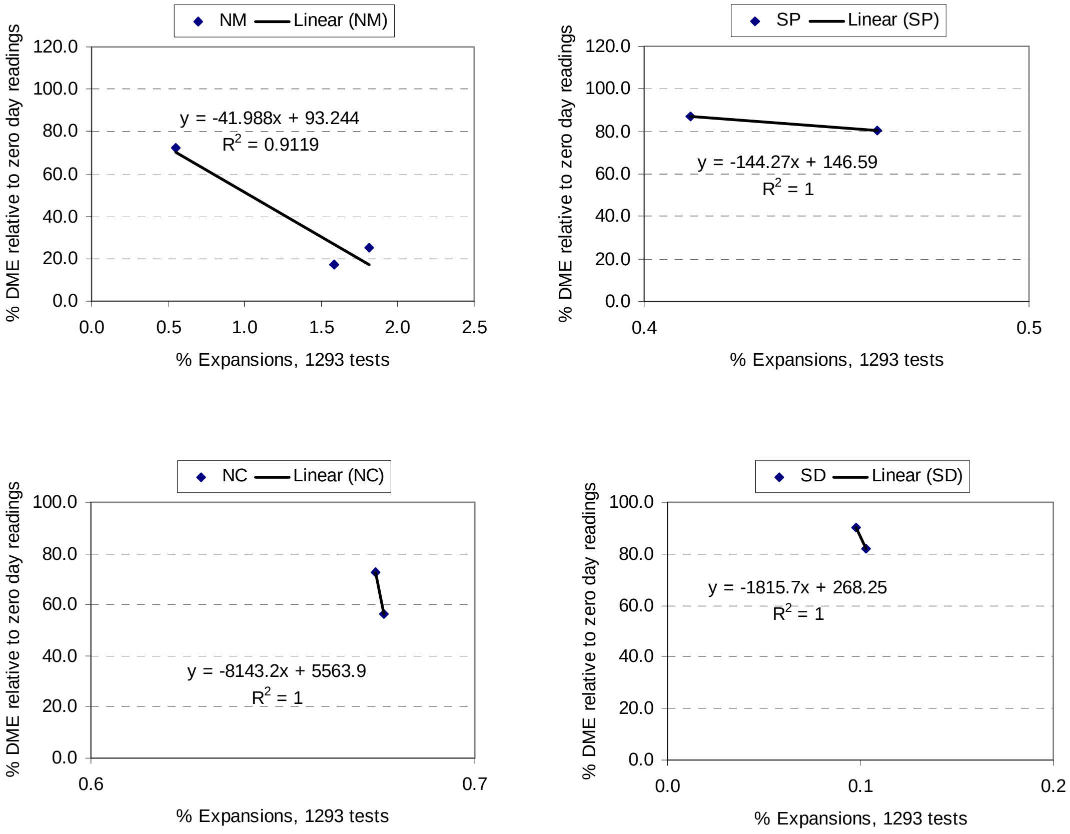


Figure 4.58 Percentage DME Relative to Zero Day Reading and Expansions in ASTM C 1293 Tests

4.15 Results and Discussion from pH measurement on Soak Solution in the Modified ASTM C 1293 Test

Figure 4.59 shows the pH of soak solutions exposed to concrete prisms at 38 ºC after 12 months in the modified ASTM C 1293 tests for NM, SP, NC and SD aggregates made with high-alkali and low-alkali cement. The pH was measured at the end of 12 months of the test program and compared with the pH of the soak solution before contact with prisms at 0 day. From these figures it can be observed that all the soak solutions evaluated, showed a significant increase in their pH upon exposure to concrete prisms. Further, it can also be observed that with an increase in the lithium acetate dosage in the soak solution, the pH slightly decreased at both 0 day and 360 days. Although an increase in pH of soak solution was observed even in presence of LiAc, significant reduction in concrete prism expansions were observed as ASR gel found in presence of LiAc was not expansive. It is likely that the ASR gel product formed in the presence of lithium bearing soak solution is not as expansive as that formed in KAc soak solution. The trends in the pH changes of soak solutions in ASTM C 1293 tests were very similar to those observed in the ASTM C 1260 tests.

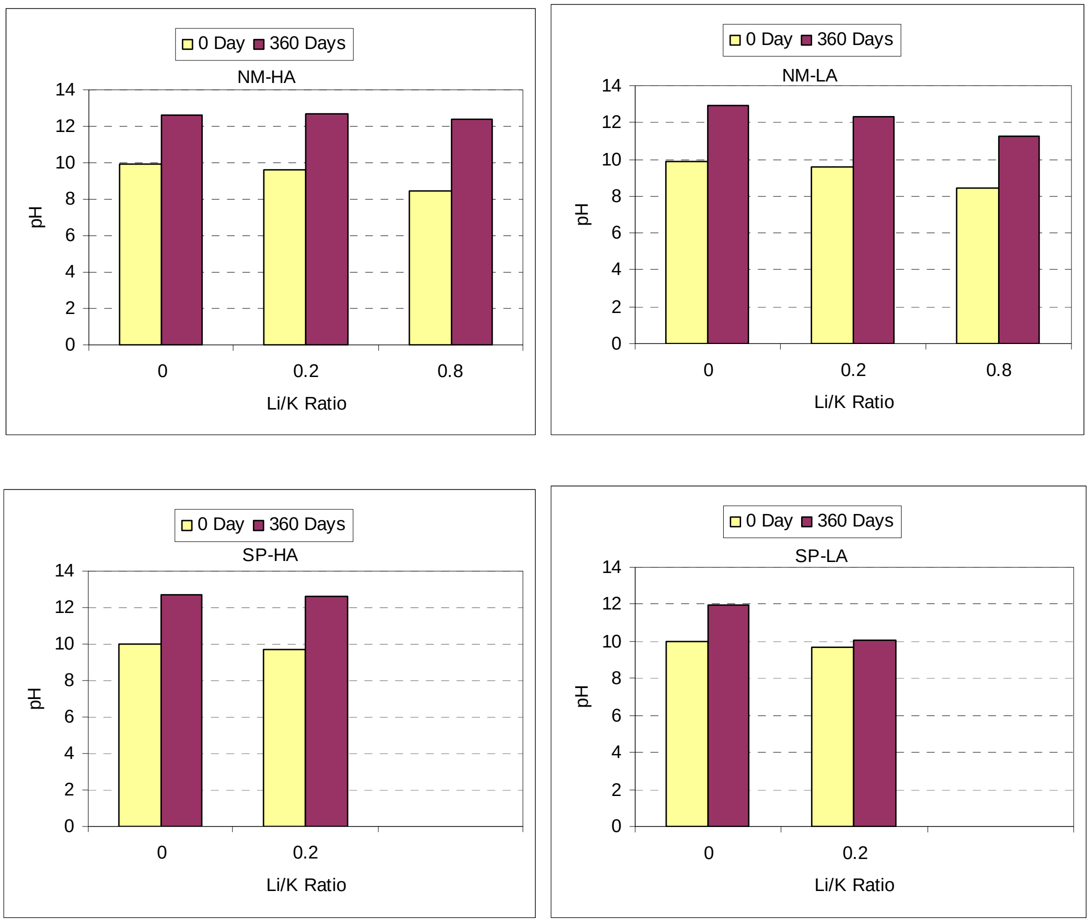
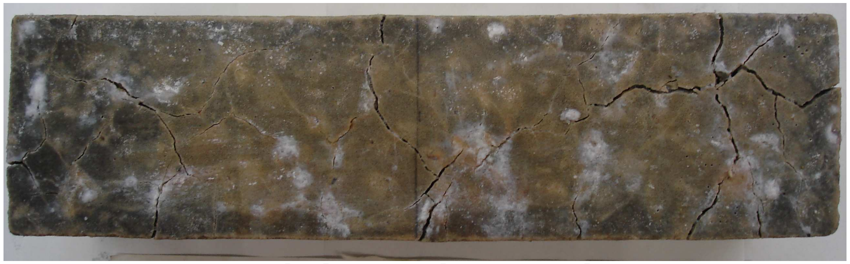


Figure 4.59 pH Values of Soak Solution from Modified ASTM C 1293 Tests for all Aggregates made with high-alkali and low-alkali cement.

4.16 Visual and SEM-EDX Analysis on Concrete Prisms

Visual and SEM-EDX analyses were conducted on concrete prisms exposed to deicer solution to study the reaction products formed due to interactions between the soak solutions and concrete prisms. SEM-EDX analyses were conducted on concrete prisms at the end of 12 months. SEM and EDX analysis of concrete prisms made with NM and SP aggregate are discussed in detail.

Figure 4.60 shows the visual images of NM-HA soaked in KAc with different Li/K ratios. From these visual images, the influence on LiAc in mitigating expansion due to ASR is clearly observed, with an increase in Li/K ratio of soak solution, the intensity of cracking in prisms had reduced for a given base concentration of KAc. However, for a given Li/K ratio, as the base concentration of KAc increased, the intensity of cracking increased. Also, similar effects were observed in prisms made with low-alkali cement. These results suggest that the level of lithium needed in the blended deicer to control the deterioration is dependent on both Li/K molar ratio and the base concentration of KAc.



Soaked in 3 Molar KAc Solution

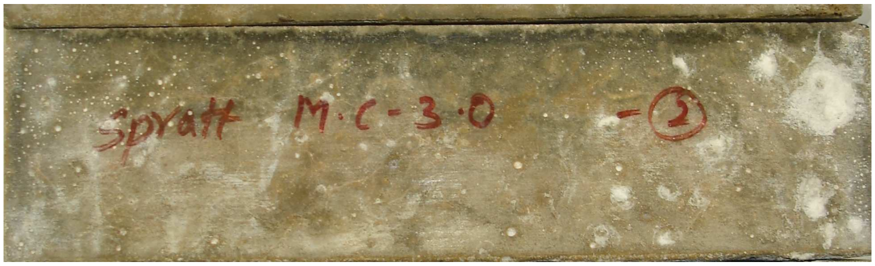
Soaked in 3 Molar KAc Solution and Blended Deicers with Li/K 0.2

Soaked in 3 Molar KAc Solution and Blended Deicers with Li/K 0.8

Soaked in 6.4 Molar KAc Solution and Blended Deicers with Li/K 0.2

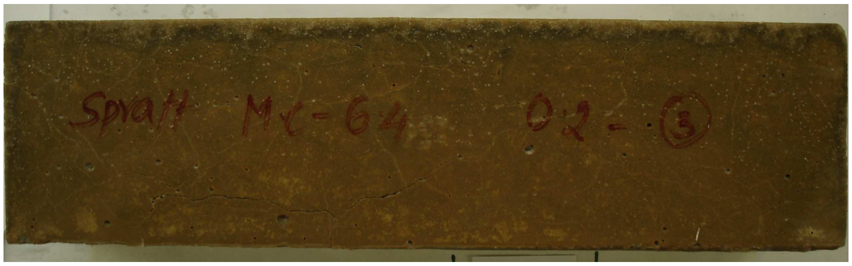
Figure 4.60 Figures shows the visual images of NM-HA exposed to different Li/K ratio in Modified ASTM C 1293 Test.

Figure 4.61 shows the visual images of SP-HA soaked in 3 molar KAc solution, blended deicer of 3.0 molar KAc with Li/K of 0.2 and 6.4 molar KAc with Li/K of 0.2. Even though, visual images of prisms exposed to 3 molar KAc solution show less cracking compared to prisms exposed to 3 molar KAc solution with Li/K ratio of 0.2, it was the prisms exposed to 3 molar KAc solution that expanded more. Similar effects were seen in mortar bars.



Soaked in 3 Molar KAc Solution

Soaked in 3 Molar KAc Solution and Blended Deicers with Li/K 0.2



Soaked in 6.4 Molar KAc Solution and Blended Deicers with Li/K 0.2

Figure 4.61 Figures shows the visual images of SP-HA exposed to different Li/K ratio in Modified ASTM C 1293 Test.

Figure 4.62 shows SEM and EDX images of concrete prisms NM-HA-6.4-0.2. From the figure, it is evident that bars exposed to KAc show the deterioration of cement paste with significant cracking and some cracking through the aggregate. The EDX spectrum of the gel shows the presence of potassium in the gel and the formation of ASR gel.

Figure 4.63 and Figure 4.64 show the SEM-EDX images of NM-LA-3-0.2 and NM-LA-3-0.8, respectively. From the SEM images, it is clear that the deterioration of the bar is influenced by the lithium concentration. Lithium acetate proved to be effective in mitigating the cracking, as the mitigation of cracks is well observed in Figure 4.64. Figure 4.65 shows the SEM-EDX images of NM-LA-6.4-0.2. From the Figure, it can be seen that prisms which were exposed to blended deicer of 6.4 molar KAc with Li/K of 0.2 show the deterioration of cement paste with significant cracking and some cracking through the aggregate also in the presence of LiAc. The EDX spectrum of the gel surrounding the aggregate and through the cement paste shows the presence of potassium in the gel and the formation of ASR gel.

Figure 4.66 and Figure 4.67 show the SEM-EDX images of SP-LA-3 and SP-LA-3-0.2, respectively. From the SEM images, the Li/K ratio of 0.2 is more effective in mitigating the cracking. In both images, the cracks were observed more around the aggregate. Similar results were observed in the expansion and DME results as higher Li/K concentrations yielded higher mitigation.

Figure 4.68 shows the SEM-EDX images of SP-LA-6.4-0.2. From the SEM images it can be seen that there is a gel-like structure present around the aggregate. EDX shows the presence of potassium and calcium around the aggregate.

From these SEM-EDX images, it can be observed that prisms exposed to KAc solution showed more deterioration compared to prisms exposed to blended deicers of 3 molar and 6.4 molar KAc solution with different Li/K ratio. The reaction product around the aggregate formed in the presence of LiAc was comprised of calcium, potassium and silica, similar to the gel product for the prisms exposed to plain KAc solution. It is the gel that is formed in the presence of LiAc which is not expansive in nature which resulted in lesser expansion compared to the prisms exposed to 3 and 6.4 molar KAc solution. The effect of this non-expansive product in the presence of LiAc was well noticed in expansion and DME tests of concrete prisms, as the prisms exposed to blended deicers of KAc-LiAc solution showed less expansion and loss in DME compared to prisms exposed to soak solution without LiAc.

