

## Alkali-Silica Reaction Mitigation Performance of Unconventional and Marginal Source Fly Ash

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### Abstract

Coal fly ash is often used to mitigate alkali-silica reaction (ASR) through multiple mechanisms. The literature shows that chemical make-up, especially the amorphous, alkali, and calcium oxide contents, are the key properties controlling the efficacy of fly ash to mitigate ASR. However, the ability of fly ashes from marginal and unconventional sources with off-specification properties to mitigate ASR is not fully understood. This study investigates pastes and mortars to determine the ASR-resistance efficacy of 8 fly ash sources: 2 standard ashes, and 6 unconventional source/marginal fly ashes with varying properties. The research combines analytical characterizations (chemical composition, particle size distribution), reactivity measurements (the modified R<sup>3</sup> test), and conventional accelerated mortar bar expansion testing. The results indicate marginal and unconventional fly ashes are generally effective in controlling ASR expansion with some exceptions. Furthermore, increased expansion is shown to be correlated to higher calcium (CaO) contents, lower alumina (Al<sub>2</sub>O<sub>3</sub>) contents, and reduced portlandite (CH) consumption. The resulting data provides guidance on using these emerging and increasingly more common ashes to mitigate ASR.

**Keywords:** *alkali-silica reaction, fly ash, marginal, reactivity, unconventional*

## 1. INTRODUCTION

Coal fly ash is widely used to mitigate alkali-silica reaction (ASR) in concrete mainly due to its ability to reduce the alkalinity of the pore solution [1-4]. Inclusion of fly ash in the mixture prevents expansive reactions involving the aggregates from occurring due to insufficient quantities of sodium and potassium cations and hydroxyl anions. Fly ash also promotes reduction in permeability and calcium hydroxide, and therefore plays a role in resisting ASR expansion [4-8]. For most fly ashes (and bottom ashes), the amorphous material content and the available alkali contents are critical in controlling ASR in concrete [9]. Glass composition and ASR mitigation are also functions of the calcium (CaO) content in the fly ash [10]. For this reason, ASTM C1778 suggests that sufficient levels of Class F fly ash with a calcium content less than 18% and an alkali equivalent of less than 3% is suitable for controlling ASR, or, in other words, Class F fly ashes with lower calcium or higher primary oxide contents (SiO<sub>2</sub> + Al<sub>2</sub>O<sub>3</sub> + Fe<sub>2</sub>O<sub>3</sub>) are better suited to mitigate ASR than Class C fly ashes [4, 11]. However, these standards do not address nor provide pathways for utilization of marginal and unconventional (such as fly ash harvested from landfills) fly ash sources not in total compliance with ASTM C618. The need to use these ash sources will become increasingly important as fly ash sources meeting ASTM C618 become scarcer. Therefore, the influence of marginal and unconventional fly ashes on ASR expansion is not well-understood. The mechanism through which these alternative ashes reduce expansion, although speculated to be similar to those in conventional fly ashes, remains relatively unknown.

In the literature, Diaz-Loya et al. (2017) discovered that beneficiated (at least dried and sieved) recovered landfill ash that had been stored between 25 - 30 years not only exhibited greater Strength Activity Index (SAI), lower SO<sub>3</sub> content, lower LOI, and lower water requirement, but also similar ASR-

mitigation capability when compared to in-specification fly ash from the same source [12]. However, similar investigations linking the varied properties in the compositions of marginal and unconventional source fly ashes to ASR expansion in concrete are quite scarce in the literature [13]. Therefore, research using a suite of these fly ashes will aid in understanding their behaviour in mitigating ASR. Also, given the recent advances in understanding reactivity of supplementary cementitious materials [14-17], the establishment of correlations between fly ash reactivity-related parameters (i.e., heat release, bound water, portlandite consumption) and their ASR mitigation performance may be useful for evaluating new fly ash sources for use with ASR reactive aggregate sources.

In this investigation, the abilities of marginal and unconventional fly ashes with a wide range of marginal to out-of-specification chemical and physical properties to mitigate ASR expansion are assessed using the Accelerated Mortar Bar Test (AMBT). Correlations linking physical, chemical, and reactivity properties of these ashes to ASR-induced expansion are examined to better understand the effect these products have on concrete durability properties, and to determine pathways to use them to safeguard concrete against deleterious alkali-aggregate reaction.

