EVALUATING ASR PREVENTION STRATEGIES FOR THE RECONSTRUCTION OF CONCRETE STRUCTURES AT MACTAQUAC GENERATING STATION

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Abstract

Mactaquac Generating Station was constructed in the mid 1960's and is located in the province of New Brunswick in Eastern Canada. The effect of ASR expansion on the concrete structures of the station were first noticed approximately 10 years after construction and, ASR was conclusively diagnosed in 1986. Since 1985, various remedial measures have been undertaken to mitigate the effects of concrete expansion. Eventually reconstruction of the concrete structures will be necessary and current projections are that replacement should be complete by 2030. Due to the lack of any suitable locally-available non-reactive aggregate, consideration is being given to using the same source of reactive aggregate for reconstruction.

This paper describes a research study to determine the optimum strategy for preventing deleterious ASR expansion with this aggregate. The options being evaluated include the use of pozzolans and slag, limiting the alkali-content of the concrete, and the use of chemical admixtures. Methods of evaluation include accelerated laboratory tests and field exposure of large blocks.

Keywords: preventive measures, test methods, fly ash, pozzolans, slag

1 INTRODUCTION

Mactaquac Generating Station is located on the St. John River approximately 20 km west of the city of Fredericton in the province of New Brunswick. It is the second largest hydroelectric plant in Atlantic Canada with a total generating capacity of 672 MW. Construction began in 1964 and the first three of six generating units were commissioned in 1968 (three more units were installed between 1972 and 1980). Approximately 10 years after initial construction, the concrete structures, which consist of an intake structure, a powerhouse and two spillways, started to exhibit distress which was subsequently attributed to alkali-silica reaction (ASR) and, since 1985, various remedial measures have been undertaken to mitigate the effects of concrete expansion. The problems at Mactaquac and the remedial measures used to keep the structure in service have been well-documented and the "AAR Project" at Mactaquac is considered to be at the forefront of the implementation of technologies for addressing continuing ASR growth in large concrete structures [1, 2].

To date, the height of the intake structure is estimated to have increased by more than 175 mm since construction and an estimated 450 mm of concrete has been removed by slot cutting perpendicular to the longitudinal axis of the same structure. The unrestrained expansion of the concrete is currently estimated to be between 120 to 150 microstrain per annum ($\mu\varepsilon$/y). The continued expansion of the structure means that replacement of the concrete structures is inevitable and current projections are that reconstruction should be complete by the year 2030, to coincide with the predicted end of the practical service life of many of the concrete structures and electrical and mechanical equipment (e.g. turbines and generators). A number of replacement alternatives are currently being considered. Each includes the constriction of a similar powerhouse, intake and 10-bay spillway structures on either end of the existing facility. Each alternative will involve a massive excavation for the intake and spillway channel and the production of close to 500,000 cubic metres of new concrete. Because of the lack of suitable locally-available non-reactive aggregate, consideration is being given to utilizing the rock from the excavation of these channels. This rock is predominantly a greywacke from the same geological formation as the rock used in the construction of the existing dam, which was also produced during excavation (but on the opposite bank of the river).

A research study was initiated in 2005 to determine the most effective (and economic) method for preventing damaging ASR in concrete containing reactive rock from the site of the proposed

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excavation. Currently, the most obvious strategy is to use fly ash as a suitable source of low-calcium fly ash is currently being produced at NB Power Generation's Belledune coal-fired station in the same province. In addition, the use of fly ash has a good field-performance record with regards to controlling expansion due to ASR in hydraulic structures constructed with reactive aggregates [3]. Both the Lower Notch Dam in Ontario (completed in 1969) and the Nant-y-Moch Dam in Wales (built sometime between 1957 to 1962) were constructed using greywacke aggregate, but show no signs of ASR damage after 40 years or more, and this has been attributed to the use of low-calcium fly ash [3]. However, because it is possible that suitable low-calcium fly ash will not be available in 2030, other prevention strategies are also being considered, these include the use of other types of fly ash, ground granulated blastfurnace slag, ternary cement blends consisting of combinations of pozzolans and slag, lithium-based chemical admixtures, and the use of low-alkali cement to limit the alkali content of the concrete. The various preventive strategies are being evaluated using a combination of test methods; these include laboratory expansion tests on mortar and concrete, field exposure of concrete blocks, and the construction of massive instrumented monoliths at the site of the dam.

2 MATERIALS AND METHODS

2.1 Aggregates

Two samples of reactive aggregate have been used in this study to date; these are designated as (i) Mactaquac, obtained by crushing borehole samples collected from the proposed location of the excavation of the intake and spillway channels, and (ii) Springhill, obtained from a quarry in the vicinity of Mactaquac. The reactive rock used at Mactaquac is principally composed of greywacke with lesser amounts of slate and the reactive minerals are strained and microcrystalline quartz in the greywacke. Interestingly, the material was tested during construction to determine its reactivity, however, the test method used, ASTM C 227 "Mortar Bar Test", failed to identify the material as reactive. Recent testing (discussed below) has indicted this material to be highly reactive according to the criteria used in Canada [4].

