APPENDIX F
Development of Deicer-Modified Mortar Bar Test Method

Part I - Assessing Potential Reactivity of Aggregates in Presence of Potassium Acetate Deicer – Revised EB-70 Test Method

Part II – Evaluation of ASR Mitigation Potential of Supplementary Cementing Materials and Lithium Admixture in the Presence of Potassium Acetate Deicer – Revised EB-70 Test Method

PART I

ASSESSING POTENTIAL REACTIVITY OF AGGREGATES IN PRESENCE OF POTASSIUM ACETATE DEICER – REVISED EB-70 METHOD

ABSTRACT

Existing test methods such as the standard ASTM C 1260 and ASTM C 1293 test methods focus on identifying aggregate reactivity in presence of alkali hydroxides. The sensitivity of these test methods to assess aggregate reactivity in presence of deicing chemicals is unknown. Preliminary efforts to develop a test method to identify aggregate reactivity in presence of deicing chemicals yielded a mortar bar test (EB-70 test) that was based on soaking the mortar bars containing the suspect aggregates in a 6.4M KAc deicer solution, instead of 1N NaOH solution as in the standard ASTM C 1260 test. While the EB-70 test method was effective in identifying highly reactive aggregates, it was erratic in assessing moderate and slowly reactive aggregates. Deficiencies in EB-70 test method were attributed to lack of precise understanding of the mechanisms involved in high "pH jump" observed upon interaction of KAc with alkali hydroxides and calcium hydroxide. The knowledge gained in recent studies in understanding the "pH jump" mechanism has provided a sound basis for making some modifications to the EB-70 test method. This paper presents a revised EB-70 test method that employs a soak solution having 1N NaOH and 3M KAc deicer as its soak solution. Evidence from testing 31 different aggregates with a range of aggregate mineralogy and reactivity indicates that the revised EB-70 test method is effective in characterizing a range of aggregate reactivity in presence of deicing chemicals. Also, limited studies were conducted on evaluating a low-lime fly ash (Class F) in mitigating the mortar-bar expansions in the EB-70 test method. Results from these investigations find that a low-lime fly ash is indeed very effective in controlling mortar bar expansion in the revised EB-70 test method.

Key Words: *potassium acetate deicer, alkali silica reaction (ASR), EB-70 test method, standard ASTM C 1260 test method*

1. INTRODUCTION

Premature deterioration of concrete pavements at several major airports in the US raised concerns about the role of pavement deicing and anti-icing chemicals in promoting alkali-aggregate reactions in concrete (*1*). Extensive laboratory studies to assess the potential of these deicing chemicals to induce and/or accelerate ASR confirmed that indeed all the alkali-acetate and alkali-formate deicers have a considerable potential to cause alkali-silica reactions (ASR) in mortars and concrete (*2*-*5*). However, forensic investigations of core specimens from selected airports that experienced premature deterioration revealed that while effects of ASR were evident from the pavement surface to several inches below, the deicer penetration into a solid concrete surface was only about ½ inch from the pavement surface *(6, 7)*. In locations where some cracks were observed, deeper penetration of deicer into concrete was observed in the vicinity of the crack typically extending ¼" to ½" from the cracked surface. With such minimal deicer penetration, the findings from forensic studies raised doubts about the role of deicers in causing ASR. Further complicating the situation was the fact the concrete in question from these airports was constructed with aggregates that were known to be reactive in the standard ASTM C 1260 test method, and little to no ASR mitigation was employed to combat the potential ASR problems. Thus, these pavements had an inherent potential to undergo ASR distress even in the absence of deicer solutions. This makes it difficult to isolate the effect of deicers. The absence of conclusive evidence of KAc deicer induced ASR damage in field concrete specimens should not be construed as lack of potential for such reaction to take place under right exposure conditions (for instance, extensive cracking due to freeze-thaw cycles, shrinkage, wetting-drying cycles, construction defects, fatigue cracking from heavy aircraft loading or accidental high application rates of deicers). Considering the sensitive nature of airfield pavements and the potential for foreign object debris (such as loose fragments of concrete) to cause serious damage to aircrafts and personnel on ground, the lack of consensus between field and the laboratory results should be further investigated under broader set of exposure conditions. In the interim, an effective aggregate and ASR mitigation screening protocol is necessary to minimize potential failures.

Preliminary research as part of Innovative Pavement Research Foundation (IPRF) 03-9 and 04-8 studies led to development of an accelerated mortar bar test (*2, 10, 11*). This method was adopted by Federal Aviation Administration (FAA) under Engineering Brief No. 70 and came to be known as EB-70 test method (*1*). EB–70 test method is a modified version of standard ASTM C 1260 test, wherein a 6.4M KAc deicer is used as a soak solution for the mortar bars containing the suspect aggregate, instead of 1N NaOH solution.

In the IPRF 03-9 study four well-known reactive aggregates (NM rhyolite, Spratt limestone, SD quartzite, and NC argillite) were used in initial development of EB-70 test method. More details about the test method and the aggregate mineralogy can be found in the IPRF 03-9 report (*10*). The results from EB-70 tests using these four aggregates are shown in Figure 1, and are compared with the expansion of mortar bars in the standard ASTM C 1260 test.

Data in Figure 1 shows that in all cases the KAc deicer induced significantly higher expansion in mortar bars than 1N NaOH solution. While the EB-70 test method was effective in identifying highly reactive aggregates, the shortcomings of this test method became evident when the test method was employed to assess moderately and slowly reactive aggregates in field projects around the country. Poor correlations between the results from EB-70 test method and the standard ASTM C 1260 led to difficulty in adequately characterizing aggregate reactivity and understanding the impact of deicers. The deficiencies of EB-70 test method were also attributed to lack of precise understanding of the mechanisms that are involved in interaction of KAc with alkali hydroxides and calcium hydroxide in hydrated cement paste.

Subsequent fundamental studies conducted by Diamond et al. showed the interaction of KAc deicer with alkali hydroxides was quite complex that involved abrupt and rapid jump in pH of the deicer solution due to an increase in apparent activity coefficient of hydroxyl ions in concentrated KAc solutions (*8, 9)*. However there was little to no increase in hydroxyl ion concentration itself. Giebson et al. postulated that high pH observed in deicer solution upon reacting with calcium hydroxide was due to increased solubility of calcium hydroxide in the deicer solution at lower temperatures and the associated formation of Ca-acetate and Ca-formate complexes (*5*). Based on these findings the deficiencies of EB-70 test method were identified and a revised EB-70 test method was developed.

This paper examines the discrepancies between the results of EB-70 test method and the standard ASTM C 1260 test method. Fundamental investigations on interactions between sodium hydroxide and KAc deicer solution were examined and an apparent activity coefficient was developed to help explain the discrepancy. Based on this knowledge a revised EB-70 test method employing a 1N NaOH + 3M KAc deicer soak solution was developed. Thirty one different aggregates representing a range of mineralogy and geographic distribution were evaluated in the revised EB-70 test method and compared against their performance in the standard ASTM C 1260 test method and the existing EB-70 test method. In addition, the effectiveness of a low-lime fly ash in mitigating deicer-induced ASR was explored in the revised EB-70 test method.

2. OBJECTIVES

The principal objectives of this research study were:

1. To develop a revised EB-70 test method that correctly identifies the potential reactivity of the aggregates in presence of KAc deicer.
2. To correlate the aggregate reactivity results from the revised EB-70 test method and the standard ASTM C 1260 test method.
3. To evaluate the effectiveness of a fly ash in mitigating deicer-induced ASR in the revised EB-70 test method.

3. EXPERIMENTAL PROGRAM

3.1. Materials

3.1.1. Cement

High alkali cement (Type I) with a Na_2O equivalent of 0.82% (Na2Oeq) and an autoclave expansion of 0.12% was used for this study. The chemical composition of this cement is provided in Table 1.

3.1.2. Fly Ash

In this study, a low-lime fly ash was used as a supplementary cementitious material (SCM) for evaluation of a typical ASR mitigation measure in the test methods. The chemical composition of this fly ash is provided in Table 1. The fly ash had a specific gravity of 2.20 g/cc and an autoclave expansion of -0.04 %. Based on the information provided in Table 1, the fly ash meets the requirements of ASTM C 618-05 and AASHTO M 295 specifications for a Class F fly ash.

3.1.3. Aggregates

Aggregates from different locations across the US were used in this study. A total of 31 aggregates were selected based on their mineralogy and reactivity as indicated based on their performance in the field and standard lab tests. The field performance information for aggregate was based on the experience of respective state highway agencies and some airport authorities. Table 2 shows the aggregates labeled from AGG1 through AGG31 along with the principal reactive component in each of the aggregates and their respective field performance. It should be noted that the field performance of a majority of the aggregates does not reflect exposure to deicers.

3.1.4. Deicers and Reagents

In this study, Cryotech E-36, a commercial grade runway liquid deicer was used as the soak solution in some of the test methods. This deicer is a 50% wt. solution of KAc (6.4 molar concentration) with a pH of 10.85. The deicer contains a proprietary organic corrosion inhibitor and a dyeing agent. The deicer solution contains less than 200 ppm of sulfate as impurities. Limited tests were also conducted in this investigation using soak solutions prepared with reagent grade KAc at 6.4M concentration. In addition, reagent grade NaOH pellets were used to prepare the soak solutions for conducting the standard ASTM C 1260/ASTM C 1567 tests. Soak solutions for all of the revised EB-70 test method (1N NaOH + 3M KAc) were prepared by using combination of reagent grade NaOH and commercial grade KAc deicer. In titration studies conducted to study the pH jump phenomenon, all reagent grade chemicals were used and all the acids and based were standardized to eliminate any possible errors.

3.2. Test Methods

3.2.1. Standard ASTM C 1260/C 1567 Tests (1N NaOH Soak Solution)

In this test method, mortar bars (25mm X 25mm X 285 mm) with gauge studs embedded at the ends were cast and moist cured for 24 hours in a curing room. After demolding, the bars were cured at 80°C for 24 hours in a water bath. After curing in the water bath, the bars were kept in 1N NaOH soak solution, which was preheated to 80°C for 24 hours. Periodic length change measurements were taken at regular intervals up to 28 days, and percent expansions were calculated. The expansions of mortar bars less than 0.1% at 14 days were considered to be non-reactive aggregates, and expansions of mortar bars over 0.2% were considered as reactive aggregates. Mortar bar expansions between 0.1% and 0.2% were considered potentially reactive with additional confirmation required using petrographic examination, concrete prism tests (ASTM C 1293) and/or past field performance. In the standard ASTM C 1567 tests, 25% of portland cement was replaced with fly ash.

3.2.2. EB – 70 test method (KAc deicer Soak Solution)

In this test method, the mortar bars are soaked in 6.4 Molar concentration KAc deicer soak solution instead of 1N NaOH soak solution. The length change in mortar bars was measured with age, similar to the standard ASTM C 1260 test procedure.

To investigate the effects of deicers at lower concentration a modified EB-70 test with 3 Molar concentration KAc deicer soak solution was also used. Sixteen aggregates were evaluated in this study.

3.2.3. Revised EB – 70 test method (1N NaOH+ 3M KAc deicer Soak Solution)

The principal revision in the revised EB-70 test method was the use of a soak solution that has a concentration of 1N NaOH and 3M KAc, instead of the 6.4M KAc solution as used in EB-70 test method. The basis for using this combination of NaOH and KAc deicer is presented in the results section. The average length change in mortar bars was measured at periodic intervals similar to EB-70 test and standard ASTM C 1260 test procedures. To evaluate ASR mitigation measures such as fly ash, a portion of portland cement was replaced with fly ash in this test method with no other changes to the soak solution composition. The soak solution for the revised

EB-70 test method was prepared by dissolving 40 g of NaOH in sufficient amount of 6.4M KAc deicer solution and then diluting to one liter with water, to achieve a concentration of 1N NaOH + 3M KAc in the resulting solution.

3.2.4. pH Measurements and Titration

The pH of different soak solutions used in this study was measured by using an Oakton pH 110 series pH meter with an electrode consisting of an amber glass bulb for low sodium error. The pH meter was calibrated using standard buffer solutions of pH 4, 7 & 10 @ 25°C. In addition, the pH of a saturated $Ca(OH)_2$ at 21ºC was measured as a check on the calibration of the pH meter.

The titration experiments were conducted on the soak solutions to measure the concentration of OH- ions. The acid & base used for titration experiment were the standard (Fisher Scientific UN1824) 1N NaOH solution and (Fisher Scientific UN1789) 1N HCl solution with different dilution levels, to investigate the influence of KAc deicer concentration on the apparent activity coefficient of hydroxyl ions in the soak solution. Diamond et al. showed that in solutions of high deicer concentration, the activity of hydroxyl ions introduced by bases such as calcium hydroxide or other alkali hydroxides can be significant and therefore can result in very high pH values even when the hydroxyl ion concentrations are relatively low (Diamond et al., 2006). In this investigation, an apparent activity coefficient term is introduced that captures this increase in activity of hydroxyl ions. The apparent activity coefficient is defined as the ratio of electrode measured pH (measured pH) to that of the calculated pH from the hydroxyl ion concentration determined from the titration (calculated pH). By the very nature of the pH measurement by an electrode, the activity coefficient of hydroxyl ions is captured. However, calculated pH from measured hydroxyl ion concentration does not account for the increased activity coefficient. Phenolphthalein indicator solution was used in these studies to determine the end point of the titration.

3.2.5. Scanning Electron Microscope and Energy Dispersive X-Ray Analyses

The microstructure analysis on mortar bar samples was performed using a variable pressure, back scatter electron, scanning electron microscope (SEM). The analyses were run using Hitachi S-3400N SEM on fractured and epoxy impregnated polished samples of mortar bars at a voltage of 20KV. The Energy Dispersive X-ray (EDX) analysis was also performed to identify presence of any reaction products.

3.3. Test Program

In this study, a total of 132 mortar bar tests were conducted using standard ASTM C 1260, standard C 1567, EB-70 and revised EB-70 test methods. In addition, numerous pH measurements and titration experiments were conducted to determine the influence of KAc deicer on the “pH jump” and apparent activity coefficient of hydroxyl ion concentration in the soak solutions.

4. RESULTS AND DISCUSSIONS

4.1. Results from Standard ASTM C 1260 and EB-70 (6.4 M KAc) test methods

Figures 2a & 2b shows the 14-day expansion behavior of 31 different aggregates in the standard ASTM C 1260 (1N NaOH) and EB-70 (6.4M KAc) soak solution. Figure 2b shows the percent difference between expansions of EB-70 test method when compared with standard ASTM C 1260 test method. It is evident that aggregates from different sources and mineralogical structure behave differently. Some aggregates are more susceptible to alkali solutions (1N NaOH) and expand more comparatively to deicer (6.4 M KAc) soak solutions and vice versa. Figures 3a and 3b show similar data at 28-days of testing. Comparing Figures 2 and 3, it is evident that there is no substantial difference in the overall trends in the results.

4.2. Results from EB 70 test (with 3 M KAc deicer)

Figures 4a and 4b show the comparison of 1N NaOH with 3M KAc soak solution for 16 aggregate sources at 14-days and 28-days of testing, respectively. It is evident that the aggregates with 3M KAc soak solution expand less compared to 1N NaOH soak solution; with the exception of AGG-1 aggregate expanding more than the 1N NaOH soak solution. Also, comparing the results of the same aggregates in Figure 2 (with 6.4M KAc deicer solution), it is evident that 3M KAc by itself is not as aggressive as the 6.4M KAc deicer solution.

4.3. Results from Investigation into Interaction of KAc deicer with Alkali Hydroxides

The fundamental studies conducted by Diamond et al. showed the interaction of KAc deicer with calcium hydroxide solution can result in significant pH jump in deicer solutions. The interaction phenomenon was quite complex and involved abrupt pH jump due to increase in apparent activity coefficient of hydroxyl ions in concentrated KAc solutions, with little to no increase in hydroxyl ion concentration itself (Diamond et al., 2006; Chandni et al., 2009).

In this paper, the high pH jump and the apparent activity coefficient of hydroxyl ions in KAc in the presence of calcium hydroxide and sodium hydroxide was studied. All the chemicals used in this study were of reagent grade. Figure 5 shows the pH of different solutions at room temperature, and in particular highlights the influence of calcium hydroxide and sodium hydroxide on pH of KAc solution. From Figure 5a it is evident that the pH of 3M KAc solution is only 9.79 and that of 1N NaOH solution was 13.69; however, when the pH of the 3M KAc and 1N NaOH was evaluated it was found to be 14.47, almost an order of magnitude over the pH of 1N NaOH solution. Similar but more dramatic jump can be observed when pH of 6.4M KAc solution is compared with 6.4M KAc with a small addition of calcium hydroxide (0.5 grams of CH was added to 50 ml of 6.4M KAc). The increase in pH from 10.76 to 14.54 is not entirely justified by slight increase in hydroxyl ion concentration due to calcium hydroxide dissolution. The difference in the observed pH in both cases (i.e. with NaOH and $Ca(OH)_2$) can be attributed to the apparent activity coefficient of hydroxyl ions in these concentrated solutions.