## **2. MATERIALS AND METHODS**

### **2.1 Materials**

An investigation on the alkali-silica reaction performance of a suite of fly ashes were conducted using the standard accelerated mortar bar test (AMBT) (ASTM C1260 and ASTM C1567) [18,19]. The tested fly ashes included two standard ashes meeting the specifications of ASTM C618, three beneficiated marginal and unconventional ashes with close-to-marginal and out-of-specification properties, and three non-beneficiated marginal and unconventional ashes including two with out-of-specification properties (G and L) (Table 1) [20]. The two standard ashes included an in-specification Class C fly ash (D) and a Class F fly ash with moderate LOI (P). The three beneficiated marginal and unconventional ashes included a reclaimed fly ash, dried and sieved pre-processing, with out-of-specification fineness (M), a surfactant treated class C fly ash with marginal sum of primary oxide contents ( $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ ) (K), and a marginally high-water demand fly ash subjected to electrostatic beneficiation (O). The three non-beneficiated marginal and unconventional fly ashes included a cyclone collector ash (J), a fly ash with off-specification primary oxide contents and off-specification high sulfate content (G), and a fly ash with off-specification low fineness and high total alkali equivalent (L). All mortar bars representative of the eight fly ash sources were prepared with commercial OPC Type I/II cement and with the same water, cement, fly ash, and sand proportions by mass. The investigation also included two additional sets of bars made for comparison purposes, one mixture with inert pulverized limestone replacing cement by 20% mass and a mixture with 100% cement (control set).

Table 1: Classifications and properties of the fly ashes based on ASTM C618 criteria.

Samples	Descriptions	SiO <sub>2</sub> + Al <sub>2</sub> O <sub>3</sub> + Fe <sub>2</sub> O <sub>3</sub> , %	CaO, %	SO <sub>3</sub> , %	Na <sub>2</sub> O <sub>eq</sub> , %	Moisture Content, %	Water Req, %	Fineness, %	LOI, %
		50, min	N/A	5, max	4.5% max – R80 <sup>***</sup>	3, max	105, max	34, max	6, max
Standard Ashes									
P	Class F moderate LOI	88.70	1.70	0.10	1.89	0.23	100	20.20	3.83
D	Class C, in-specification	63.50	19.90	0.80	1.80	0.30	100	24.50	0.69
Marginal and Unconventional Ashes									
O	LOI Electrostatic Beneficiation	82.40	4.70	1.27	2.23	0.77	104 <sup>*</sup>	24.10	2.57
K	Surfactant Treated	51.20 <sup>*</sup>	24.80	2.05	1.85	0.15	88	21.90	0.95
M	Harvested ash, dried and sieved	83.30	2.10	0.21	1.76	0.30	94	36.20 <sup>**</sup>	2.90
J	Cyclone collector ash	61.50	15.30	2.28	2.92	0.28	94	15.70	3.10
G	High SO <sub>3</sub>	37.80 <sup>**</sup>	25.50	17.45 <sup>**</sup>	3.94	1.05	94	15.50	2.08
L	Low Fineness	86.40	3.90	0.10	5.29 <sup>**</sup>	0.09	100	63.10 <sup>**</sup>	0.22

<sup>\*</sup> Close to limit (marginal)