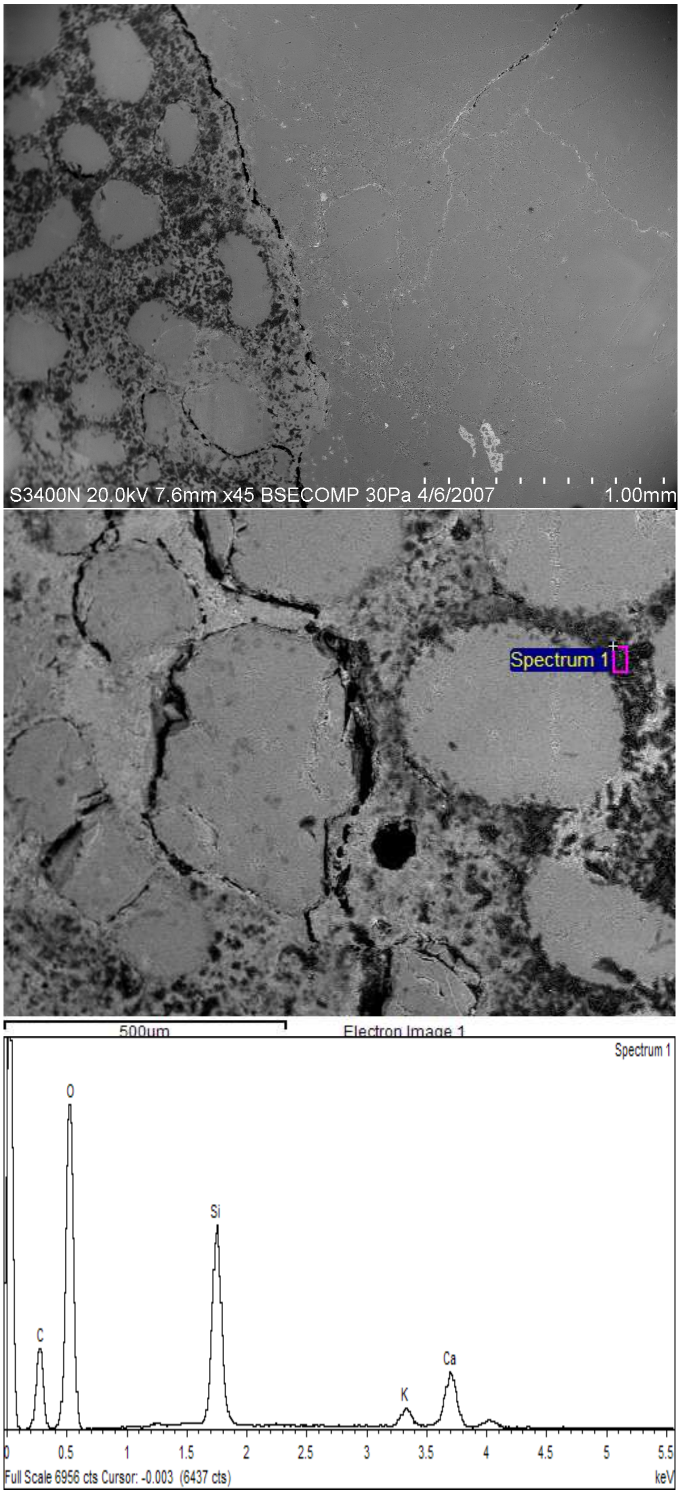


Figure 4.62 Figures show SEM-EDX images of NM-HA-6.4-0.2 prisms

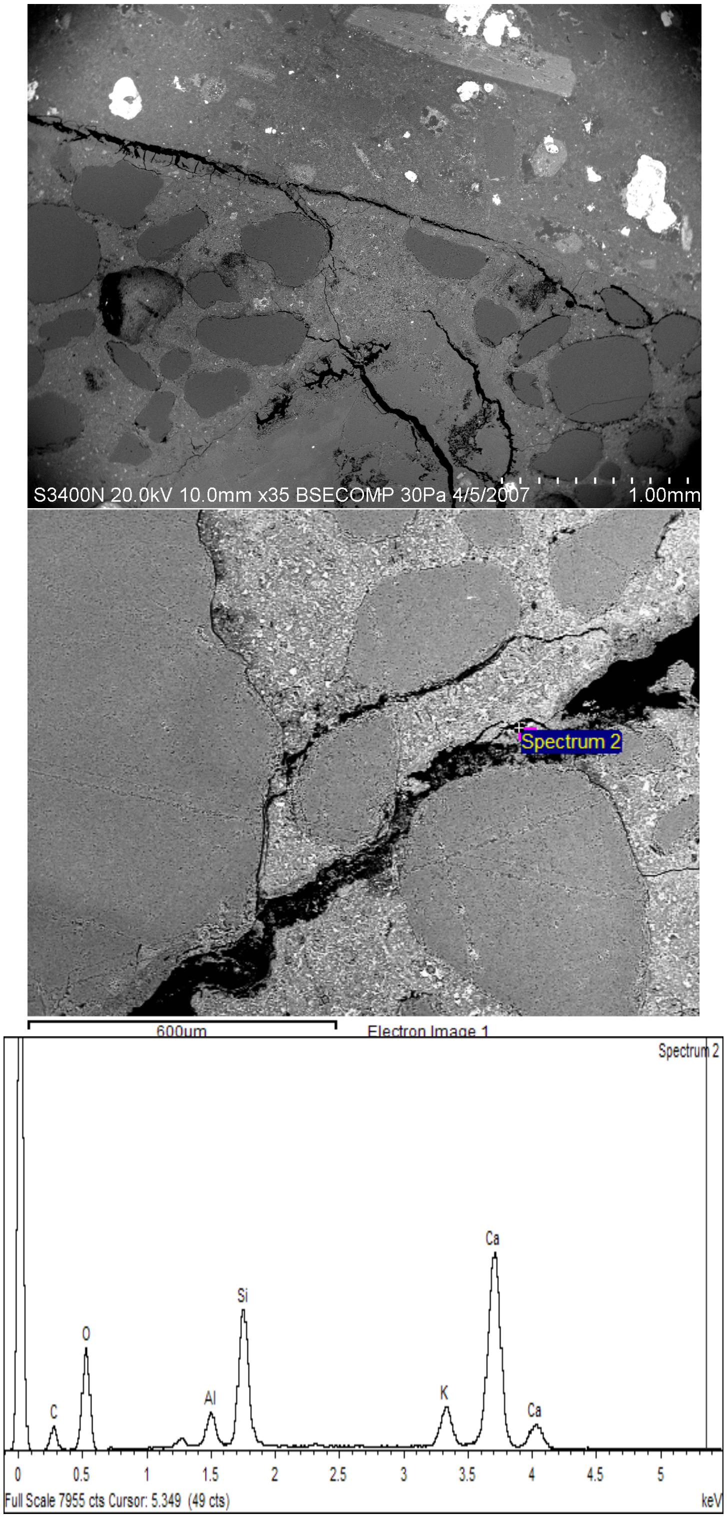


Figure 4.63 Figures show SEM-EDX images of NM-LA-3-0.2 prisms

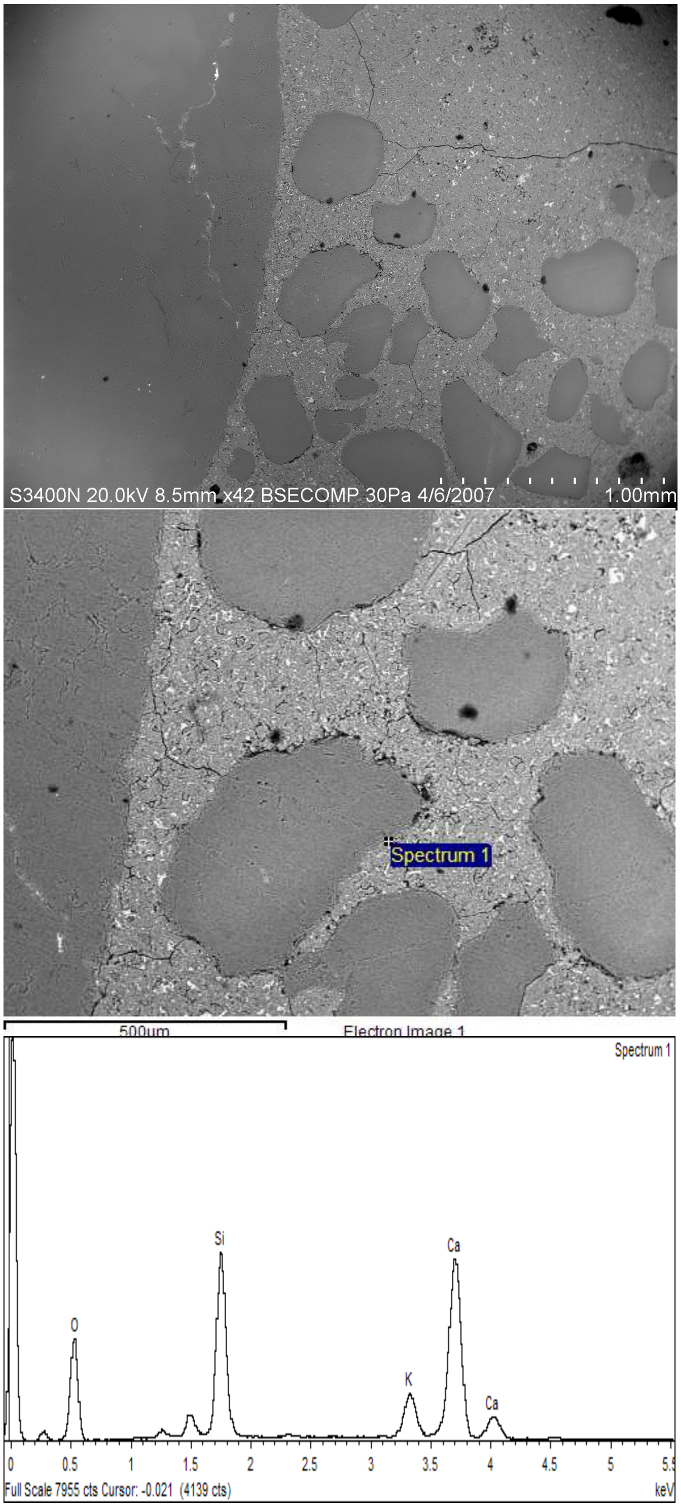


Figure 4.64 Figures show SEM-EDX images of NM-LA-3-0.8 prisms

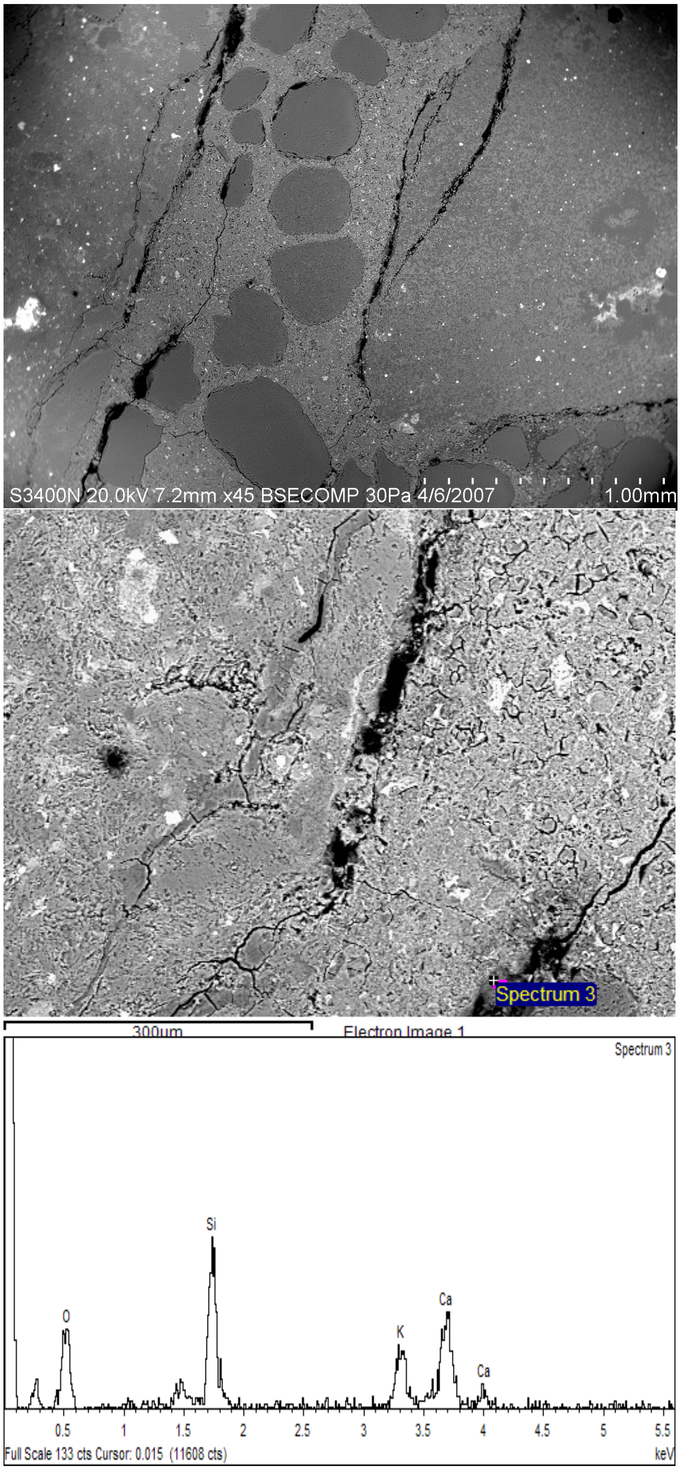


Figure 4.65 Figures show SEM-EDX images of NM-LA-6.4-0.2 prisms

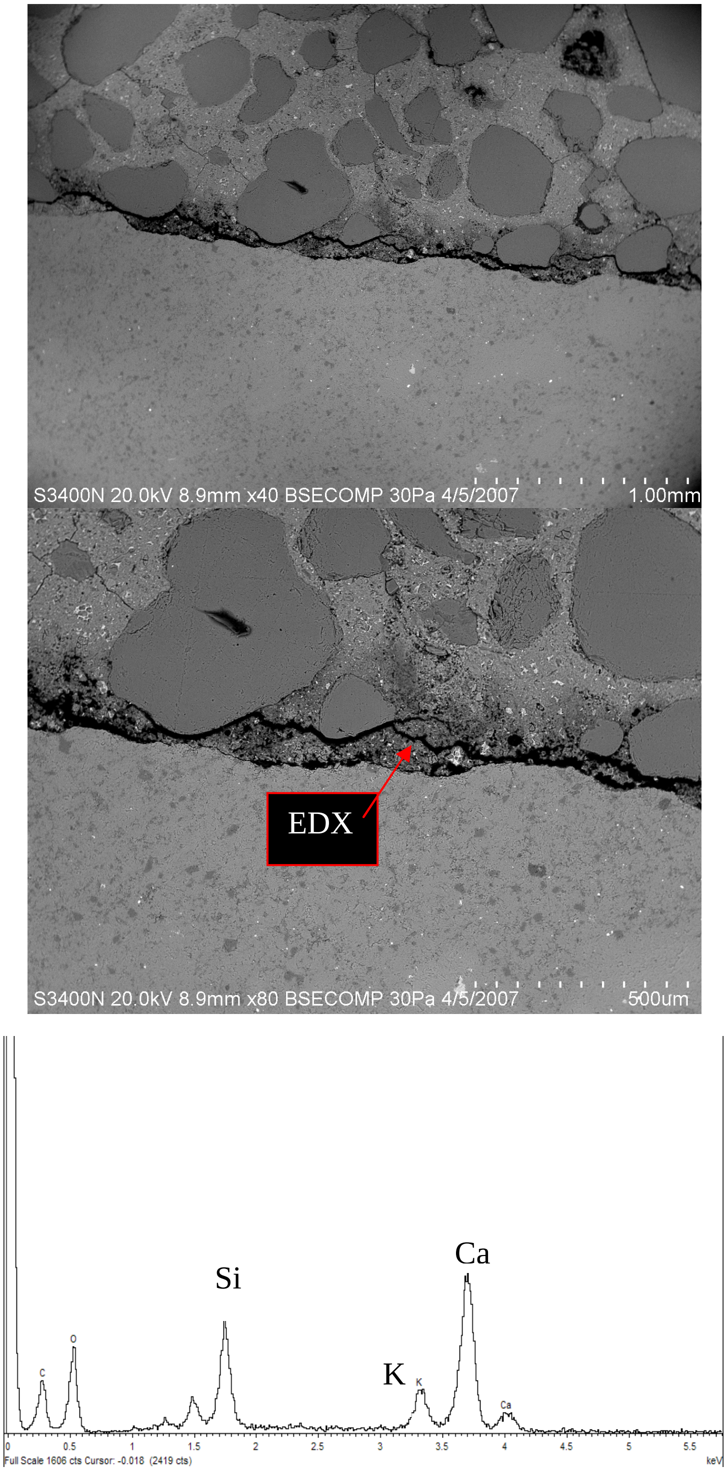


Figure 4.66 Figures show SEM-EDX images of SP-LA-3.0 prisms

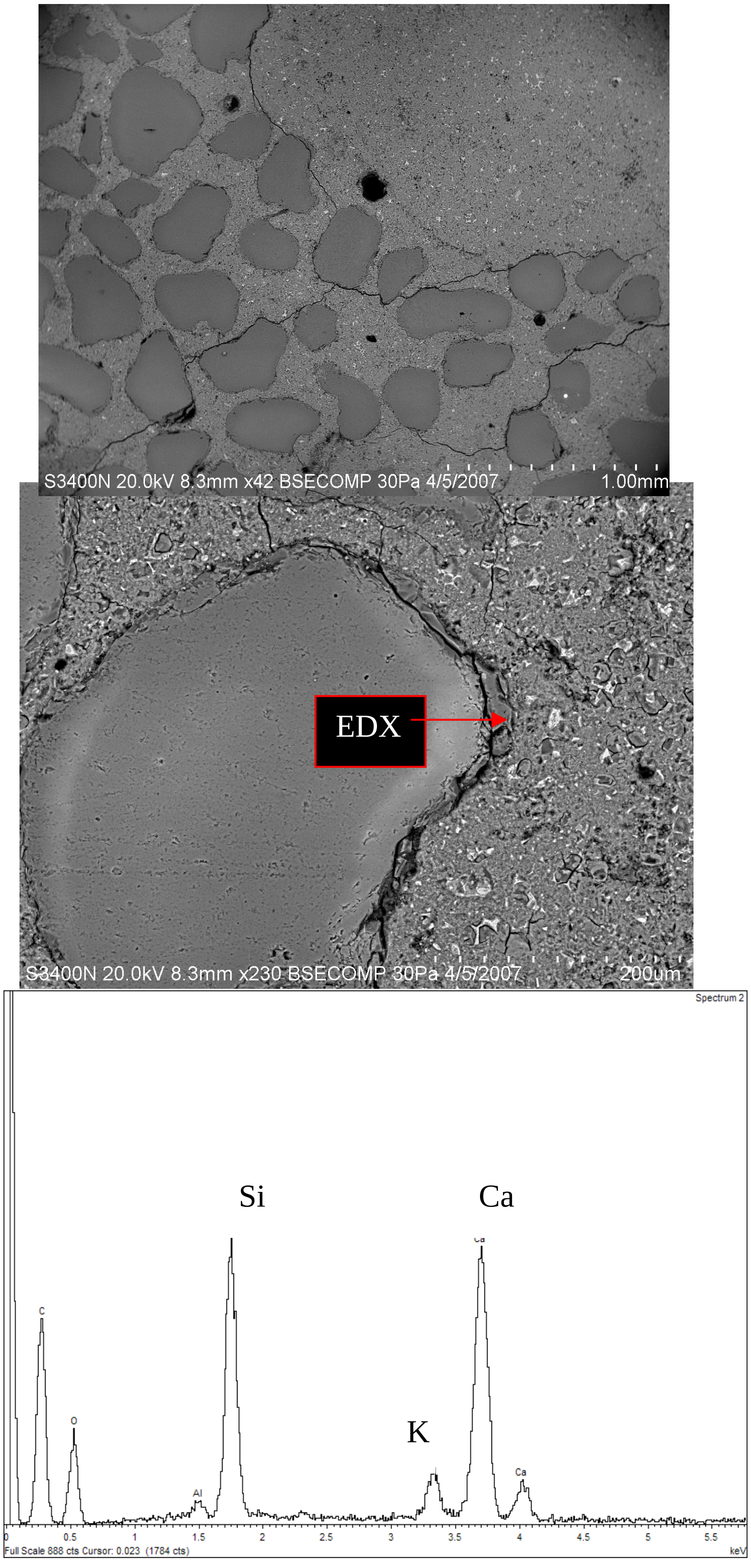


Figure 4.67 Figures show SEM-EDX images of SP-LA-3-0.2 prisms

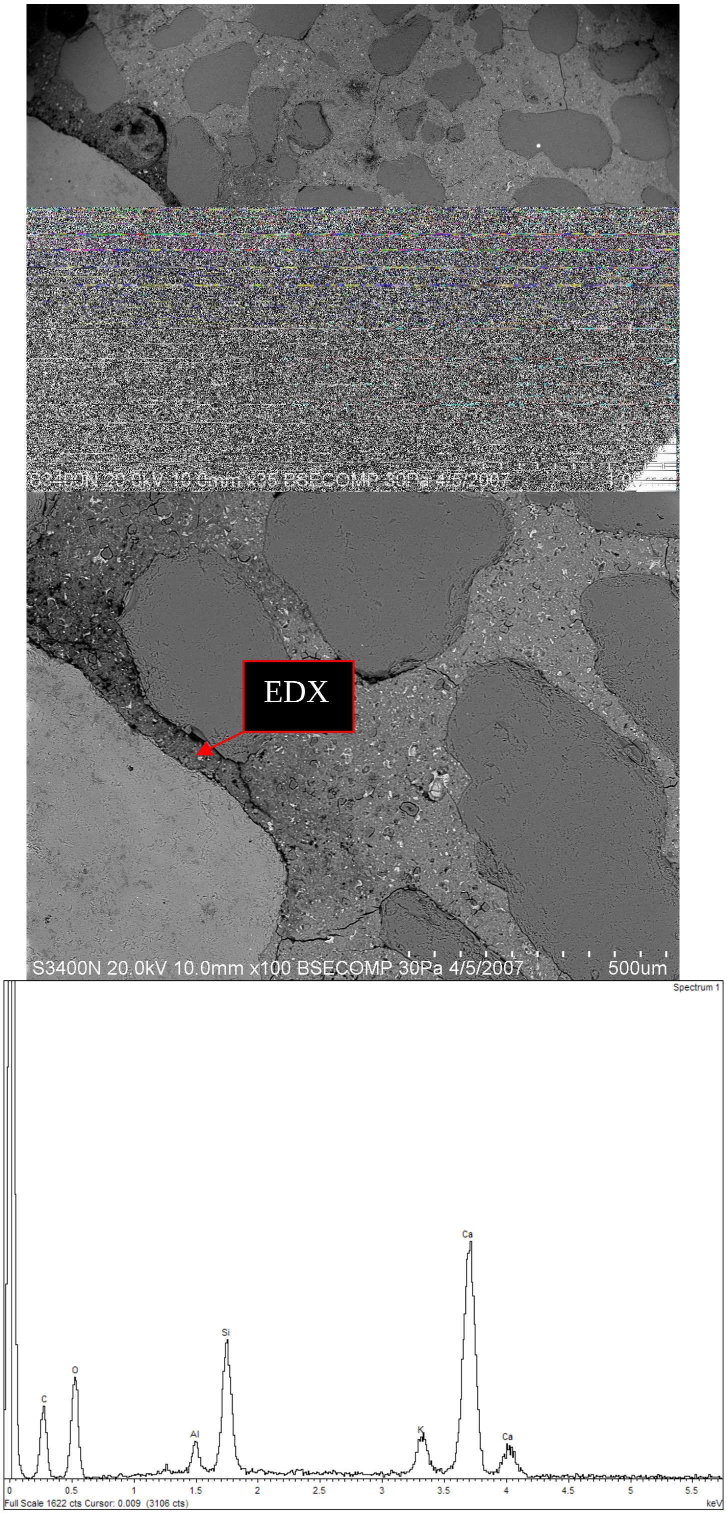


Figure 4.68 Figures show SEM-EDX images of SP-LA-6.4-0.2 prisms

4.17 Statistical Analyses for Modified ASTM 1293 Test

Statistical analyses were conducted on the data obtained from the modified ASTM C 1293 tests. The objectives of these analyses were:

1. To study if there was any significant influence of Li/K ratio on expansion of concrete prisms in modified ASTM C 1293 tests.
2. To study if the expansions of concrete prism specimens made with high-alkali cement were higher than expansions of the corresponding specimens made with low-alkali cement.
3. To determine the nature of the relationship between lithium content of the soak solution and the expansion in modified ASTM C 1293 tests.

Results from Statistical Analysis

Hypothesis testing for two or more population means was conducted using the SAS program to determine if there was any significant difference between various Li/K ratios in mitigating expansion in modified ASTM C 1293 test as explained in section 4.8.

The tests were conducted for concrete prisms made with NM, SP, NC and SD aggregate with HA cement exposed to different Li/K ratios. From the Least Significant Difference (LSD) procedure, the test results are presented in Table 4.4. For a given aggregate, the same letter for different Li/K ratios indicates that there is no significant difference in the effectiveness of different dosages of lithium. If the letters are different then there was a difference in expansion with respect to Li/K ratio. From these results, it is seen that in NM aggregate, soak solutions with different Li/K ratios had a different effect on the level of mitigation. In case of prisms with SP, NC and SD aggregates, soak solution with Li/K ratio of 0.2 have similar effect as compared to 3 molar KAc soak solution (i.e., Li/K=0).

Table 4.4 Comparison of effect of soak solution with different Li/K ratio in mitigating expansion for concrete prisms within aggregate source at modified ASTM C 1293 tests, at 12 months (X- no data).

Soak Solution Li/K ratio	NM	SP	NC	SD
0	A	A	A	A
0.2	B	A	A	A
0.8	C	X	X	X

Statistical analyses were conducted on all aggregate types with different soak solution combinations to find relative levels of mitigation offered for different aggregates, and if a significant difference exists between the different levels of mitigation. From the LSD procedure, the test results are presented in Table 4.5. The treatments with same letters means that there is no significant difference between those soak solution ratios and the effect of aggregate type. From the Table it is found that Li/K ratio does not seem to produce similar results between the aggregate reactivities. This may be due to aggregate mineralogy, as highly reactive aggregate responds quickly, compared to slow reactive aggregate.

Table 4.5 Comparison of effect of soak solution with different Li/K ratio in mitigating expansion for concrete prisms between aggregate sources at modified ASTM C 1293 tests, at 12 months (X- no data).

Soak Solution Li/K ratio	NM	SP	NC	SD
0	A	E	C	F
0.2	B	E	C	F
0.8	D	X	X	X

Expansions of low and high-alkali concrete prisms

Hypothesis testing for two population means were conducted using the SAS program, to determine whether expansions of concrete prisms were influenced by alkali content of cement. From the hypothesis testing, it was seen that concrete prisms made with high-alkali cement showed more expansion than bars made with low-alkali cement except for the prisms soaked in Li/K ratio of 0.2 with 3 Molar KAc solution. The results from the tests are presented in Table 4.6. The notation used in Table 4.6 is same as in Table 4.3.

Table 4.6 Comparison of expansions in modified ASTM C 1293 tests for concrete prisms made with high-alkali and low-alkali cement at 12 months.

Soak Solution Li/K ratio	NM
0	HA>LA
0.2	HA=LA
0.8	HA>LA

Regression Analysis

To study the relationship between lithium acetate additions in mitigating expansion in modified ASTM C 1293 tests regression analyses were conducted. In this research, concrete prisms were prepared with NM aggregate soaked in different Li/K ratios prepared with both high and low-alkali cement. To establish the relationship, regression analysis was carried out by plotting expansion of ASTM C 1293 test on Y-axis and the Li/K ratio in X-axis on a graph.

Comparing the relationship between the increase in Li/K ratio and the expansion of concrete prisms, it can be said that there is a good exponential relationship in NM aggregate with high-alkali and low-alkali cements, when soaked with different Li/K ratio. The results are comparable to mortar bar made with NM aggregate as there is a similar pattern in both test methods.

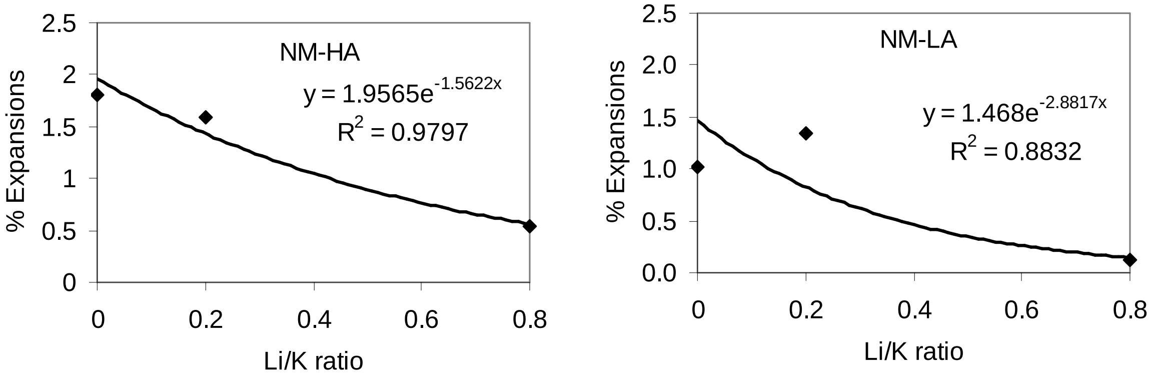
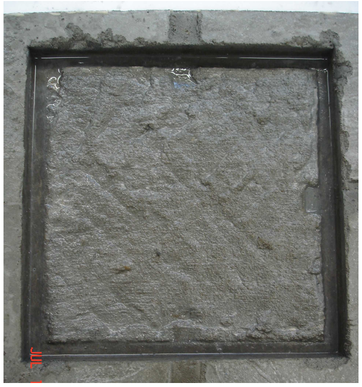


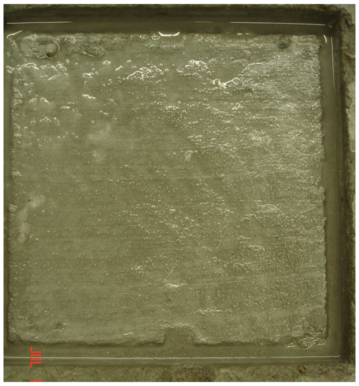
Figure 4.69 Expansions in Modified ASTM C 1293 tests at 12 months made with high-alkali and low-alkali cement for Li/K ratio of 0, 0.2, and 0.8 solutions with 3 molar KAc.

4.18 Results and Discussion from Modified ASTM C 672 Tests

Figure 4.70 shows the visual images of the concrete slabs made with NM, SP and IL aggregate which were exposed to 6.4 molar KAc solution and 3 molar LiAc solution. From the images, it is seen that no scaling occurred after 50 cycles. Also, there was no residue and no expansion in the concrete slabs. The visual ratings of the surfaces were rated as 0 since no scaling was observed. It was also noticed that LiAc solution freezes at high temperature as the freezing point is high compared to KAc solution. The KAc solution did not freeze and no scaling was observed because of the freezing temperature of the solution.



NM-LA-KAc



NM- LA-LiAc

SP- LA-KAc

SP- LA-LiAc

IL- LA-KAc

IL- LA-LiAc

Figure 4.70 Images showing the scaling resistance of concrete surface in Modified ASTM C 672 Test

4.19 Results and Discussion from Modified ASTM C 227 Tests

Figure 4.71 shows the expansion results of the mortar bars from the modified ASTM C 227 tests. The mortar bars were made with non-reactive Ottawa sand with 5% fused silica and low-alkali cement. The mortar bars which were not pre-treated with lithium nitrate showed the highest expansion. Mortar bars with 1(T-1), 3(T-3) and 5(T-5) with coating of lithium nitrate showed very low levels of expansion, even after exposing the bars to subsequent coatings of KAc at 3 days, 7 days, 14 days, and 28 days. The application of lithium nitrate to the mortar bars before exposing to KAc can, therefore, be an better alternative to mitigate the distress caused by deicer solutions like KAc.

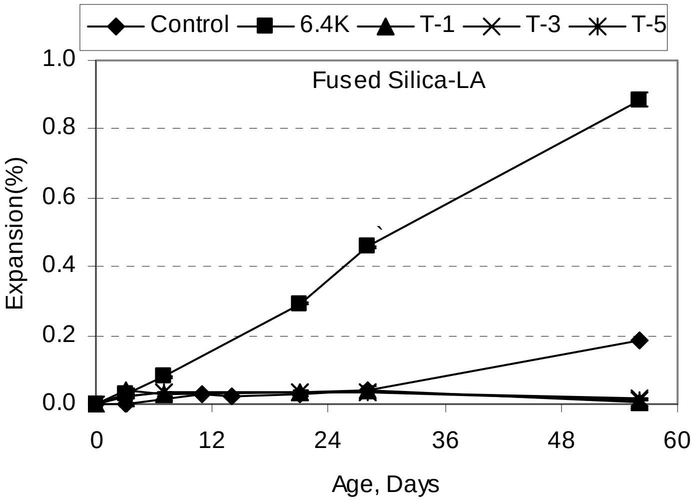


Figure 4.71 Expansion of Mortar Bars in Modified ASTM C 227 Test with pre-treatment with Lithium Nitrate before exposing to Potassium Acetate Deicer Solution with Fused Silica, Ottawa Sand and Low-Alkali Cement

Figure 4.72 shows the results of the changes in dynamic modulus of elasticity of mortar bar specimens in the modified ASTM C 227 test. From this figure, it can be seen that mortar bars which were pre-treated with lithium nitrate before exposing to coats of KAc showed little or no loss in DME at all dosage level. However, mortar bars not pre-treated with lithium nitrate coats and exposed to KAc showed a major loss in DME compared to bars which were pre-treated with lithium nitrate.

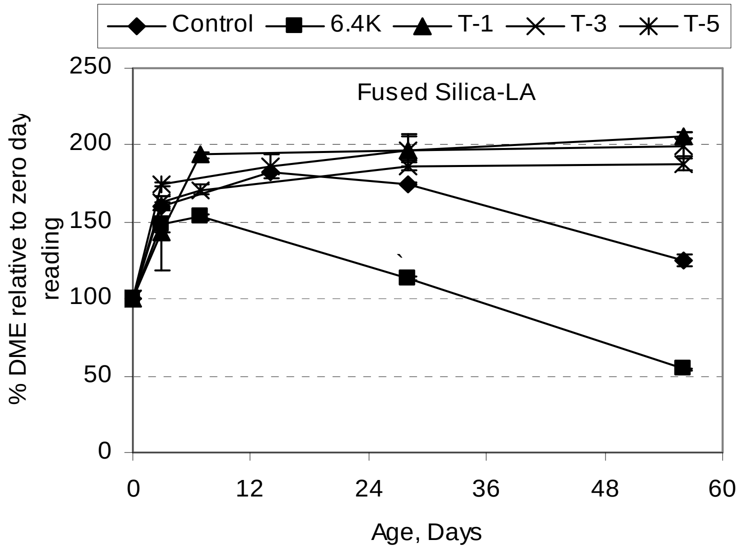


Figure 4.72 Change in Dynamic Modulus of Mortar Bars made with Ottawa Sand with 5% Fused Silica by Mass in Modified ASTM C 227 Test

Figure 4.73 shows graphs of % DME relative to zero day reading compared to the % expansion in 227 tests at similar ages of mortar bars made with Ottawa sand, low-alkali cement with no treatment and bars which are pre-treated with lithium nitrate at 1 coat, 3 coat and 5 coats. It can be observed that whenever there is change in DME, a corresponding change in the linear expansion of the mortar bars was observed in ASTM C 227 tests.