The increase in apparent activity coefficient of hydroxyl ions for a more or less constant concentration of hydroxyl ions (i.e. due to 1N NaOH) is shown in Figure 5b. In this study, a series of solutions having 1N NaOH concentration along with KAc at 0.1M, 1.0M, 3M, 5M and 6.4M concentration were prepared. The KAc itself does not contribute any appreciable hydroxyl ions compared to NaOH in these solutions. Therefore, the net change in hydroxyl ion concentration should be minimal in each of the solutions described above. Consequently the measured pH and the calculated pH should be similar to each other. However, as evident in Figure 5b, a significant increase in measured pH (owing to the increase in the activity coefficient of hydroxyl ions in concentrated deicer solution) was realized and consequently the apparent activity coefficient of hydroxyl ions increased with an increase in KAc concentration. Ideally, the ratio of measured pH to calculated pH should be 1.0, even at low concentrations of KAc. However, some minor deviations were observed from this trend at lower concentrations of KAc and the reason for this deviation is unknown at this time. Overall, these results show that the pH jump effect is solely due to increase in apparent activity coefficient of hydroxyl ions in the deicer solution and not by any unexpected increase in their concentrations. The symbiotic effects of KAc and alkali hydroxides could potentially exacerbate ASR in concrete containing reactive aggregates. The decision to use a 3M KAc concentration level with 1N NaOH was based on the two factors. Firstly, 3M KAc concentrations affect a substantial jump in the activity coefficient compared to lower concentrations. Secondly, the 3M KAc concentration represents a diluted deicer solution, which is a more realistic field condition rather than using higher concentrations, such as 6.4M KAc. Based on these findings it was decided that a solution composed of 1N NaOH and 3M KAc deicer solution would be used as the soak solution in the revised EB-70 test method that can clearly identify reactive aggregates.

4.4. Results from Revised EB-70 test (with 1N NaOH + 3M KAc deicer soak solution)

Figure 6a shows the 14-day expansion values of mortar bars prepared with 31 different aggregates and subjected to 1N NaOH + 3M KAc soak solution. Also, in this figure the performance of mortar bars in the standard ASTM C 1260 test is shown for comparison. Figure 6b shows the percent difference in the 14-day expansions of mortar bars subjected to revised EB-70 test method as compared to expansion in the standard ASTM C 1260 test. The 28-day mortar bar expansion data is shown in Figures 7a and 7b. From these figures it is evident that all aggregates tested in the revised EB-70 test method tend to show either similar mortar bar expansion to standard ASTM C 1260 test (18 out of 31 aggregates based on 14 day expansion values, and 15 out of 31 aggregates based on 28 day expansion values) or greater (13 out of 31 aggregates based on 14-day expansion values, and 15 out of 31 aggregates, based on 28-day expansion values). The reason why some aggregates tend to show significantly higher expansion in revised EB-70 test method as compared to standard ASTM C 1260 test method appears to be related to aggregate mineralogy. However, that aspect has not yet been investigated in this study, and is a subject of future investigation. These results show that the 1N NaOH + 3M KAc deicer solution captures the effects of both increased concentration of hydroxyl ions and their increased activity in concentrated solutions. Thus a revised test method consisting of combination (1N NaOH+3M KAc) soak solution appears to be beneficial in evaluating the potential of aggregate to cause ASR in presence of potassium acetate deicer. Based on the results obtained thus far, it appears that an expansion limit of 0.10% at 14 days of exposure in the revised EB-70 test method appears to be adequate to characterize aggregate reactivity. However, this limit is based on the correlations with standard ASTM C 1260 expansion data and further investigation is needed to validate these findings with field exposure data.

4.5. Reagent and Commercial grade KAc comparison in EB-70 Test

Commercial grade deicers often contain additives such as corrosion inhibitors and dyeing agents. In order to assess their specific impact on the results in the EB-70 test method, a comparative study was conducted using 6.4M KAc soak solution prepared with reagent grade chemical. The results from this investigation are shown in Figure 8. From the results it can be seen that there is little difference in the expansions of mortar bars subjected to commercial grade and reagent grade KAc, for each of the four aggregates evaluated. Therefore a commercial grade deicer, such as Cryotech E-36 can be used in preparing the soak solution, as long as its precise composition is known.

4.6. Evaluation of Fly Ash as an ASR Mitigation Measure in Revised EB-70 Test

The effectiveness of a low-lime fly ash in mitigating ASR was evaluated in the revised EB-70 (1N NaOH + 3M KAc) test, and the results were compared with the performance of the fly ash in EB-70 (6.4M KAc) and ASTM C 1567 (1N NaOH) tests. Figures 9a and 9b show the mortar bar expansions in these tests at 14-days and 28-days, respectively, for each of the 19 aggregates. The 14-day results show that the low-lime fly ash is indeed very effective in mitigating ASR even under the aggressive exposure conditions of the revised EB-70 test method with all the 19 aggregates. However, with some of the highly reactive aggregates such as rhyolite (AGG1) and siliceous limestone (AGG4), the 28-day expansions are over 0.1%. Findings from this limited study suggest that a low-lime fly ash at 25% dosage level can effectively be used in mitigating ASR for a majority of the aggregates even in the presence of KAc deicer. Higher dosage levels may be needed for highly reactive aggregates.

4.7. SEM/EDX Examination

In order to compare the effects of the two different soak solutions, the microstructure of AGG 16 mortar bars subjected to the standard ASTM C 1260 and the revised EB-70 test method were examined in scanning electron microscope. Figures 10a and 10b show the fractured faces of the mortar bar specimens. The presence of ASR gel (exhibiting cracks) is evident in both figures, clearly showing active ASR distress in both test methods. Figures 11a and 11b shows the EDX spectra of reaction product from the revised EB-70 test method and ASTM C 1260 test method, respectively. The predominant alkali present in the gel product in mortar bars subjected to the revised EB-70 test was potassium, while the dominant alkali in the gel product in mortar bars subjected ASTM C 1260 test was sodium, consistent with the respective soak solution compositions.

5. CONCLUSIONS

- Deicers have a significant potential to cause alkali silica reaction in lab test specimens containing reactive aggregates.
- The EB-70 test as originally proposed (i.e. containing a 6.4 M KAc deicer soak solution) was found to correlate positively with results from standard ASTM C 1260 test results in assessing only highly reactive aggregate. However, it produced erratic results when evaluating moderate to slowly reacting aggregates, and did not correctly characterize their reactivity.
- The apparent activity coefficient determined from the measured (pH probe) and calculated pH (from titration) values of the deicer solutions clearly indicates the role of activity of hydroxyl ions in elevating the pH values, even when the hydroxyl ion concentrations are high.

- The revised EB-70 test method with a soak solution consisting of 1N NaOH+3M KAc deicer appears to capture the effect of increased hydroxyl ion activity and consequently its effect on promoting ASR distress in test specimens.
- Results from evaluating 31 different aggregates in the standard ASTM C 1260 and revised EB-70 test method clearly indicate that the revised EB-70 test has the ability to characterize aggregate reactivity, and identify those that are sensitive to KAc deicer solution.
- Based on correlations between test data from 31 aggregates in the standard ASTM C 1260 and revised EB-70 methods, an expansion limit of 0.10% at 14 days in the revised EB-70 test appears to adequately characterize the aggregate reactivity. However, this limit needs to be calibrated with data from field exposure sites and from concrete prism tests.
- No significant difference in the test results from revised EB-70 procedure could be deciphered when reagent grade KAc and commercial KAc were used.
- Limited studies on evaluating the effectiveness of ASR mitigation measures in the revised EB-70 test method showed that a low-lime fly ash (Class F fly ash) is very effective in mitigating expansions in test specimens exposed to KAc deicer solution.

6. RECOMMENDATIONS

The sensitivity of the aggregate mineralogy in the revised EB-70 test method should be evaluated. It appears that certain reactive forms of silica are more sensitive to deicers than other forms. This relation needs to be clearly established. In addition, SCMs of different composition need to be evaluated in the revised EB-70 test method to establish the expansion limits for effective ASR mitigation in airfield pavements.

7. ACKNOWLEDGMENTS

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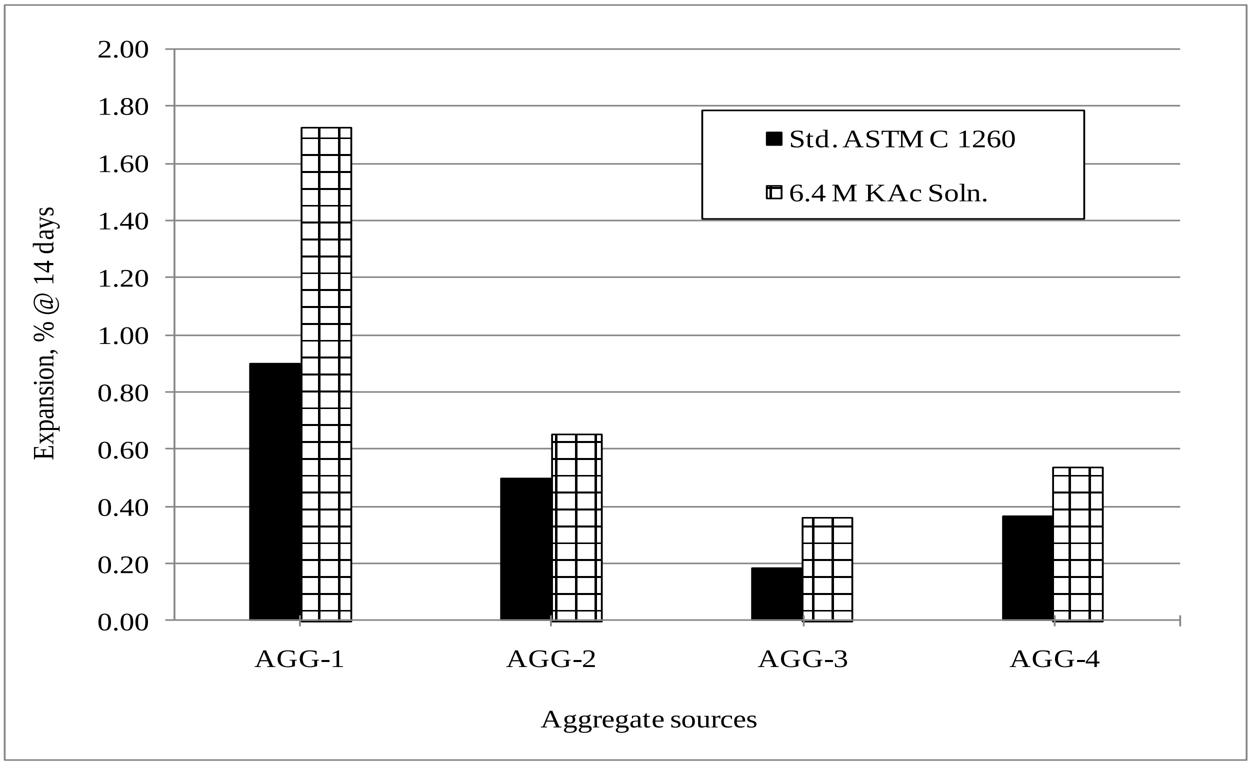
Table 1: Chemical Composition of Cementitious Material

Chemical Compositions	**Oxide, %**	
	Cement	**Low-Lime Fly Ash**
SiO_2	19.74	59.50
Al_2O_3	4.98	28.69
Fe_2O_3	3.13	3.96
Total S+A+F	--	92.1
CaO	61.84	1.02
MgO	2.54	0.99
SO_3	4.15	0.14
Na_2O	--	0.35
$Na_2Oeq = Na_2O + 0.68K_2O$	0.82	2.13
K_2O	--	2.70
TiO_2	--	1.48
Loss on Ignition (LOI)	1.9	1.10
Insoluble Residue	0.25	--
C_3A	8	--
C_3S	52	--

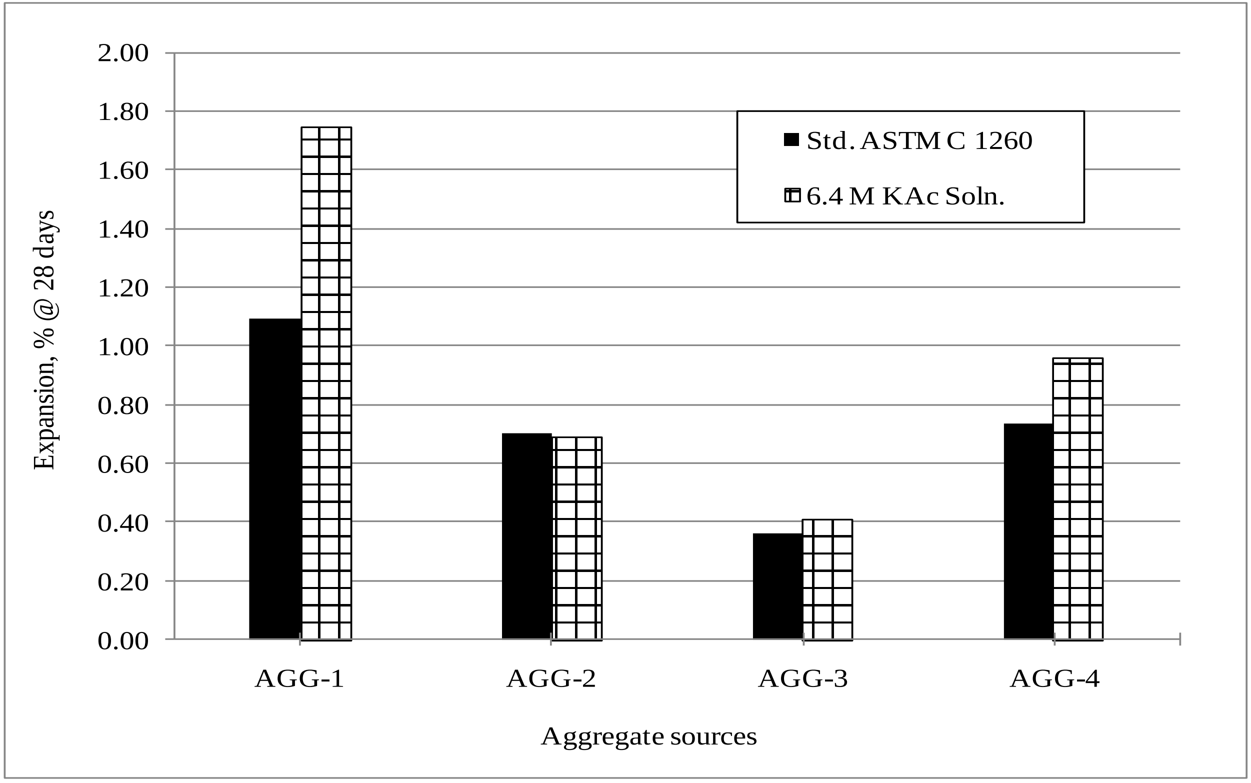
Table 2: Mineralogy and Field Performance of Aggregates*

Label	**Field Performance/Reactivity**	**Reactive Component in Aggregate (Mineralogy)**
AGG1	Reactive	Rhyolite
AGG2	Reactive	Argillite
AGG3	Reactive	Quartzite
AGG4	Reactive	Chert
AGG5	Reactive	Chert
AGG6	Reactive	Chert
AGG7	Reactive	Chert
AGG8	Reactive	Chert
AGG9	Reactive	Chert/Shale
AGG10	Reactive	Chert/Shale
AGG11	Non-reactive	None
AGG12	Non-reactive	None
AGG13	Non-reactive	None
AGG14	Reactive	Microcrystalline Quartz
AGG15	Non-reactive	None
AGG16	Reactive	Greywacke
AGG17	Reactive	Chert/Shale (D)
AGG18	Reactive	Siliceous Limestone (D)
AGG19	Non-reactive	None (D)
AGG20	Non-reactive	None (D)
AGG21	Reactive	Chert (D)
AGG22	Reactive	Chert (D)
AGG23	Non-reactive	None
AGG24	Reactive	Argillite
AGG25	Non-reactive	None
AGG26	Non-reactive	None
AGG27	Reactive	Chert/Sandstone (D)
AGG28	Reactive	Sandstone (D)
AGG29	Non-reactive	None (D)
AGG30	Reactive	Quartzite
AGG31	Reactive	Microcrystalline Quartz

* Field performance of aggregate reactivity was based on assessment by respective DOT or Airfield personnel. “D” indicates field performance of aggregate under KAc deicer exposure.