<sup>\*\*</sup> Outside of limit

<sup>\*\*\*</sup>Not an ASTM C618 criteria

## 2.2 Accelerated Mortar Bar Test (AMBT)

Alkali-silica reaction measurements followed the accelerated mortar bar test (AMBT) procedures of ASTM C1260 and ASTM C1567 [18,19]. Four mortar bars (1-inch x 1-inch x 11.25-inch) were made for each fly ash mixture. A nominal gauge length of 250 ± 2.50 mm (10-inch ± 0.1inch) was maintained by placing a ruler 10-inch in length into the molds between the gage studs prior to casting. Immediately after the molds had been filled, the molds were placed in a curing chamber with a temperature set to 23 ± 2°C and a relative humidity maintained at 55% (ASTM C511) for 24 hours [21]. After demolding, initial readings were made, and the bars were then immersed in water maintained at 80°C for another 24 hours. Zero-reading measurements were taken prior to immersion of the bars in 1 N NaOH solution maintained at 80°C, and a solution-to-bar volume was maintained at a ratio of 4:1, for the remaining duration of the testing period. A length comparator was used to measure bar expansion every two days until 14 days, and every seven days thereafter until 28-day age was reached (twice the testing duration recommended by AMBT). Per ASTM C1260, 14-day ASR expansion measurements represented a performance-based property and followed classification ratings of: (1) less than 0.10% indicates non-reactive aggregate; (2) greater than 0.20% indicates susceptible to ASR damage; and (3) between 0.10% and 0.20% indicates further testing to determine reactivity potential [18]. A more detailed classification of aggregate reactivity for selecting appropriate preventive measures was also recognized in ASTM C1778 with specific ratings corresponding to expansion ranges [11].

For mortar bar proportioning, fly ash and limestone filler were used to replace 30% by mass of cement. Water-to-cementitious content was maintained at 0.47 with graded fine aggregate to cementitious content set at a ratio of 2.25. The control mixture followed the same proportioning scheme except with cementitious content at 100% cement. All mortars were prepared with reactive aggregate originating from a sand pit in Gregory, South Dakota, USA. The aggregate consisted of natural quartz, feldspar,

and lithic sand with reactive shale contents. Aggregate was sieved and proportioned as per ASTM C1567 [19]. Mortar bars were produced following the mixing guideline of ASTM C305 [22].

### 2.3 Chemical Analysis (XRF)

Chemical compositions of the cement and fly ashes were determined using X-ray fluorescence (XRF) spectrometer with borate fusion sample preparation [23,24]. The samples were ground and mixed with a lithium borate flux inside a crucible heated to greater 1000°C, and fused beads were subsequently analyzed by XRF for common chemicals expressed as oxides (i.e., SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, CaO, MgO, K<sub>2</sub>O, Na<sub>2</sub>O, SO<sub>3</sub>, TiO<sub>2</sub>, and P<sub>2</sub>O<sub>5</sub>). Alkali contents were also expressed as total alkali equivalent (Na<sub>2</sub>O<sub>eq</sub>) per ASTM C311 [22]. Loss on ignition (LOI), consisting of both CO<sub>2</sub> and H<sub>2</sub>O, was determined per ASTM C311 by igniting the samples in a furnace until an end temperature of 750 °C [25].

### 2.4 Particle Size Distribution Analysis (PSD)

The particle size distributions (PSDs) of the cement and fly ashes were measured using Sympatic MYTOS equipment with dry-dispersion and laser diffraction measurement. An average Refractive Index value of 1.55 or similar to clay was used for all samples. Each specimen was measured with 5 replicates and the average value was reported. The median particle size, D<sub>50</sub>, of the specimens was extracted from the PSD data.

### 2.5 Modified Rapid, Robust, and Relevant Reactivity Rest (MR<sup>3</sup>)

Reactivity of the fly ash was evaluated in model systems using the modified R<sup>3</sup> test [26,27]. Calcium hydroxide and fly ash were proportioned at 3:1 ratio by mass, placed inside a plastic container, and dry-mixed for four minutes using a spatula. A 0.5 M potassium hydroxide solution was immediately added to the dry mixture and manually stirred for another four minutes to form a homogenous paste. About 7 grams of the paste were transferred to a glass ampoule, tightened, and placed into the calorimetry measurement chamber before 10 minutes had elapsed from initial mixing. Heat release data were recorded at 50 ± 0.05°C for 240 hours (10 days) after mixing. TGA was immediately performed on 30 to 50 milligrams of the representative bulk sample to determine calcium hydroxide contents. Calcium hydroxide content was determined from the mass loss that occurred at the temperature range of 380°C to 460°C using the tangential method [29]. Calcium hydroxide contents were then used to compute the calcium hydroxide consumption normalized to units of grams per 100 grams of SCM. Heat release data on these ashes can be found in [28].