Because of the need for large quantities of reactive aggregate for this test program, a greywacke aggregate from a local quarry was also used. The Springhill quarry is approximately 15 km from Mactaquac and this aggregate has been implicated as the cause of ASR in a number of structures in the Fredericton area (this aggregate is no longer used for concrete construction). This aggregates has been identified as being highly reactive in recently published studies [5] and a detailed analysis of the sample collected for this study revealed that it was compositionally similar to the Mactaquac sample and was suitable for use as a surrogate for evaluating preventive measures [6]. A detailed petrographic description and the results of chemical and mineralogical analysis for both of these aggregates are presented elsewhere [6].

A small sample (approx. 20 kg) of aggregate was collected from the site of Carn Owen in Wales; this quarry was the source of the aggregate used in the Nant-y-Moch Dam. A slightly larger sample (approx. 40 kg) was collected from the site of the Lower Notch Dam. Both of these structures were constructed with reactive greywacke aggregate together with low-calcium fly ash [3].

2.2 Cementitious Materials

All of the cementing materials used in this study met the requirements of CSA A3001 [7]. The data reported in this paper were collected from mortar and concrete samples produced using a portland cement meeting the requirements of CSA A3001 Type GU (general use). The alkali content of the cement was 0.91% Na_2Oe and 0.86% Na_2Oe for the two batches used during this study. Nine different fly ashes have been used to date. The calcium content of the fly ashes ranged from 2.4% to 29.1% CaO. Eight of the fly ashes had alkali contents between 0.77% to 3.62% Na_2Oe and one fly ash had an alkali content of 8.98% Na_2Oe. One of the fly ashes, from the Belledune generating station in New Brunswick, met the requirements of CSA A3001 for Type F (low-calcium, < 8% CaO) fly ash, four fly ashes met the requirements for Type CI (moderate-calcium, 8-20% CaO) fly ash, and four met the requirements for Type CH (high-calcium, >20% CaO) fly ash. A single source of silica fume and one of slag were used and these materials met the requirements of CSA A3001 for Type SF and Type S cementing materials. The complete chemical analysis of these materials can be found elsewhere [6].

The generating station at Belledune burns a combination of bituminous coal and petroleum coke, and this produces a fly ash with high carbon content. The fly ash is processed using electrostatic separation to reduce the carbon to an acceptable and consistent level. This processed fly ash from the co-combustion of coal and coke has been found to behave like a typical low-carbon fly ash produced using bituminous coal as the only fuel [8].

2.3 Test Methods

Accelerated mortar bar tests (AMBT) were conducted in accordance with the procedures in ASTM C 1260 (for mixes without pozzolans or slag) [9] or ASTM C 1567 [10] (for materials with pozzolans or slag). The test durations was extended to 28 days. Concrete prism tests (CPT) were conducted in accordance with ASTM C 1293 [11]; the test duration was 2 years.

Concrete blocks measuring 0.4 x 0.4 x 0.7 m were produced from mixes containing either Mactaquac or Springhill aggregate and a wide range of different cementing materials (over 36 blocks have been produced to date). In all cases, the blocks contain a total cementing materials content of 420 kg/m^3. For some mixes the alkali content of the portland cement component of the mix was boosted to 1.25% Na_2Oe by the addition of NaOH to the mix water (as per ASTM C 1293). The concrete mixtures are air-entrained with 5 to 8% air. The majority of the blocks are exposed to the weather on a site at the University of New Brunswick and are periodically measured to determine expansion using a 500-mm Demec gauge to determine the length change between 4 pairs of stainless steel pins embedded in the concrete. Four blocks are exposed in the inspection gallery of the main spillway at Mactaquac Generating Station.

In the spring of 2008 six concrete monoliths with dimensions of 3 x 3 x 3 m will be cast at the toe of the main earth dam at Mactaquac Generating Station. These blocks will be instrumented to monitor temperature and dimensional changes.

3 RESULTS

Expansion data for mortar bars and concrete prisms cast with Mactaquac and Springhill aggregates together with Belledune Fly Ash are shown in Figures 1 and 2. These data show that the two aggregates expand to a similar extent in both the AMBT and the CPT, and show a similar response to the incorporation of fly ash in the mix. The expansion results confirm the findings from petrographic and mineralogical analysis with regards to the acceptability of using the two samples of Springhill aggregate (#1 and #3) obtained for this study as a surrogate for studying preventive measures for the Mactaquac aggregate. Figure 1 also shows expansion results for rock samples collected from Carn Owen and Lower Notch. The expansion of mortars with these aggregates is significantly lower than the Mactaquac and Springhill aggregates, perhaps indicating a lower reactivity, although expansion data from ongoing concrete prisms tests is required to confirm this. The Carn Owen and Lower Notch aggregates seem to respond to fly ash in a similar manner to the Mactaquac and Springhill aggregates when tested in the AMBT.