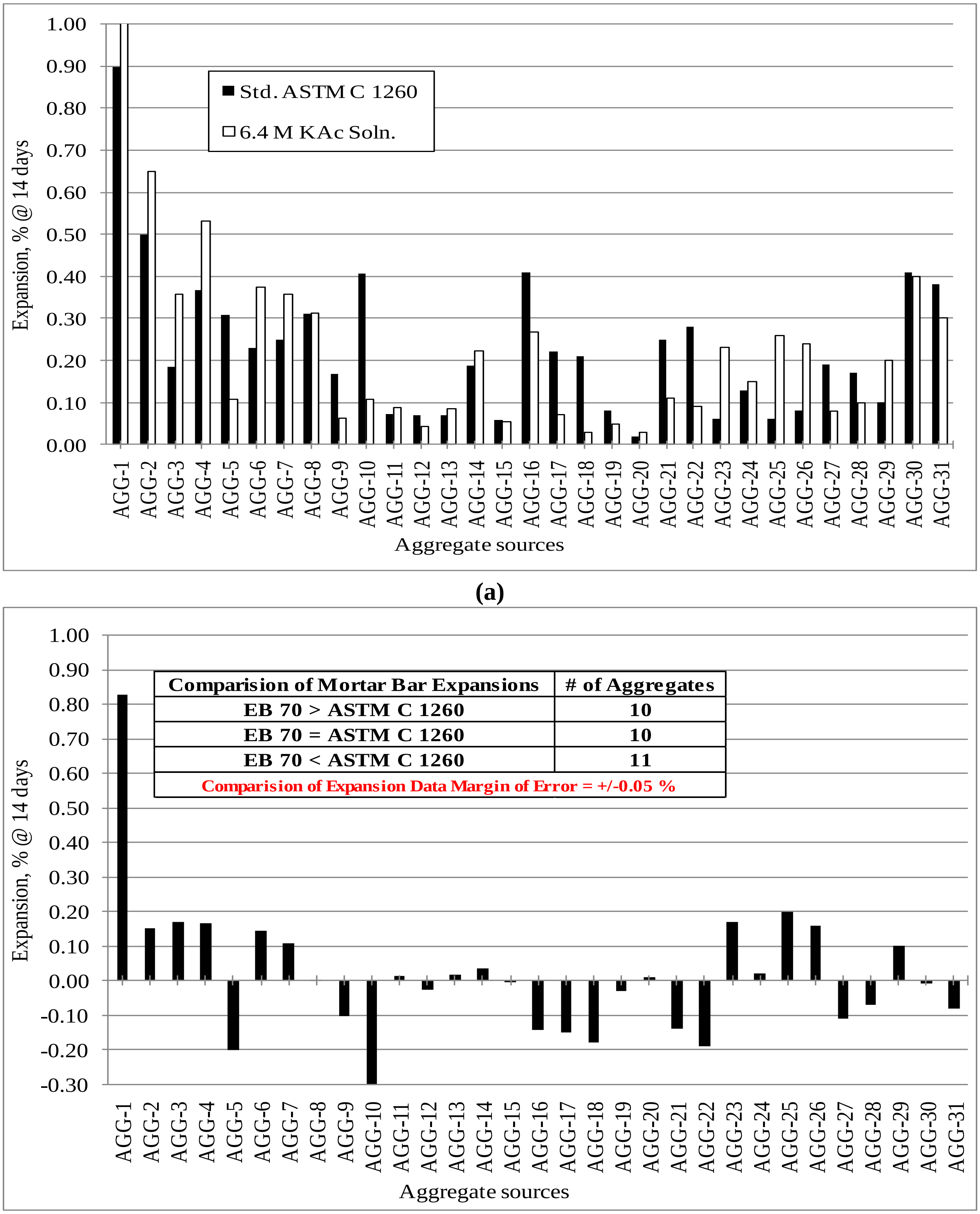


(a)



(b)

Figure 1 – Comparison of EB-70 Test Method and Standard ASTM C 1260 Test Method (a)14-day Mortar Bar Expansions (b)28-day Mortar Bar Expansions

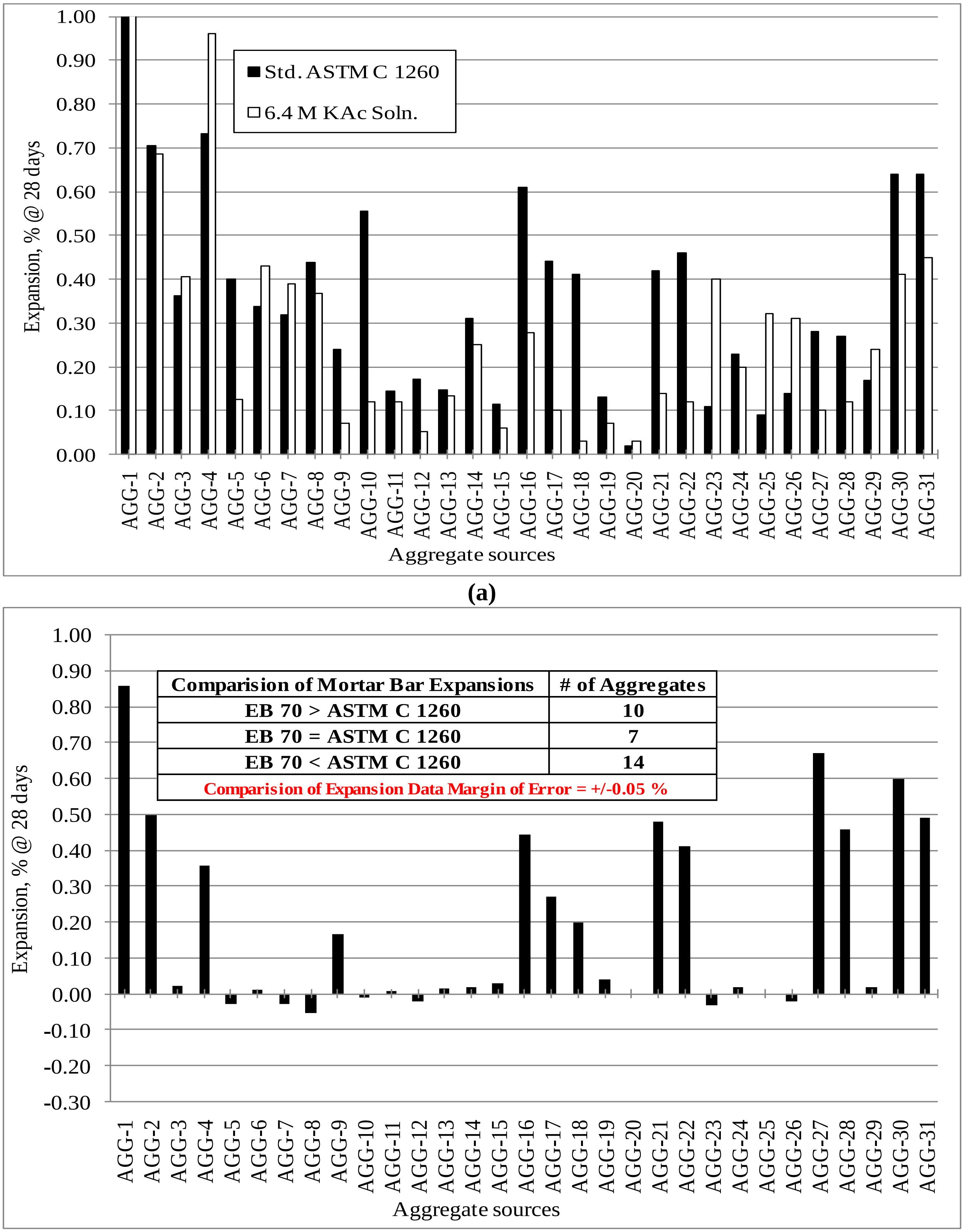


Comparision of Mortar Bar Expansions	# of Aggregates
EB 70 > ASTM C 1260	10
EB 70 = ASTM C 1260	10
EB 70 < ASTM C 1260	11
Comparision of Expansion Data Margin of Error = +/-0.05 %	

(a)

(b)

Figure 2: Expansions of mortar bars at 14-days (a) Std. ASTM C 1260 compared with EB – 70 test (b) Percent difference in expansions of EB – 70 test compared with Std. ASTM C 1260.

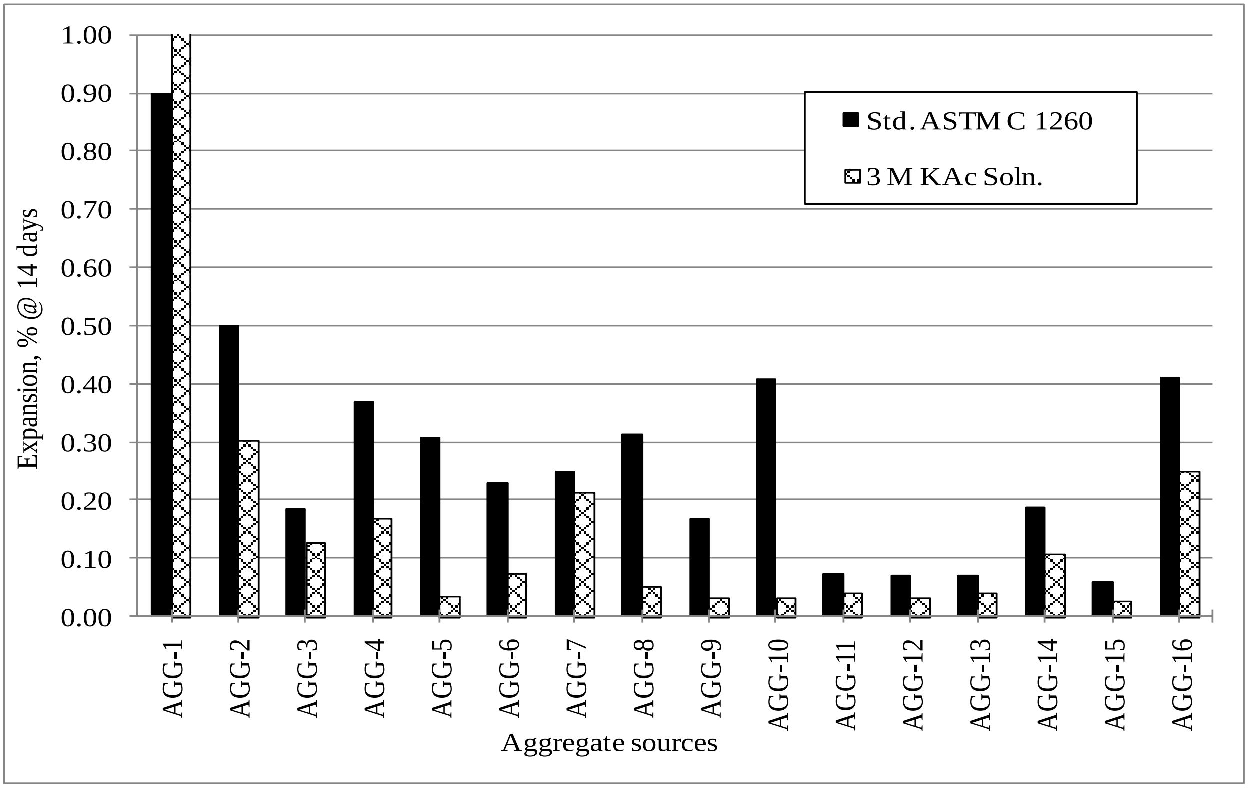


Comparision of Mortar Bar Expansions	# of Aggregates
EB 70 > ASTM C 1260	10
EB 70 = ASTM C 1260	7
EB 70 < ASTM C 1260	14
Comparision of Expansion Data Margin of Error = +/-0.05 %	

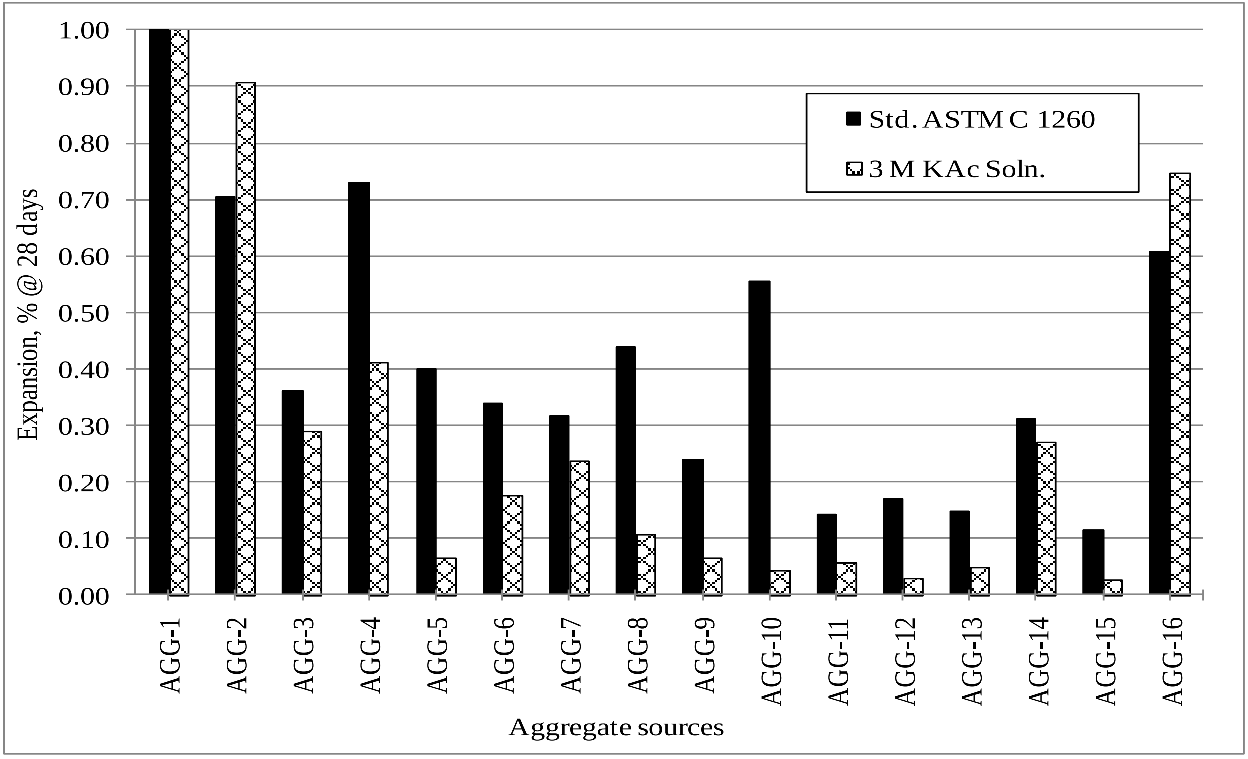
(a)

(b)

Figure 3: Expansions of mortar bars at 28 days (a) Std. ASTM C 1260 compared with EB – 70 test (b) Percent difference in expansions of EB – 70 test compared with Std. ASTM C 1260.