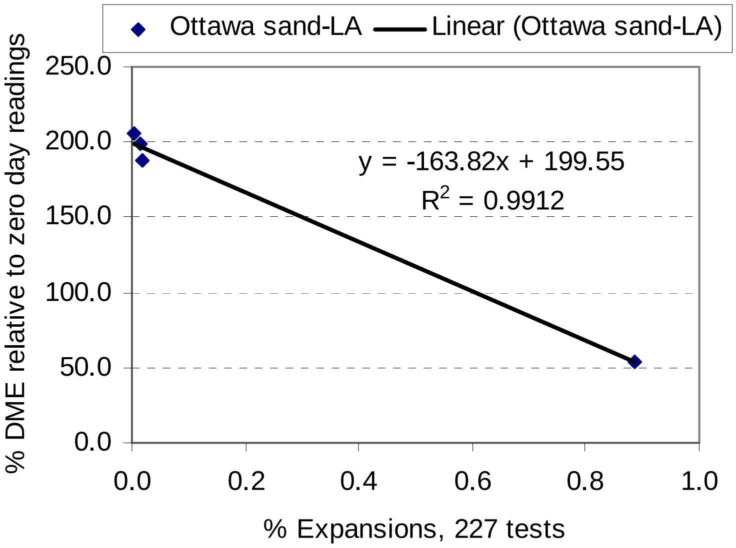


Figure 4.73 Percentage DME Relative to Zero Day Reading and Expansions in C 227 Tests

4.20 Results and Discussion from ICP Tests

This test was conducted to determine the depth of penetration of deicers into concrete. The specimens used in this study were taken from scaling studies. The concentration of solution used was 6.4 molar KAc solution and 3 molar LiAc solution. Figure 4.74 shows the results from the ICP testing which were done on the crushed powder of the cores of the concrete slabs which were exposed to these soak solution. The X axis shows the depth from the top of the slab and the Y axis shows the concentration. From the figures, both K and Li ion concentration decreases along the depth. From these results, it appears that for six month exposure duration, to deicers solution, both K and Li penetrated to a depth of 1.5 inch to 2 inch into concrete. Since the concentration of KAc and LiAc is different, no quantitative assessment could be conducted to compare the relative penetration of K and Li ions into concrete.

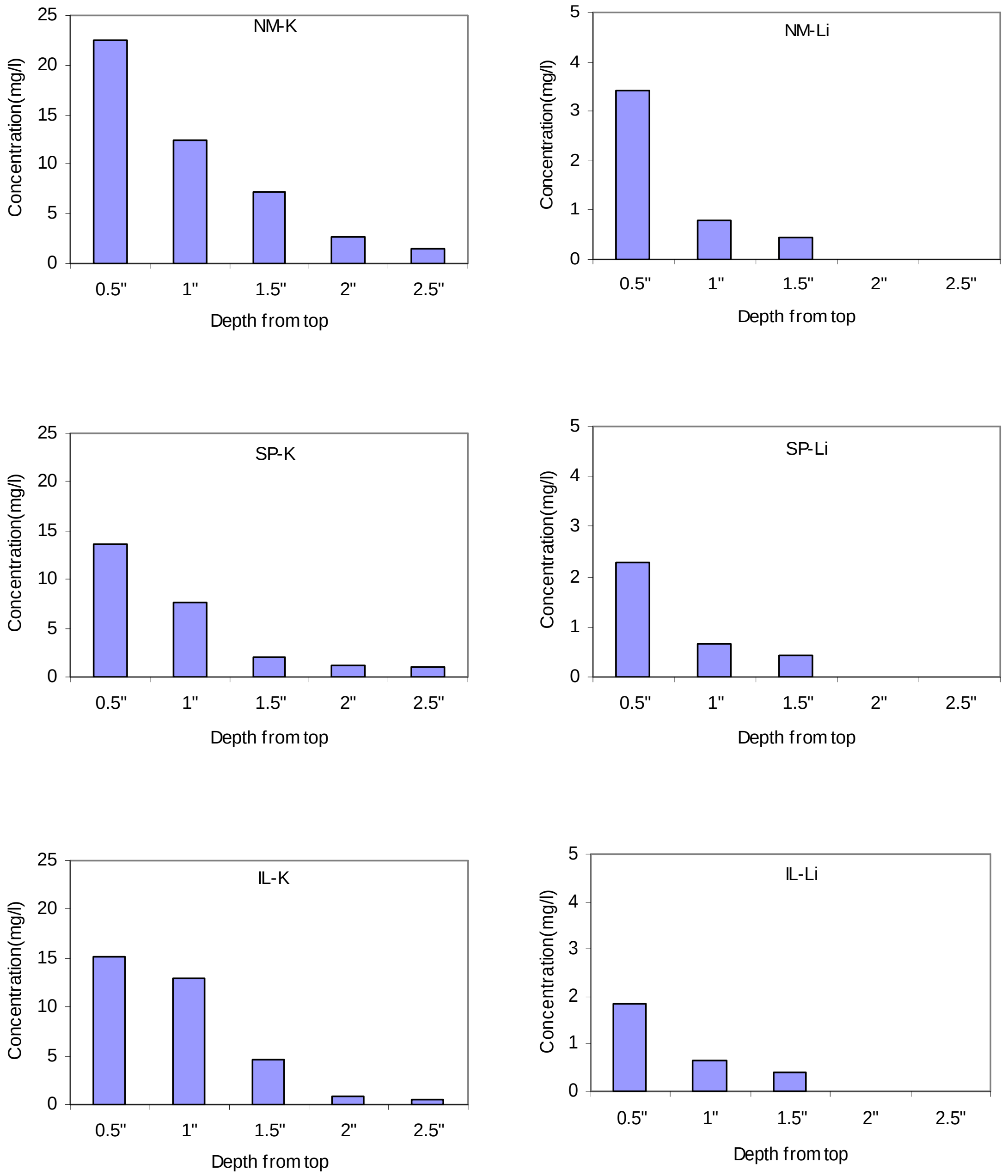


Figure 4.74 Figures shows the profile of K and Li penetration in the concrete slabs along the depth

4.21 Results from XRF Testing

Figures 4.75 through 4.76 show the penetration of K in a concrete slab made with SP aggregate and low-alkali cement, exposed to KAc concentration. Figure 4.75 shows the three color overlay image of IL-KAc which shows the penetration of K along the depth of the concrete slab. Potassium was found all over the cement matrix and around the aggregate forming the ASR gel around the aggregate.

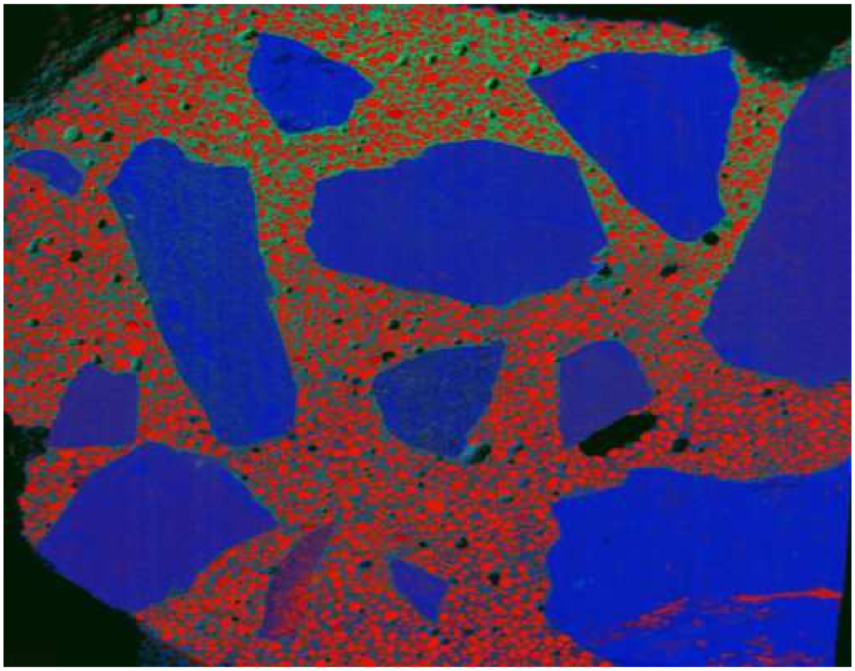


Figure 4.75 Three color overlay image of SP-KAc made with LA cement. Calcium = Blue, Silicon = Red, Potassium = Green.

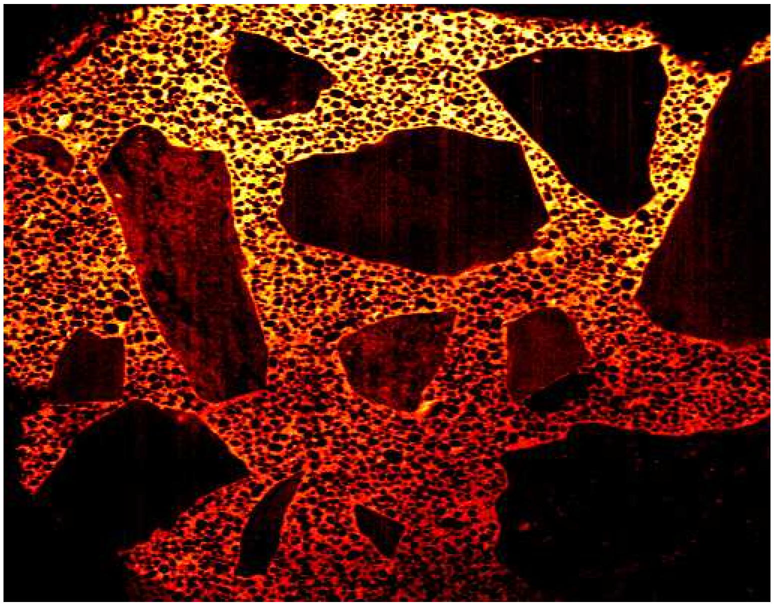


Figure 4.76 Thermal colorization of SP-KAc made with LA cement.

Figure 4.77 shows the spectra of the concrete specimens at the top and bottom location of the slab. In this graph, it can be seen that K concentration is higher in the top portion of the concrete when compared to bottom portion.

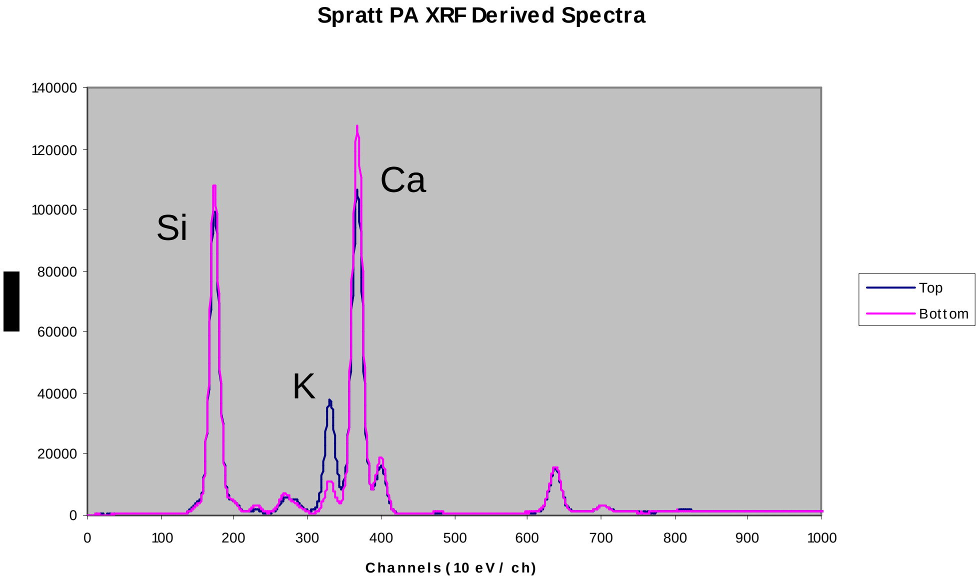


Figure 4.77 XRF Spectra of SP-KAc made with LA cement.

Figures 4.78 and 4.79 show the various images used to understand the penetration of K in IL-LA exposed to KAc. The penetrations of K were similar to that of concrete made with SP aggregate.

Figure 4.78 gives the three color overlay image of IL-KAc. This shows the penetration of K along the depth of the concrete slab. Potassium was found all over the cement matrix and around the aggregate forming the ASR gel around the aggregate as similar images were also seen in the SEM images.

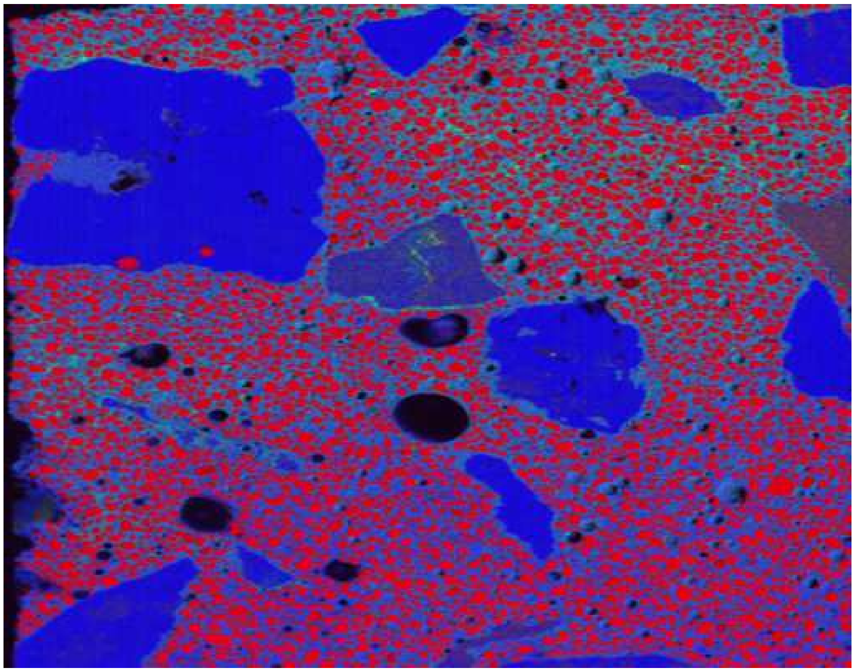


Figure 4.78 Three color overlay image of IL-KAc made with LA cement. Calcium = Blue, Silicon = Red, Potassium = Green.

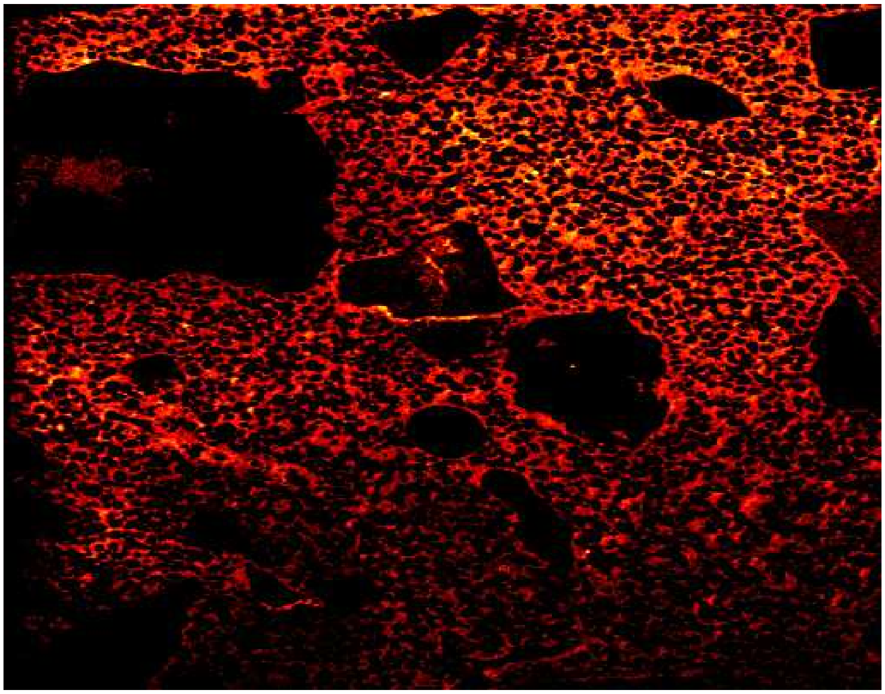


Figure 4.79 Thermal colorization of SP-KAc made with LA cement.

Figure 4.80 shows the spectra of the concrete specimens at top, middle and bottom locations of the slab. In this graph, it can be seen that K concentration is higher in the top portion of the concrete and the concentration drops with depth.

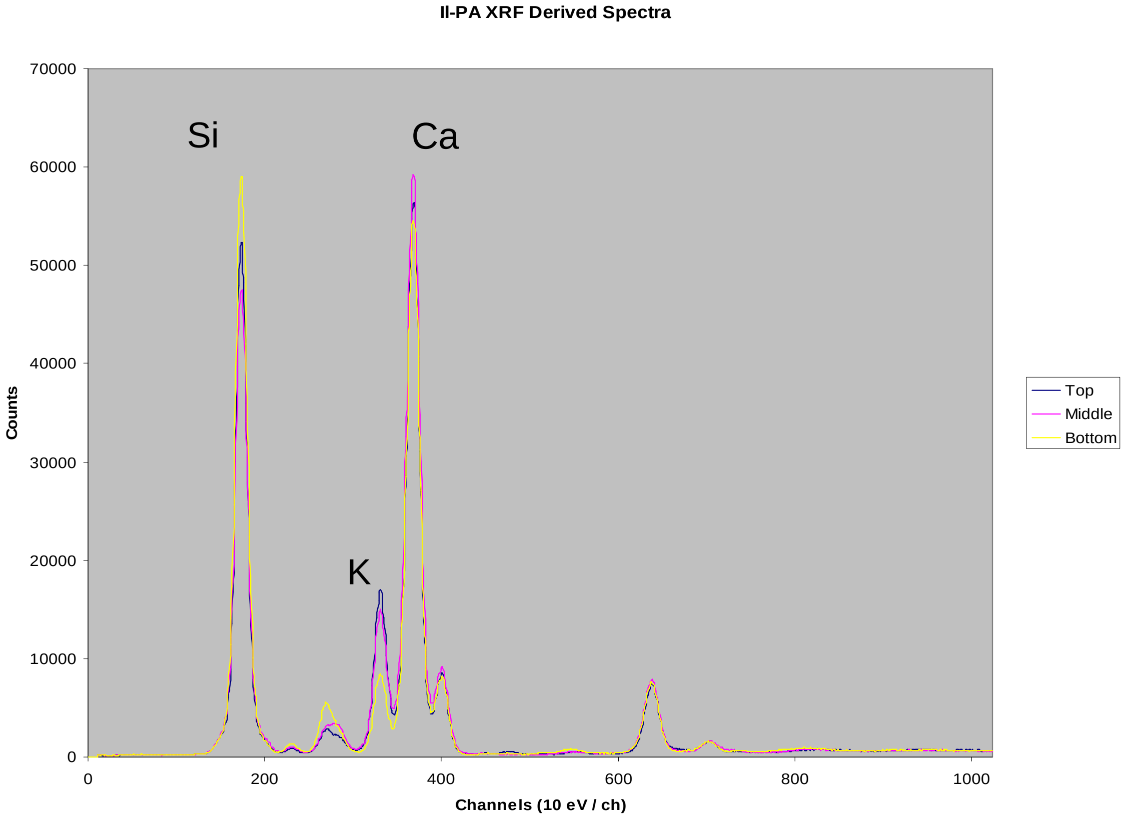


Figure 4.80 XRF Spectra of IL-KAc made with LA cement.

CHAPTER FIVE

SUMMARY AND CONCLUSIONS

5.1 Summary

This chapter presents a summary of the principal findings and the conclusions from the research study of standard and modified ASTM C 1260 tests, modified ASTM C 1293 tests, modified ASTM C 672 tests, ICP tests, XRF tests and modified ASTM C 227 tests, followed by recommendations.

5.1.1 Standard and Modified ASTM C 1260 Tests

The principal findings from the standard and modified ASTM C 1260 tests were:

1. Mortar bars made with reactive aggregate exposed to plain potassium acetate at both 3 and 6.4 molar KAc solution showed significant potential to cause distress.
2. The level of expansion in mortar bars made with NM and NC aggregate increased significantly when exposed to KAc with 3 molar KAc solution, as compared to 6.4 molar KAc solution. Mortar bars made with SP and SD aggregate showed more expansion when exposed to 6.4 molar KAc solution when compared to 3 molar KAc solution.
3. Lithium acetate, when blended with 3 molar and 6.3 molar KAc, was found to be effective in mitigating ASR expansion associated with SP, NC and SD aggregates. NM aggregate could only be mitigated by blended deicers of 3 molar KAc with Li/K of 0.6 and 0.8 molar ratios.

4. The alkali content of the cement had a significant influence on the expansions of the mortar bars. Bars made with high-alkali cement expand more when compared with bars made with low-alkali cement.
5. The changes in DME of mortar bars upon exposure to different deicers corresponded well with the linear expansions observed.
6. SEM and EDX analysis of mortar bars showed severe deterioration in the aggregate particles and the cement paste of the mortar bars when exposed to 3 and 6.4 molar KAc solution. There was a significant reduction in deterioration when LiAc was added to KAc. This trend was more apparent in mortar bars exposed to blended deicers with higher Li/K molar ratios (i.e., 0.6 and 0.8). The gel formed within a crack, or the residue outside an aggregate crack was mainly comprised of silica, potassium and calcium.

5.1.2 Modified ASTM C 1293 Tests

The principal findings from the modified ASTM C 1293 tests were:

1. Concrete prisms made with all of the reactive aggregates showed significant expansions when exposed to 3 and 6.4 molar KAc solutions. The level of expansion of concrete prisms exposed to 6.4 molar KAc solution was greater when compared to 3 Molar KAc solution.
2. The addition of LiAc to KAc deicer was found to not be as effective in controlling expansion of concrete prisms in ASTM C 1293 tests, compared to its effect on mortar bars in ASTM C 1260 tests.

3. The alkali content of the cement had a significant influence on the expansion of the concrete prisms in the modified ASTM C 1293 tests. Prisms made with high-alkali cement expanded more when compared with bars made with low-alkali cement.
4. Concrete prisms made with NM aggregate were the most affected by the deicers used in the study, followed by SP, NC and SD aggregate, respectively.
5. The dynamic modulus of elasticity (DME) of concrete prisms made with all aggregates showed a significant drop upon exposure to 6.4 molar KAc solution and 3 Molar KAc solution. The reduction in DME was observed with the addition of LiAc and more in increase of Li/K ratio.
6. SEM and EDX analysis of concrete prisms showed severe deterioration within the aggregate particles and the cement paste of the concrete prisms when exposed to 3 and 6.4 molar KAc solution. This effect was similar to that observed in the mortar bars. There was a significant reduction in deterioration when LiAc was added to KAc solutions. There were fewer cracks observed in concrete prisms when soaked in blended deicers with higher Li/K molar ratio.

5.1.3 Modified ASTM C 672 Tests

The principal findings from the modified ASTM C 672 tests were:

1. No scaling was observed in concrete slabs made with both reactive and non-reactive aggregate exposed to 3 and 6.4 molar KAc solutions.
2. No mass loss or expansion was observed.

5.1.4 ICP and XRF Tests

The principal findings from ICP and XRF tests were:

1. The concentration of K was high in the top surface and reduces with depth.
2. The gradient from top to bottom showed the influence of K in concrete samples.
3. The reaction products formed around the aggregate were mainly comprised of silica, potassium and calcium.

5.1.5 Modified ASTM C 227 Tests

The principal findings from the modified ASTM C 227 tests were:

1. Mortar bars that were exposed to KAc and not pre-treated with $LiNO_3$ showed higher expansion than those that were pre-treated with $LiNO_3$.
2. There was a significant drop in dynamic modulus of elasticity (DME) in mortar bars exposed to KAc without pre-treatment, and no such loss was observed bars pre-treated with lithium nitrate. The loss in DME correlated well with corresponding increase in the expansions of mortar bars.