With regards to the performance of supplementary cementing materials (SCM's) such as fly ash, slag and silica fume, satisfactory performance in these tests is generally considered to be indicated by an expansion of less than 0.10% at 14 days or, sometimes, 28 days in the AMBT or an expansion of less than 0.040% in the CPT.

In the AMBT, 20% Belledune fly ash appears to be sufficient to control expansion to less than 0.10% at 14 days, but up to 30% fly ash is required to maintain the expansion below this limit at 28 days. In the concrete prism test, 20% and 25% fly ash were sufficient to control expansion of the Mactaquac aggregate to less than 0.040% at 2 years. However, the expansion of concrete with the Springhill aggregate still exceeded this limit even with 30% Belledune fly ash. It is somewhat surprising that the mixture with 30% fly ash expanded more than that with 25% fly ash and this is considered to be an anomaly.

Figures 3 and 4 show, respectively, the 14-day and 28-day expansion results for mortars cast with Springhill aggregate and different fly ashes with a range of chemical compositions. The data indicate that fly ashes with low to moderate levels of calcium (up 16% CaO) are effective at controlling the expansion of mortars at levels of replacement of between 20 to 30%. Fly ashes with calcium contents in the range of 18 to 24% CaO need to be used at replacement levels around 40% to control expansion at 14 days and up to 60% to control expansion at 28 days. Fly ashes with calcium contents above 17% CaO need to be used at levels in excess of 50% and maybe as high as 70% to control the expansion at 14 or 28 days. It is noteworthy that the high-alkali fly ash was not able to control expansion of mortars to less than 0.10% at 24 or 28 days, even when it was used at a replacement level of 70%. This highlights the importance of the alkali content of the fly ash in terms of its efficacy in controlling ASR expansion. Figure 5 shows the expansion of mortars with 25% fly ash plotted against the calcium content of the fly ash and reinforces the importance of the composition (especially calcium and alkali contents) of the fly ash.

Table 1 and Figure 6 show expansion data for mortar bars with Springhill aggregate and slag or ternary blends of high-calcium fly ash with either slag or silica fume. The data indicate that moderate levels (25 to 30%) of high-calcium fly ash can be used to control ASR expansion if they are combined with either silica fume or slag in a ternary blend. The use of slag in a binary blend is also an effective preventive measure provided a sufficient level or replacement (30 to 50%) is used. These blends are currently being evaluated in the CPT.

4 DISCUSSION

The data presented here confirm that fly ash is able to control expansion of concrete mixes containing these aggregates provided a sufficient amount is used. The level of fly ash required is clearly dependent on its composition and can be reduced if another pozzolan or slag is also incorporated in the mix. The role of fly ash composition and the efficacy of ternary blends containing fly ash are well established [12, 13]. However, the methodology for determining how much fly ash (or other SCM) to use to prevent deleterious expansion in the field is not so well established. It is clear from a number of studies that this will vary depending on the aggregate type [5, 14, 15]. The Canadian approach [4] allows for the use of either the AMBT or the CPT to determine the amount of pozzolan or slag required with a particular aggregate and specifies that the combination must expand by less than 0.10% at 14 days in the AMBT and less than 0.040% at 2 years in the CPT. Studies have shown that the use of these two tests with these same performance criteria generally give a good prediction of whether the combination of materials will suppress ASR in the field [5, 15]. Some agencies use a more conservative approach specifying that the combination of materials when tested in the AMBT must pass the 0.10% expansion limit after 28 days soaking in 1M NaOH solution at 80^{o}C. It has been suggested that this approach is too conservative for most aggregates as significantly more SCM is required to meet this limit with a particular aggregate than the amount required to produce satisfactory performance in concrete [15].

For the aggregates tested here 15 to 20% fly ash was required to keep expansion ≤ 0.10% at 14 days in the AMBT whereas 25 to 30% was required to meet the same expansion limit at 28 days. The amount required in the CPT (for expansion ≤ 0.040% at 2 years) was 20% for Mactaquac aggregate and somewhere in excess of 30% for the Springhill aggregate, although the expansion in the CPT was only marginally higher than the 0.040% limit in mixtures with Springhill and 25% and 30% fly ash (values were 0.044 and 0.045%, respectively).