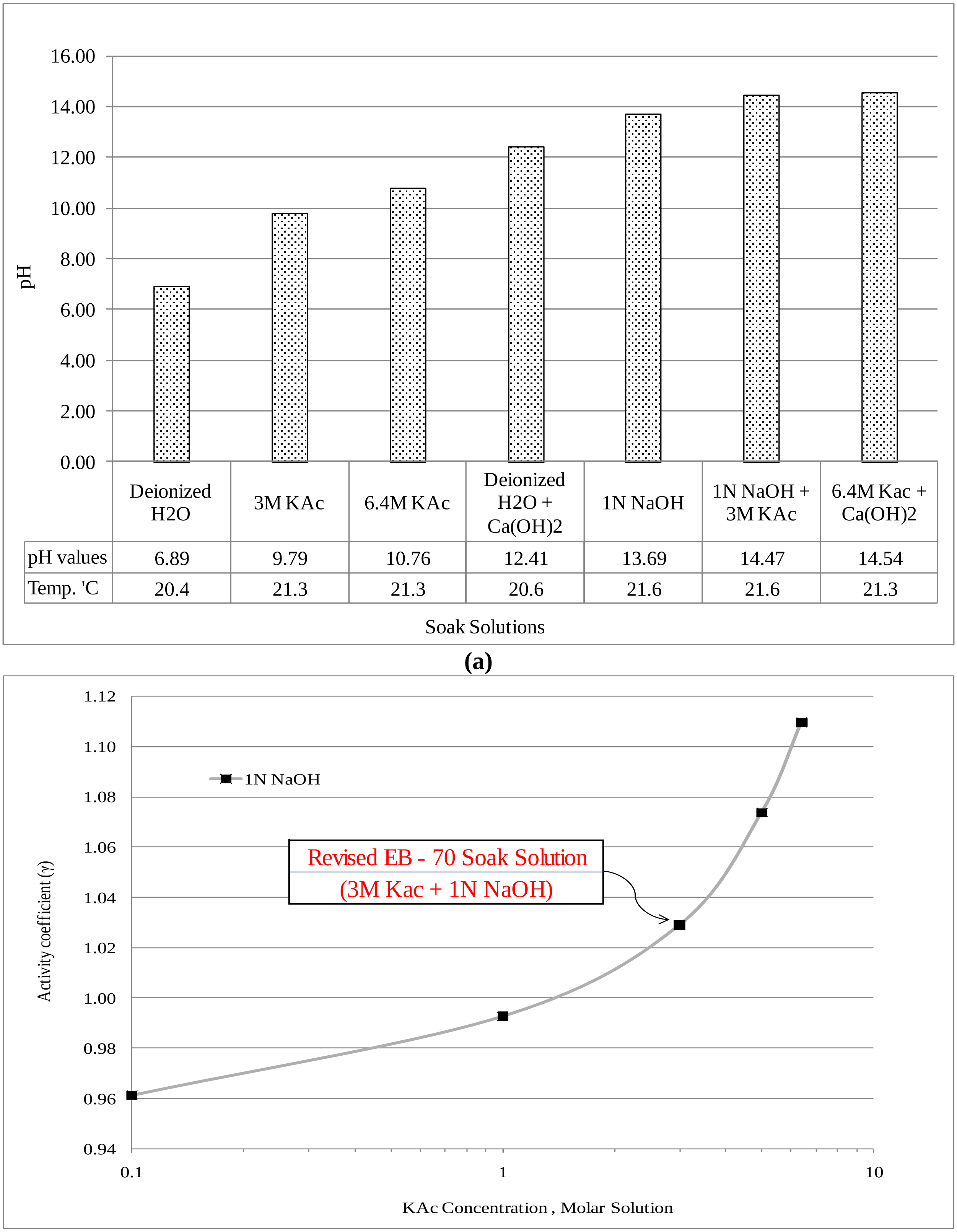


(a)



(b)

Figure 4 : Expansions of mortar bars Standard ASTM C 1260 compared with 3M KAc solution (a) 14-day Mortar Bar Expansions (b) 28-day Mortar Bar Expansions.

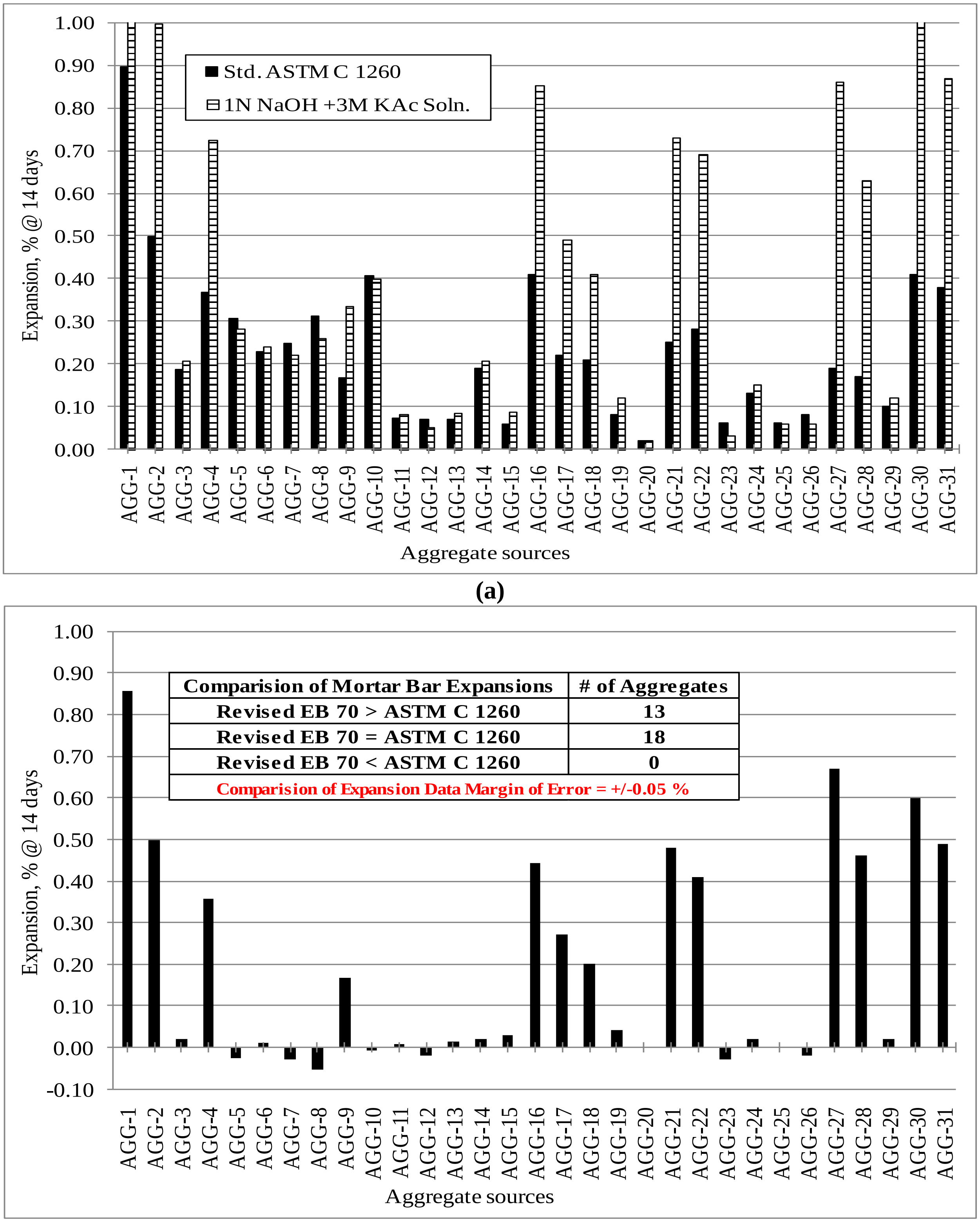


	Deionized H2O	3M KAc	6.4M KAc	Deionized H2O + Ca(OH)2	1N NaOH	1N NaOH + 3M KAc	6.4M Kac + Ca(OH)2
pH values	6.89	9.79	10.76	12.41	13.69	14.47	14.54
Temp. 'C	20.4	21.3	21.3	20.6	21.6	21.6	21.3

(a)

(b)

Figure 5: pH values for soak solutions (a) deicers and alkali solutions (b) Increase in apparent activity coefficient (γ) with increased concentration of KAc soln.

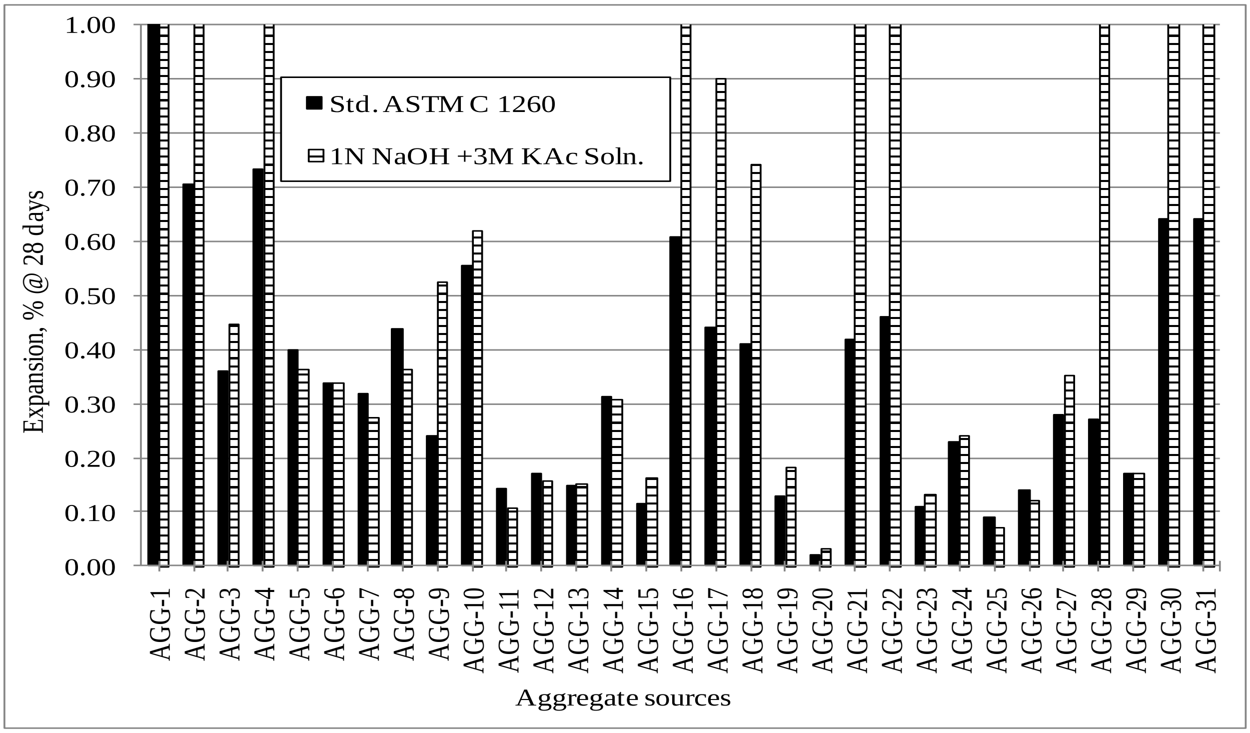


(a)

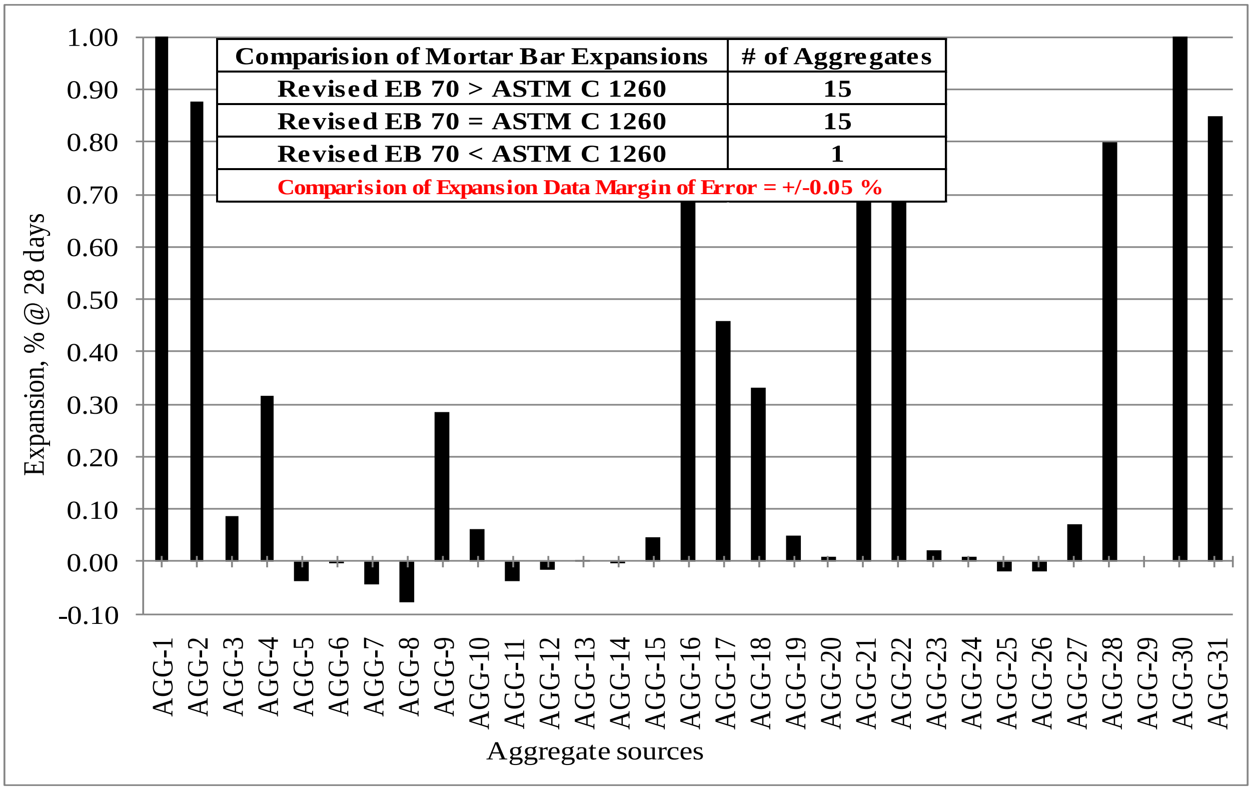
Comparision of Mortar Bar Expansions	# of Aggregates
Revised EB 70 > ASTM C 1260	13
Revised EB 70 = ASTM C 1260	18
Revised EB 70 < ASTM C 1260	0
Comparision of Expansion Data Margin of Error = +/-0.05 %	

(b)

Figure 6: Expansions of mortar bars at 14 days (a) Std. ASTM C 1260 compared with Revised EB – 70 test (b) Percent difference in expansions of Revised EB – 70 test compared with Std. ASTM C 1260.



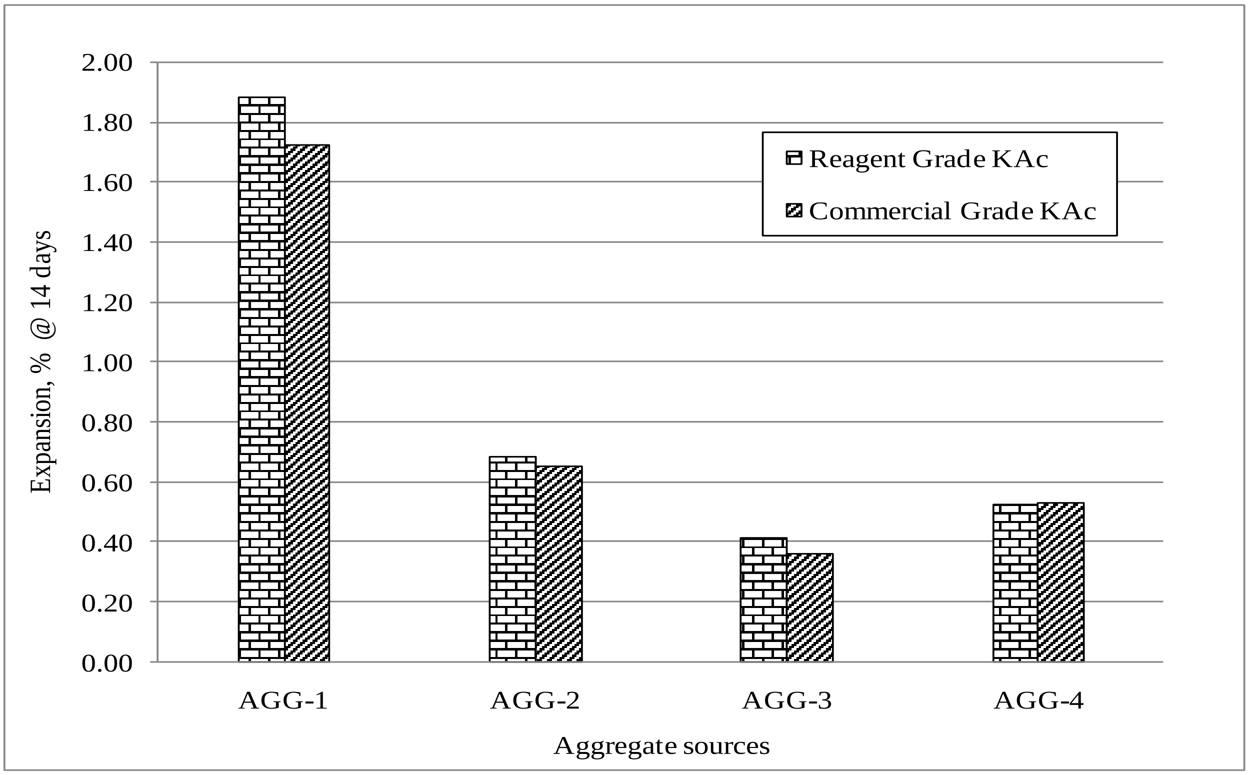
(a)