5.2 Conclusions

The following conclusions can me made from this study:

1. A saturated solution of LiAc or blends of LiAc-KAc at Li/K molar ratio of 0.2 and higher appear to be effective in mitigating ASR related effects in mortar bars prepared with 3 out of 4 reactive aggregates. Only mortar bars with NM aggregate, the most reactive of all aggregates, could not be mitigated to below 0.1% at 14 days.
2. While blends of LiAc-KAc deicer solutions were found to reduce expansion in concrete prisms, the magnitude of reduction was not comparable to that observed in mortar bars. Consequently tests on concrete prisms showed that blended deicers at Li/K of 0.2 were not effective in controlling expansion induced by ASR.\
3. The use of low-alkali cement significantly reduced expansion in mortar bars in the presence of lithium bearing deicing solutions.
4. The type of aggregate and the alkali level in the concrete, both influence the minimum levels of lithium compounds needed to successfully mitigate ASR.
5. None of the deicers evaluated in this study (i.e., KAc and LiAc) caused scaling in concrete slabs.
6. No pessimum effects were observed with lithium acetate, when evaluated in ASTM C 1260 and ASTM C 1293 tests.
7. Pre-treatment of mortar bars with $LiNO_3$ before exposure to KAc deicer solution was effective in controlling expansion in mortar bars. No significant expansion or drop in DME was observed in mortar bars which were pre-treated.

5.3 Recommendations

Based on the research findings, the following recommendations are suggested into two groups:

5.3.1 Recommendations for Practice

1. Using LiAc with KAc is a viable approach to mitigate expansion due to ASR. For highly reactive aggregate like NM aggregate Li/K of 0.8 with 3 molar KAc can be used to mitigate the expansion. For moderate reactive aggregate Li/K ratio of 0.4 to 0.6 can be used to mitigate the expansion.
2. It is suggested to use low-alkali cement compared to high-alkali cement as it is observed from this research that alkali content of cement has significant influence on the expansion due to ASR.
3. Since the gel formed in the presence of LiAc is not expansive in nature which results in lesser expansion, it is strongly suggested that use of LiAc in addition to KAc should be considered as an alternative to regular deicers like KAc.

5.3.2 Recommendations for Future Research

1. In future studies, it is recommended that quantitative chemical analyses on the gel composition be carried out to ascertain the level of mitigation obtained as a function of lithium dosage.
2. Even though, the ASTM C 1260 accelerated mortar bar test helps in assessing the ability of lithium compounds to reduce expansion due to ASR, lithium

compounds should be evaluated by conducting ASTM C 1293 tests, to gain a better understanding of the specimen size effect on mitigation.

3. It is established in this study that lithium acetate is effective in mitigating ASR. In future, studies should be carried out to optimize the composition of blended deicers to meet the specification of the Environmental Protection Agency and Aerospace Materials Specifications for deicers
4. Pre-treatment of mortar bars with $LiNO_3$ before exposing to KAc was effective in all dosage levels. Further research should be done on concrete prisms to find the specimen size effect in mitigation and the pre-treatment effectiveness.

APPENDIX

Table A1 Expansion readings and percentage expansions of the Standard ASTM C 1260 test for New Mexico Rhyolite using High Alkali cement

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.01	0.2969	0.2752	0.332	0.3206	0	0	0	0	0
3	0.0036	0.3477	0.3264	0.3798	0.3820	0.5720	0.5760	0.5420	0.6780	0.5920
7	0.0036	0.3902	0.3705	0.4213	0.4095	0.9970	1.0170	0.9570	0.9530	0.9810
10	0.0038	0.4128	0.3947	0.4439	0.4311	1.2210	1.2570	1.1810	1.1670	1.2065
14	0.0036	0.4340	0.4170	0.4677	0.4521	1.4350	1.4820	1.4210	1.3790	1.4293
21	0.0033	0.4550	0.4387	0.4909	0.4725	1.6480	1.7020	1.6560	1.5860	1.6480
28	0.0031	0.4693	0.4532	0.5064	0.4865	1.7930	1.8490	1.8130	1.7280	1.7958

Note:

1. % Expansion value on n^{th} day =

$$\frac{[(\text{mortar bar reading of } n^{th} \text{ day- ref. bar reading of } n^{th} \text{ day}) - (\text{mortar bar reading of } 0^{th} \text{ day- ref. bar reading of } 0^{th} \text{ day})] \text{ X } 100}{\text{Original length of the mortar bar}}$$

Table A2 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for New Mexico Rhyolite using High Alkali cement and 3 MC of Potassium Acetate deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.0050	0.3056	0.3174	0.2875	0.3141	0.0000	0.0000	0.0000	0.0000	0.0000
3	0.0059	0.4497	0.4511	0.4245	0.4507	1.4320	1.3280	1.3610	1.3570	1.3695
7	0.0064	0.5098	0.5058	0.4793	0.5020	2.0280	1.8700	1.9040	1.8650	1.9168
11	0.0058	0.5280	0.5224	0.4979	0.5164	2.2160	2.0420	2.0960	2.0150	2.0923
14	0.0056	0.5334	0.5280	0.5031	0.5219	2.2720	2.1000	2.1500	2.0720	2.1485
21	0.0064	0.5384	0.5332	0.5080		2.3140	2.1440	2.1910		2.2163
28	0.0072	0.5405	0.5352	0.5102		2.3270	2.1560	2.2050		2.2293

Table A3 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for New Mexico Rhyolite using High Alkali cement and 6.4 MC of Potassium Acetate deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.01	0.3017	0.3135	0.325	0.3132	0	0	0	0	0
3	0.0036	0.4212	0.4293	0.4441	0.4299	1.2590	1.2220	1.2550	1.2310	1.2418
7	0.0036	0.4519	0.4594	0.4747	0.4614	1.5660	1.5230	1.5610	1.5460	1.5490
10	0.0038	0.4533	0.4605	0.4760	0.4629	1.5780	1.5320	1.5720	1.5590	1.5603
14	0.0036	0.4539	0.4612	0.4765	0.4635		1.5410	1.5790	1.5670	1.5623
21	0.0033	0.4541	0.4618	0.4770	0.4639	1.5910	1.5500	1.5870	1.5740	1.5755
28	0.0031	0.4554	0.4628	0.4781	0.4652	1.6060	1.5620	1.6000	1.5890	1.5893

Table A4 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for New Mexico Rhyolite using High Alkali cement and Lithium Acetate deicer

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0093	0.3143	0.3141	0.3132	0	0	0	0
3	0.0097	0.314	0.3145	0.313	-0.007	0	-0.006	-0.0043
7	0.0094	0.3143	0.314	0.3137	-0.001	-0.002	0.004	0.0003
11	0.0096	0.315	0.3152	0.315	0.004	0.008	0.015	0.0090
14	0.0095	0.3158	0.3154	0.3148	0.013	0.011	0.014	0.0127
21	0.0102	0.3153	0.314	0.3139	0.001	-0.01	-0.002	-0.0037
28	0.0103	0.3161	0.3158	0.3136	0.008	0.007	-0.006	0.0030

Table A5 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for New Mexico Rhyolite using High Alkali cement and Li/K 3-0.2 deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.005	0.3071	0.2618	0.2809	0.2914	0	0	0	0	0
3	0.0059	0.3656	0.3202	0.3363	0.3439	0.576	0.575	0.545	0.516	0.5530
7	0.0064	0.4111	0.3636	0.3791	0.385	1.026	1.004	0.968	0.922	0.9800
11	0.0058	0.426	0.3783	0.393	0.3966	1.181	1.157	1.113	1.044	1.1238
14	0.0056	0.4303	0.3823	0.3975	0.4003	1.226	1.199	1.16	1.083	1.1670
21	0.0064	0.4353	0.3807	0.402		1.268	1.175	1.197		1.2133
28	0.0066	0.4372	0.388	0.4035		1.285	1.246	1.21		1.2470

Table A6 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for New Mexico Rhyolite using High Alkali cement and Li/K 3-0.4 deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.0064	0.366	0.3992	0.3899	0.4311	0	0	0	0	0
3	0.0056	0.3862	0.4198	0.4168	0.4564	0.21	0.214	0.277	0.261	0.2405
7	0.0057	0.3912	0.4249	0.4119	0.4621	0.259	0.264	0.227	0.317	0.2668
11	0.0057	0.3962	0.4306	0.4268	0.4682	0.309	0.321	0.376	0.378	0.3460
14	0.0058	0.3971	0.4318	0.4278	0.4702	0.317	0.332	0.385	0.397	0.3578
21	0.0067	0.399	0.4331	0.4299		0.327	0.336	0.397		0.3533
28	0.0059	0.3985	0.4329	0.4294		0.33	0.342	0.4		0.3573

Table A7 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for New Mexico Rhyolite using High Alkali cement and Li/K 3-0.6 deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.0064	0.3738	0.4108	0.4939	0.3736	0	0	0	0	0
3	0.0056	0.3799	0.4177	0.4971	0.3761	0.069	0.077	0.04	0.033	0.0548
7	0.0057	0.3809	0.4189	0.498	0.3772	0.078	0.088	0.048	0.043	0.0643
11	0.0057	0.3819	0.42	0.4989	0.3785	0.088	0.099	0.057	0.056	0.0750
14	0.0058	0.3825	0.4206	0.4993	0.3786	0.093	0.104	0.06	0.056	0.0783
21	0.0067	0.384	0.4224	0.501		0.099	0.113	0.068		0.0933
28	0.0059	0.3834	0.4218	0.5003		0.101	0.115	0.069		0.0950

Table A8 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for New Mexico Rhyolite using High Alkali cement and Li/K 3-0.8 deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.0064	0.428	0.3908	0.4994	0.4569	0	0	0	0	0
3	0.0056	0.4305	0.3935	0.5026	0.4583	0.033	0.035	0.04	0.022	0.0325
7	0.0057	0.431	0.3942	0.5034	0.4597	0.037	0.041	0.047	0.035	0.0400
11	0.0057	0.4321	0.3949	0.5043	0.4611	0.048	0.048	0.056	0.049	0.0503
14	0.0058	0.4329	0.3956	0.5048	0.4615	0.055	0.054	0.06	0.052	0.0553
21	0.0067	0.4343	0.3969	0.5065		0.06	0.058	0.068		0.0620
28	0.0059	0.4335	0.3963	0.5057		0.06	0.06	0.068		0.0627

Table A9 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for New Mexico Rhyolite using High Alkali cement and Li/K 6.4-0.2 deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.0051	0.2909	0.3036	0.2819	0.2912	0	0	0	0	0
3	0.0051	0.3354	0.3464	0.3268	0.3346	0.445	0.428	0.449	0.434	0.4390
7	0.0054	0.3765	0.3885	0.3695	0.3746	0.853	0.846	0.873	0.831	0.8508
11	0.0059	0.389	0.4018	0.3838	0.3874	0.973	0.974	1.011	0.954	0.9780
14	0.005	0.3907	0.4036	0.3849	0.3889	0.999	1.001	1.031	0.978	1.0023
21	0.0058	0.3933	0.4026	0.3879		1.017	0.983	1.053		1.0177
28	0.006	0.3944	0.407	0.3887		1.026	1.025	1.059		1.0367

Table A10 Expansion readings and percentage expansions of the Standard ASTM C 1260 test for New Mexico Rhyolite using Low Alkali cement

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.01	0.2926	0.3225	0.3191	0.318	0	0	0	0	0
3	0.0036	0.3405	0.37	0.3665	0.3661	0.543	0.539	0.538	0.545	0.5413
7	0.0036	0.384	0.4126	0.4121	0.4094	0.978	0.965	0.994	0.978	0.9788
10	0.0038	0.4062	0.4353	0.4364	0.4323	1.198	1.19	1.235	1.205	1.2070
14	0.0036	0.4269	0.4575	0.4583	0.4535	1.407	1.414	1.456	1.419	1.4240
21	0.0033	0.4476	0.48	0.4796	0.4734	1.617	1.642	1.672	1.621	1.6380
28	0.0031	0.4621	0.4948	0.4942	0.4878	1.764	1.792	1.82	1.767	1.7858

Table A11 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for New Mexico Rhyolite using Low Alkali cement and 3 MC of Potassium Acetate deicer

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0093	0.3065	0.3429	0.2989	0	0	0	0
3	0.0096	0.3715	0.4173	0.3742	0.647	0.741	0.75	0.7127
7	0.0098	0.3926	0.4417	0.3784	0.856	0.983	0.79	0.8763
11	0.01	0.451	0.4937		1.438	1.501		1.4695
14	0.0095	0.4608	0.5027		1.541	1.596		1.5685
21	0.0102	0.4719	0.5126		1.645	1.688		1.6665
28	0.0103	0.481	0.52		1.735	1.761		1.7480

Table A12 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for New Mexico Rhyolite using Low Alkali cement and 6.4 MC of Potassium Acetate deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.01	0.2805	0.2997	0.2892	0.3093	0	0	0	0	0
3	0.0036	0.3955	0.4146	0.4071	0.4236	1.214	1.213	1.243	1.207	1.2193
7	0.0036	0.4277	0.4444	0.4411	0.4547	1.536	1.511	1.583	1.518	1.5370
10	0.0038	0.4294	0.4454	0.4424	0.4562	1.551	1.519	1.594	1.531	1.5488
14	0.0036	0.4296	0.446	0.4428	0.4565	1.555	1.527	1.6	1.536	1.5545
21	0.0033	0.4301	0.4466	0.4436	0.457	1.563	1.536	1.611	1.544	1.5635
28	0.0031	0.4313	0.4476	0.4446	0.4581	1.577	1.548	1.623	1.557	1.5763

Table A13 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for New Mexico Rhyolite using Low Alkali cement and Lithium Acetate deicer

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0093	0.3317	0.2232	0.3156	0	0	0	0
3	0.01	0.332	0.2236	0.316	-0.004	-0.003	-0.003	-0.0033
7	0.0093	0.332	0.2238	0.3163	0.003	0.006	0.007	0.0053
11	0.0096	0.333	0.2259	0.3177	0.01	0.024	0.018	0.0173
14	0.0095	0.3333	0.2259	0.3174	0.014	0.025	0.016	0.0183
21	0.01	0.3326	0.2245	0.3166	0.002	0.006	0.003	0.0037
28	0.0103	0.3337	0.2259	0.3171	0.01	0.017	0.005	0.0107

Table A14 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for New Mexico Rhyolite using Low Alkali cement and Li/K 3-0.2 deicer

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0093	0.2845	0.3434	0.2952	0	0	0	0
3	0.0096	0.3018	0.3564	0.3136	0.17	0.127	0.181	0.1593
7	0.0098	0.3191	0.3737	0.3341	0.341	0.298	0.384	0.3410
11	0.01	0.3495	0.4091	0.372	0.643	0.65	0.761	0.6847
14	0.0095	0.3535	0.416	0.3767	0.688	0.724	0.813	0.7417
21	0.0102	0.3549	0.4189	0.3794	0.695	0.746	0.833	0.7580
28	0.0103	0.3563	0.4214	0.3806	0.708	0.77	0.844	0.7740

Table A15 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for New Mexico Rhyolite using Low Alkali cement and Li/K 3-0.8 deicer

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0093	0.2782	0.3268	0.286	0	0	0	0
3	0.0102	0.2807	0.328	0.2882	0.016	0.003	0.013	0.0107
7	0.0094	0.2809	0.3292	0.2879	0.026	0.023	0.018	0.0223
11	0.0098	0.2822	0.3306	0.2893	0.035	0.033	0.028	0.0320
14	0.0095	0.2824	0.3303	0.2892	0.04	0.033	0.03	0.0343
21	0.0102	0.2808	0.329	0.288	0.017	0.013	0.011	0.0137
28	0.0103	0.2826	0.3309	0.29	0.034	0.031	0.03	0.0317

Table A16 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for New Mexico Rhyolite using Low Alkali cement and Li/K 6.4-0.2 deicer

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0093	0.3207	0.3158	0.3062	0	0	0	0
3	0.01	0.3362	0.3609	0.3468	0.148	0.444	0.399	0.3303
7	0.0094	0.3731	0.3683	0.3624	0.523	0.524	0.561	0.5360
11	0.0096	0.3864	0.3806	0.3757	0.654	0.645	0.692	0.6637
14	0.0095	0.387	0.381	0.3763	0.661	0.65	0.699	0.6700
21	0.0102	0.3875	0.3807	0.3765	0.659	0.64	0.694	0.6643
28	0.0103	0.3887	0.3824	0.3781	0.67	0.656	0.709	0.6783

Table A17 Changes in DME in standard ASTM C 1260 tests using NM aggregate, high alkali cement

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	3.82	3.73	4.00	3.86	3.85	100.00
3	2.35	2.36	2.52	2.40	2.41	62.52
28	1.51	1.37	1.31	1.35	1.38	35.94

Table A18 Changes in DME in modified ASTM C 1260 tests using NM aggregate, high alkali cement and KAc 6.4

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.25	4.17	4.44	4.41	4.32	100.00
3	0.87	0.87	0.92	0.90	0.89	20.61
28	1.86	1.68	1.88	1.90	1.83	42.41

Table A19 Changes in DME in modified ASTM C 1260 tests using NM aggregate, high alkali cement and KAc 3.0

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.12	4.14	4.11	4.03	4.10	100.00
3	0.93	1.01	0.98	0.97	0.97	23.69
14	1.30	1.39	1.54	1.33	1.39	33.92
28	1.55	1.72	1.63		1.63	39.85

Table A20 Changes in DME in modified ASTM C 1260 tests using NM aggregate, high alkali cement and LiAc

	Dynamic Young's Modulus, (E) * 10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	2.27	2.47	2.46	2.40	100.00
3	2.46	2.69	2.54	2.56	106.77
14	2.38	2.68	2.53	2.53	105.51
28	2.73	2.84	3.04	2.87	119.57

Table A21 Changes in DME in modified ASTM C 1260 tests using NM aggregate, high alkali cement and Li/K 6.4-0.2

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.09	4.12	4.05	4.36	4.16	100.00
3	2.01	1.84	2.00	2.28	2.03	48.89
14	1.28	1.35	1.40	1.77	1.45	34.91
28	1.41	1.28	1.66		1.45	34.95

Table A22 Changes in DME in modified ASTM C 1260 tests using NM aggregate, high alkali cement and Li/K 3-0.2

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.10	4.13	4.36	4.25	4.21	100.00
3	0.86	0.94	1.05	1.12	0.99	23.59
14	0.66	0.69	0.88	0.78	0.75	17.87
28	0.60	0.58	0.68		0.62	14.69

Table A23 Changes in DME in modified ASTM C 1260 tests using NM aggregate, high alkali cement and Li/K 3-0.4

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.00	3.98	3.90	3.87	3.94	100.00
3	2.24	2.06	1.35	1.45	1.77	45.06
14	2.66	2.73	1.98	1.89	2.31	58.79
28	2.25	2.89	2.05		2.39	60.82

Table A24 Changes in DME in modified ASTM C 1260 tests using NM aggregate, high alkali cement and Li/K 3-0.6

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	3.98	4.07	4.02	4.00	4.02	100.00
3	3.49	3.33	3.83	3.89	3.63	90.36
14	3.95	3.90	4.19	4.17	4.05	100.80
28	3.98	3.95	4.27		4.07	101.17

Table A25 Changes in DME in modified ASTM C 1260 tests using NM aggregate, high alkali cement and Li/K 3-0.8

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.08	4.02	3.99	4.07	4.04	100.00
3	4.10	3.95	3.94	4.01	4.00	99.02
14	4.27	4.24	4.17	4.31	4.25	105.10
28	4.28	4.22	4.18		4.23	104.60

Table A26 Changes in DME in standard ASTM C 1260 tests using NM aggregate, low alkali cement

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	3.79	3.97	3.85	3.75	3.84	100.00
3	2.43	2.55	2.44	2.34	2.44	63.51
28	1.42	1.54	1.41	1.51	1.47	38.33

Table A27 Changes in DME in modified ASTM C 1260 tests using NM aggregate, low alkali cement and KAc 6.4

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.28	4.14	4.20	4.28	4.23	100.00
3	0.92	0.98	0.84	0.91	0.91	21.59
28	1.69	1.68	1.57	1.75	1.68	39.66

Table A28 Changes in DME in modified ASTM C 1260 tests using NM aggregate, low alkali cement and KAc 3.0

	Dynamic Young's Modulus, (E) * 10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	4.87	4.79	4.50	4.72	100.00
3	1.39	1.22	1.04	1.22	25.78
14	1.37	1.24		1.31	27.64
28	1.28	1.20		1.24	26.29

Table A29 Changes in DME in modified ASTM C 1260 tests using NM aggregate, low alkali cement and LiAc

	Dynamic Young's Modulus, (E) * 10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	4.67	4.57	4.40	4.55	100.00
3	4.91	4.81	4.52	4.75	104.33
14	4.63	4.49	4.24	4.45	97.85
28	4.08	4.39	3.73	4.07	89.35

Table A30 Changes in DME in modified ASTM C 1260 tests using NM aggregate, low alkali cement and Li/K 6.4-0.2

	Dynamic Young's Modulus, (E) * 10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	4.38	4.33	4.90	4.54	100.00
3	2.03	1.91	1.96	1.97	43.36
14	1.54	1.39	1.61	1.52	33.37
28	1.52	1.49	1.48	1.50	33.00

Table A31 Changes in DME in modified ASTM C 1260 tests using NM aggregate, low alkali cement and Li/K 3-0.2

	Dynamic Young's Modulus, (E) * 10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	4.99	4.57	5.00	4.85	100.00
3	2.68	3.21	2.71	2.87	59.09
14	1.34	1.22	0.90	1.15	23.80
28	1.29	0.75	1.18	1.07	22.12

Table A32 Changes in DME in modified ASTM C 1260 tests using NM aggregate, low alkali cement and Li/K 3-0.8

	Dynamic Young's Modulus, (E) * 10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	5.09	4.19	4.13	4.47	100.00
3	4.99	4.17	4.11	4.42	98.84
14	5.08	3.60	4.14	4.27	95.52
28	4.16	4.25	4.15	4.19	93.58

Table A33 Expansion readings and percentage expansions of the Standard ASTM C 1260 test for Spratt Limestone using High Alkali cement

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.151	0.4668	0.4857	0.4457	0.455	0	0	0	0	0
2	0.1513	0.4737	0.4922	0.452	0.4612	0.066	0.062	0.06	0.059	0.0618
4	0.1512	0.4816	0.4995	0.4592	0.4683	0.146	0.136	0.133	0.131	0.1365
6	0.1503	0.4861	0.5038	0.4634	0.4721	0.2	0.188	0.184	0.178	0.1875
8	0.1499	0.4892	0.5069	0.4661	0.4751	0.235	0.223	0.215	0.212	0.2213
10	0.1507	0.4938	0.5114	0.4706	0.4792	0.273	0.26	0.252	0.245	0.2575
12	0.1501	0.4977	0.5152	0.4742	0.4829	0.318	0.304	0.294	0.288	0.3010
14	0.151	0.5037	0.5206	0.4793	0.4881	0.369	0.349	0.336	0.331	0.3463
16	0.1511	0.5088	0.5257	0.4845	0.4934	0.419	0.399	0.387	0.383	0.3970
20	0.1511	0.5203	0.5302	0.4949	0.5038	0.534	0.444	0.491	0.487	0.4890
24	0.151	0.5333	tall	0.508	0.5172	0.665		0.623	0.622	0.6367
28	0.1499	tall	tall	0.5203	0.5299			0.757	0.76	0.7585
32	0.1501	tall	tall	0.5321	tall			0.873		0.8730

Table A34 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for Spratt Limestone using High Alkali cement and 3 MC of Potassium Acetate deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.005	0.3357	0.3083	0.3213	0.2784	0	0	0	0	0
3	0.0059	0.3397	0.3127	0.3254	0.2825	0.031	0.035	0.032	0.032	0.0325
7	0.0064	0.3438	0.3173	0.3293	0.2866	0.067	0.076	0.066	0.068	0.0693
11	0.0058	0.3488	0.3221	0.339	0.2917	0.123	0.13	0.169	0.125	0.1368
14	0.0056	0.3523	0.3257	0.3357	0.2949	0.16	0.168	0.138	0.159	0.1563
21	0.0064	0.3761	0.3496	0.3607		0.39	0.399	0.38		0.3897
28	0.0066	0.4033	0.3764	0.3873		0.66	0.665	0.644		0.6563

Table A35 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for Spratt Limestone using High Alkali cement and 6.4 MC of Potassium Acetate deicer

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.1504	0.4791	0.4698	0.4537	0	0	0	0
1	0.1503	0.4795	0.4701	0.454	0.005	0.004	0.004	0.0043
3	0.1504	0.4857	0.4766	0.4606	0.066	0.068	0.069	0.0677
5	0.1503	0.5024	0.4936	0.4777	0.234	0.239	0.241	0.2380
7	0.1498	0.5147	0.5065	0.4908	0.362	0.373	0.377	0.3707
9	0.15	0.5261	0.5178	0.502	0.474	0.484	0.487	0.4817
11	0.149	0.5331	0.5269	0.5114	0.554	0.585	0.591	0.5767
13	0.149		0.5353	0.5217		0.669	0.694	0.6815
15	0.1513			0.5351			0.805	0.8050
19	0.1513							
24	0.1528							
30	0.1527							