Data from CANMET [5] for aggregate from the same quarry (Springhill) and a fly ash of similar calcium content to the Belledune, indicates that not only does the AMBT fail to predict the performance of this aggregate-fly ash combination in concrete, but the CPT fails to accurately predict its performance in field-exposed concrete block (Figure 7). In that study, concrete mixes were produced at two alkali loadings; these were an "unboosted mix" with 420 kg/m^3 of cementing materials and a high-alkali cement (0.90% Na_2Oe) and a "boosted mix" with the same materials and proportions, but with the portland cement alkalis boosted to 1.25% Na_2Oe by adding NaOH to the mix water as per ASTM C1293. Concrete prisms were stored under normal laboratory conditions (over water in sealed containers at 38^{o}C). Concrete blocks (0.4 x 0.4 x 0.7 m) and slabs (0.7 x 0.7 x 0.15 m) were cast from the same mixes as the prisms and these larger elements were placed on the CANMET exposure site in Ottawa [5]. The data shown in Figure 7 include 14-day and 28-day expansion results for the AMBT, 2-year expansion results for the CPT and 10-year expansion results for the field-exposed concrete blocks.

For most aggregates tested in the CANMET program there is a good correlation between the performance of an aggregate-SCM combination in the AMBT at 14 days and the boosted (as per ASTM C1293) CPT at 2 years, and between the boosted CPT at 2 years and the long-term performance of unboosted blocks [5]. This correlation, together with similar correlations between the AMBT, CPT and either field-exposed blocks or structures, was presented in a recent publication [16]. However, the correlation does not hold in all cases for the Springhill aggregate. In the AMBT, 20% fly ash was sufficient to meet the 14-day limit, but 30% was required to meet the 28-day limit. In the CPT, 20% fly ash was sufficient in unboosted mixes, but 30% was required when the alkalis were boosted as per ASTM C1293. All of the field-exposed concretes with 20% fly ash expanded by more that 0.040% after 10 years and both specimens with 30% fly ash expanded by more than 0.040% when the alkalis were boosted. For the concrete with 30% fly ash that was unboosted, the 10-year expansion of the blocks was 0.023% and for the slabs it was 0.046%. The increased expansion of the slabs is thought to be due to the fact that the length change is only measured on the exposed top surface of the slab, whereas length change measurements are made on both long sides and the top surface of the blocks. The increased expansion of the top horizontal surface is likely a consequence of the forces of freeze-thaw acting on the water-filled cracks.

The inability of 25 to 30% low-calcium fly ash to completely control deleterious expansion in concrete prisms and field-exposed concrete blocks containing the Springhill aggregate is a cause for concern and requires that higher fly ash replacement levels be evaluated (such tests are underway). The data presented here also stress the importance of long-term studies of large concrete elements stored under realistic conditions to allow proper calibration of laboratory test methods.

The reason for the relatively poor performance of moderate levels of low-calcium fly ash with this aggregate warrants further study. Low-calcium fly ashes are generally effective in controlling expansion with reactive aggregates when they are used at replacement levels in the range of 25 to 30%. This has been demonstrated in the laboratory and in the field, including cases where large structures have been built with high-alkali cement, highly reactive aggregate and 20 to 30% low-calcium fly ash [3]. Clearly this aggregate is very highly reactive and requires a greater level of prevention than most reactive aggregates.

Further evidence of the high reactivity of these aggregates is provided by the experiences with the Mactaquac Generating Station. The relatively rapid rate of unrestrained expansion (estimated to be between 120 and 150 $\mu\varepsilon$/y) occurs despite a relatively low alkali loading in the concrete. The cement used at Mactaquac was 0.71% Na_2Oe (average of monthly composites during construction) and the estimated alkali content of the concrete was between 1.3 and 2.8 kg/m^3 Na_2Oe, depending on the class of concrete (178 to 395 kg/m^3 of cement were used in the different classes). The most commonly used concrete mixes contained between 220 and 285 kg/m^3 of cement yielding estimated alkali contents in the range of 1.6 to 2.0 kg/m^3 Na_2Oe. Such alkali levels are around the lowest alkali limit in the Canadian specification [4], which imposes maximum limits of 3.0, 2.4 and 1.8 kg/m^3 Na_2Oe, respectively, when mild, moderate and strong preventive action is required. Testing of cores from the concrete structures at Mactaquac showed the water-soluble alkali content to range from 1.8 to 3.3 kg/m^3 Na_2Oe, suggesting a significant quantity of alkali has been contributed by the aggregate. The water-soluble alkali content may significantly underestimate the alkalis actually available for ASR in a concrete mix as the test conditions do not extract all of the available alkali in the cement hydrates, the alkali-silica reaction product that has already formed and the aggregate. Berube et al [16] showed that only a fraction of the alkalis present in most aggregates are soluble in water, but that significantly higher quantities can be extracted by alkaline solutions representative of the pore solution of concrete. For example, the amount of alkali extracted by alkaline solution from a greywacke aggregate used in their study was in excess of 0.145% [16]. Assuming that all of this alkali is leached from the aggregate into the concrete pore solution during the life of the concrete, the total alkali contribution of the aggregate to the concrete is more than 2.68 kg/m^3 Na_2Oe, assuming an aggregate content in the concrete of 1850 kg/m^3 [16]. All of the aggregates used in this study are currently being tested using the alkaline-solution extraction method to see if differences in the alkali availability can explain the differences in the reactivity of and the level of prevention required for the Springhill, Mactaquac, Carn Owen and Lower Notch aggregates. Also, core samples from the concrete structures at Mactaquac will be tested to determine the amount of alkalis available to an alkaline solution.