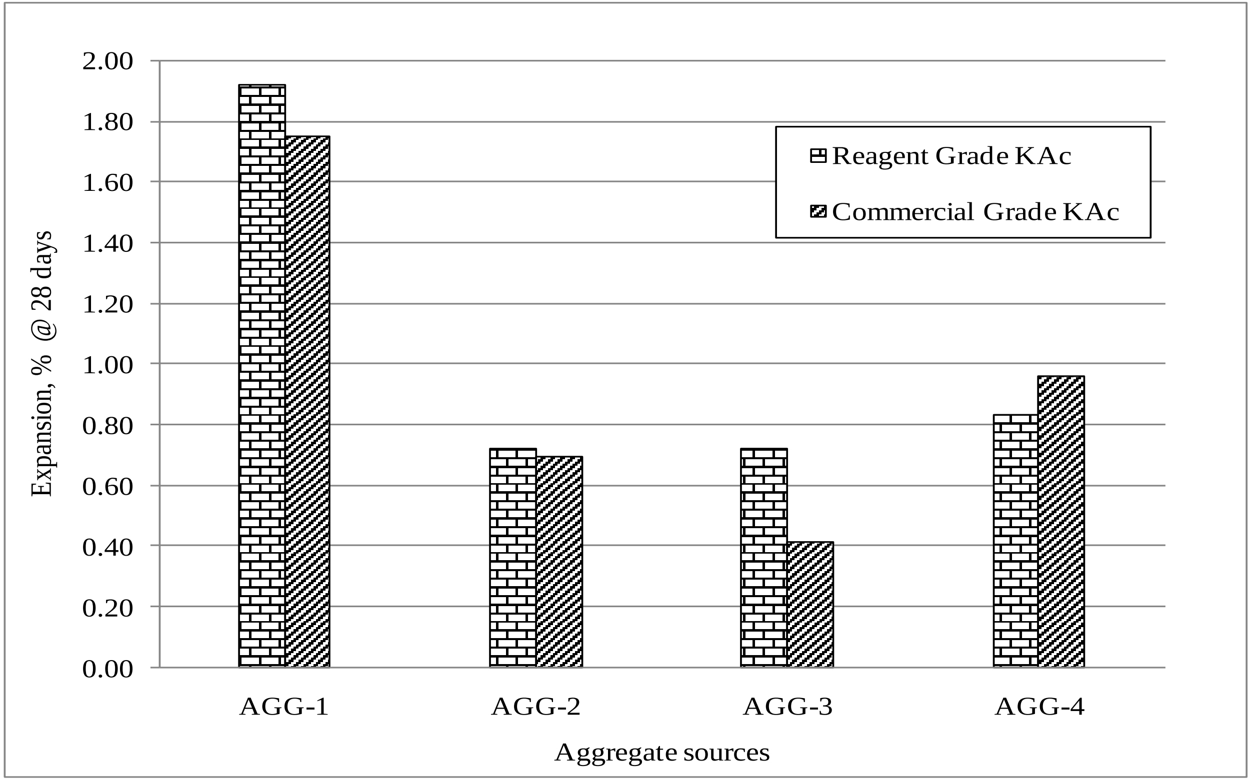
Comparision of Mortar Bar Expansions	# of Aggregates
Revised EB 70 > ASTM C 1260	15
Revised EB 70 = ASTM C 1260	15
Revised EB 70 < ASTM C 1260	1
Comparision of Expansion Data Margin of Error = +/-0.05 %	

(b)

Figure 7: Expansions of mortar bars at 28 days (a) Std. ASTM C 1260 compared with Revised EB – 70 test (b) Percent difference in expansions of Revised EB – 70 test compared with Std. ASTM C 1260.



(a)



(b)

Figure 8: Comparison of Reagent grade and Commercial grade KAc soln. (a) 14-day Mortar Bar Expansions (b) 28-day Mortar Bar Expansions.

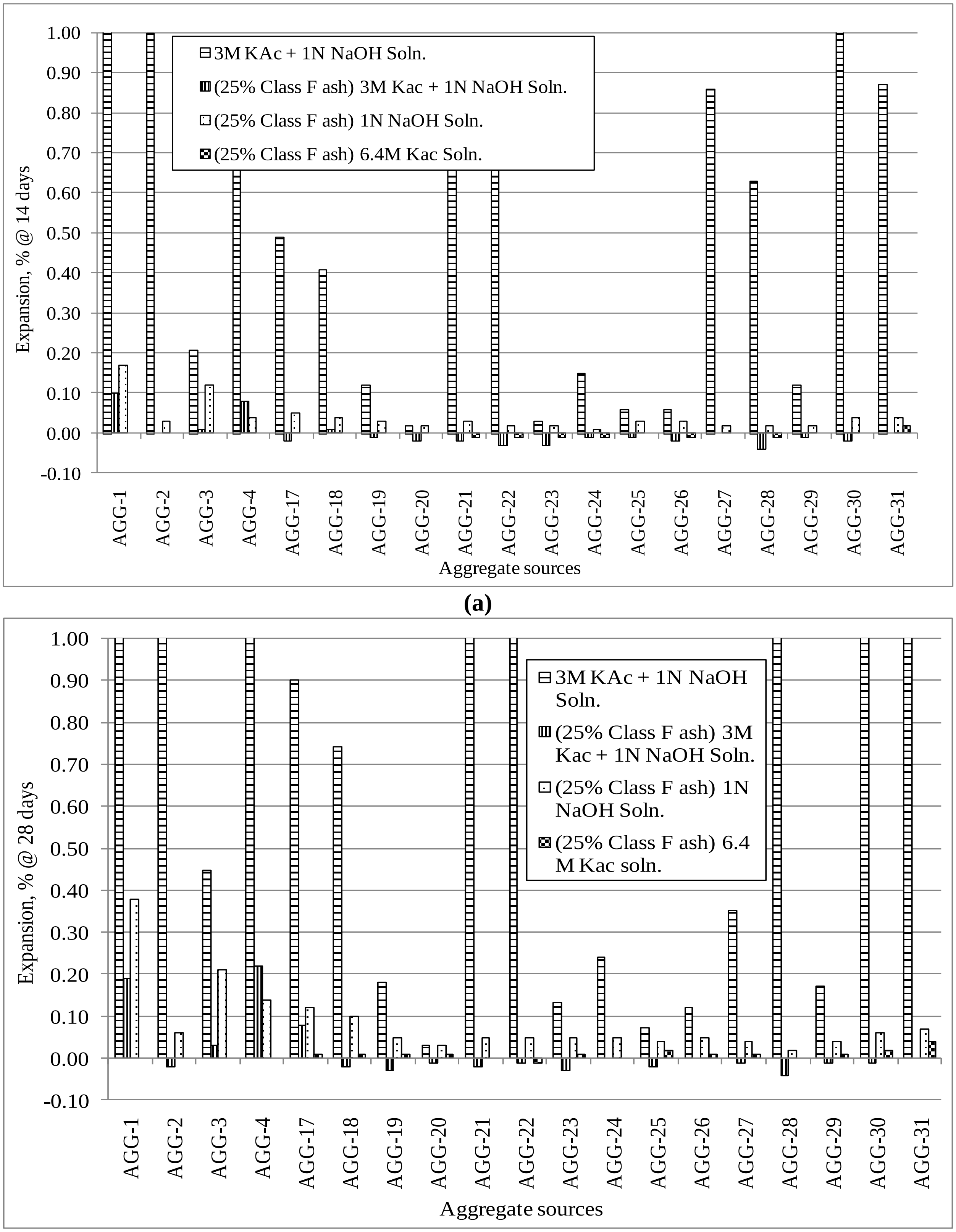


Figure 9: Comparision of Revised EB-70 test with ASTM C 1567 test (a) 14-day Mortar Bar Expansions (b) 28-day Mortar Bar Expansions.

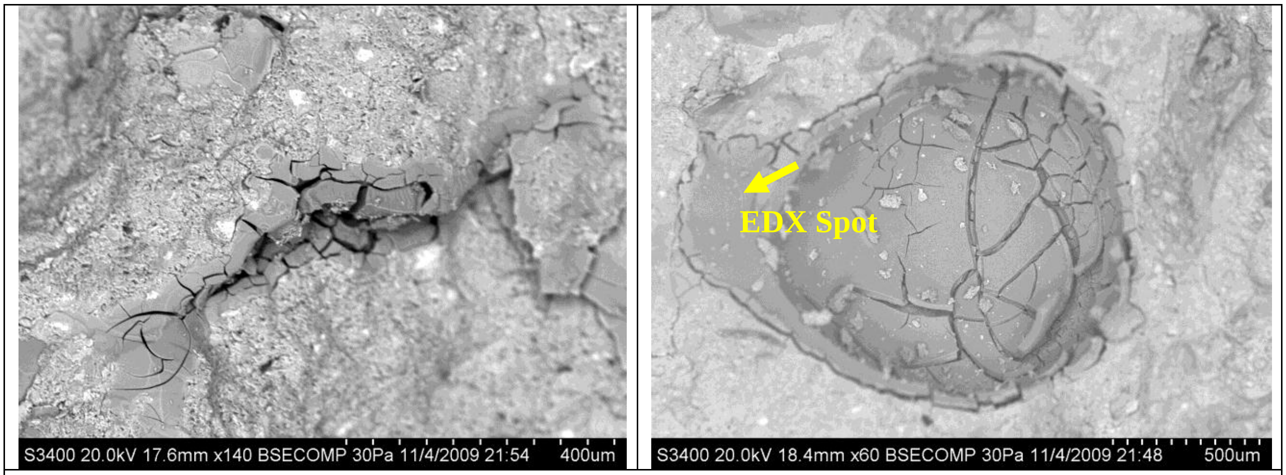


Figure 10a – Mortar Bar with AGG 16 in 1N NaOH Soak Solution

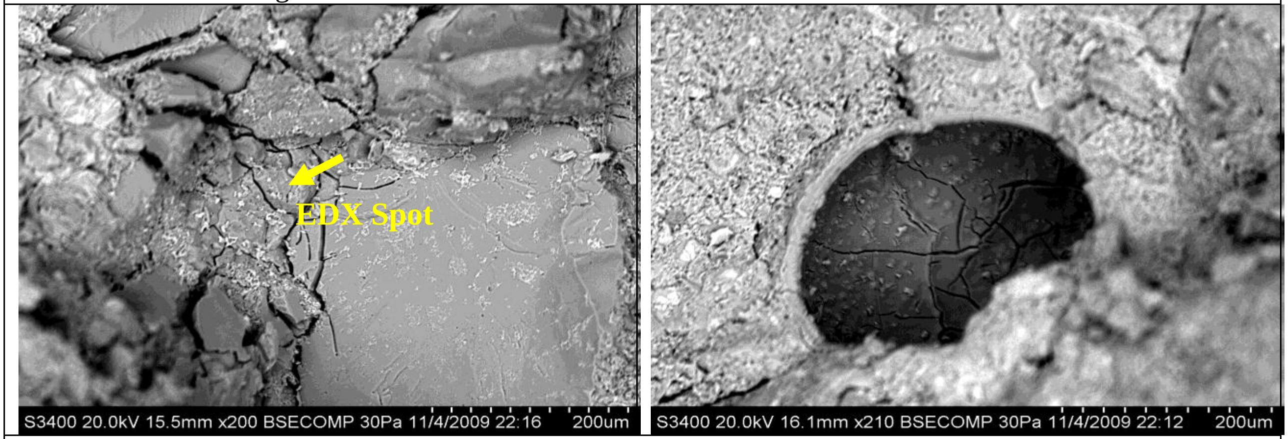


Figure 10b – Mortar Bar with AGG 16 in 1N NaOH + 3M KAc Deicer Soak Solution

Figure 10: SEM evidence of aggregate reactivity in the standard ASTM C 1260 and revised EB-70 test methods

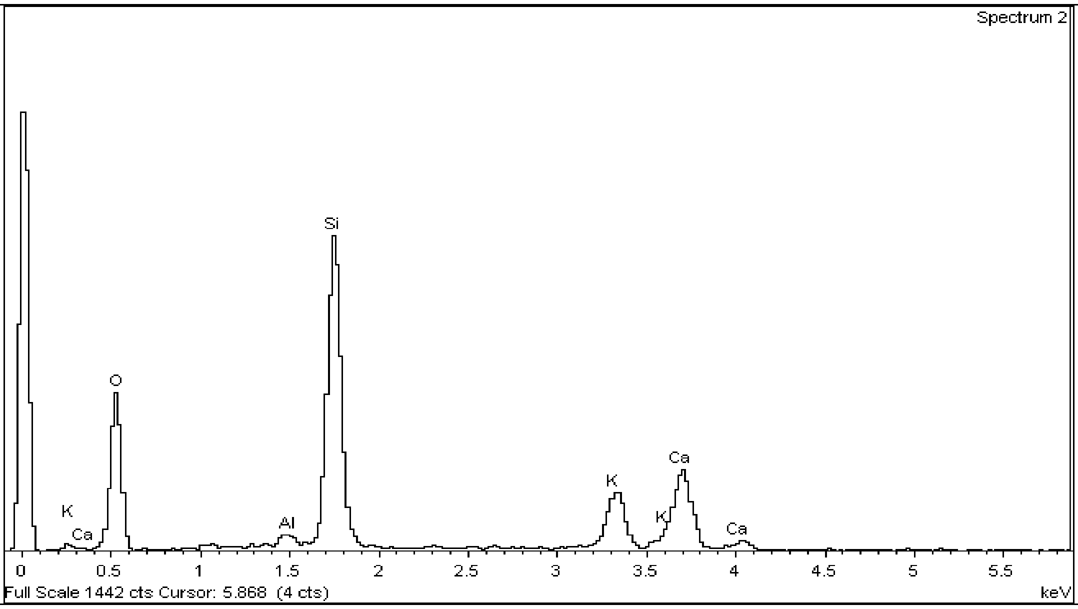


Figure 11a – EDX Spectra of reaction product in AGG 16 in revised EB-70 test (3M KAc + 1N NaOH)

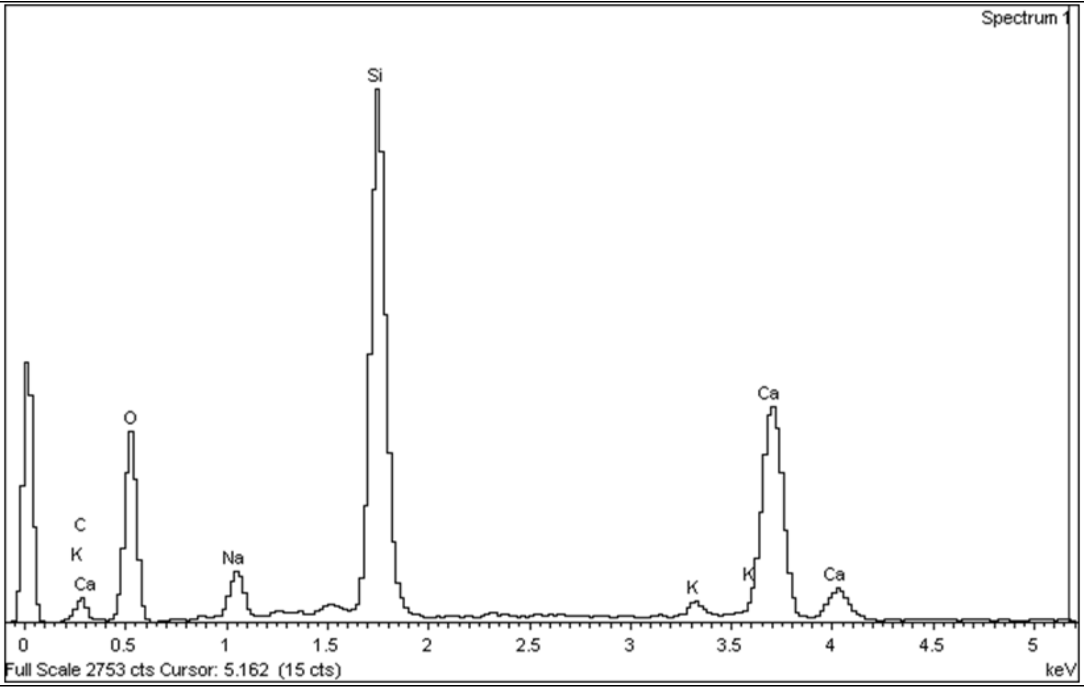


Figure 11b – EDX Spectra of reaction product in AGG 16 in ASTM C1260 test (1N NaOH) method

Figure 11 – EDX Spectra of ASR gel from AGG 16 in revised EB-70 test and ASTM C 1260 test methods

PART II

EVALUATING ASR MITIGATION POTENTIAL OF SUPPLEMENTARY CEMENTING MATERIALS AND LITHIUM ADMIXTURE IN THE PRESENCE OF POTASSIUM ACETATE DEICER – REVISED EB-70 TEST METHOD

ABSTRACT

Recently a deicer-modified mortar bar test method, revised EB-70 test method, was developed to evaluate aggregate reactivity in the presence of potassium acetate deicer. This test employs a soak solution with a composition of 3M KAc and 1N NaOH, wherein the mortar bars with the suspect aggregates are exposed over a period of 28 days, and the mortar bar expansion is periodically recorded. Previous research has shown that this test captures the interactions that occur between a concentrated deicer solution and a highly alkaline environment within the pore solution of concrete. Results from investigation of over 30 aggregates in this test method yielded positive correlation with the field performance of the aggregate. In this paper the applicability of this test method to evaluate effectiveness of typical ASR mitigation measures such as fly ashes, slag and lithium admixtures, was investigated. Findings from these studies suggest that the revised EB-70 test method can be employed to evaluate the effectiveness of ASR mitigation measures in the presence of potassium acetate deicer. Factors such as the chemical composition of the SCM and its dosage rate in the mixture appear to play a significant role in effectively mitigating ASR in the presence of deicers.