Table A36 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for Spratt Limestone using High Alkali cement and Lithium Acetate deicer

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0099	0.3072	0.2335	0.321	0	0	0	0
3	0.0093	0.3067	0.2329	0.3209	0.001	-2.776E-16	0.005	0.0020
7	0.0097	0.3074	0.2329	0.3221	0.004	-0.004	0.013	0.0043
11	0.0098	0.3088	0.2345	0.3232	0.017	0.011	0.023	0.0170
14	0.0095	0.3089	0.2349	0.3234	0.021	0.018	0.028	0.0223
21	0.0085	0.3086	0.234	0.3215	0.028	0.019	0.019	0.0220
28	0.0097	0.3093	0.2355	0.3229	0.023	0.022	0.021	0.0220

Table A37 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for Spratt Limestone using High Alkali cement and Li/K 3-0.2 deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.005	0.3127	0.3187	0.3064	0.2824	0	0	0	0	0
3	0.0059	0.3156	0.3216	0.3093	0.2853	0.02	0.02	0.02	0.02	0.0200
7	0.0064	0.3174	0.3234	0.311	0.2869	0.033	0.033	0.032	0.031	0.0323
11	0.0058	0.3176	0.3237	0.3112	0.2872	0.041	0.042	0.04	0.04	0.0408
14	0.0056	0.318	0.324	0.3118	0.2875	0.047	0.047	0.048	0.045	0.0468
21	0.0064	0.3191	0.3252	0.3128		0.05	0.051	0.05		0.0503
28	0.0066	0.32	0.3265	0.3138		0.057	0.062	0.058		0.0590

Table A38 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for Spratt Limestone using High Alkali cement and Li/K 3-0.4 deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.0064	0.3137	0.3768	0.29	0.3221	0	0	0	0	0
3	0.0056	0.3143	0.3772	0.2906	0.3226	0.014	0.012	0.014	0.013	0.0133
7	0.0057	0.3152	0.378	0.2915	0.3235	0.022	0.019	0.022	0.021	0.0210
11	0.0057	0.3156	0.3785	0.292	0.3239	0.026	0.024	0.027	0.025	0.0255
14	0.006	0.3163	0.3792	0.2925	0.3246	0.03	0.028	0.029	0.029	0.0290
21	0.0067	0.3172	0.3803	0.2935		0.032	0.032	0.032		0.0320
28	0.0058	0.3164	0.3795	0.2928		0.033	0.033	0.034		0.0333

Table A39 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for Spratt Limestone using High Alkali cement and Li/K 3-0.6 deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.0064	0.2783	0.3234	0.2914	0.3114	0	0	0	0	0
3	0.0056	0.2795	0.325	0.2927	0.3125	0.02	0.024	0.021	0.019	0.0210
7	0.0057	0.28	0.3256	0.2931	0.3131	0.024	0.029	0.024	0.024	0.0253
11	0.0057	0.2804	0.326	0.2933	0.3136	0.028	0.033	0.026	0.029	0.0290
14	0.006	0.2812	0.3266	0.294	0.314	0.033	0.036	0.03	0.03	0.0323
21	0.0067	0.282	0.3276	0.2951		0.034	0.039	0.034		0.0357
28	0.0058	0.2815	0.3267	0.2945		0.038	0.039	0.037		0.0380

Table A40 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for Spratt Limestone using High Alkali cement and Li/K 3-0.8 deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.0064	0.4082	0.3934	0.2939	0.3072	0	0	0	0	0
3	0.0056	0.4092	0.3944	0.2949	0.3081	0.018	0.018	0.018	0.017	0.0178
7	0.0057	0.4096	0.3949	0.2953	0.3088	0.021	0.022	0.021	0.023	0.0218
11	0.0057	0.4098	0.3951	0.2956	0.3092	0.023	0.024	0.024	0.027	0.0245
14	0.006	0.4109	0.396	0.2964	0.3098	0.031	0.03	0.029	0.03	0.0300
21	0.0067	0.4119	0.3969	0.2972		0.034	0.032	0.03		0.0320
28	0.0058	0.4113	0.3962	0.2965		0.037	0.034	0.032		0.0343

Table A41 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for Spratt Limestone using High Alkali cement and Li/K 6.4-0.2 deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.0051	0.3077	0.2884	0.3194	0.2561	0	0	0	0	0
3	0.0044	0.3085	0.2893	0.3209	0.2575	0.015	0.016	0.022	0.021	0.0185
7	0.0054	0.3113	0.2923	0.3232	0.2597	0.033	0.036	0.035	0.033	0.0342
11	0.0059	0.3138	0.2947	0.3254	0.2618	0.053	0.055	0.052	0.049	0.0522
14	0.005	0.3131	0.2942	0.3246	0.2612	0.055	0.059	0.053	0.052	0.0547
21	0.0058	0.3155	0.2967	0.3272		0.071	0.076	0.071		0.0727
28	0.006	0.3164	0.2973	0.3277		0.078	0.08	0.074		0.0773

Table A42 Expansion readings and percentage expansions of the Standard ASTM C 1260 test for Spratt Limestone using Low Alkali cement

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.1506	0.4539	0.4608	0.4529	0.4609	0	0	0	0	0
3	0.1512	0.4627	0.4704	0.4626	0.4701	0.082	0.09	0.091	0.086	0.0873
5	0.1503	0.4713	0.4797	0.4716	0.4778	0.177	0.192	0.19	0.172	0.1828
7	0.1499	0.4769	0.4857	0.4773	0.483	0.237	0.256	0.251	0.228	0.2430
9	0.1507	0.4818	0.4907	0.4824	0.4875	0.278	0.298	0.294	0.265	0.2838
11	0.1501	0.4855	0.4944	0.4861	0.4912	0.321	0.341	0.337	0.308	0.3268
13	0.151	0.4901	0.4989	0.4901	0.4959	0.358	0.377	0.368	0.346	0.3623
15	0.1511	0.4944	0.5032	0.4953	0.5001	0.4	0.419	0.419	0.387	0.4063
19	0.1512	0.5036	0.5117	0.5047	0.5089	0.491	0.503	0.512	0.474	0.4950
23	0.151	0.5143	0.5213	0.5156	0.5189	0.6	0.601	0.623	0.576	0.6000
27	0.1499	0.5249	0.5311	0.5278	0.5296	0.717	0.71	0.756	0.694	0.7193

Table A43 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for Spratt Limestone using Low Alkali cement and 6.4 MC of Potassium Acetate deicer

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.1504	0.4812	0.4415	0.4481	0	0	0	0
1	0.1503	0.4815	0.4418	0.4486	0.004	0.004	0.006	0.0047
3	0.1504	0.4838	0.4443	0.4511	0.026	0.028	0.03	0.0280
5	0.1503	0.4974	0.4577	0.4638	0.163	0.163	0.158	0.1613
7	0.1498	0.5101	0.4706	0.4769	0.295	0.297	0.294	0.2953
9	0.15	0.5193	0.48	0.4854	0.385	0.389	0.377	0.3837
11	0.149	0.5249	0.4855	0.4907	0.451	0.454	0.44	0.4483
13	0.149	0.5303	0.491	0.4965	0.505	0.509	0.498	0.5040
15	0.1513	0.5354	0.4965	0.502	0.533	0.541	0.53	0.5347
19	0.1513	0.54	0.504	0.5084	0.579	0.616	0.594	0.5963
24	0.1528		0.5147	0.5186		0.75	0.64	0.6950
30	0.1527		0.5244	0.5292		0.806	0.788	0.7970

Table A44 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for Spratt Limestone using Low Alkali cement and Lithium Acetate deicer

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0099	0.3441	0.3542	0.2927	0	0	0	0
3	0.0093	0.3428	0.352	0.2919	-0.007	-0.016	-0.002	-0.0083
7	0.0095	0.3442	0.35269	0.2924	0.005	-0.0111	0.001	-0.0017
11	0.0098	0.3449	0.3536	0.2934	0.009	-0.005	0.008	0.0040
14	0.0095	0.3451	0.354	0.293	0.014	0.002	0.007	0.0077
21	0.0089	0.3438	0.3532	0.2918	0.007	0	0.001	0.0027
28	0.0097	0.3434	0.3543	0.294	-0.005	0.003	0.015	0.0043

Table A45 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for Spratt Limestone using Low Alkali cement and Li/K 3-0.2 deicer

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0099	0.2115	0.323	0.2894	0	0	0	0
3	0.0099	0.2116	0.3228	0.289	0.001	-0.002	-0.004	-0.0017
7	0.0093	0.2122	0.324	0.2905	0.013	0.016	0.017	0.0153
11	0.0098	0.2133	0.325	0.2911	0.019	0.021	0.018	0.0193
14	0.0095	0.214	0.3254	0.2914	0.029	0.028	0.024	0.0270
21	0.0087	0.2133	0.3246	0.2914	0.03	0.028	0.032	0.0300
28	0.0103	0.2147	0.3264	0.293	0.028	0.03	0.032	0.0300

Table A46 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for Spratt Limestone using Low Alkali cement and Li/K 3-0.8 deicer

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0099	0.3343	0.3309	0.3152	0	0	0	0
3	0.0099	0.3349	0.3315	0.3156	0.006	0.006	0.004	0.0053
7	0.0095	0.3354	0.3316	0.3152	0.015	0.011	0.004	0.0100
11	0.0098	0.336	0.3375	0.3168	0.018	0.067	0.017	0.0340
14	0.0095	0.336	0.3324	0.3166	0.021	0.019	0.018	0.0193
21	0.0087	0.335	0.3308	0.3154	0.019	0.011	0.014	0.0147
28	0.0097	0.3363	0.332	0.3175	0.022	0.013	0.025	0.0200

Table A47 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for Spratt Limestone using Low Alkali cement and Li/K 6.4-0.2 deicer

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0099	0.3443	0.2584	0.3446	0	0	0	0
3	0.0099	0.3447	0.2595	0.3461	0.004	0.011	0.015	0.0100
7	0.0095	0.3456	0.2597	0.3464	0.017	0.017	0.022	0.0187
11	0.0098	0.3481	0.2615	0.3488	0.039	0.032	0.043	0.0380
14	0.0095	0.3488	0.2617	0.3498	0.049	0.037	0.056	0.0473
21	0.0089	0.348	0.2618	0.349	0.047	0.044	0.054	0.0483
28	0.0103	0.3495	0.264	0.3509	0.048	0.052	0.059	0.0530

Table A48 Changes in DME in standard ASTM C 1260 tests using Spratt aggregate, high alkali cement

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	3.84	3.91	3.97	3.74	3.87	100.00
13	3.82	3.90	3.93	3.72	3.84	99.42
21	3.22	3.35	3.38	3.16	3.28	84.79
28	2.56	2.73	2.70	2.50	2.62	67.81

Table A49 Changes in DME in modified ASTM C 1260 tests using Spratt aggregate, high alkali cement and KAc 6.4

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.19	4.09	4.09	4.03	4.10	100.00
13	2.71	2.39	2.58	2.42	2.53	61.61
21	1.58	1.49	1.54	1.47	1.52	37.08
28	0.92	0.89	0.91	0.89	0.90	22.07

Table A50 Changes in DME in modified ASTM C 1260 tests using Spratt aggregate, high alkali cement and KAc 3.0

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.01	4.03	4.20	4.08	4.08	100.00
3	4.08	4.08	4.27	4.23	4.16	102.09
14	3.87	3.84	4.10	4.03	3.96	97.02
28	2.56	2.58	2.79		2.64	64.78

Table A51 Changes in DME in modified ASTM C 1260 tests using Spratt aggregate, high alkali cement and LiAc

	Dynamic Young's Modulus, (E) * 10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	3.97	4.28	3.93	4.06	100.00
3	4.32	4.57	4.22	4.37	107.48
14	4.16	4.45	4.09	4.24	104.20
28	4.11	4.06	3.91	4.03	99.09

Table A52 Changes in DME in modified ASTM C 1260 tests using Spratt aggregate, high alkali cement and Li/K 6.4-0.2

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.33	4.46	3.98	4.21	4.24	100.00
3	4.52	4.54	4.08	4.34	4.37	103.01
14	4.63	4.56	4.27	4.48	4.49	105.73
28	4.71	4.61	4.39		4.57	107.65

Table A53 Changes in DME in modified ASTM C 1260 tests using Spratt aggregate, high alkali cement and Li/K 3-0.2

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.24	4.27	4.19	3.98	4.17	100.00
3	4.34	4.35	4.30	4.15	4.28	102.70
14	4.49	4.50	4.44	4.28	4.43	106.09
28	4.49	4.41	4.37		4.42	106.08

Table A54 Changes in DME in modified ASTM C 1260 tests using Spratt aggregate, high alkali cement and Li/K 3-0.4

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	3.65	4.04	3.83	3.82	3.84	100.00
3	3.79	4.17	3.85	3.95	3.94	102.72
14	3.95	4.25	3.68	4.09	3.99	104.12
28	4.00	4.28	4.06	0.00	4.11	107.24

Table A55 Changes in DME in modified ASTM C 1260 tests using Spratt aggregate, high alkali cement and Li/K 3-0.6

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	3.92	3.77	3.51	3.89	3.77	100.00
3	3.99	3.82	3.64	4.10	3.89	102.95
14	4.12	3.97	3.76	4.16	4.00	106.07
28	4.12	3.95	3.74		3.94	104.36

Table A56 Changes in DME in modified ASTM C 1260 tests using Spratt aggregate, high alkali cement and Li/K 3-0.8

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	3.72	3.92	3.65	3.76	3.76	100.00
3	3.84	4.00	3.74	3.83	3.85	102.40
14	4.05	4.14	3.84	4.04	4.02	106.78
28	3.98	4.15	3.86		3.99	106.15

Table A57 Changes in DME in standard ASTM C 1260 tests using Spratt aggregate, low alkali cement

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.29	4.31	4.17	4.21	4.24	100.00
13	4.21	4.22	4.12	4.12	4.17	98.16
21	3.85	3.80	3.72	3.74	3.78	89.06
28	3.26	3.21	3.12	2.97	3.14	73.96

Table A58 Changes in DME in modified ASTM C 1260 tests using Spratt aggregate, low alkali cement and KAc 6.4

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	3.90	4.10	4.04	4.08	4.03	100.00
13	2.32	2.67	2.60	2.54	2.53	62.81
21	2.15	2.42	2.19	2.23	2.25	55.72
28	2.01	2.27	2.19	2.12	2.15	53.35

Table A59 Changes in DME in modified ASTM C 1260 tests using Spratt aggregate, low alkali cement and LiAc

	Dynamic Young's Modulus, (E) * 10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	4.13	4.23	4.35	4.24	100.00
3	4.36	4.51	4.52	4.46	105.39
14	4.31	4.43	4.39	4.38	103.32
28	4.04	4.28	4.19	4.17	98.39

Table A60 Changes in DME in modified ASTM C 1260 tests using Spratt aggregate, low alkali cement and Li/K 6.4-0.2

	Dynamic Young's Modulus, (E) * 10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	4.56	4.63	4.39	4.53	100.00
3	4.76	4.80	4.51	4.69	103.67
14	4.79	4.71	4.53	4.68	103.35
28	4.61	4.45	4.36	4.47	98.87

Table A61 Changes in DME in modified ASTM C 1260 tests using Spratt aggregate, low alkali cement and Li/K 3-0.2

	Dynamic Young's Modulus, (E) * 10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	4.46	3.65	4.03	4.05	100.00
3	4.63	4.45	4.26	4.44	109.80
14	4.69	4.46	4.31	4.49	110.84
28	4.49	4.26	4.24	4.33	106.92

Table A62 Changes in DME in modified ASTM C 1260 tests using Spratt aggregate, low alkali cement and Li/K 3-0.8

	Dynamic Young's Modulus, (E) * 10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	4.45	4.25	4.35	4.35	100.00
3	4.62	4.33	4.44	4.46	102.55
14	4.64	4.43	4.49	4.52	103.82
28	4.17	4.13	4.23	4.17	95.92

Table A63 Expansion readings and percentage expansions of the Standard ASTM C 1260 test for NC aggregate using High Alkali cement

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.14	0.3767	0.4485	0.4548	0.4315	0	0	0	0	0
3	0.1401	0.3892	0.4614	0.4675	0.4446	0.124	0.128	0.126	0.13	0.1270
7	0.1403	0.4105	0.4831	0.4899	0.4675	0.335	0.343	0.348	0.357	0.3458
10	0.1403	0.4189	0.4915	0.4982	0.4757	0.419	0.427	0.431	0.439	0.4290
14	0.1402	0.4273	0.5002	0.5072	0.4847	0.504	0.515	0.522	0.53	0.5178
21	0.1406	0.4402	0.5108	TALL	0.4975	0.629	0.617	TALL	0.654	0.6333
28	0.011	0.3215	0.3942	0.4031	0.3801	0.738	0.747	0.773	0.776	0.7585

Table A64 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for NC aggregate using High Alkali cement and 3 MC of Potassium Acetate deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.005	0.3091	0.3285	0.2873	0.3186	0	0	0	0	0
3	0.0059	0.3131	0.3316	0.2902	0.3175	0.031	0.022	0.02	-0.02	0.0132
7	0.0064	0.3171	0.3362	0.2947	0.3218	0.066	0.063	0.06	0.018	0.0517
11	0.0058	0.3281	0.3488	0.3069	0.3329	0.182	0.195	0.188	0.135	0.1750
14	0.0056	0.3377	0.359	0.3168	0.3422	0.28	0.299	0.289	0.23	0.2745
21	0.0064	0.3894	0.4117	0.3678		0.789	0.818	0.791		0.7993
28	0.0066	0.4246	0.4476	0.4027		1.139	1.175	1.138		1.1507

Table A65 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for NC aggregate using High Alkali cement and 6.4 MC of Potassium Acetate deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.14	0.447	0.4478	0.412	0.4209	0	0	0	0	0
3	0.1401	0.4516	0.4523	0.4162	0.4254	0.045	0.044	0.041	0.044	0.0435
7	0.1403	0.4847	0.4879	0.45	0.4591	0.374	0.398	0.377	0.379	0.3820
10	0.1403	0.5032	0.5027	0.4634	0.4727	0.559	0.546	0.511	0.515	0.5328
14	0.1402	0.5062	0.5061	0.4666	0.4761	0.59	0.581	0.544	0.55	0.5663
21	0.1406	0.5091	0.5093	0.4692	0.4788	0.615	0.609	0.566	0.573	0.5908
28	0.011	0.3813	0.3817	0.3416	0.3511	0.633	0.629	0.586	0.592	0.6100

Table A66 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for NC aggregate using High Alkali cement and Li/K 3-0.2 deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.005	0.3262	0.3203	0.285	0.2905	0	0	0	0	0
3	0.0059	0.3291	0.3231	0.2879	0.2934	0.02	0.019	0.02	0.02	0.0198
7	0.0064	0.3305	0.3247	0.2895	0.295	0.029	0.03	0.031	0.031	0.0303
11	0.0058	0.3309	0.3249	0.2896	0.295	0.039	0.038	0.038	0.037	0.0380
14	0.0056	0.3312	0.3253	0.29	0.2953	0.044	0.044	0.044	0.042	0.0435
21	0.0064	0.332	0.3264	0.2911		0.044	0.047	0.047		0.0460
28	0.0066	0.333	0.3273	0.2919		0.052	0.054	0.053		0.0530

Table A67 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for NC aggregate using High Alkali cement and Li/K 3-0.4 deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.0064	0.2679	0.3193	0.315	0.2984	0	0	0	0	0
3	0.0056	0.2673	0.3191	0.3144	0.2977	0.002	0.006	0.002	0.001	0.0028
7	0.0059	0.269	0.3207	0.3159	0.2997	0.016	0.019	0.014	0.018	0.0168
11	0.006	0.2696	0.3212	0.3165	0.3	0.021	0.023	0.019	0.02	0.0208
14	0.006	0.2697	0.3213	0.3165	0.3001	0.022	0.024	0.019	0.021	0.0215
21	0.0067	0.2706	0.3223	0.3175		0.024	0.027	0.022		0.0243
28	0.0057	0.2697	0.3215	0.3168		0.025	0.029	0.025		0.0263

Table A68 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for NC aggregate using High Alkali cement and Li/K 3-0.6 deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.0064	0.2991	0.3039	0.2737	0.3067	0	0	0	0	0
3	0.0056	0.2991	0.3038	0.2737	0.3065	0.008	0.007	0.008	0.006	0.0073
7	0.0059	0.3006	0.3054	0.2753	0.3082	0.02	0.02	0.021	0.02	0.0203
11	0.006	0.301	0.3057	0.2755	0.3083	0.023	0.022	0.022	0.02	0.0218
14	0.006	0.301	0.3058	0.2757	0.3083	0.023	0.023	0.024	0.02	0.0225
21	0.0067	0.3018	0.3066	0.2766		0.024	0.024	0.026		0.0247
28	0.0057	0.3011	0.3058	0.2759		0.027	0.026	0.029		0.0273

Table A69 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for NC aggregate using High Alkali cement and Li/K 3-0.8 deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.0064	0.3454	0.309	0.2874	0.3184	0	0	0	0	0
3	0.0056	0.3459	0.3094	0.2878	0.3188	0.013	0.012	0.012	0.012	0.0123
7	0.0059	0.3474	0.3111	0.2895	0.3199	0.025	0.026	0.026	0.02	0.0243
11	0.006	0.3478	0.3113	0.2896	0.3208	0.028	0.027	0.026	0.028	0.0273
14	0.006	0.3479	0.3113	0.2896	0.3208	0.029	0.027	0.026	0.028	0.0275
21	0.0067	0.3488	0.3122	0.2905		0.031	0.029	0.028		0.0293
28	0.0057	0.3477	0.3113	0.2896		0.03	0.03	0.029		0.0297

Table A70 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for NC aggregate using High Alkali cement and Li/K 6.4-0.2 deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.0051	0.3097	0.3211	0.2821	0.2941	0	0	0	0	0
3	0.0044	0.3119	0.3232	0.2842	0.2962	0.029	0.028	0.028	0.028	0.0282
7	0.0047	0.3135	0.3252	0.2862	0.298	0.042	0.045	0.045	0.043	0.0438
11	0.0059	0.3156	0.3267	0.2876	0.2998	0.051	0.048	0.047	0.049	0.0487
14	0.005	0.315	0.3259	0.2871	0.2991	0.054	0.049	0.051	0.051	0.0513
21	0.0058	0.3161	0.3275	0.2881		0.057	0.057	0.053		0.0557
28	0.006	0.3166	0.3279	0.2884		0.06	0.059	0.054		0.0577

Table A71 Changes in DME in standard ASTM C 1260 tests using NC aggregate, high alkali cement

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.39	4.19	4.15	4.16	4.22	100.00
3	3.76	3.57	3.50	3.53	3.59	84.97
7	3.33	3.24	3.17	3.17	3.23	76.39
14	3.07	2.97	2.90	2.89	2.96	70.01
21	2.81	2.76	2.68	2.66	2.73	64.56
28	2.63	2.59	2.51	2.50	2.56	60.49

Table A72 Changes in DME in modified ASTM C 1260 tests using NC aggregate, high alkali cement and KAc 6.4

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	3.80	4.19	4.30	4.23	4.13	100.00
3	3.77	4.19	4.28	4.18	4.11	99.42
7	2.15	2.37	2.55	2.37	2.36	57.12
14	2.13	2.19	2.46	2.35	2.28	55.27
21	2.12	2.31	2.50	2.25	2.30	55.65
28	2.14	2.31	2.60	2.34	2.35	56.88

Table A73 Changes in DME in modified ASTM C 1260 tests using NC aggregate, high alkali cement and KAc 3.0

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.31	4.13	4.26	4.23	4.23	100.00
3	4.41	4.22	4.32	4.32	4.32	102.05
14	3.11	2.89	2.96	3.04	3.00	70.90
28	1.89	1.76	1.89		1.85	43.66

Table A74 Changes in DME in modified ASTM C 1260 tests using NC aggregate, high alkali cement and Li/K 6.4-0.2

6.4-0.2	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.23	4.23	4.26	4.32	4.26	100.00
3	4.29	4.25	4.29	4.45	4.32	101.38
14	4.47	4.33	4.53	4.60	4.48	105.18
28	4.59	4.51	4.58		4.56	106.95

Table A75 Changes in DME in modified ASTM C 1260 tests using NC aggregate, high alkali cement and Li/K 3-0.2

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.43	4.27	4.31	4.21	4.30	100.00
3	4.46	4.41	4.47	4.32	4.41	102.54
14	4.66	4.55	4.62	4.53	4.59	106.60
28	4.56	4.48	4.53		4.52	105.13