In the context of ASR testing, deleterious expansion of concrete is defined as an expansion greater than 0.040% as this level of expansion has often been observed to coincide with the onset of visible cracking due to ASR. However, in a large structure, expansions significantly less than 0.040% can be translated into very significant movements, especially when mechanical equipment with very small clearances, such as turbines or sluice gates, are embedded or attached to the structure. In order to conclusively determine the magnitude of volume changes in concrete containing Mactaquac aggregate and to confirm the ability of relatively high levels of Belledune fly ash to control ASR expansion six large concrete monoliths (3 x 3 x 3 m) will be cast in Spring 2008 at the location of the Mactaquac Generating Station. These monoliths will be instrumented with embedded strain gauges and thermocouples, and Demec-type reference points will be embedded in the surface of the concrete. Four concrete mixtures will be cast with Springhill aggregate, high-alkali cement, and Belledune fly ash at replacement levels of 0, 30, 40 and 50%. The fifth concrete mixture will contain Springhill aggregate but with 50% fly ash reclaimed from the landfill at Belledune; this material is currently being tested to determine its suitability for use in concrete should suitable fly ash not be available from Belledune at the time of reconstruction. The sixth concrete mixture will contain 50% Belledune fly ash with non-reactive coarse and fine aggregates.

5 CONCLUSIONS

Testing of aggregates from Mactaquac Generating Station and Springhill Quarry in New Brunswick has indicated that damaging ASR can be reduced using low-calcium fly ash from the Belledune Generating Station in the same province. However, the amount of fly ash required to reduce expansion to acceptable levels is likely to be in excess of 30% due to the highly reactive nature of the aggregates and their potential to contribute significant quantities of alkali to the concrete. If suitable low-calcium fly ash is not commercially available at the time of reconstruction, consideration is being given to the use of waste ash stored in landfill. Also the use of other SCM's, including combinations of different pozzolans and slag, is being considered. The current versions of the accelerated mortar bar test and concrete prism test, even using 28-day and 2-year expansion criteria, may not be suitable for determining the level of prevention required with aggregates that contribute significant quantities of alkali to the concrete.

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TABLE 1: Results of Accelerated Mortar Bar Test for Springhill Aggregate with Slag or with Ternary Blends Containing High-Calcium Fly Ash with Either Silica Fume or Slag.

Proportion of Cementing Materials (%)				Expansion (%)	
Portland Cement	Slag	Silica Fume	High-CaO Fly Ash	14-Day	28-Day
100	-	-	-	0.497	0.723
70	30	-	-	0.081	0.187
60	40	-	-	0.028	0.091
50	50	-	-	0.014	0.061
50	20	-	30	0.067	0.108
50	25	-	25	0.055	0.094
40	30	-	30	0.043	0.055
70	-	5	25	0.057	0.114
60	-	5	35	0.050	0.069

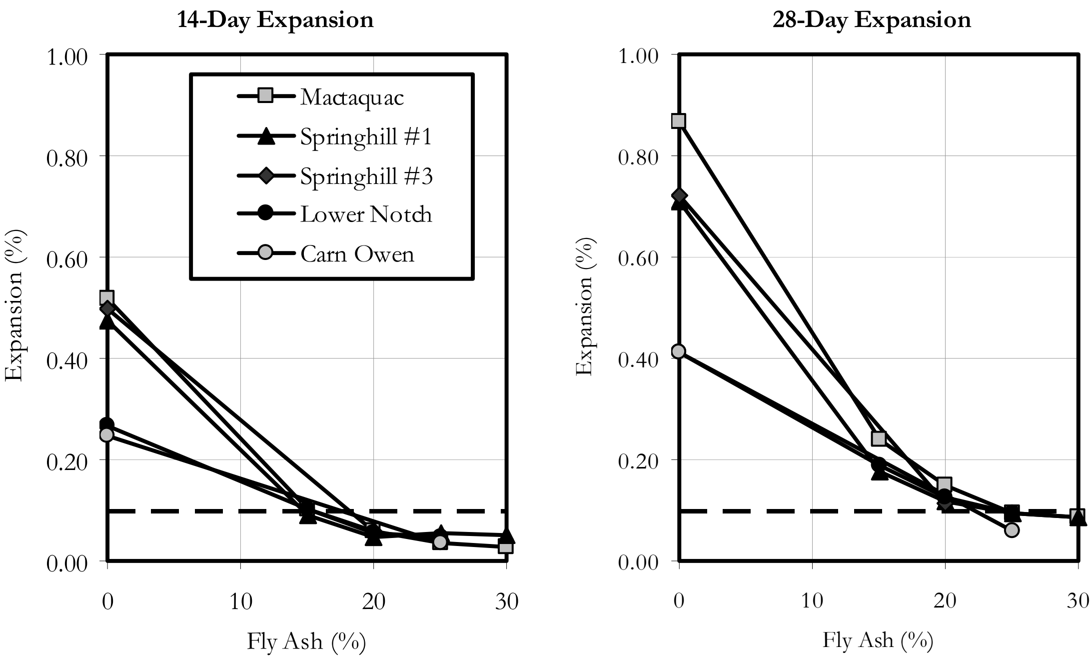

Figure 1: Results of the Accelerated Mortar Bar Test for Belledune (Type F) Fly Ash.