Key Words: *potassium acetate deicer, alkali silica reaction (ASR), mitigation, EB-70 test method, standard ASTM C 1260 test method*

1. INTRODUCTION

Recent laboratory investigations on the impact of airfield deicing chemicals on concrete durability have shown that deicers such as potassium acetate (KAc) are capable of inducing deleterious alkali-silica reaction (ASR) in concrete (*1-3*). Evidence from forensic field investigations suggested that while the penetration of potassium acetate into sound concrete was minimal (only to an extent of 10-15 mm from the pavement surface), its penetration into concrete with pre-existing cracks was found to be significant, particularly along the length of the crack (4-*5*). It is therefore conceivable that when deicers do penetrate concrete, its potential to inflict ASR distress can be significant. In order to investigate the susceptibility of aggregates to under ASR in the presence of potassium acetate deicer, a deicer-modified mortar bar test method (EB-70 test method and revised EB-70 test method) was recently developed (*1,6-9*). A detailed description of this test method and its comparison with the standard ASTM C 1260 test method is presented elsewhere (*7*). The principal difference between the deicer-modified test and the standard ASTM C1260 test is the composition of the soak solution employed in the test method. In the deicer-modified test method, a 3M KAc + 1N NaOH solution is employed as soak solution instead of the standard 1N NaOH solution. The reason for using the 3M KAc + 1N NaOH soak solution is to capture the pH jump that is observed in deicer solutions when blended with alkali hydroxide solutions. It was shown that the increase in the pH observed in the proposed soak solution (i.e. 3M KAc + 1N NaOH) was not just based on the concentration of the hydroxyl ions, but due to an increase in the activity coefficient of the hydroxyl ions (*7, 10*). It should be noted that in a previous version of the deicer-modified test method (EB-70 test method), where 6.4 M KAc was employed as a soak solution, the high pH observed in the soak solution was entirely due to interaction of the KAc deicer with $Ca(OH)_2$ (from the hydration of portland cement) (*10,11)*. The use of 6.4M KAc deicer soak solution in the test method resulted in a high pH of the soak solution (owing to the increase in the activity of the hydroxyl ions contributed by $Ca(OH)_2$) however, owing to the limited solubility of $Ca(OH)_2$ in water, the concentration of hydroxyl ions was low.

The proposed soak solution 3M KAc + 1N NaOH not only provides for a high pH resulting from the increased activity coefficient of hydroxyl ions, but also maintains a high enough hydroxyl ion concentration over the course of the test method of 28 days. The details of the chemistry involved in the interactions between the deicer and alkaline solutions are presented elsewhere (*10*). The revised EB-70 test method was validated by conducting tests on 32 aggregates of various lithologies and of known reactivity and comparing the results with those obtained from the standard ASTM C 1260 tests. Figure 1 shows the 14-day mortar bar expansion of aggregates in the standard ASTM C 1260 and revised EB-70 test method. Findings from this study showed that the deicer-modified mortar bar test method was not only able to identify aggregates that were alkali-silica reactive in nature, with similar accuracy as the standard ASTM C 1260 test method, but also was able to screen aggregates that were sensitive to KAc deicer compared to 1N NaOH alone.

As an extension in the development of the revised EB-70 test method, in this paper the effectiveness of typical supplementary cementing materials (SCMs) such as Class F fly ash, Class C fly ash, slag and lithium admixtures, in mitigating ASR was evaluated in the presence of KAc deicer using the deicer-modified mortar bar test method. The performance of these SCMs and lithium admixture in the deicer-modified mortar bar test is compared with the results from the standard ASTM C 1567 test method. In this investigation, six fly ashes of different chemical composition, one slag, and a 30% solution of lithium nitrate were evaluated in combination with twenty aggregates of different levels of reactivity.

2. OBJECTIVES

The principal objectives of this research study were:

1. To evaluate the effectiveness of selected SCMs and lithium admixture in mitigating ASR in the presence of deicing chemicals in the revised EB-70 test method.
2. Compare the performance of the SCMs and lithium admixture in the revised EB-70 test method with their performance in the standard ASTM C 1567 test method.
3. Determine the influence of chemical composition of fly ashes on their ability to mitigate ASR in the revised EB-70 test method and the standard ASTM C 1567 test method.

3. EXPERIMENTAL PROGRAM

3.1. Materials

3.1.1. Aggregates

Table 1 shows the aggregates used in this study that have a known historical performance. The field performance of the aggregates was based on assessment of several highway and airfield pavement structures by the authors and/or by respective DOT personnel from where a specific aggregate was obtained.

3.1.2. Cement

High alkali cement (Type I) with a Na_2O equivalent of 0.82% (Na2Oeq) and an autoclave expansion of 0.12% was used for this study. The chemical composition of this cement is provided in Table 2.

3.1.3. Fly Ash

In this study, six different fly ashes were used as supplementary cementitious material (SCM). The chemical composition of the fly ashes is provided in Table 2. In this study, all fly ashes were used at a dosage of 25% by mass replacement of cement.

3.1.3. Slag

A grade 120 ground granulated blast furnace slag (GGBFS) was used as a supplementary cementitious material (SCM) at a dosage of 40% by mass replacement of cement, in this study. The chemical composition of the slag is provided in Table 2.

3.1.4. Lithium Nitrate

The lithium nitrate ($LiNO_3$) used in this study was a 30% wt. solution in water. The properties as described by the manufacturer are as follows: density @25°C (77°F) is 1.20 g/cm^3 (10.0 lb/gal), pH (1:6 dilution) at 25°C ranging from 7 – 10, freezing point (incipient crystallization) -8°C (18°F), boiling point 110°C (230°F). In this study, lithium admixture was evaluated at a single dosage of 100%, as represented by the amount of $LiNO_3$ needed to achieve a Li/Na molar ratio of 0.74 in the mortar bar, where the Na content is based only on the cement alkali content. Only a 50% dosage (i.e. a Li/Na molar ratio of 0.37) was employed in all the soak solutions. In revised EB-70 test method, the contribution of 3KAc to the alkalinity of the soak solution was minimal in comparison to the 1N NaOH, and therefore the lithium dosage in soak solution was also based on 1N NaOH.

3.1.5. Deicers and Reagents

In this study, Cryotech E-36, a commercial grade runway liquid deicer was used as the soak solution. This deicer is a 50% wt. solution of KAc (~6.4 molar concentration) with a pH of 10.85 at room temperature and a density of approximately 1.25-1.30 g/cc. The deicer contains a proprietary organic corrosion inhibitor and a dyeing agent. The deicer solution contains less than 200 ppm of sulfate as impurities. In addition, reagent grade NaOH pellets were used to prepare the 1N NaOH soak solutions for conducting the standard ASTM C 1260 and C 1567 tests. Soak solutions for all of the revised EB-70 test method (1N NaOH + 3M KAc) were prepared by using combination of reagent grade NaOH and commercial grade KAc deicer.

3.2 Test Methods

3.2.1. Standard ASTM C 1260 (1N NaOH Soak Solution)

In this test method, mortar bars (25mm X 25mm X 285 mm) with gage studs embedded at the ends were cast and moist cured for 24 hours in a curing room. After demolding, the bars were cured at 80°C for 24 hours in a water bath. After curing in the water bath, the bars were kept in 1N NaOH soak solution, which was preheated to 80°C for 24 hours. Periodic length change measurements were taken at regular intervals up to 28 days, and percent expansions were calculated. In this study, the expansions of mortar bars less than 0.10% at 14 days were considered to reflect the non-reactive nature aggregates, and expansions of mortar bars over 0.10% were considered to reflect the reactive nature of the aggregates.

3.2.2. Revised EB – 70 test method (1N NaOH+ 3M KAc deicer Soak Solution)

The principal revision in the revised EB-70 test method was the use of a soak solution that has a concentration of 1N NaOH + 3M KAc, instead of the 6.4M KAc solution as used in EB-70 test method. The basis for using this combination of 1N NaOH and 3M KAc deicer was previously discussed and presented in depth elsewhere (*7,10*). One liter of the soak solution for the revised EB-70 test method was prepared by dissolving 40 g of NaOH in 460 ml of 6.4M KAc deicer solution and then diluting the combination to one liter with deionized water, to achieve a concentration of 1N NaOH + 3M KAc in the resulting solution.

3.3. Test Program

A comparative evaluation of the aggregate reactivity in the standard ASTM C 1260 test method and the revised EB-70 test methods were conducted on 32 aggregates (REFERENCE). These results serve as a reference point for evaluating the efficacy of ASR mitigation measures.

All the mitigation measures were evaluated in the standard ASTM C 1567 test and the revised EB-70 test method. To evaluate ASR mitigation measures such as fly ashes and slag, a portion of portland cement was replaced by the respective SCM.

In evaluating the lithium admixture, a modified version of CRD–C 662-10 method was employed. In this method, the 30% solution of lithium nitrate was added to the mix water at 100% dosage level (Li/Na molar ratio of 0.74), and to the soak solution at 50% dosage level (Li/Na molar ratio of 0.37) with no other changes to the soak solution composition.

In this study, six fly ashes were evaluated at a 25% dosage level using aggregates #1 through #4 and #32 in order to understand the impact of chemical composition of fly ash on their ability to mitigate ASR in presence of deicing chemical. A more extensive study was conducted with Ash-1 at 25% dosage using a range of aggregates, i.e. #17 through #31, to better understand how different aggregates behaved in the revised EB-70 test method in presence of a given ash. In investigations involving slag and lithium admixtures, aggregates #1 through # 4 were employed. Using the revised EB-70 protocol, limited studies using aggregate #1 were conducted in which combinations of lithium admixture with 25% Ash-1 were evaluated.

4. RESULTS AND DISCUSSIONS

4.1. Evaluation of Effectiveness of Fly Ashes in Mitigating ASR in the Revised EB-70 Test Method

Figures 2 and 3 show a comparison of 14-day expansions in mortar bars with and without Ash-1 in 1N NaOH soak solution, and a combination of 3M KAc + 1N NaOH solutions, respectively. It is evident from these figures that the use of Ash-1 at 25% dosage level is highly effective in reducing the mortar bar expansions, regardless of the soak solution composition. Figure 4 shows a comparison of 14-day mortar bar expansions in the 1N NaOH solution and a combination of 3M KAc + 1N NaOH solution. These results clearly illustrate that Ash-1, which a low-lime Class F fly ash, is highly effective in both test methods in suppressing the mortar bar expansions with a wide range of aggregate types. With an exception of a couple of aggregates (Agg-1, Agg-3, and Agg-4), in all the other cases the 14-day mortar bar expansion were below 0.10% at 14 days in both the test methods.

Figure 5 shows the 14-day expansion behavior of mortar bars containing Ash-1 through Ash-6 in combinations with five different aggregates (Agg-1 through Agg-5). Ash-1 and Ash-2 represent low lime fly ashes, with an average lime content of 1.15%. Ash-3 and Ash-4 represent intermediate lime content with an average lime content of 17.26%. Ash-5 and Ash-6 represent high lime fly ashes with an average lime content of 27.05%. The results shown in Figure 5 illustrate that as the lime content of the fly ash increases, the 14-day mortar bar expansion in the revised EB-70 test method increase proportionately with all the aggregates. It can also be observed that with majority of the reactive aggregates (3 out of 4 reactive aggregates), the high-lime fly ash does not offer any significant mitigation in expansion compared to the control mixtures without fly ash.

4.2. Evaluation of Effectiveness of Slag in Mitigating ASR in the Revised EB-70 Test Method

Figure 6 shows the 14-day mortar bar expansion behavior of test specimens prepared with and without slag in the revised EB-70 test method. It is evident from these results that while the presence of 40% slag in the mix significantly reduces the expansion compared to the control specimen, the reduction in expansion is not below 0.10 % for majority of the aggregates (3 out of 4 aggregates evaluated). Therefore, it appears that a slag dosage of 40% may not be adequate to effectively mitigate ASR in the presence of KAc deicer, and higher dosage levels would be required.

4.3. Evaluation of Effectiveness of Lithium Admixture in Mitigating ASR in the Revised EB-70 Test Method

Effectiveness of lithium admixture in mitigating ASR in the presence of KAc deicer was evaluated using a method similar to that used in the CRD-C 662-10 test procedure. Results from these tests are shown in Figure 7. These results illustrate that in the presence of potassium acetate deicer, lithium admixture used at nominal dosage level (based on Li/Na molar ratio of 0.74) of 100% was not adequate in mitigating deleterious levels of expansions in mortar bars. In case of all the four aggregates, the reduction in expansion of the mortar bars was minimal, and in the case of aggregate #3, the use of lithium resulted in slightly increased expansion. It should be noted that in these studies, the lithium dosage in the soak solution of the revised EB-70 test method (i.e. Li/Na molar ratio of 0.37) was based on 1N NaOH alone and not based on the 3M KAc + 1N NaOH. The reason for this approach lies in the fact that 3M KAc solution by itself does not contribute any significant amount of hydroxyl ions in the soak solution.

Additional investigation was conducted to evaluate the effectiveness of combination of fly ash with lithium admixture to mitigate mortar bar expansion of Agg-1 mixture in the revised EB-70 test method. These results are shown in Figure 8. Based on these findings, it appears that the combination of a class F fly ash (Ash-1) and lithium admixture produces a synergistic effect and the mortar bar expansion in the revised EB-70 test method is virtually eliminated.

5. CONCLUSIONS

Based on the tests conducted in this investigation, the following conclusions can be drawn:

1. The sensitivity of an aggregate to undergo alkali-silica reactivity in the presence of potassium acetate deicer can be ascertained using the proposed revised EB-70 test method.
2. The proposed EB-70 test method can be used to evaluate the effectiveness of typical supplementary cementing materials such as fly ashes and slags in mitigating alkali-silica reaction in the presence of potassium acetate deicer.
3. The chemical composition of fly ash, particularly its lime content, appears to bear a significant relationship to the ability of a fly ash to mitigate mortar bar expansion in the revised EB-70 test method. This behavior is identical to the performance of fly ashes in the presence of 1N NaOH solution, as observed in the standard ASTM C 1567 test method.
4. Fly ashes with lime content less than 15% appear to be effective in mitigating mortar bar expansions to below 0.10% for majority of the aggregates at a dosage rate of 25%. Higher lime content fly ashes are generally ineffective in mitigating ASR at the 25% dosage level in the presence of potassium acetate deicer.
5. Use of slag at 40% cement replacement level can significantly reduce mortar bar expansions in the presence of potassium acetate deicer, however, higher dosage levels may be needed to effectively mitigate mortar bar expansions to below 0.10% with majority of the reactive aggregates evaluated in this study.
6. In the presence of potassium acetate deicer, lithium admixture by itself does not appear to be as effective in controlling mortar bar expansions to below 0.10% at 14 days, however, in combination with a low-lime fly ash, lithium admixtures are highly effective in controlling ASR.

6. RECOMMENDATIONS

While the findings from this research study provide a rational basis to evaluate ASR mitigation measures in the presence of deicing chemicals such as potassium acetate, these results should be calibrated using larger specimens and field exposure conditions. In the interim, however, it is recommended that the revised EB-70 test method be employed as a screening protocol to evaluate aggregate sensitivity to deicers and also to evaluate effectiveness of SCMs and lithium admixtures in mitigating ASR in the presence of deicing chemicals.