Table A76 Changes in DME in modified ASTM C 1260 tests using NC aggregate, high alkali cement and Li/K 3-0.4

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.38	4.44	4.44	4.33	4.40	100.00
3	4.41	4.49	4.43	4.32	4.41	100.38
14	4.60	4.63	4.67	4.58	4.62	105.07
28	4.68	4.72	4.68	0.00	4.69	106.67

Table A77 Changes in DME in modified ASTM C 1260 tests using NC aggregate, high alkali cement and Li/K 3-0.6

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.53	4.50	4.43	4.59	4.51	100.00
3	4.53	4.49	4.48	4.61	4.53	100.38
14	4.82	4.76	4.74	4.84	4.79	106.21
28	4.85	4.75	4.74		4.78	106.03

Table A78 Changes in DME in modified ASTM C 1260 tests using NC aggregate, high alkali cement and Li/K 3-0.8

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.41	4.55	4.69	4.33	4.49	100.00
3	4.38	4.59	4.65	4.36	4.49	100.03
14	4.64	4.82	4.95	4.55	4.74	105.51
28	4.61	4.82	4.87		4.77	106.07

Table A79 Expansion readings and percentage expansions of the Standard ASTM C 1260 test for SD aggregate using High Alkali cement

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.1402	0.454	0.4434	0.424	0.4514	0	0	0	0	0
3	0.14	0.4578	0.4472	0.4279	0.4553	0.04	0.04	0.041	0.041	0.0405
7	0.1404	0.4659	0.4553	0.4356	0.463	0.117	0.117	0.114	0.114	0.1155
10	0.1406	0.4717	0.4611	0.4409	0.4684	0.173	0.173	0.165	0.166	0.1693
14	0.141	0.4773	0.4677	0.4472	0.4748	0.225	0.235	0.224	0.226	0.2275
21	0.0754	0.4222	0.4128	0.3914	0.4193	0.33	0.342	0.322	0.327	0.3303
28	0.0118	0.3668	0.3577	0.3361	0.3639	0.412	0.427	0.405	0.409	0.4133

Table A80 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for SD aggregate using High Alkali cement and 3 MC of Potassium Acetate deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.0054	0.2916	0.3108	0.2877	0.3008	0	0	0	0	0
3	0.0059	0.2943	0.3133	0.2903	0.3032	0.022	0.02	0.021	0.019	0.0205
7	0.0064	0.2984	0.3175	0.2945	0.3076	0.058	0.057	0.058	0.058	0.0577
11	0.0058	0.3016	0.3207	0.2982	0.3108	0.096	0.095	0.101	0.096	0.0970
14	0.0056	0.3038	0.3228	0.3005	0.3129	0.12	0.118	0.126	0.119	0.1208
21	0.0064	0.3118	0.3311	0.3092		0.192	0.193	0.205		0.1967
28	0.0067	0.32	0.3399	0.3185		0.271	0.278	0.295		0.2813

Table A81 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for SD aggregate using High Alkali cement and 6.4 MC of Potassium Acetate deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.1402	0.4261	0.415	0.44	0.4288	0	0	0	0	0
3	0.14	0.4298	0.4186	0.4438	0.4326	0.039	0.038	0.04	0.04	0.0392
7	0.1404	0.4444	0.4327	0.4575	0.4469	0.181	0.175	0.173	0.179	0.1770
10	0.1406	0.4563	0.445	0.4708	0.4593	0.298	0.296	0.304	0.301	0.2998
14	0.141	0.4645	0.4536	0.4802	0.4687	0.376	0.378	0.394	0.391	0.3848
21	0.0754	0.4025	0.3919	0.4189	0.4069	0.412	0.417	0.437	0.429	0.4238
28	0.0118	0.3408	0.3301	0.3573	0.3452	0.431	0.435	0.457	0.448	0.4428

Table A82 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for SD aggregate using High Alkali cement and Li/K 3-0.2 deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.0054	0.2747	0.3068	0.307	0.2918	0	0	0	0	0
3	0.0059	0.2784	0.3102	0.3103	0.2954	0.032	0.029	0.028	0.031	0.0300
7	0.0064	0.2794	0.3113	0.3116	0.2964	0.037	0.035	0.036	0.036	0.0360
11	0.0058	0.2797	0.3115	0.3118	0.2962	0.046	0.043	0.044	0.04	0.0433
14	0.0056	0.2804	0.3119	0.3124	0.2968	0.055	0.049	0.052	0.048	0.0510
21	0.0064	0.281	0.3127	0.3133		0.053	0.049	0.053		0.0517
28	0.0066	0.2819	0.3138	0.314		0.06	0.058	0.058		0.0587

Table A83 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for SD aggregate using High Alkali cement and Li/K 3-0.4 deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.0064	0.4726	0.2911	0.3235	0.3121	0	0	0	0	0
3	0.0056	0.4729	0.2909	0.323	0.3122	0.011	0.006	0.003	0.009	0.0073
7	0.0059	0.4734	0.2914	0.3235	0.3132	0.013	0.008	0.005	0.016	0.0105
11	0.006	0.4749	0.2929	0.325	0.3144	0.027	0.022	0.019	0.027	0.0238
14	0.006	0.475	0.293	0.325	0.3144	0.028	0.023	0.019	0.027	0.0243
21	0.0067	0.4756	0.2938	0.3259		0.027	0.024	0.021		0.0240
28	0.0058	0.4746	0.293	0.325		0.026	0.025	0.021		0.0240

Table A84 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for SD aggregate using High Alkali cement and Li/K 3-0.6 deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.0064	0.423	0.3789	0.3243	0.3075	0	0	0	0	0
3	0.0056	0.4238	0.3796	0.3251	0.3082	0.016	0.015	0.016	0.015	0.0155
7	0.0059	0.4243	0.3802	0.3257	0.3091	0.018	0.018	0.019	0.021	0.0190
11	0.006	0.4256	0.3816	0.3273	0.31	0.03	0.031	0.034	0.029	0.0310
14	0.006	0.4256	0.3812	0.3271	0.3101	0.03	0.027	0.032	0.03	0.0298
21	0.0067	0.4263	0.3824	0.328		0.03	0.032	0.034		0.0320
28	0.0058	0.4254	0.3815	0.328		0.03	0.032	0.043		0.0350

Table A85 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for SD aggregate using High Alkali cement and Li/K 3-0.8 deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.0064	0.2197	0.307	0.3128	0.3059	0	0	0	0	0
3	0.0051	0.2188	0.3059	0.3119	0.3042	0.004	0.002	0.004	-0.004	0.0015
7	0.0059	0.2196	0.307	0.3128	0.3058	0.004	0.005	0.005	0.004	0.0045
11	0.006	0.2207	0.3077	0.3137	0.3064	0.014	0.011	0.013	0.009	0.0117
14	0.006	0.2204	0.3076	0.3138	0.3065	0.011	0.01	0.014	0.01	0.0113
21	0.0067	0.2215	0.3087	0.3146		0.015	0.014	0.015		0.0147
28	0.0058	0.2208	0.3079	0.3138		0.017	0.015	0.016		0.0160

Table A86 Expansion readings and percentage expansions of the Modified ASTM C 1260 test for SD aggregate using High Alkali cement and Li/K 6.4-0.2 deicer

	Comparator readings					Expansion, %				
Days	Ref bar	Bar1	Bar2	Bar3	Bar4	Bar1	Bar2	Bar3	Bar4	Avg
0	0.0051	0.3092	0.2761	0.2995	0.2875	0	0	0	0	0
3	0.0044	0.3101	0.277	0.3005	0.2885	0.016	0.016	0.017	0.017	0.0165
7	0.0054	0.3116	0.2788	0.3023	0.2905	0.021	0.024	0.025	0.027	0.0242
11	0.0059	0.313	0.2801	0.3039	0.2921	0.03	0.032	0.036	0.038	0.0340
14	0.005	0.312	0.2794	0.3028	0.2912	0.029	0.034	0.034	0.038	0.0338
21	0.0058	0.3138	0.2808	0.3042		0.039	0.04	0.04		0.0397
28	0.006	0.3136	0.2809	0.3045		0.035	0.039	0.041		0.0383

Table A87 Changes in DME in standard ASTM C 1260 tests using SD aggregate, high alkali cement

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.04	4.42	4.28	4.32	4.26	100.00
3	3.44	3.79	3.68	3.73	3.66	85.80
14	2.83	3.09	2.99	2.95	2.96	69.46
21	2.72	2.95	2.90	2.96	2.88	67.58
28	2.65	2.89	2.87	2.84	2.81	65.91

Table A88 Changes in DME in modified ASTM C 1260 tests using SD aggregate, high alkali cement and KAc 6.4

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.37	4.38	4.57	4.23	4.39	100.00
3	4.13	4.19	4.39	4.08	4.20	95.65
14	2.97	3.09	3.17	3.02	3.06	69.79
21	3.26	3.30	3.32	3.21	3.27	74.57
28	3.34	3.46	3.49	3.36	3.41	77.82

Table A89 Changes in DME in modified ASTM C 1260 tests using SD aggregate, high alkali cement and KAc 3.0

3	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.18	4.57	4.50	4.16	4.35	100.00
3	4.36	4.64	4.61	4.31	4.48	102.95
14	4.01	4.25	4.19	3.87	4.08	93.78
28	3.57	3.84	3.82		3.74	86.04

Table A90 Changes in DME in modified ASTM C 1260 tests using SD aggregate, high alkali cement and Li/K 6.4-0.2

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.75	4.49	4.31	4.48	4.50	100.00
3	4.75	4.45	4.28	4.47	4.49	99.66
14	5.05	4.77	4.60	4.77	4.80	106.54
28	5.08	4.84	4.61		4.84	107.53

Table A91 Changes in DME in modified ASTM C 1260 tests using SD aggregate, high alkali cement and Li/K 3-0.2

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.61	3.98	4.54	4.20	4.33	100.00
3	4.54	4.04	4.55	4.23	4.34	100.15
28	4.66	4.13	4.36		4.38	101.19

Table A92 Changes in DME in modified ASTM C 1260 tests using SD aggregate, high alkali cement and Li/K 3-0.4

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.56	4.51	4.30	4.49	4.46	100.00
3	4.51	4.29	4.37	4.55	4.43	99.21
14	4.76	4.60	4.47	4.69	4.63	103.76
28	4.86	4.72	4.52	0.00	4.70	105.19

Table A93 Changes in DME in modified ASTM C 1260 tests using SD aggregate, high alkali cement and Li/K 3-0.6

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.67	4.47	4.47	4.48	4.52	100.00
3	4.51	4.51	4.43	4.42	4.46	98.75
14	4.74	4.74	4.72	4.64	4.71	104.23
28	4.75	4.74	4.74		4.74	104.88

Table A94 Changes in DME in modified ASTM C 1260 tests using SD aggregate, high alkali cement and Li/K 3-0.8

	Dynamic Young's Modulus, (E) * 10^6					% Change in DME
Days	Bar1	Bar2	Bar3	Bar4	Avg	
0	4.50	4.48	4.56	4.48	4.50	100.00
3	4.50	4.48	4.56	4.48	4.50	100.00
14	4.83	4.73	4.83	4.71	4.77	106.01
28	4.80	4.74	4.82		4.79	106.34

Table A95 pH Changes in soak solution in Modified ASTM C 1260 tests at 0 day

Soak Solution	NM		SP		NC		SD	
	PH	Temp,° C	PH	Temp,° C	PH	Temp,° C	PH	Temp,° C
3- 0	10.19	23.2	10	23.1	10.05	23.1	9.98	23.3
3-0.2	9.27	23.2	9.32	23.2	8.49	23.1	9.1	23.2
3-0.4	8.39	23.7	8.45	23.8	8.45	23.8	8.39	23.7
3-0.6	8.43	23.8	8.44	23.8	8.44	23.8	8.43	23.8
3-0.8	8.5	23.9	8.51	23.8	8.51	23.8	8.5	23.9

Table A96 pH Changes in soak solution in Modified ASTM C 1260 tests at 28 days

Soak Solution	NM		SP		NC		SD	
	PH	Temp,° C	PH	Temp,° C	PH	Temp,° C	PH	Temp,° C
3- 0	13.55	21.3	13.64	21.6	13.63	21.4	13.59	21.8
3-0.2	13.29	21.7	13.37	21.7	13.44	21.5	13.38	21.8
3-0.4	13.07	21.4	13.1	21.1	13.03	21.3	13.12	21.3
3-0.6	13.01	21.3	13.01	21	12.98	21.2	13	21.3
3-0.8	12.87	21.2	12.92	21.1	12.89	21.3	12.93	21.3

Table A97 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with NM aggregate, high alkali cement and soaked in 1N NaOH solution

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0019	0.3723	0.3444	0.3478	0	0	0	0
7	0.0006	0.3724	0.3441	0.3475	0.014	0.01	0.01	0.0113
28	0.0038	0.3803	0.3518	0.3547	0.061	0.055	0.05	0.0553
90	0.0015	0.3869	0.36	0.3605	0.15	0.16	0.131	0.1470
120	0.0151	0.4037	0.3776	0.3767	0.182	0.2	0.157	0.1797
150	0.0045	0.3943	0.368	0.3672	0.194	0.21	0.168	0.1907
180	0.0056	0.3978	0.3731	0.3706	0.218	0.25	0.191	0.2197
270	0.0055	0.402	0.3773	0.3742	0.261	0.293	0.228	0.2607
360	0.0058	0.4073	0.3838	0.3784	0.311	0.355	0.267	0.3110

Table A98 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with NM aggregate, high alkali cement and soaked in 3 MC of KAc solution

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0052	0.2193	0.3584	0.3391	0	0	0	0
7	0.0052	0.2216	0.3602	0.3412	0.023	0.018	0.021	0.0207
28	0.0051	0.2346	0.3763	0.3559	0.154	0.18	0.169	0.1677
56	0.0051	0.2545	0.3948	0.3767	0.353	0.365	0.377	0.3650
90	0.0055	0.2702	0.412	0.399	0.506	0.533	0.596	0.5450
120	0.0061	0.2867	0.4283	0.4077	0.665	0.69	0.677	0.6773
180	0.0094	0.3212	0.4601	0.4394	0.977	0.975	0.961	0.9710
270	0.0097	0.3676	0.5043	0.477	1.438	1.414	1.334	1.3953
360	0.0093	0.4105	0.5466	0.515	1.871	1.841	1.718	1.8100

Table A99 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with NM aggregate, high alkali cement and soaked in 6.4 MC of KAc solution

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0019	0.344	0.3194	0.3677	0	0	0	0
7	0.0006	0.3444	0.3197	0.3672	0.017	0.016	0.008	0.0137
28	0.0038	0.361	0.3363	0.3842	0.151	0.15	0.146	0.1490
90	0.0015	0.4144	0.3966	0.4399	0.708	0.776	0.726	0.7367
120	0.0151	0.5147	0.4951	0.5156	1.575	1.625	1.347	1.5157
150	badly cracked, cant take readings							
180								
270								
360								

Table A100 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with NM aggregate, high alkali cement and soaked in 6.4 MC of KAc solution with Li/K ratio of 0.2

	Comparator readings				Expansion, %			
Date	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0052	0.2372	0.3265	0.3069	0	0	0	0
7	0.0052	0.2388	0.3267	0.308	0.016	0.002	0.011	0.0097
28	0.0051	0.2507	0.3362	0.3184	0.136	0.098	0.116	0.1167
56	0.0051	0.2713	0.3564	0.3382	0.342	0.3	0.314	0.3187
90	0.0057	0.2888	0.3729	0.3569	0.511	0.459	0.495	0.4883
120	0.0061	0.3099	0.3949	0.3819	0.718	0.675	0.741	0.7113
180	0.0094	0.3889	0.4737		1.475	1.43		1.4525
270	0.0097	0.4881	0.5711		2.464	2.401		2.4325
360	badly cracked, cant take readings							

Table A101 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with NM aggregate, high alkali cement and soaked in 3 MC of KAc solution with Li/K ratio of 0.2

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0052	0.2921	0.3239	0.2263	0	0	0	0
7	0.0052	0.2939	0.3245	0.2279	0.018	0.006	0.016	0.0133
28	0.0051	0.3054	0.3279	0.2393	0.134	0.041	0.131	0.1020
56	0.0051	0.3258	0.3494	0.2578	0.338	0.256	0.316	0.3033
90	0.0057	0.341	0.3675	0.274	0.484	0.431	0.472	0.4623
120	0.0061	0.3565	0.3845	0.2883	0.635	0.597	0.611	0.6143
180	0.0094	0.3874	0.4175	0.325	0.911	0.894	0.945	0.9167
270	0.0097	0.4224	0.4548	0.3654	1.258	1.264	1.346	1.2893
360	0.0093	0.4518	0.4855	0.3937	1.556	1.575	1.633	1.5880

Table A102 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with NM aggregate, high alkali cement and soaked in 3 MC of KAc solution with Li/K ratio of 0.8

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0052	0.4314	0.2867	0.2998	0	0	0	0
7	0.0052	0.432	0.2873	0.3009	0.006	0.006	0.011	0.0077
28	0.0051	0.4384	0.295	0.314	0.071	0.084	0.143	0.0993
56	0.0051	0.4556	0.3082	0.3276	0.243	0.216	0.279	0.2460
90	0.0057	0.4656	0.3166	0.3361	0.337	0.294	0.358	0.3297
120	0.0061	0.47	0.3209	0.3406	0.377	0.333	0.399	0.3697
180	0.0094	0.4775	0.3282	0.3484	0.419	0.373	0.444	0.4120
270	0.0097	0.4807	0.3313	0.3518	0.448	0.401	0.475	0.4413
360	0.0093	0.489	0.3521	0.353	0.535	0.613	0.491	0.5463

Table A103 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with NM aggregate, low alkali cement and soaked in 1N NaOH solution

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.002	0.2679	0.3378	0.2623	0	0	0	0
7	0.0016	0.2676	0.3373	0.262	0.001	-0.001	0.001	0.0003
28	0.003	0.2667	0.3365	0.2613	-0.022	-0.023	-0.02	-0.0217
56	0.0027	0.2689	0.3388	0.2637	0.003	0.003	0.007	0.0043
90	0.002	0.2696	0.3397	0.2643	0.017	0.019	0.02	0.0187
120	0.0207	0.2891	0.3593	0.284	0.025	0.028	0.03	0.0277
150	0.0061	0.2757	0.3461	0.2708	0.037	0.042	0.044	0.0410
180	0.0059	0.2774	0.3485	0.2729	0.056	0.068	0.067	0.0637
270	0.0055	0.2832	0.356	0.2807	0.118	0.147	0.149	0.1380
360	0.0051	0.2918	0.3631	0.2887	0.208	0.222	0.233	0.2210

Table A104 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with NM aggregate, low alkali cement and soaked in 3 MC of KAc solution

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0049	0.2333	0.1743	0.3026	0	0	0	0
7	0.0051	0.2326	0.1735	0.3023	-0.009	-0.01	-0.005	-0.0080
28	0.0051	0.2331	0.1737	0.3026	-0.004	-0.008	-0.002	-0.0047
56	0.0096	0.2418	0.182	0.3106	0.038	0.03	0.033	0.0337
90	0.0098	0.2486	0.1943	0.3188	0.104	0.151	0.113	0.1227
180	0.01	0.2834	0.2383	0.3513	0.45	0.589	0.436	0.4917
270	0.0093	0.3113	0.2724	0.3753	0.736	0.937	0.683	0.7853
360	0.0091	0.339	0.2961	0.394	1.015	1.176	0.872	1.0210

Table A105 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with NM aggregate, low alkali cement and soaked in 6.4 MC of KAc solution

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.002	0.3411	0.3588	0.3694	0	0	0	0
7	0.0016	0.3417	0.3591	0.3695	0.01	0.007	0.005	0.0073
28	0.003	0.3521	0.3635	0.3744	0.1	0.037	0.04	0.0590
56	0.0027	0.3803	0.3858	0.3981	0.385	0.263	0.28	0.3093
90	0.002	0.423	0.4219	0.434	0.819	0.631	0.646	0.6987
150	0.0061	0.502	0.493	0.514	1.568	1.301	1.405	1.4247
180	0.0059	0.5303			1.853			1.8530
270								
360								

Table A106 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with NM aggregate, low alkali cement and soaked in 6.4 MC of KAc solution with Li/K ratio of 0.2

	Comparator readings				Expansion, %			
Date	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0049	0.3347	0.3323	0.2215	0	0	0	0
7	0.0051	0.3362	0.3331	0.2219	0.013	0.006	0.002	0.0070
28	0.0051	0.3367	0.3336	0.2219	0.018	0.013	0.002	0.0110
56	0.0096	0.3424	0.3407	0.2275	0.03	0.039	0.013	0.0273
90	0.0098	0.354	0.3475	0.2379	0.144	0.15	0.115	0.1363
180	0.01	0.3909	0.3878	0.273	0.511	0.553	0.464	0.5093
270	0.0093	0.4133	0.4173	0.2941	0.742	0.857	0.682	0.7603
360	0.0091	0.4201	0.4236	0.3001	0.812	0.915	0.744	0.8237

Table A107 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with NM aggregate, low alkali cement and soaked in 3 MC of KAc solution with Li/K ratio of 0.2

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0049	0.2426	0.2268	0.3726	0	0	0	0
7	0.0051	0.2411	0.2283	0.3712	-0.017	0.013	-0.016	-0.0067
28	0.0051	0.2413	0.228	0.3714	-0.015	0.01	-0.014	-0.0063
56	0.0096	0.2467	0.2338	0.3786	-0.006	0.023	0.013	0.0100
90	0.0098	0.255	0.2416	0.3926	0.075	0.099	0.151	0.1083
180	0.01	0.2977	0.2834	0.4555	0.5	0.515	0.778	0.5977
270	0.0093	0.3306	0.3297	0.5036	0.836	0.985	1.266	1.0290
360	0.0091	0.3593	0.3617	0.5352	1.125	1.307	1.584	1.3387

Table A108 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with NM aggregate, low alkali cement and soaked in 3 MC of KAc solution with Li/K ratio of 0.8

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0049	0.3434	0.364	0.3327	0	0	0	0
7	0.0051	0.3444	0.3642	0.3333	0.008	5.551E-16	0.004	0.0040
28	0.0051	0.3443	0.3638	0.3332	0.007	-0.004	0.003	0.0020
56	0.0096	0.3495	0.368	0.3381	0.014	-0.007	0.007	0.0047
90	0.0098	0.3512	0.3683	0.3396	0.029	-0.006	0.02	0.0143
180	0.01	0.3517	0.3694	0.3412	0.032	0.003	0.034	0.0230
270	0.0093	0.3602	0.3768	0.3452	0.124	0.084	0.081	0.0963
360	0.0091	0.3629	0.3798	0.3489	0.153	0.116	0.12	0.1297

Table A109 Changes in DME in standard ASTM C 1293 tests using NM aggregate, high alkali cement

	Dynamic Young's Modulus, (E) * 10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	5.75	5.72	5.65	5.71	100.00
28	7.09	6.68	7.13	6.96	121.99
120	6.35	6.16	5.53	6.01	105.33
150	5.13	5.50	5.46	5.36	93.96
270	4.76	4.44	4.59	4.60	80.50
360	4.89	4.69	4.84	4.81	84.23

Table A110 Changes in DME in modified ASTM C 1293 tests using NM aggregate, high alkali cement and KAc 6.4

	Dynamic Young's Modulus, (E) * 10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	5.64	5.59	5.65	5.63	100.00
28	5.03	5.25	5.22	5.17	91.83
120	0.58	0.58	0.59	0.58	10.35
150					
270					
360					

Table A111 Changes in DME in modified ASTM C 1293 tests using NM aggregate, high alkali cement and KAc 3.0

	Dynamic Young's Modulus, (E)*10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	3.91	3.90	3.91	3.91	100.00
7	5.93	5.58	5.77	5.76	147.37
28	4.84	4.72	4.37	4.64	118.73
56	3.93	3.73	3.86	3.84	98.29
90	3.15	3.01	3.17	3.11	79.62
120	2.51	2.57	2.84	2.64	67.60
150	2.14	2.24	2.67	2.35	60.11
180	1.72	1.95	2.18	1.95	49.93
270	1.20	1.33	1.63	1.39	35.51
360	0.80	0.87	1.27	0.98	25.09

Table A112 Changes in DME in modified ASTM C 1293 tests using NM aggregate, high alkali cement and Li/K 6.4-0.2

	Dynamic Young's Modulus, (E)*10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	3.98	3.95	3.92	3.95	100.00
7	5.77	5.86	5.77	5.80	146.84
28	4.86	4.86	4.94	4.89	123.74
56	3.29	3.20	3.36	3.28	83.08
90	2.55	2.39	2.60	2.51	63.61
120	1.96	1.70	1.99	1.88	47.70
150	1.34	1.01	1.34	1.23	31.16
180	0.89	0.43	0.76	0.70	17.61
270	0.18	0.28		0.23	5.89
360					