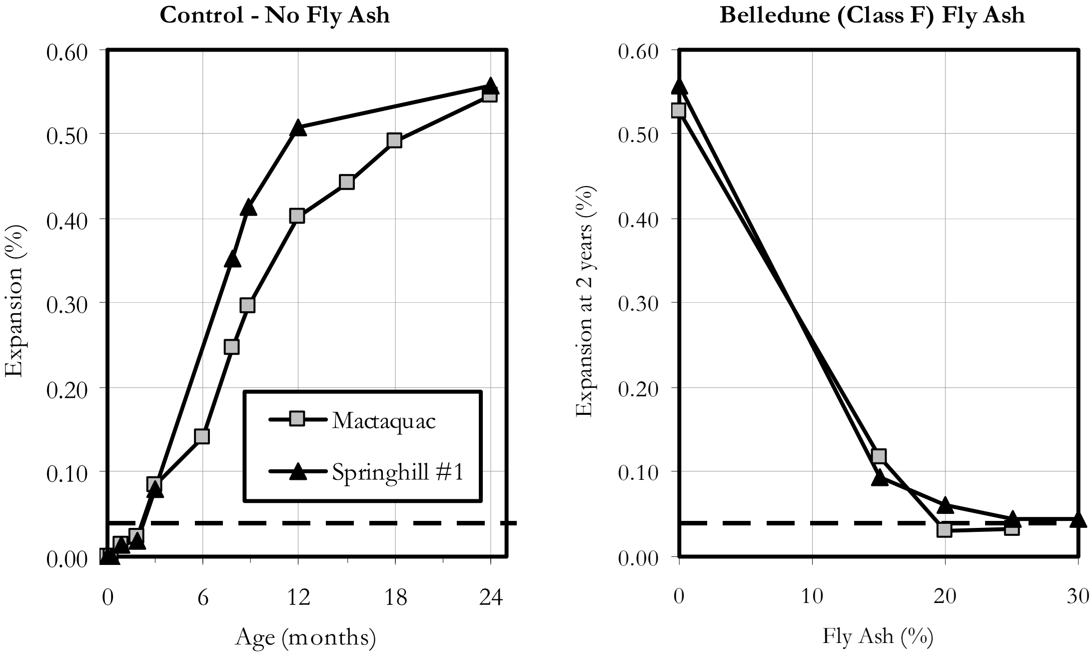

Figure 2: Results of the Concrete Prism Test for Belledune (Type F) Fly Ash.

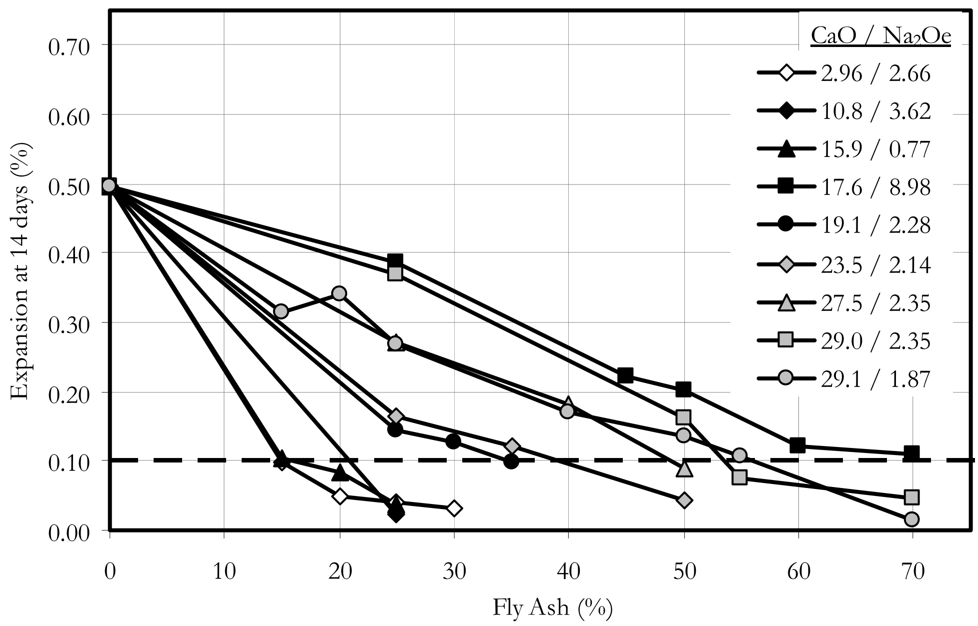

Figure 3: Results of the Accelerated Mortar Bar Test for Springhill Aggregate withVarious Fly Ashes: 14-Day Expansion.