7. ACKNOWLEDGEMENTS

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LIST OF TABLES

LIST OF FIGURES

Table 1 - Mineralogy and Field Performance of Aggregates*

Label	Field Performance/Reactivity	Reactive Component in Aggregate (Mineralogy)
AGG-1	Reactive	Rhyolite
AGG-2	Reactive	Argillite
AGG-3	Reactive	Quartzite
AGG-4	Reactive	Chert
AGG-5	Reactive	Chert
AGG-6	Reactive	Chert
AGG-7	Reactive	Chert
AGG-8	Reactive	Chert
AGG-9	Reactive	Chert/Shale
AGG-10	Reactive	Chert/Shale
AGG-11	Non-reactive	None
AGG-12	Non-reactive	None
AGG-13	Non-reactive	None
AGG-14	Reactive	Microcrystalline Quartz
AGG-15	Non-reactive	None
AGG-16	Reactive	Greywacke
AGG-17	Reactive	Chert/Shale (D)
AGG-18	Reactive	Siliceous Limestone (D)
AGG-19	Non-reactive	None (D)
AGG-20	Non-reactive	None (D)
AGG-21	Reactive	Chert (D)
AGG-22	Reactive	Chert (D)
AGG-23	Non-reactive	None
AGG-24	Reactive	Argillite
AGG-25	Non-reactive	None
AGG-26	Non-reactive	None
AGG-27	Reactive	Chert/Sandstone (D)
AGG-28	Reactive	Sandstone (D)
AGG-29	Non-reactive	None (D)
AGG-30	Reactive	Quartzite
AGG-31	Reactive	Microcrystalline Quartz
AGG-32	Non-reactive	None

* Field performance of aggregate reactivity was based on assessment by respective DOT or Airfield personnel. “D” indicates field performance of aggregate under KAc deicer exposure.

Table 2 - Chemical Composition of Cementitious Materials

Chemical Compositions	**Oxide, %**							
	Low Lime		**Intermediate Lime**		**High Lime**		**Slag**	**Cement**
	Ash-1	**Ash-2**	**Ash-3**	**Ash-4**	**Ash-5**	**Ash-6**		
SiO_2	60.3	54.1	49.7	41.9	34.6	34.6	38.17	19.74
Al_2O_3	28.6	27.8	15.0	21.1	18.1	19.5	7.31	4.98
Fe_2O_3	3.2	8.0	6.6	5.6	5.7	5.7	0.78	3.13
Total S+A+F	92.1	89.9	71.3	68.6	58.3	60.1	--	--
CaO	1.0	1.3	15.6	18.9	27.5	26.6	39.12	61.84
MgO	NA	0.9	4.9	4.2	5.0	5.0	12.48	2.54
SO_3	0.0	0.2	0.9	1.0	2.8	2.0	2.56	4.15
Na_2O	0.1	0.3	2.5	2.2	1.6	NA	--	--
$Na_2Oeq = Na_2O + 0.68K_2O$	0.6	2.2	3.9	2.7	1.8	1.4	--	0.82
K_2O	0.7	2.8	2.1	0.7	0.4	NA	0.34	--
Loss on Ignition (LOI)	1.3	2.5	0.0	0.5	0.2	0.3	--	1.9
Specific Gravity	2.2	2.3	2.6	2.6	2.6	2.6		3.15
C_3A	--	--	--	--	--	--	--	8.0
C_3S	--	--	--	--	--	--	--	52.0

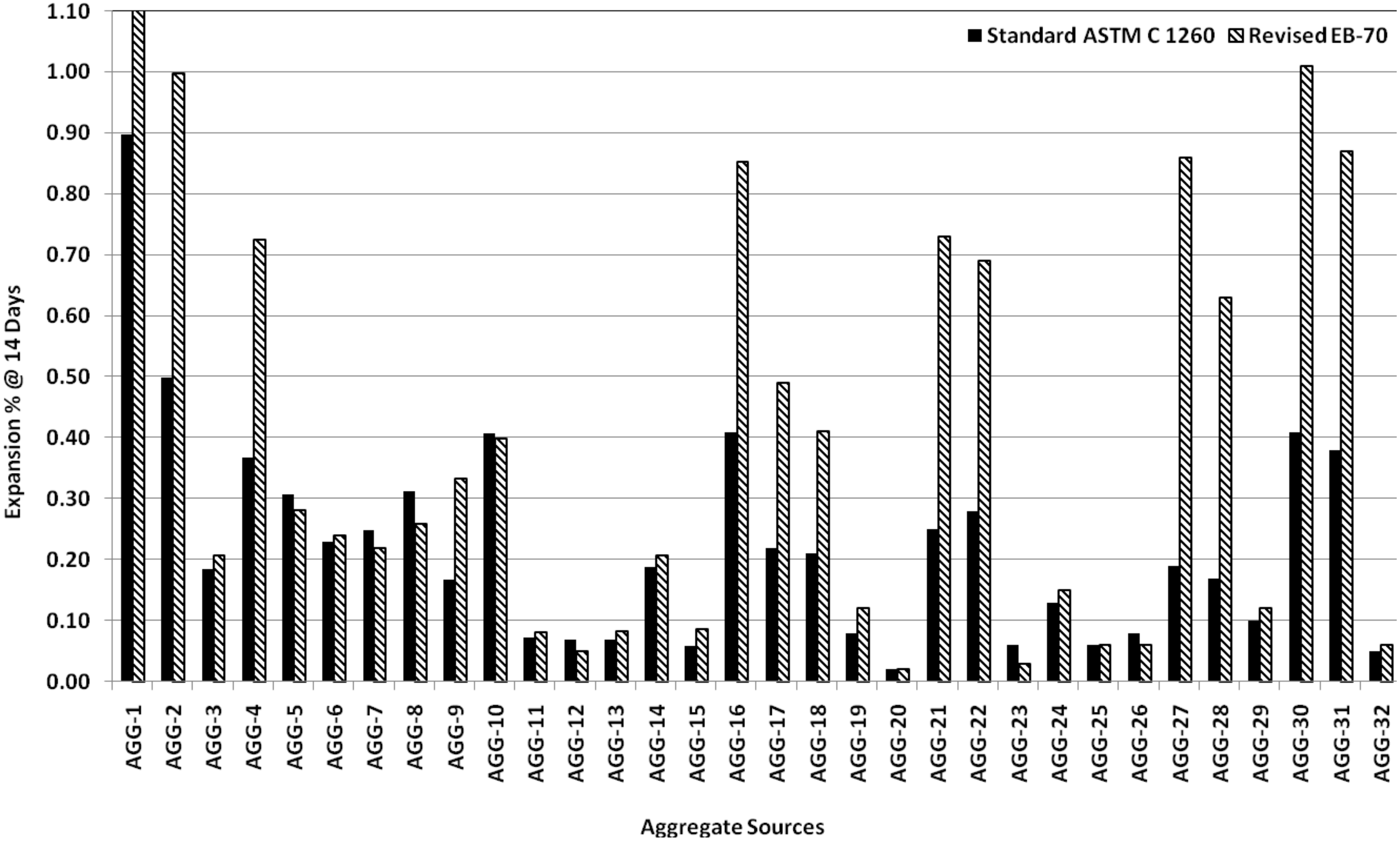

Figure 1 – Comparison of 14-day mortar bar expansions in the standard ASTM C 1260 test and revised EB-70 test method.

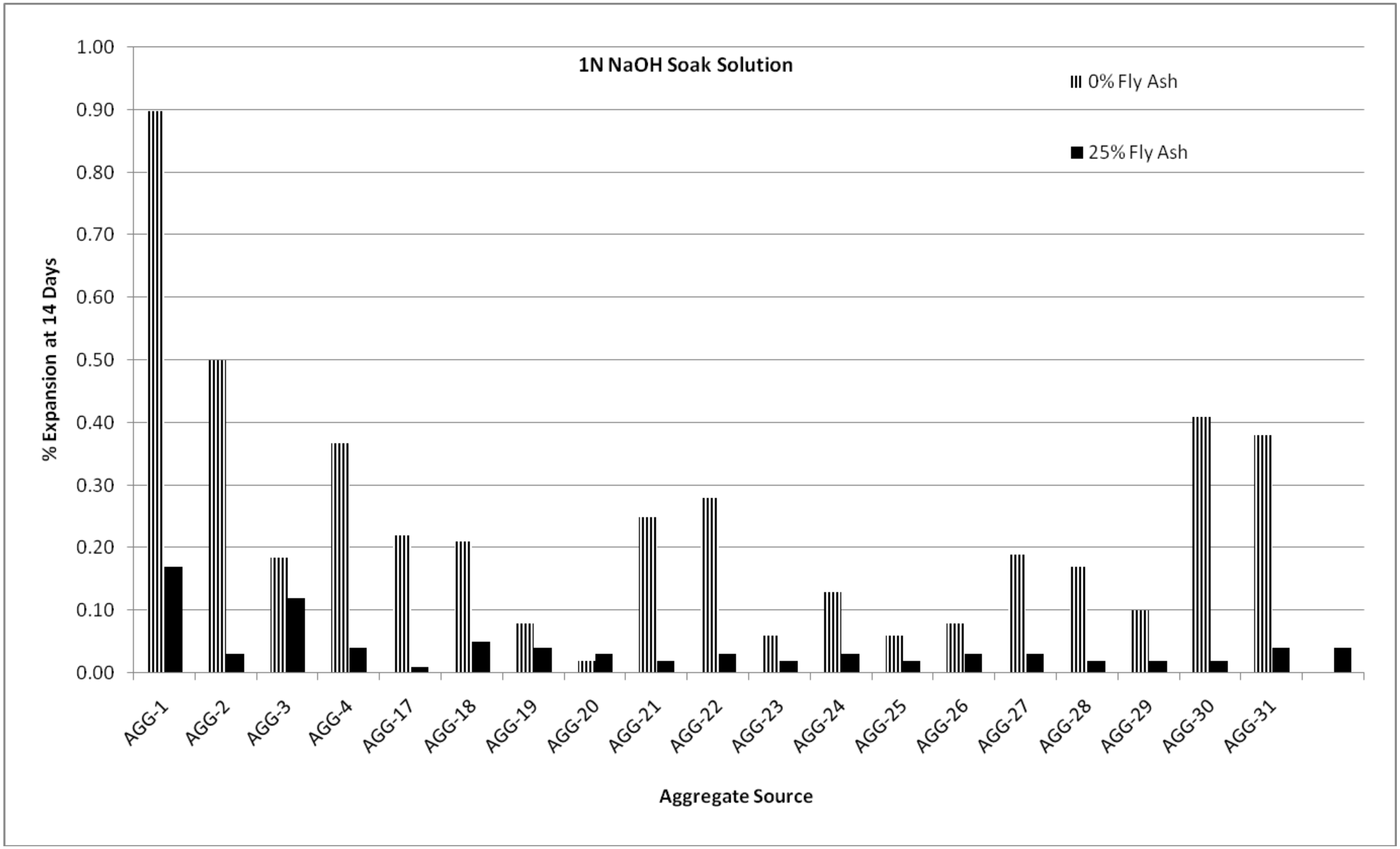

Figure 2 – Comparison of 14-day mortar bar expansions of test specimens with and without Ash-1 in 1N NaOH soak solution.

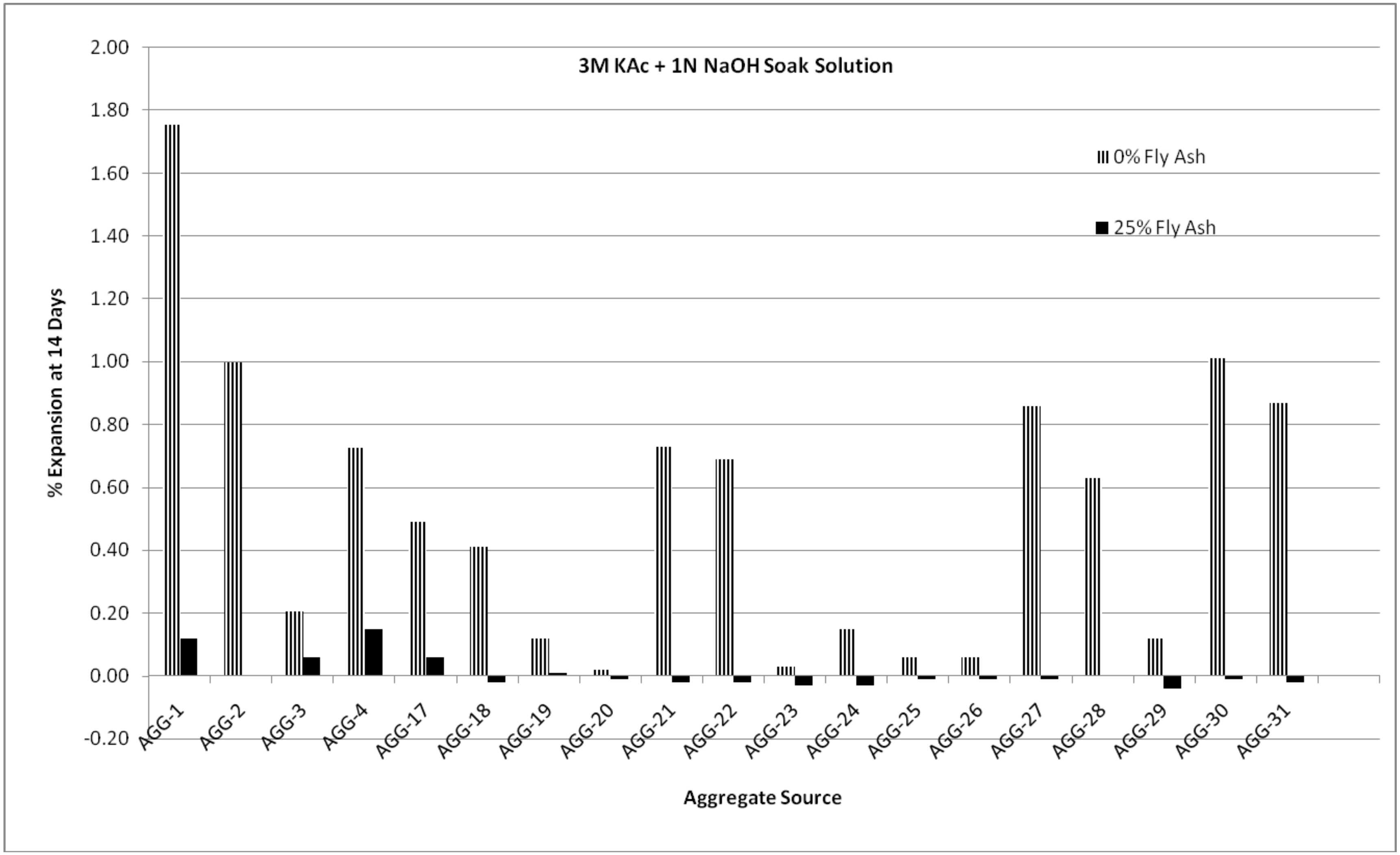

Figure 3 – Comparison of 14-day mortar bar expansions of test specimens with and without Ash-1 in 3M KAc + 1N NaOH soak solution.

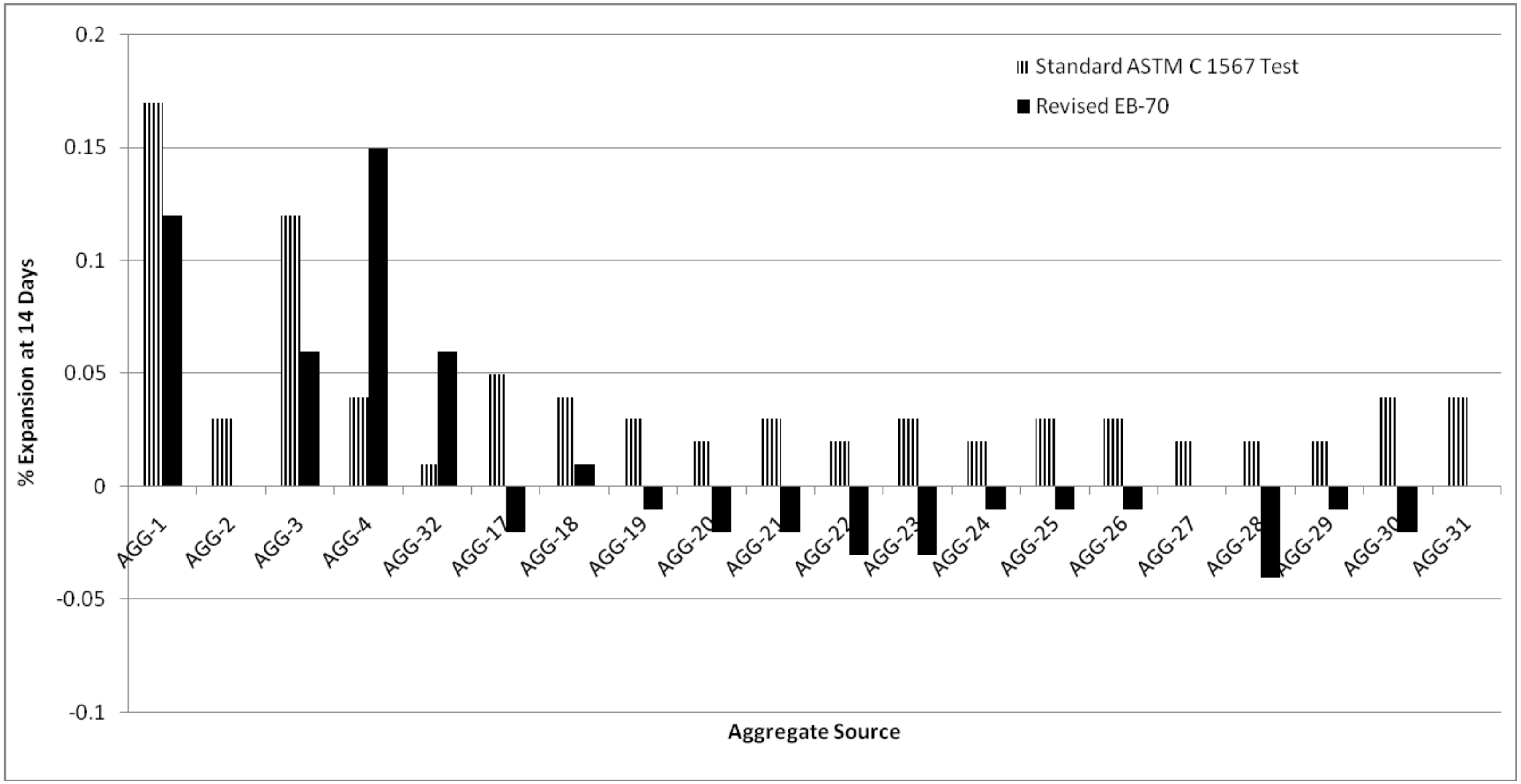

Figure 4 – Comparison of 14-day mortar bar expansion of test specimens with and without Ash-1 in 1N NaOH solution (ASTM C 1567) and combination of 3M KAc + 1N NaOH solution (Revised EB-70).