Table A113 Changes in DME in modified ASTM C 1293 tests using NM aggregate, high alkali cement and Li/K 3-0.2

	Dynamic Young's Modulus, (E)*10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	4.01	3.93	3.86	3.93	100.00
7	5.83	5.93	5.65	5.80	147.61
28	4.69	4.81	4.60	4.70	119.50
56	3.39	3.51	3.60	3.50	88.98
90	2.88	2.93	3.04	2.95	75.00
120	2.39	2.43	2.61	2.48	62.98
150	1.96	2.07	1.98	2.01	51.05
180	1.67	1.74	1.70	1.70	43.33
270	1.12	1.12	0.94	1.06	26.93
360	0.58	0.80	0.63	0.67	17.04

Table A114 Changes in DME in modified ASTM C 1293 tests using NM aggregate, high alkali cement and Li/K 3-0.8

	Dynamic Young's Modulus, (E)*10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	3.84	3.97	3.92	3.91	100.00
7	5.79	5.93	5.80	5.84	149.23
28	5.30	5.25	4.20	4.91	125.61
56	3.24	3.75	3.13	3.37	86.21
90	2.47	2.70	2.70	2.63	67.09
120	2.16	2.07	2.38	2.20	56.35
150	2.31	2.98	2.58	2.63	67.09
180	2.31	2.64	2.53	2.49	63.71
270	2.67	3.18	2.56	2.81	71.73
360	2.70	3.15	2.60	2.82	71.98

Table A115 Changes in DME in standard ASTM C 1293 tests using NM aggregate, low alkali cement

	Dynamic Young's Modulus, (E) * 10^6				% Change in DME
Days	bar1	bar2	bar3	avg	
0	5.30	5.13	5.13	5.18	100.00
28	7.23	6.96	7.00	7.06	136.22
56	7.54	7.56	7.67	7.59	146.42
90	7.13	6.64	7.47	7.08	136.57
120	6.77	6.49	6.63	6.63	127.85
150	6.54	6.30	6.39	6.41	123.62
270	4.44	5.39	5.56	5.13	98.92
360	5.28	4.94	5.04	5.09	98.08

Table A116 Changes in DME in modified ASTM C 1293 tests using NM aggregate, low alkali cement and KAc 6.4

	Dynamic Young's Modulus, (E) * 10^6				% Change in DME
Days	bar1	bar2	bar3	avg	
0	5.15	5.02	5.04	5.07	100.00
28	5.42	5.97	6.24	5.87	115.84
56	8.67	8.21	6.27	7.71	152.12
90	2.88	2.63	2.43	2.65	52.19
120	0.94	1.60	1.27	1.27	25.02
150	0.51	0.49	0.58	0.53	10.41
270					
360					

Table A117 Changes in DME in modified ASTM C 1293 tests using NM aggregate, low alkali cement and KAc 3.0

	Dynamic Young's Modulus, (E)*10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	4.02	3.72	4.00	3.91	100.00
7	6.21	6.21	6.34	6.26	159.94
28	6.38	6.22	6.35	6.32	161.45
56	5.83	5.56	6.01	5.80	148.22
90	4.67	4.73	4.85	4.75	121.35
180	3.00	2.49	2.85	2.78	71.07
270	1.88	1.27	2.00	1.72	43.90
360	1.26	0.98	1.53	1.26	32.21

Table A118 Changes in DME in modified ASTM C 1293 tests using NM aggregate, low alkali cement and Li/K 6.4-0.2

	Dynamic Young's Modulus, (E)*10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	3.85	4.22	3.52	3.86	100.00
7	5.81	6.16	5.81	5.92	153.27
28	6.12	6.40	6.11	6.21	160.72
56	6.16	6.42	5.93	6.17	159.73
90	5.04	5.73	4.51	5.10	131.86
180	1.70	2.18	1.74	1.87	48.45
270	0.87	1.06	0.88	0.94	24.20
360	0.75	1.03	0.89	0.89	23.07

Table A119 Changes in DME in modified ASTM C 1293 tests using NM aggregate, low alkali cement and Li/K 3-0.2

	Dynamic Young's Modulus, (E)*10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	3.99	3.79	3.73	3.84	100.00
7	6.04	5.89	5.93	5.96	155.21
28	6.41	6.17	6.12	6.23	162.42
56	6.42	6.12	6.15	6.23	162.46
90	5.70	5.98	4.15	5.27	137.44
180	2.23	2.37	1.18	1.93	50.19
270	1.22	1.07	0.68	0.99	25.79
360	0.86	0.70	0.53	0.70	18.17

Table A120 Changes in DME in modified ASTM C 1293 tests using NM aggregate, low alkali cement and Li/K 3-0.8

	Dynamic Young's Modulus, (E)*10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	3.95	3.85	3.69	3.83	100.00
7	6.11	5.97	5.81	5.96	155.71
28	6.29	6.28	5.88	6.15	160.57
56	6.43	6.28	6.17	6.30	164.37
90	6.53	6.40	6.24	6.39	166.80
180	6.44	6.50	6.00	6.31	164.76
270	4.16	4.05	4.99	4.40	114.92
360	4.46	4.26	4.54	4.42	115.39

Table A121 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with Spratt aggregate, high alkali cement and soaked in 1N NaOH solution

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0024	0.2986	0.3619	0.3456	0	0	0	0
7	0.002	0.2983	0.3612	0.3453	0.001	-0.003	0.001	-0.0003
28	0.0016	0.2988	0.3617	0.3458	0.01	0.006	0.01	0.0087
56	0.0029	0.3031	0.3668	0.3502	0.04	0.044	0.041	0.0417
90	0.0024	0.306	0.3699	0.3532	0.074	0.08	0.076	0.0767
120	0.0216	0.3273	0.3914	0.3748	0.095	0.103	0.1	0.0993
150	0.0045	0.3118	0.3759	0.3595	0.111	0.119	0.118	0.1160
180	0.0059	0.3147	0.3787	0.3622	0.126	0.133	0.131	0.1300
270	0.0054	0.3165	0.381	0.3641	0.149	0.161	0.155	0.1550
360	0.0038	0.3171	0.3818	0.3648	0.171	0.185	0.178	0.1780

Table A122 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with Spratt aggregate, high alkali cement and soaked in 3 MC of KAc solution

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0058	0.3407	0.3351	0.2957	0	0	0	0
7	0.0064	0.3413	0.3353	0.2967	0	-0.004	0.004	0.0000
28	0.0064	0.3419	0.3354	0.2964	0.006	-0.003	0.001	0.0013
56	0.0055	0.3465	0.3403	0.3013	0.061	0.055	0.059	0.0583
90	0.0053	0.353	0.3466	0.3079	0.128	0.12	0.127	0.1250
120	0.006	0.3602	0.3537	0.3148	0.193	0.184	0.189	0.1887
150	0.0052	0.3662	0.3584	0.3205	0.261	0.239	0.254	0.2513
180	0.0057	0.3713	0.3627	0.3257	0.307	0.277	0.301	0.2950
210	0.0061	0.3753	0.3663	0.3298	0.343	0.309	0.338	0.3300
240	0.0044	0.3771	0.368	0.3316	0.378	0.343	0.373	0.3647
270	0.0098	0.3856	0.3755	0.34	0.409	0.364	0.403	0.3920
360	0.0098	0.3869	0.3766	0.3436	0.422	0.375	0.439	0.4120

Table A123 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with Spratt aggregate, high alkali cement and soaked in 6.4 MC of KAc solution

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0024	0.3648	0.373	0.3437	0	0	0	0
7	0.002	0.3644	0.3725	0.3432	0	-0.001	-0.001	-0.0007
28	0.0016	0.3643	0.3724	0.3435	0.003	0.002	0.006	0.0037
56	0.0029	0.3676	0.3761	0.3471	0.023	0.026	0.029	0.0260
90	0.0024	0.3718	0.3809	0.3573	0.07	0.079	0.136	0.0950
120	0.0216	0.3966	0.406	0.3771	0.126	0.138	0.142	0.1353
150	0.0045	0.3845	0.3946	0.3661	0.176	0.195	0.203	0.1913
180	0.0059	0.3908	0.4023	0.3731	0.225	0.258	0.259	0.2473
270	0.0054	0.4084	0.4236	0.394	0.406	0.476	0.473	0.4517
360	0.0038	0.4262	0.4474	0.4229	0.6	0.73	0.778	0.7027

Table A124 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with Spratt aggregate, high alkali cement and soaked in 6.4 MC of KAc solution with Li/K ratio of 0.2

	Comparator readings				Expansion, %			
Date	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0058	0.3559	0.3358	0.3329	0	0	0	0
7	0.006	0.356	0.3361	0.3336	-0.001	0.001	0.005	0.0017
28	0.0064	0.3563	0.3366	0.3342	-0.002	0.002	0.007	0.0023
56	0.0055	0.3576	0.3387	0.3364	0.02	0.032	0.038	0.0300
90	0.0053	0.3608	0.343	0.3401	0.054	0.077	0.077	0.0693
120	0.006	0.366	0.3475	0.3454	0.099	0.115	0.123	0.1123
150	0.0052	0.3705	0.3521	0.3498	0.152	0.169	0.175	0.1653
180	0.0057	0.3762	0.3577	0.3545	0.204	0.22	0.217	0.2137
210	0.0061	0.3823	0.3636	0.3594	0.261	0.275	0.262	0.2660
240	0.0044	0.3873	0.3671	0.3624	0.328	0.327	0.309	0.3213
270	0.0098	0.3961	0.3769	0.3724	0.362	0.371	0.355	0.3627
360	0.0098	0.4022	0.3832	0.3778	0.423	0.434	0.409	0.4220

Table A125 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with Spratt aggregate, high alkali cement and soaked in 3 MC of KAc solution with Li/K ratio of 0.2

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0058	0.3454	0.2063	0.3377	0	0	0	0
7	0.0062	0.3463	0.2063	0.3383	0.005	-0.004	0.002	0.0010
28	0.0064	0.3474	0.2066	0.3384	0.014	-0.003	0.001	0.0040
56	0.0055	0.3524	0.2116	0.3442	0.073	0.056	0.068	0.0657
90	0.0053	0.359	0.2199	0.3507	0.141	0.141	0.135	0.1390
120	0.006	0.3672	0.2271	0.358	0.216	0.206	0.201	0.2077
150	0.0052	0.3734	0.2342	0.3634	0.286	0.285	0.263	0.2780
180	0.0057	0.3784	0.2403	0.368	0.331	0.341	0.304	0.3253
210	0.0061	0.3836	0.2449	0.3721	0.379	0.383	0.341	0.3677
240	0.0044	0.3865	0.2473	0.3738	0.425	0.424	0.375	0.4080
270	0.0098	0.3934	0.2551	0.3829	0.44	0.448	0.412	0.4333
360	0.0098	0.3961	0.258	0.3855	0.467	0.477	0.438	0.4607

Table A126 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with Spratt aggregate, low alkali cement and soaked in 1N NaOH solution

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0016	0.358	0.4304	0.3659	0	0	0	0
7	0.0017	0.3581	0.4307	0.3662	0	0.002	0.002	0.0013
28	0.0012	0.358	0.4307	0.3663	0.004	0.007	0.008	0.0063
56	0.0027	0.36	0.4324	0.3681	0.009	0.009	0.011	0.0097
90	0.0021	0.3612	0.433	0.3691	0.027	0.021	0.027	0.0250
120	0.0215	0.3823	0.4541	0.3895	0.044	0.038	0.037	0.0397
150	0.0062	0.3681	0.4402	0.3754	0.055	0.052	0.049	0.0520
180	0.006	0.3706	0.4428	0.3794	0.082	0.08	0.091	0.0843
270	0.0054	0.3735	0.4469	0.3808	0.117	0.127	0.111	0.1183
360	0.0043	0.3768	0.4508	0.384	0.161	0.177	0.154	0.1640

Table A127 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with Spratt aggregate, low alkali cement and soaked in 3 MC of KAc solution

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0049	0.3017	0.3213	0.3717	0	0	0	0
7	0.0052	0.3034	0.3233	0.3668	0.014	0.017	-0.052	-0.0070
28	0.0051	0.3036	0.3232	0.3666	0.017	0.017	-0.053	-0.0063
56	0.0096	0.3092	0.328	0.372	0.028	0.02	-0.044	0.0013
90	0.0098	0.3095	0.3298	0.373	0.029	0.036	-0.036	0.0097
180	0.01	0.3252	0.3435	0.3861	0.184	0.171	0.093	0.1493
270	0.0093	0.3359	0.3525	0.396	0.298	0.268	0.199	0.2550
360	0.0091	0.3409	0.3575	0.4017	0.35	0.32	0.258	0.3093

Table A128 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with Spratt aggregate, low alkali cement and soaked in 6.4 MC of KAc solution

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0016	0.4179	0.3523	0.3528	0	0	0	0
7	0.0017	0.4181	0.3525	0.3519	0.001	0.001	-0.01	-0.0027
28	0.0012	0.418	0.3524	0.3518	0.005	0.005	-0.006	0.0013
56	0.0027	0.4198	0.3541	0.3533	0.008	0.007	-0.006	0.0030
90	0.0021	0.4213	0.3556	0.3548	0.029	0.028	0.015	0.0240
120	0.0215	0.4448	0.3786	0.3791	0.07	0.064	0.064	0.0660
150	0.0062	0.4354	0.3697	0.3702	0.129	0.128	0.128	0.1283
180	0.006	0.4434	0.3821	0.3779	0.211	0.254	0.207	0.2240
270	0.0054	0.4595	0.3972	0.3938	0.378	0.411	0.372	0.3870
360	0.0043	0.4754	0.4113	0.4078	0.548	0.563	0.523	0.5447

Table A129 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with Spratt aggregate, low alkali cement and soaked in 6.4 MC of KAc solution with Li/K ratio of 0.2

	Comparator readings				Expansion, %			
Date	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0049	0.3319	0.2527	0.2225	0	0	0	0
7	0.0051	0.3359	0.2545	0.2226	0.038	0.016	-0.001	0.0177
28	0.0051	0.3356	0.2549	0.2249	0.035	0.02	0.022	0.0257
56	0.0096	0.3407	0.26	0.228	0.041	0.026	0.008	0.0250
90	0.0098	0.3414	0.2603	0.2295	0.046	0.027	0.021	0.0313
180	0.01	0.3454	0.266	0.2326	0.084	0.082	0.05	0.0720
270	0.0093	0.3487	0.269	0.2357	0.124	0.119	0.088	0.1103
360	0.0091	0.3515	0.272	0.2391	0.154	0.151	0.124	0.1430

Table A130 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with Spratt aggregate, high alkali cement and soaked in 3 MC of KAc solution with Li/K ratio of 0.2

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0049	0.2866	0.2784	0.3185	0	0	0	0
7	0.0052	0.2891	0.2797	0.3225	0.022	0.01	0.037	0.0230
28	0.0051	0.2889	0.2794	0.3201	0.021	0.008	0.014	0.0143
56	0.0096	0.294	0.2847	0.3253	0.027	0.016	0.021	0.0213
90	0.0098	0.2949	0.2847	0.3259	0.034	0.014	0.025	0.0243
180	0.01	0.3016	0.2917	0.3337	0.099	0.082	0.101	0.0940
270	0.0093	0.308	0.2975	0.3393	0.17	0.147	0.164	0.1603
360	0.0091	0.312	0.3022	0.343	0.212	0.196	0.203	0.2037

Table A131 Changes in DME in standard ASTM C 1293 tests using SP aggregate, high alkali cement

	Dynamic Young's Modulus, (E) * 10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	5.54	5.54	5.58	5.55	100.00
28	6.97	7.09	6.98	7.01	126.29
56	7.01	7.31	7.35	7.22	130.08
90	6.43	6.45	6.50	6.46	116.29
120	6.29	6.38	6.39	6.35	114.43
150	6.14	6.27	6.24	6.22	111.95
270	5.01	6.31	6.23	5.85	105.35
360	6.11	6.25	6.23	6.19	111.54

Table A132 Changes in DME in modified ASTM C 1293 tests using SP aggregate, high alkali cement and KAc 6.4

	Dynamic Young's Modulus, (E) * 10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	5.51	5.51	5.50	5.50	100.00
28	6.69	6.76	6.83	6.76	122.81
90	6.57	6.55	6.62	6.58	119.56
120	6.22	6.24	6.24	6.23	113.29
150	5.97	6.03	5.20	5.74	104.23
270	4.75	4.77	4.24	4.59	83.40
360	3.92	3.49	3.34	3.58	65.15

Table A133 Changes in DME in modified ASTM C 1293 tests using SP aggregate, high alkali cement and KAc 3.0

	Dynamic Young's Modulus, (E)*10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	6.02	6.05	5.93	6.00	100.00
7	6.86	6.92	6.72	6.83	113.80
28	7.02	7.06	6.89	6.99	116.46
56	6.64	6.65	6.47	6.58	109.69
90	6.32	6.21	5.75	6.09	101.53
120	5.78	5.81	5.63	5.74	95.65
150	5.46	5.52	5.11	5.36	89.36
180	5.30	5.40	5.32	5.34	88.96
210	5.22	5.33	4.97	5.17	86.19
240	5.18	5.27	4.84	5.09	84.86
270	5.15	5.25	5.09	5.16	86.04
300	5.14	5.22	5.09	5.15	85.76

360	5.46	5.37	4.86	5.23	87.15

Table A134 Changes in DME in modified ASTM C 1293 tests using SP aggregate, high alkali cement and Li/K 6.4-0.2

	Dynamic Young's Modulus, (E)*10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	6.02	6.09	6.01	6.04	100.00
7	6.83	6.98	6.78	6.86	113.53
28	6.96	6.98	6.99	6.98	115.47
56	6.87	6.99	6.89	6.92	114.49
90	6.65	6.79	6.63	6.69	110.72
120	6.36	6.51	6.40	6.43	106.34
150	6.02	6.26	5.99	6.09	100.76
180	5.50	5.93	5.63	5.69	94.10
210	5.10	5.56	5.22	5.29	87.58
240	4.45	5.32	4.82	4.86	80.48
270	4.02	5.03	4.37	4.47	73.99
300	3.79	4.62	3.98	4.13	68.40
360	3.31	3.91	3.29	3.50	57.98

Table A135 Changes in DME in modified ASTM C 1293 tests using SP aggregate, high alkali cement and Li/K 3-0.2

	Dynamic Young's Modulus, (E)*10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	5.79	5.92	5.87	5.86	100.00
7	6.60	6.74	6.73	6.69	114.11
28	6.78	6.95	6.93	6.89	117.48
56	6.35	6.54	6.54	6.48	110.44
90	5.75	5.93	6.05	5.91	100.80
120	5.36	5.37	5.56	5.43	92.59
150	5.05	5.03	5.22	5.10	86.95
180	4.81	4.88	5.09	4.92	84.00
210	4.71	4.79	4.88	4.79	81.75
240	4.67	4.74	4.79	4.73	80.73
270	4.60	4.65	4.64	4.63	78.95
300	4.59	4.64	4.64	4.62	78.85
360	4.68	4.71	4.70	4.70	80.13

Table A136 Changes in DME in standard ASTM C 1293 tests using SP aggregate, low alkali cement

	Dynamic Young's Modulus, (E) * 10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	5.27	5.49	5.30	5.35	100
28	7.12	7.31	7.19	7.21	134.66
56	6.77	7.64	7.60	7.34	137.10
90	6.95	7.37	7.00	7.11	132.75
120	6.81	7.13	6.85	6.93	129.44
150	6.65	6.96	6.96	6.86	128.17
270	6.28	6.43	6.28	6.33	118.25
360	6.03	6.20	6.05	6.09	113.85

Table A137 Changes in DME in modified ASTM C 1293 tests using SP aggregate, low alkali cement and KAc 6.4

	Dynamic Young's Modulus, (E) * 10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	5.58	5.34	5.30	5.40	100
28	7.02	6.84	6.75	6.87	127.06
56	7.09	7.56	7.98	7.54	139.59
90	7.43	7.65	6.93	7.34	135.72
120	6.76	6.66	6.61	6.68	123.56
150	6.66	6.22	6.58	6.49	120.05
270	4.23	4.58	4.50	4.44	82.07
360	3.46	3.80	3.15	3.47	64.23

Table A138 Changes in DME in modified ASTM C 1293 tests using SP aggregate, low alkali cement and KAc 3.0

	Dynamic Young's Modulus, (E)*10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	3.43	3.32	3.48	3.41	100
7	6.16	6.17	6.13	6.15	180.66
28	6.52	6.48	6.57	6.52	191.45
56	6.53	6.63	6.64	6.60	193.69
90	6.49	6.51	6.49	6.50	190.69
180	5.31	5.10	5.36	5.26	154.30
270	4.95	4.76	5.02	4.91	144.02
360	5.01	4.89	5.20	5.03	147.76

Table A139 Changes in DME in modified ASTM C 1293 tests using SP aggregate, low alkali cement and Li/K 6.4-0.2

	Dynamic Young's Modulus, (E)*10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	3.58	3.53	3.29	3.47	100
7	5.74	5.73	5.59	5.69	164.08
28	6.23	6.18	6.04	6.15	177.34
56	6.38	6.33	6.16	6.29	181.33
90	6.45	6.35	6.26	6.35	183.23
180	5.94	5.53	5.32	5.60	161.47
270	5.44	5.08	4.29	4.94	142.44
360	5.26	4.75	4.20	4.74	136.65

Table A140 Changes in DME in modified ASTM C 1293 tests using SP aggregate, low alkali cement and Li/K 3-0.2

	Dynamic Young's Modulus, (E)*10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	3.40	3.48	3.61	3.50	100
7	6.07	6.04	6.30	6.14	175.44
28	6.42	6.39	6.65	6.49	185.37
56	6.55	6.51	6.76	6.60	188.77
90	6.59	6.57	6.82	6.66	190.29
180	5.81	5.93	5.93	5.89	168.27
270	5.13	5.28	5.32	5.24	149.80
360	4.93	4.98	4.57	4.83	137.92

Table A141 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with NC aggregate, high alkali cement and soaked in 1N NaOH solution

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0017	0.3048	0.3422	0.3108	0	0	0	0
7	0.0019	0.3049	0.3427	0.3108	-0.001	0.003	-0.002	0.0000
28	0.003	0.3066	0.3445	0.3126	0.005	0.01	0.005	0.0067
56	0.0023	0.3092	0.3482	0.315	0.038	0.054	0.036	0.0427
90	0.0021	0.3134	0.3528	0.3191	0.082	0.102	0.079	0.0877
120	0.0055	0.3202	0.3599	0.3263	0.116	0.139	0.117	0.1240
150	0.0065	0.3231	0.3628	0.3296	0.135	0.158	0.14	0.1443
180	0.0063	0.3239	0.3636	0.3308	0.145	0.168	0.154	0.1557
270	0.0048	0.3248	0.3643	0.3324	0.169	0.19	0.185	0.1813
360	0.0055	0.3282	0.3673	0.336	0.196	0.213	0.214	0.2077

Table A142 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with NC aggregate, high alkali cement and soaked in 3 MC of KAc solution

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0058	0.343	0.3322	0.2689	0	0	0	0
7	0.0067	0.3433	0.3325	0.2699	-0.006	-0.006	0.001	-0.0037
28	0.0055	0.3425	0.3317	0.2692	-0.002	-0.002	0.006	0.0007
56	0.0055	0.3466	0.3341	0.2734	0.039	0.022	0.048	0.0363
90	0.006	0.3603	0.3429	0.2862	0.171	0.105	0.171	0.1490
120	0.0052	0.3713	0.3518	0.2977	0.289	0.202	0.294	0.2617
150	0.0057	0.38	0.3591	0.3063	0.371	0.27	0.375	0.3387
180	0.0061	0.3875	0.3654	0.3084	0.442	0.329	0.392	0.3877
210	0.0044	0.3922	0.3693	0.317	0.506	0.385	0.495	0.4620
240	0.0098	0.4025	0.3785	0.3267	0.555	0.423	0.538	0.5053
270	0.0098	0.4026	0.3828	0.3285	0.556	0.466	0.556	0.5260
360	0.009	0.4196	0.3936	0.3428	0.734	0.582	0.707	0.6743

Table A143 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with NC aggregate, high alkali cement and soaked in 6.4 MC of KAc solution

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0017	0.3572	0.3287	0.3543	0	0	0	0
7	0.0019	0.3575	0.3294	0.3541	0.001	0.005	-0.004	0.0007
28	0.003	0.3588	0.3304	0.3554	0.003	0.004	-0.002	0.0017
56	0.0023	0.3604	0.3324	0.3571	0.026	0.031	0.022	0.0263
90	0.0021	0.3671	0.3388	0.3627	0.095	0.097	0.08	0.0907
120	0.0055	0.3784	0.3494	0.3735	0.174	0.169	0.154	0.1657
150	0.0065	0.3881	0.359	0.3824	0.261	0.255	0.233	0.2497
180	0.0063	0.397	0.3685	0.3909	0.352	0.352	0.32	0.3413
270	0.0048	0.4247	0.3961	0.4178	0.644	0.643	0.604	0.6303
360	0.0055	0.4649	0.44	0.4555	1.039	1.075	0.974	1.0293