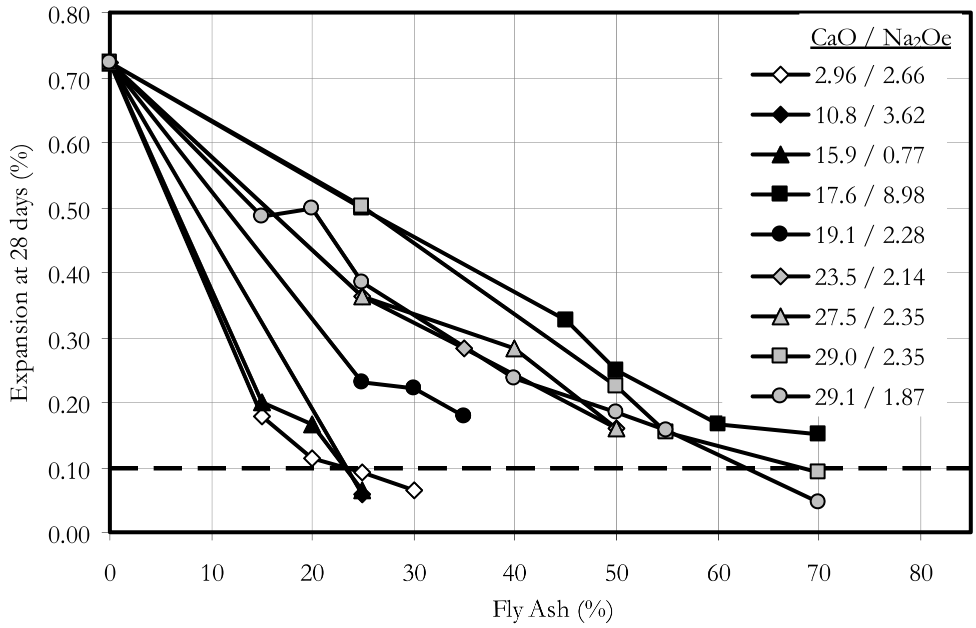

Figure 4: Results of Accelerated Mortar Bar Test for Springhill Aggregate withVarious Fly Ashes: 28-Day Expansion.

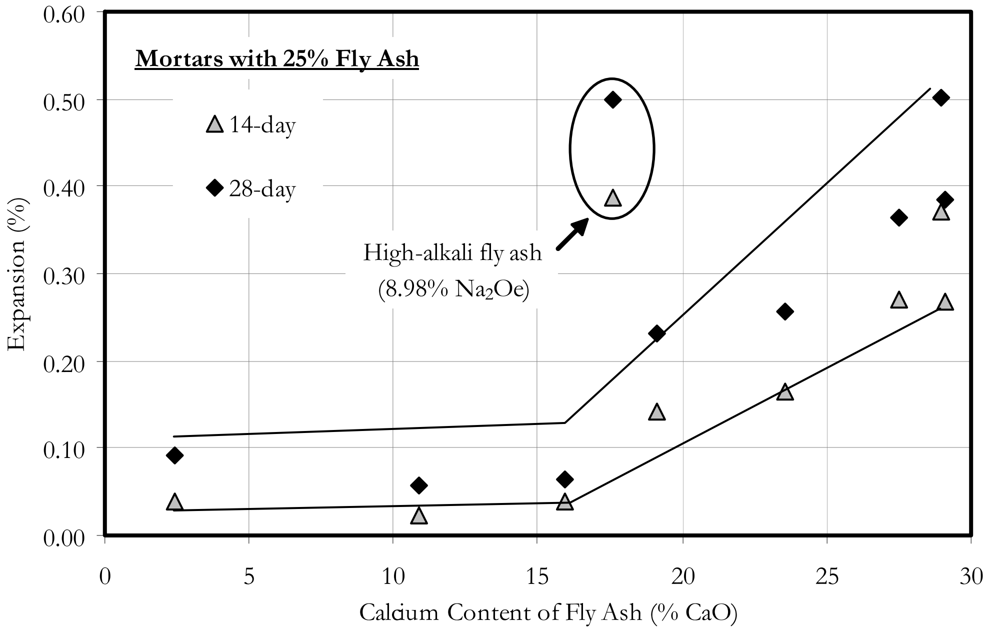

Figure 5: Effect of Calcium (and Alkali) Content of Fly Ashes on Expansion of Mortar Bars Containing Springhill Aggregate and 25% Fly Ash.