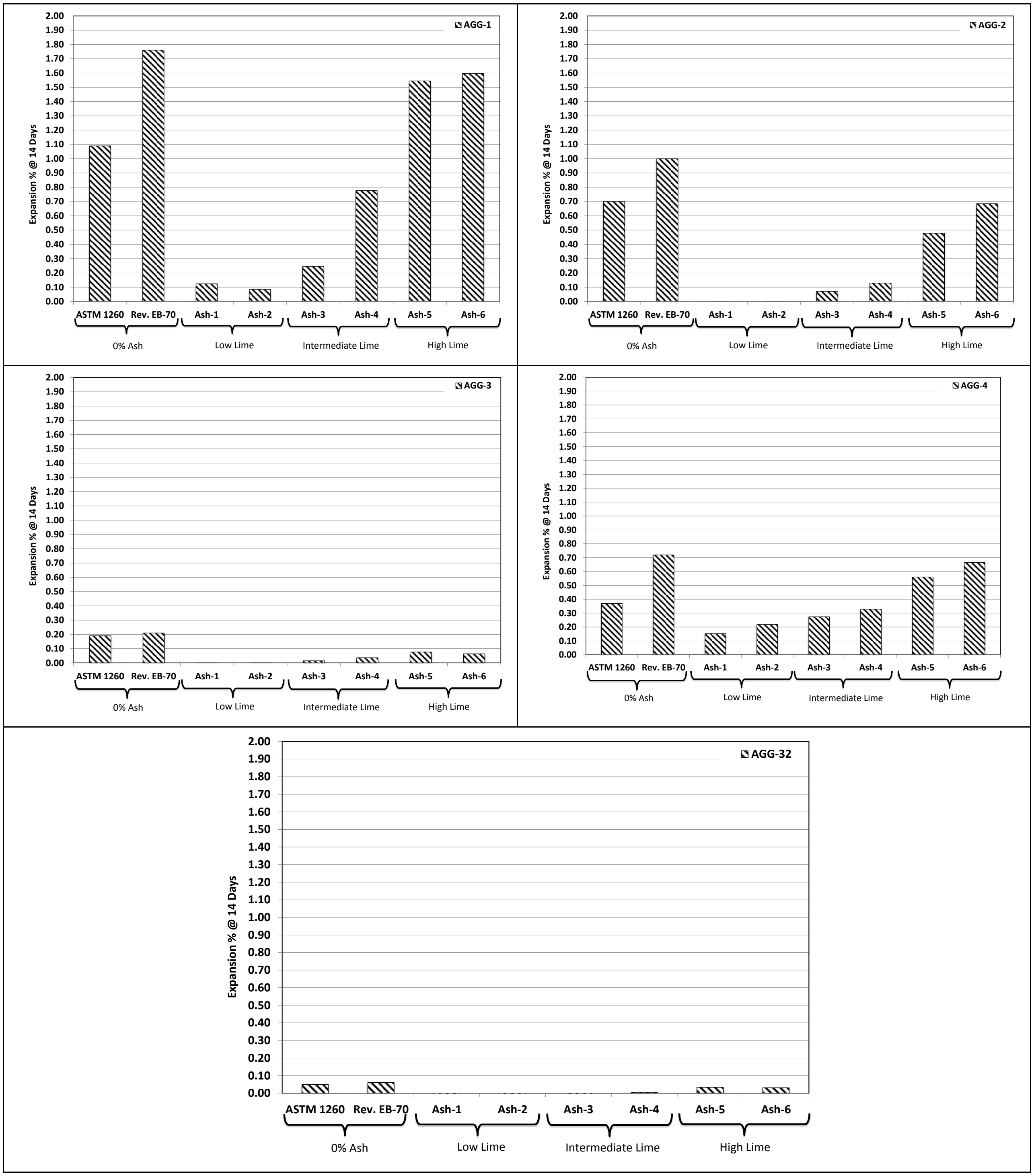

Figure 5 – Influence of chemical composition (lime content) of fly ash on mortar bar expansion in revised EB-70 test method.

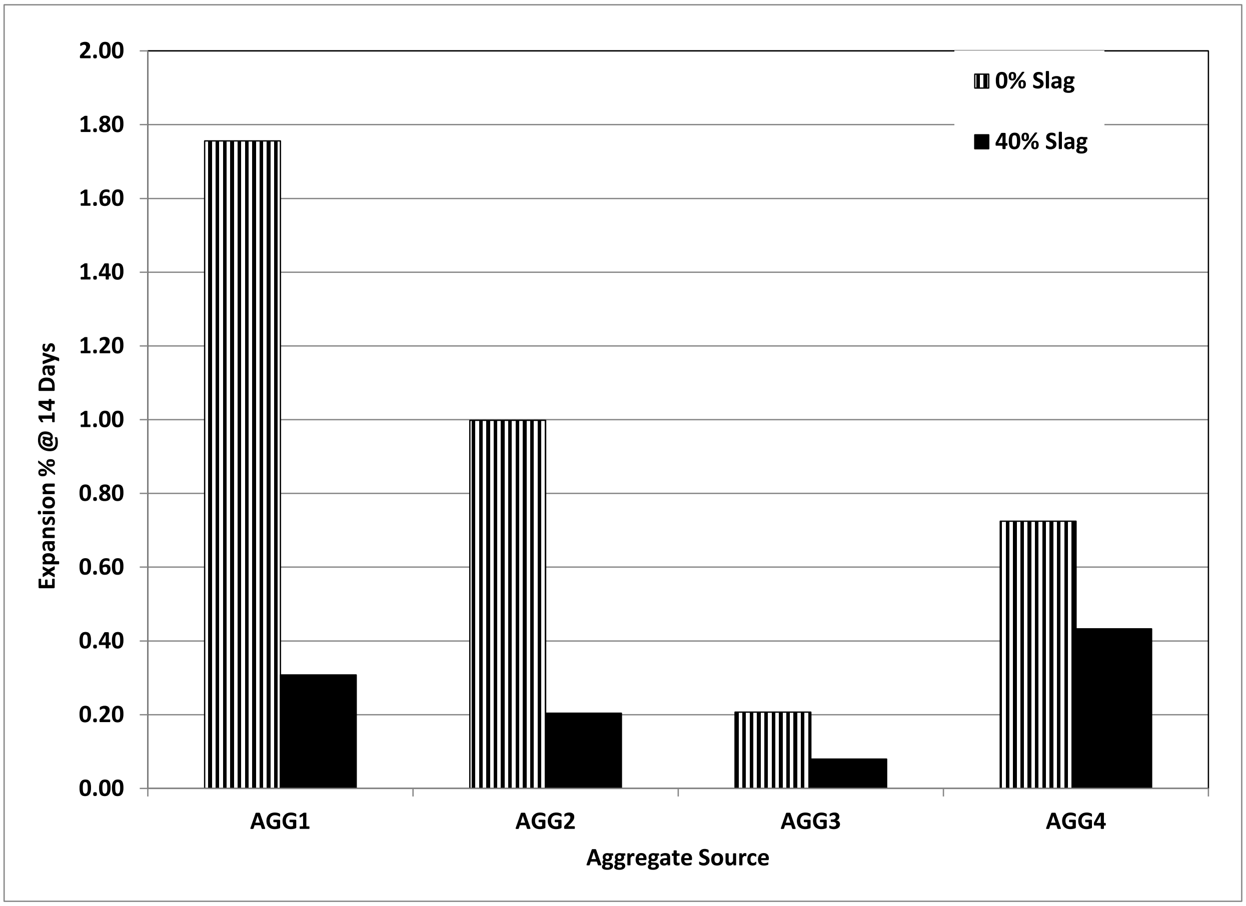

Figure 6 – 14 Day Mortar Bar Expansions of Mortar Bars Containing 0% and 40% Slag in the Revised EB-70 Test Method

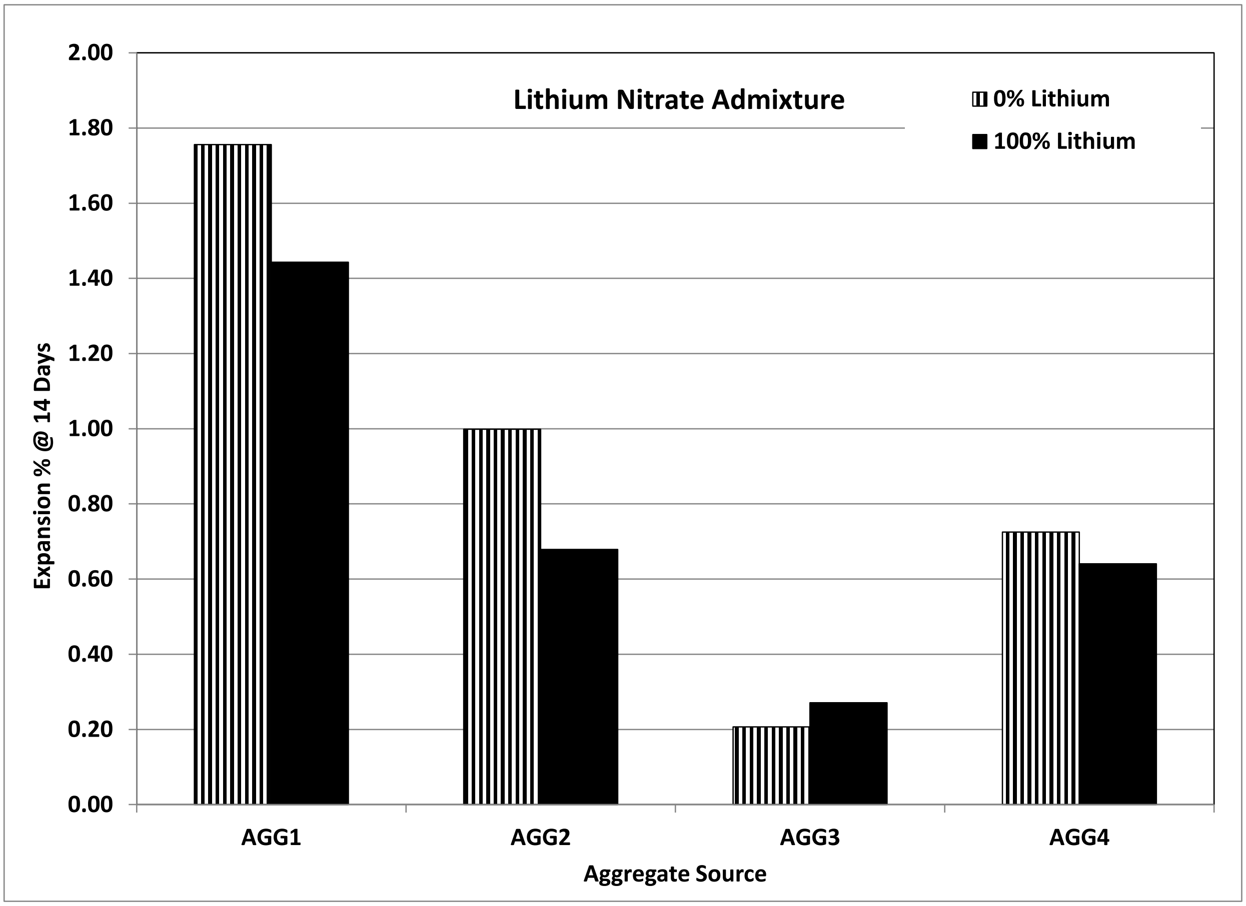

Figure 7 – 14 Day Mortar Bar Expansions of Mortar Bars Containing 100% Lithium Dosage in CRD-C 662-10 Test and Revised EB-70 Test Methods

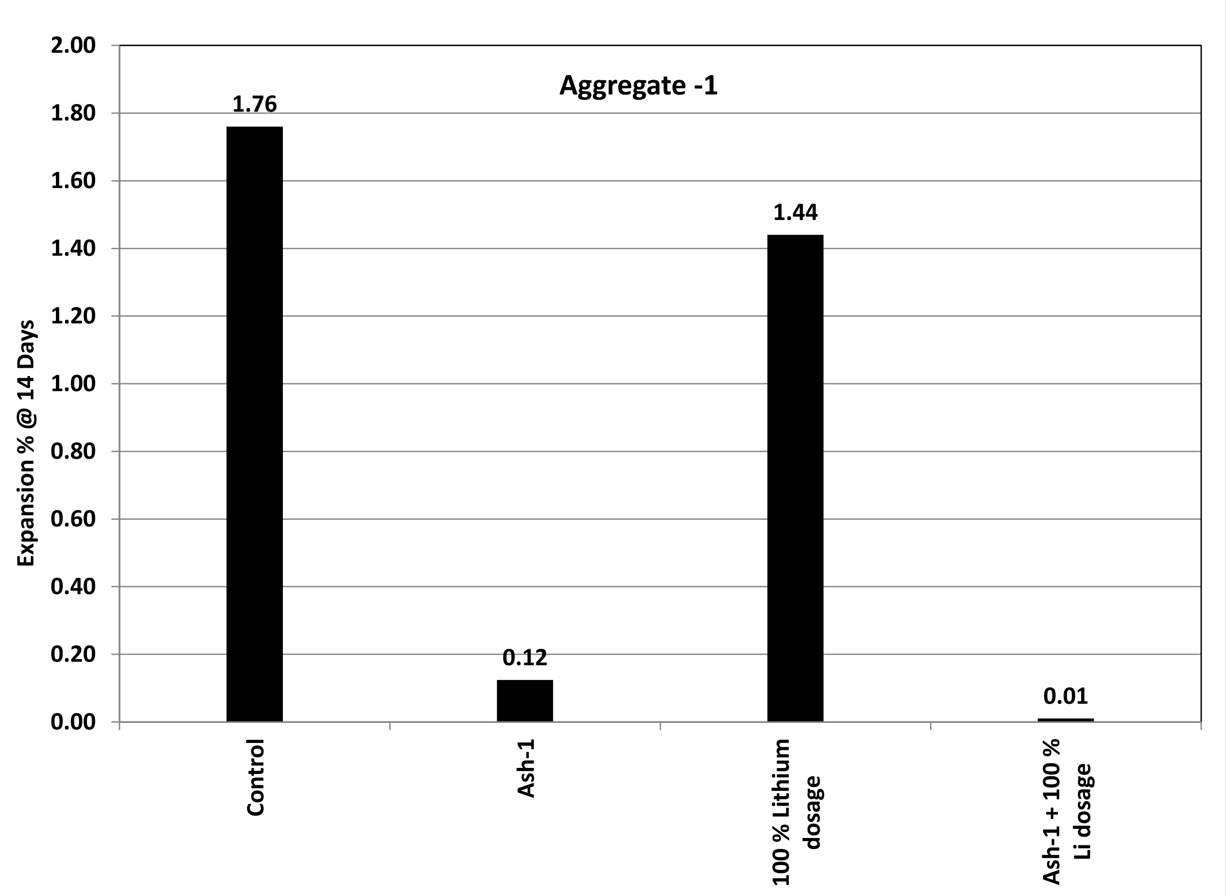

Figure 8 – Synergistic Effect of Combination of Class F Fly Ash (Ash-1) and Lithium Admixture in the Revised EB-70 Test Method Using Aggregate-1 as a Reference Reactive Aggregate