Table A144 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with NC aggregate, high alkali cement and soaked in 6.4 MC of KAc solution with Li/K ratio of 0.2

	Comparator readings				Expansion, %			
Date	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0058	0.3489	0.3466	0.2323	0	0	0	0
7	0.0067	0.3496	0.3468	0.2329	-0.002	-0.007	-0.003	-0.0040
28	0.0055	0.3491	0.346	0.2332	0.005	-0.003	0.012	0.0047
56	0.0055	0.3506	0.3477	0.2335	0.02	0.014	0.015	0.0163
90	0.006	0.3589	0.3562	0.2465	0.098	0.094	0.14	0.1107
120	0.0052	0.3676	0.3658	0.2504	0.193	0.198	0.187	0.1927
150	0.0057	0.3777	0.3768	0.2606	0.289	0.303	0.284	0.2920
180	0.0061	0.387	0.3874	0.2694	0.378	0.405	0.368	0.3837
210	0.0044	0.3921	0.3948	0.2716	0.446	0.496	0.407	0.4497
240	0.0098	0.4044	0.4071	0.2879	0.515	0.565	0.516	0.5320
270	0.0098	0.4108	0.4127	0.2957	0.579	0.621	0.594	0.5980
360	0.009	0.4135	0.4365	0.3228	0.614	0.867	0.873	0.7847

Table A145 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with NC aggregate, high alkali cement and soaked in 3 MC of KAc solution with Li/K ratio of 0.2

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0058	0.3458	0.3601	0.2547	0	0	0	0
7	0.0067	0.3448	0.3602	0.2502	-0.019	-0.008	-0.054	-0.0270
28	0.0055	0.3437	0.3585	0.2494	-0.018	-0.013	-0.05	-0.0270
56	0.0055	0.3467	0.3625	0.252	0.012	0.027	-0.024	0.0050
90	0.006	0.3596	0.3746	0.2643	0.136	0.143	0.094	0.1243
120	0.0052	0.3714	0.3854	0.276	0.262	0.259	0.219	0.2467
150	0.0057	0.38	0.3946	0.2852	0.343	0.346	0.306	0.3317
180	0.0061	0.3868	0.4014	0.2927	0.407	0.41	0.377	0.3980
210	0.0044	0.391	0.4057	0.2977	0.466	0.47	0.444	0.4600
240	0.0098	0.4015	0.4163	0.3075	0.517	0.522	0.488	0.5090
270	0.0098	0.4068	0.4215	0.3142	0.57	0.574	0.555	0.5663
360	0.009	0.4163	0.4325	0.3243	0.673	0.692	0.664	0.6763

Table A146 Changes in DME in standard ASTM C 1293 tests using NC aggregate, high alkali cement

	Dynamic Young's Modulus, (E) * 10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	6.04	5.87	5.90	5.94	100.00
28	7.33	7.29	7.25	7.29	122.78
56	8.19	6.94	8.67	7.93	133.65
90	6.51	6.48	6.56	6.52	109.79
120	6.29	6.22	7.44	6.65	111.99
150	6.14	6.07	6.11	6.10	102.82
270	5.91	5.85	5.89	5.88	99.09
360	5.85	5.77	5.77	5.80	97.67

Table A147 Changes in DME in modified ASTM C 1293 tests using NC aggregate, high alkali cement and KAc 6.4

	Dynamic Young's Modulus, (E) * 10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	5.96	5.96	6.09	6.00	100.00
28	8.23	7.21	7.84	7.76	129.33
56	8.52	7.72	8.33	8.19	136.41
90	6.54	6.64	6.45	6.54	109.03
120	6.68	6.27	6.16	6.37	106.08
150	5.49	5.66	5.59	5.58	92.95
270	3.83	3.82	3.76	3.80	63.30
360	2.25	2.18	2.29	2.24	37.32

Table A148 Changes in DME in modified ASTM C 1293 tests using NC aggregate, high alkali cement and KAc 3.0

	Dynamic Young's Modulus, (E)*10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	5.93	5.87	5.83	5.88	100.00
7	7.17	7.08	7.13	7.13	121.25
28	7.39	7.32	7.36	7.36	125.19
56	6.99	7.06	6.86	6.97	118.54
90	5.88	6.17	5.70	5.92	100.63
120	5.18	5.39	4.95	5.18	88.05
150	4.58	4.97	4.69	4.75	80.72
180	4.48	4.90	4.61	4.66	79.31
210	4.30	4.66	4.56	4.51	76.66
240	4.28	4.64	4.45	4.46	75.86
270	4.16	4.54	4.36	4.35	74.08
360	4.11	4.34	4.36	4.27	72.68

Table A149 Changes in DME in modified ASTM C 1293 tests using NC aggregate, high alkali cement and Li/K 6.4-0.2

	Dynamic Young's Modulus, (E)*10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	5.90	5.66	6.03	5.86	100.00
7	7.09	6.93	7.34	7.12	121.45
28	7.16	7.09	7.55	7.27	123.92
56	7.06	6.99	7.38	7.14	121.82
90	6.43	6.34	6.61	6.46	110.23
120	5.54	5.14	5.43	5.37	91.60
150	4.72	3.95	4.01	4.23	72.09
180	4.02	3.56	3.87	3.82	65.08
210	3.71	3.10	3.31	3.37	57.51
240	3.41	2.76	3.09	3.09	52.63
270	3.04	2.44	3.11	2.86	48.80
360	2.00	1.53	1.55	1.69	28.83

Table A150 Changes in DME in modified ASTM C 1293 tests using NC aggregate, high alkali cement and Li/K 3-0.2

	Dynamic Young's Modulus, (E)*10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	6.04	6.07	5.85	5.99	100.00
7	7.33	7.23	7.13	7.23	120.83
28	7.56	7.45	7.34	7.45	124.47
56	7.17	7.21	7.04	7.14	119.31
90	5.78	6.12	5.74	5.88	98.21
120	4.71	3.58	4.69	4.33	72.33
150	4.37	4.59	4.47	4.48	74.80
180	4.22	4.50	4.05	4.26	71.10
210	4.00	4.23	3.78	4.00	66.89
240	3.82	4.03	3.67	3.84	64.17
270	3.71	3.82	3.40	3.64	60.84
360	3.36	3.37	3.39	3.38	56.39

Table A151 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with SD aggregate, high alkali cement and soaked in 1N NaOH solution

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0008	0.3469	0.3428	0.3374	0	0	0	0
7	0.0019	0.3481	0.3436	0.3381	0.001	-0.003	-0.004	-0.0020
28	0.0027	0.3499	0.3453	0.3405	0.011	0.006	0.012	0.0097
56	0.0024	0.3503	0.346	0.3411	0.018	0.016	0.021	0.0183
90	0.0021	0.3516	0.347	0.3423	0.034	0.029	0.036	0.0330
120	0.0058	0.3563	0.3521	0.3474	0.044	0.043	0.05	0.0457
150	0.0064	0.358	0.3536	0.3489	0.055	0.052	0.059	0.0553
180	0.0055	0.3582	0.3539	0.3493	0.066	0.064	0.072	0.0673
270	0.0048	0.359	0.3548	0.3501	0.081	0.08	0.087	0.0827
360	0.006	0.3621	0.3577	0.3531	0.1	0.097	0.105	0.1007

Table A152 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with SD aggregate, high alkali cement and soaked in 3 MC of KAc solution

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0056	0.3305	0.2793	0.337	0	0	0	0
7	0.0064	0.331	0.2797	0.3349	-0.003	-0.004	-0.029	-0.0120
28	0.0064	0.3311	0.2806	0.3347	-0.002	0.005	-0.031	-0.0093
56	0.0055	0.3304	0.2794	0.3338	0	0.002	-0.031	-0.0097
90	0.0053	0.3321	0.279	0.3336	0.019	0	-0.031	-0.0040
120	0.006	0.3333	0.2805	0.3351	0.024	0.008	-0.023	0.0030
150	0.0052	0.3343	0.2808	0.3371	0.042	0.019	0.005	0.0220
180	0.0057	0.3358	0.2825	0.3379	0.052	0.031	0.008	0.0303
210	0.0061	0.3371	0.2842	0.3394	0.061	0.044	0.019	0.0413
240	0.0044	0.3376	0.2843	0.3409	0.083	0.062	0.051	0.0653
270	0.0098	0.3445	0.2915	0.3469	0.098	0.08	0.057	0.0783
360	0.0098	0.3466	0.2941	0.3495	0.119	0.106	0.083	0.1027

Table A153 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with SD aggregate, high alkali cement and soaked in 6.4 MC of KAc solution

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0008	0.2956	0.3498	0.4532	0	0	0	0
7	0.0019	0.2963	0.35	0.4541	-0.004	-0.009	-0.002	-0.0050
28	0.0027	0.2978	0.3516	0.4556	0.003	-0.001	0.005	0.0023
56	0.0024	0.2979	0.3517	0.4557	0.007	0.003	0.009	0.0063
90	0.0021	0.2981	0.3518	0.456	0.012	0.007	0.015	0.0113
120	0.0058	0.3022	0.356	0.4601	0.016	0.012	0.019	0.0157
150	0.0064	0.3033	0.3572	0.4614	0.021	0.018	0.026	0.0217
180	0.0055	0.3037	0.3577	0.4616	0.034	0.032	0.037	0.0343
270	0.0048	0.3064	0.3602	0.465	0.068	0.064	0.078	0.0700
360	0.006	0.3157	0.3696	0.475	0.149	0.146	0.166	0.1537

Table A154 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with SD aggregate, high alkali cement and soaked in 6.4 MC of KAc solution with Li/K ratio of 0.2

	Comparator readings				Expansion, %			
Date	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0056	0.3126	0.2525	0.2408	0	0	0	0
7	0.0064	0.3128	0.254	0.2408	-0.006	0.007	-0.008	-0.0023
28	0.0064	0.3129	0.254	0.2412	-0.005	0.007	-0.004	-0.0007
56	0.0055	0.3124	0.2533	0.2406	-0.001	0.009	-0.001	0.0023
90	0.0053	0.3119	0.2535	0.2402	-0.004	0.013	-0.003	0.0020
120	0.006	0.3122	0.2542	0.2415	-0.008	0.013	0.003	0.0027
150	0.0052	0.3131	0.2544	0.2413	0.009	0.023	0.009	0.0137
180	0.0057	0.3141	0.2559	0.2426	0.014	0.033	0.017	0.0213
210	0.0061	0.3154	0.257	0.2437	0.023	0.04	0.024	0.0290
240	0.0044	0.3153	0.2578	0.2434	0.039	0.065	0.038	0.0473
270	0.0098	0.3221	0.2649	0.2512	0.053	0.082	0.062	0.0657
360	0.0098	0.324	0.2676	0.253	0.072	0.109	0.08	0.0870

Table A155 Expansion readings and percentage expansions of the Modified ASTM C 1293 tests of concrete prisms made with SD aggregate, high alkali cement and soaked in 3 MC of KAc solution with Li/K ratio of 0.2

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0056	0.1685	0.3373	0.3444	0	0	0	0
7	0.0064	0.1678	0.3373	0.3447	-0.015	-0.008	-0.005	-0.0093
28	0.0064	0.1679	0.337	0.345	-0.014	-0.011	-0.002	-0.0090
56	0.0055	0.1664	0.3357	0.3447	-0.02	-0.015	0.004	-0.0103
90	0.0053	0.167	0.3363	0.344	-0.012	-0.007	-0.001	-0.0067
120	0.006	0.168	0.3378	0.3452	-0.009	0.001	0.004	-0.0013
150	0.0052	0.1688	0.3378	0.3459	0.007	0.009	0.019	0.0117
180	0.0057	0.1703	0.3393	0.3481	0.017	0.019	0.036	0.0240
210	0.0061	0.1718	0.341	0.3501	0.028	0.032	0.052	0.0373
240	0.0044	0.172	0.3415	0.3505	0.047	0.054	0.073	0.0580
270	0.0098	0.1786	0.3487	0.3583	0.059	0.072	0.097	0.0760
360	0.0098	0.1811	0.3509	0.3602	0.084	0.094	0.116	0.0980

Table A156 Changes in DME in standard ASTM C 1293 tests using SD aggregate, high alkali cement

	Dynamic Young's Modulus, (E) * 10^6				% Change in DME
days	bar1	bar2	bar3	avg	
0	5.91	6.16	6.02	6.03	100.00
28	7.33	7.44	7.37	7.38	122.32
56	7.13	7.12	7.13	7.13	118.16
120	6.06	5.91	6.10	6.02	99.89
150	5.96	6.20	5.96	6.04	100.11
270	5.15	5.07	4.82	5.02	83.16
360	4.75	4.74	4.73	4.74	78.56

Table A157 Changes in DME in modified ASTM C 1293 tests using SD aggregate, high alkali cement and KAc 6.4

	Dynamic Young's Modulus, (E) * 10^6				% Change in DME
days	bar1	bar2	bar3	avg	
0	6.07	6.09	6.06	6.07	100.00
28	7.28	7.26	7.52	7.36	121.13
56	7.29	7.34	7.45	7.36	121.17
120	7.26	7.28	7.29	7.28	119.80
150	7.26	7.28	7.25	7.26	119.60
270	6.92	6.98	6.99	6.96	114.66
360	6.51	6.44	6.51	6.48	106.78

Table A158 Changes in DME in modified ASTM C 1293 tests using SD aggregate, high alkali cement and KAc 3.0

	Dynamic Young's Modulus, (E)*10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	6.06	6.35	6.21	6.20	100.00
7	7.04	7.33	7.20	7.19	115.92
28	7.13	7.38	7.27	7.26	116.99
56	7.12	7.38	7.29	7.26	117.08
90	7.02	7.32	7.28	7.21	116.16
120	7.02	7.26	7.22	7.17	115.51
150	6.81	7.09	6.89	6.93	111.69
180	6.73	6.97	6.69	6.80	109.52
210	6.43	6.66	6.35	6.48	104.45
240	6.20	6.40	6.19	6.26	100.93
270	5.97	6.13	5.88	5.99	96.57
300	5.67	5.74	5.57	5.66	91.26
360	5.18	5.15	4.90	5.08	81.84

Table A159 Changes in DME in modified ASTM C 1293 tests using SD aggregate, high alkali cement and Li/K 6.4-0.2

	Dynamic Young's Modulus, (E)*10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	6.31	6.22	6.17	6.23	100.00
7	7.15	7.11	7.03	7.10	113.92
28	7.22	7.10	7.14	7.16	114.84
56	7.27	7.24	7.23	7.25	116.31
90	7.36	7.24	7.36	7.32	117.45
120	7.37	7.28	7.28	7.31	117.31
150	7.37	7.29	7.29	7.32	117.39
180	7.37	7.29	7.29	7.31	117.35
210	7.24	7.16	7.25	7.21	115.78
240	7.23	7.06	7.19	7.16	114.91
270	7.14	6.86	7.02	7.01	112.48
300	7.06	6.72	6.89	6.89	110.62
360	6.65	5.97	6.45	6.36	102.04

Table A160 Changes in DME in modified ASTM C 1293 tests using SD aggregate, high alkali cement and Li/K 3-0.2

	Dynamic Young's Modulus, (E)*10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	6.36	6.25	6.14	6.25	100.00
7	7.36	7.19	7.05	7.20	115.21
28	7.44	7.23	7.11	7.26	116.14
56	7.47	7.28	7.14	7.30	116.69
90	7.44	7.24	7.12	7.26	116.19
120	7.28	7.14	7.04	7.15	114.39
150	7.02	6.98	6.83	6.94	111.08
180	6.97	6.91	6.65	6.84	109.44
210	6.66	6.64	6.46	6.59	105.33
240	6.50	6.51	6.25	6.42	102.68
270	6.34	6.33	6.08	6.25	99.95
300	6.09	6.11	5.76	5.99	95.73
360	5.79	5.76	5.39	5.65	90.31

Table A161 pH Changes in soak solution in Modified ASTM C 1293 tests for high alkali cement at 0 day

Soak Solution	NM		SP		NC		SD	
	PH	Temp,º C	PH	Temp,º C	PH	Temp,º C	PH	Temp,º C
3-0	9.92	21.6	10	24.1	10	24.1	10.04	24.3
3-0.2	9.58	22.3	9.68	24.2	9.68	24.2	9.64	24.3
3-0.8	8.47	22.1	X	X	X	X	X	X

Table A162 pH Changes in soak solution in Modified ASTM C 1293 tests for high alkali cement at 12 months

Soak Solution	NM		SP		NC		SD	
	PH	Temp,º C	PH	Temp,º C	PH	Temp,º C	PH	Temp,º C
0	12.6	20.5	12.7	21.9	12.06	30	12.9	24.5
0.2	12.7	20.5	12.6	23	12.57	25	12.5	25.3
0.8	12.36	20.8	X	X	X	X	X	X

Table A163 pH Changes in soak solution in Modified ASTM C 1293 tests for low alkali cement at 0 day

Soak Solution	NM		SP	
	PH	Temp,º C	PH	Temp,º C
0	9.92	21.6	10	24.1
0.2	9.58	22.3	9.68	24.2
0.8	8.47	22.1	X	X

Table A164 pH Changes in soak solution in Modified ASTM C 1293 tests for low alkali cement at 12 months

Soak Solution	NM		SP	
	PH	Temp,° C	PH	Temp,° C
0	12.96	24.3	11.97	23.3
0.2	12.3	23.6	10.03	24.5
0.8	11.27	24.5	X	X

Table A165 Expansion readings and percentage expansions of the Modified ASTM C 227 tests of mortar bars made with Ottawa sand and fused silica, low alkali cement and exposed to water with no pre treatment

	Comparator readings			Expansion, %		
Days	Ref bar	Bar1	Bar2	Bar1	Bar2	Avg
0	0.0092	0.2634	0.2834	0	0	0
3	0.0094	0.2635	0.2832	-0.001	-0.004	-0.0025
11	0.0096	0.2666	0.2865	0.028	0.027	0.0275
14	0.0099	0.2664	0.2863	0.023	0.022	0.0225
21	0.01	0.2674	0.2865	0.032	0.023	0.0275
28	0.0104	0.2696	0.288	0.05	0.034	0.042
56	0.0088	0.2814	0.3013	0.185	0.187	0.186

Table A166 Expansion readings and percentage expansions of the Modified ASTM C 227 tests of mortar bars made with Ottawa sand and fused silica, low alkali cement and exposed to KAc with no pre treated

	Comparator readings			Expansion, %		
Days	Ref bar	Bar1	Bar2	Bar1	Bar2	Avg
0	0.0092	0.2996	0.2927	0	0	0
3	0.01	0.3035	0.2964	0.031	0.029	0.03
7	0.0085	0.3065	0.3004	0.076	0.084	0.08
21	0.0088	0.3288	0.3213	0.296	0.29	0.293
28	0.0096	0.3462	0.3384	0.462	0.453	0.4575
56	0.0092	0.3935	0.3821	0.908	0.865	0.8865

Table A167 Expansion readings and percentage expansions of the Modified ASTM C 227 tests of mortar bars made with Ottawa sand and fused silica, low alkali cement and exposed to KAc and pre treated with $LiNO_3$ for 1 coat

	Comparator readings			Expansion, %		
Days	Ref bar	Bar1	Bar2	Bar1	Bar2	Avg
0	0.0092	0.3156	0.2538	0	0	0
3	0.01	0.3208	0.2579	0.044	0.033	0.0385
7	0.0085	0.3175	0.2567	0.026	0.036	0.031
21	0.0088	0.3188	0.2573	0.036	0.039	0.0375
28	0.0096	0.32	0.2583	0.04	0.041	0.0405
56	0.0092	0.3197	0.258	-0.003	0.009	0.003

Table A168 Expansion readings and percentage expansions of the Modified ASTM C 227 tests of mortar bars made with Ottawa sand and fused silica, low alkali cement and exposed to KAc and pre treated with $LiNO_3$ for 3 coat

	Comparator readings				Expansion, %			
Days	Ref bar	Bar1	Bar2	Bar3	Bar1	Bar2	Bar3	Avg
0	0.0092	0.2931	0.3002	0.2743	0	0	0	0
3	0.01	0.2961	0.303	0.2773	0.022	0.02	0.022	0.0213333
7	0.0085	0.2954	0.3027	0.2771	0.03	0.032	0.035	0.0323333
21	0.0088	0.2959	0.3036	0.2776	0.032	0.038	0.037	0.0356667
28	0.0096	0.297	0.304	0.2784	0.035	0.034	0.037	0.0353333
56	0.0092	0.2969	0.3042	0.2784	0.016	0.02	0.019	0.0183333

Table A169 Expansion readings and percentage expansions of the Modified ASTM C 227 tests of mortar bars made with Ottawa sand and fused silica, low alkali cement and exposed to KAc and pre treated with $LiNO_3$ for 5 coat

	Comparator readings			Expansion, %		
Days	Ref bar	Bar1	Bar2	Bar1	Bar2	Avg
0	0.0092	0.277	0.318	0	0	0
3	0.01	0.2805	0.3211	0.027	0.023	0.025
7	0.0085	0.2793	0.3207	0.03	0.034	0.032
21	0.0088	0.28	0.3213	0.034	0.037	0.0355
28	0.0096	0.2808	0.3219	0.034	0.035	0.0345
56	0.0092	0.2807	0.322	0.01	0.017	0.0135

Table A170 Changes in DME in modified ASTM C 227 tests of mortar bars made with Ottawa sand and fused silica, low alkali cement and exposed to water with no pre treatment

	Dynamic Young's Modulus, (E) * 10^6			% Change in DME
Days	Bar1	Bar2	Avg	
0	2.23	2.19	2.21	100.00
3	3.63	3.46	3.54	160.51
14	4.06	3.98	4.02	181.85
28	3.93	3.79	3.86	174.81
56	2.88	2.65	2.76	125.18

Table A171 Changes in DME in modified ASTM C 227 tests of mortar bars made with Ottawa sand and fused silica, low alkali cement and exposed to KAc with no pre treated

	Dynamic Young's Modulus, (E) * 10^6			% Change in DME
Days	Bar1	Bar2	Avg	
0	2.65	2.62	2.64	100.00
3	3.79	4.04	3.92	148.58
7	4.11	3.97	4.04	153.32
28	3.03	2.93	2.98	113.09
56	1.43	1.44	1.44	54.46

Table A172 Changes in DME in modified ASTM C 227 tests of mortar bars made with Ottawa sand and fused silica, low alkali cement and exposed to KAc and pre treated with $LiNO_3$ for 1 coat

T-1	Dynamic Young's Modulus, (E) * 10^6			% Change in DME
Days	Bar1	Bar2	Avg	
0	2.62	2.75	2.69	100.00
3	3.10	4.58	3.84	143.02
7	5.12	5.27	5.20	193.48
28	5.44	5.13	5.29	196.83
56	5.45	5.62	5.54	206.15

Table A173 Changes in DME in modified ASTM C 227 tests of mortar bars made with Ottawa sand and fused silica, low alkali cement and exposed to KAc and pre treated with $LiNO_3$ for 3 coat

T-3	Dynamic Young's Modulus, (E) * 10^6				% Change in DME
Days	Bar1	Bar2	Bar3	Avg	
0	2.89	2.77	2.53	2.73	100.00
3	4.55	4.52	4.22	4.43	162.27
7	4.86	4.64	4.42	4.64	169.96
28	5.36	5.10	4.82	5.09	186.57
56	5.41	5.08	4.86	5.12	187.42

Table A174 Changes in DME in modified ASTM C 227 tests of mortar bars made with Ottawa sand and fused silica, low alkali cement and exposed to KAc and pre treated with $LiNO_3$ for 5 coat

T-5	Dynamic Young's Modulus, (E) * 10^6			% Change in DME
Days	Bar1	Bar2	Avg	
0	2.76	2.54	2.65	100.00
3	4.77	4.47	4.62	174.34
14	4.94	4.93	4.94	186.23
28	5.21	5.23	5.22	196.98
56	5.28	5.28	5.28	199.25

Table A175 Concentration of K and Li with depth from top in Spratt, NM and IL aggregate

Aggregate		Concentration (mg/l) ppm				
		0.5”	1”	1.5”	2”	2.5”
SP	K	13.54	7.59	2.03	1.12	0.97
	Li	2.27	0.66	0.42	-0.05	-0.05
NM	K	22.45	12.43	7.24	2.72	1.45
	Li	3.42	0.8	0.44	-0.05	-0.05
IL	K	15.09	12.92	4.59	0.77	0.59
	Li	1.84	0.66	0.4	-0.05	-0.05

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