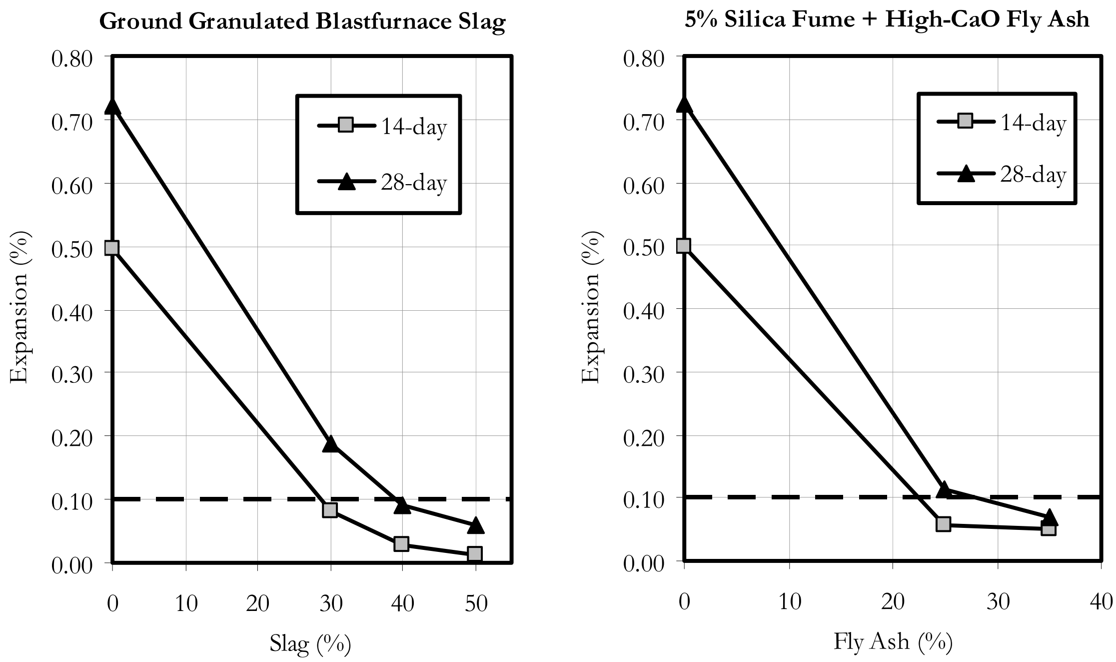

Figure 6: Results of Accelerated Mortar Bar Tests for Springhill Aggregate with Slag (left) and Ternary Blends of Silica Fume plus High-Calcium (29.1% CaO) Fly Ash (right).

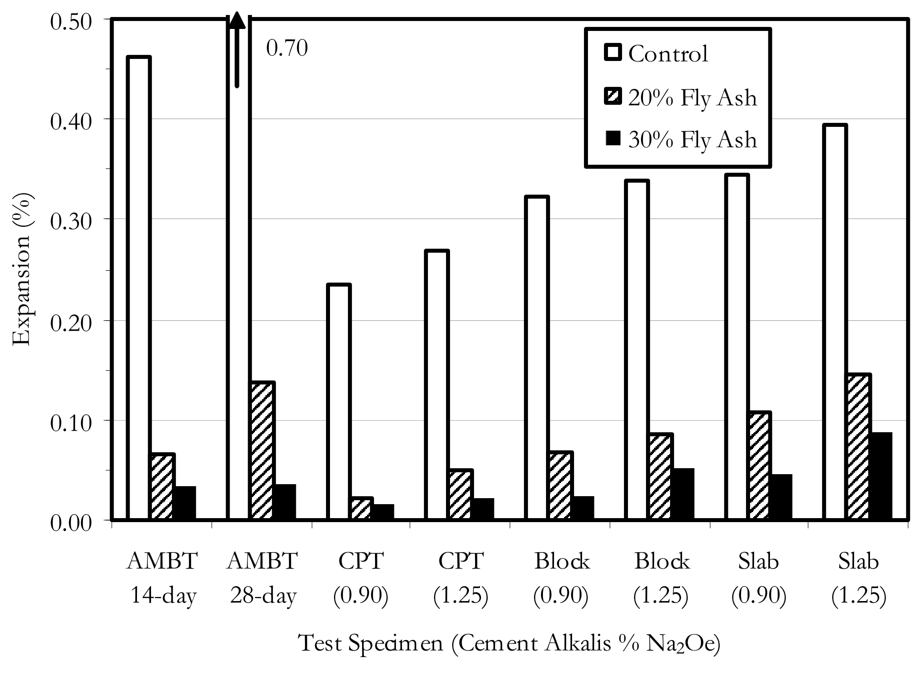

Figure 7: CANMET Expansion Data for Springhill Aggregate with Low-CaO (2.06% CaO) Fly Ash Tested in the Accelerated Mortar Bar Test, the Concrete Prism Test and Outdoor Exposure Blocks.