## 3. RESULTS

### 3.1 Fly Ash Characterization Results

Chemical analysis performed on the ashes (shown in Table 2) revealed primary oxide contents (the summation of SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and Fe<sub>2</sub>O<sub>3</sub>) greater than 50.0% (the ASTM C618 specification limit) for all fly ashes except fly ash G (with 37.8%). Calcium oxide contents varied significantly among the ashes. Using the ASTM C618 classification of fly ash based on CaO content (Class C > 18%), regardless of whether the ashes were in-specification or off-specification, one standard ash D (19.9%) and two marginal and unconventional ashes K (24.8%) and G (25.5%) were classified as Class C ashes. Standard ash P (1.7%) and four marginal and unconventional ashes O (4.7%), M (2.1%), J (15.3%) and L (3.9%) were classified as Class F fly ashes [20]. Fly Ash M, which was a harvested fly ash beneficiated by drying and sieving, had an off-specification fineness (36.2%). Among the two remaining beneficiated marginal and unconventional ashes, K ash beneficiated by surfactant treatment had marginal primary oxide contents (51.2%) while O ash treated by electrostatic beneficiation had off-specification water demand quality (104%). Non-beneficiated marginal and unconventional fly ashes included J, G, and L. Fly ash G was characterized with both off-specification primary oxide contents (37.8%) and off-specification SO<sub>3</sub> content (17.5%), while fly ash L was characterized with both off-specification total alkali equivalent (5.29%) and off-specification fineness (63.1%). The cyclone collector ash J did not have any off-specification properties but was classified as an unconventional ash because ASTM C618 does not currently cover ashes from harvested sources [20]. Specific gravity of the ashes ranged from 1.76

g/cm<sup>3</sup> to 2.83 g/cm<sup>3</sup>. LOI of the ashes ranged from 0.22% to 3.83%, below the LOI limit (6%) of ASTM C618 [20]. PSD analysis indicated that all fly ashes used for this investigation are close to the particle size range of standard coal ash (5-20 μm) except for the coarse fly ash L (66.20 μm).

Table 2: Results of LOI via gravimetric analysis, XRF, and PSD.

Measured Components, %	P	D	O	K	M	J	G	L	Cement*
LOI	3.83	0.69	2.57	0.95	2.90	3.10	2.08	0.22	2.90
SiO <sub>2</sub>	51.61	40.36	48.78	31.31	46.66	34.09	26.60	63.67	19.80
Al <sub>2</sub> O <sub>3</sub>	25.91	18.56	18.83	16.22	24.37	16.85	7.79	19.94	4.40
Fe <sub>2</sub> O <sub>3</sub>	11.22	4.56	14.77	3.69	12.26	10.58	3.39	2.76	3.20
Σ(SiO <sub>2</sub> + Al <sub>2</sub> O <sub>3</sub> + Fe <sub>2</sub> O <sub>3</sub> )	88.74	63.48	82.38	51.22	83.29	61.52	37.78	86.37	27.40
CaO	1.72	19.91	4.67	24.78	2.11	15.33	25.52	3.94	64.60
MgO	0.95	3.67	0.91	7.17	0.86	3.84	3.87	0.72	2.30
K <sub>2</sub> O	2.31	0.56	2.35	0.32	2.36	1.55	0.76	2.18	-----
Na <sub>2</sub> O	0.37	1.43	0.68	1.64	0.21	1.90	3.44	3.86	-----
Na <sub>2</sub> O <sub>eq</sub>	1.89	1.80	2.23	1.85	1.76	2.92	3.94	5.29	-----
SO <sub>3</sub>	0.10	0.80	1.27	2.05	0.21	2.28	17.45	0.10	3.30
TiO <sub>2</sub>	1.17	1.04	0.85	0.84	1.13	1.00	0.24	0.77	-----
P <sub>2</sub> O <sub>5</sub>	0.24	1.05	0.11	0.83	0.28	0.97	0.14	0.03	-----
SUM total	95.60	91.94	93.22	88.85	90.45	88.39	89.20	97.97	97.20
Median Particle Size D <sub>50</sub> (μm)	14.30	16.60	16.40	12.50	24.90	9.90	4.10	66.20	20.00

\*Bogue Potential Composition: 65.00% C<sub>3</sub>S, 6.00% C<sub>2</sub>S, 6.00% C<sub>3</sub>A, 10.00% C<sub>4</sub>AF

### 3.2 Modified R<sup>3</sup> CH Consumption Results

Calcium hydroxide consumption from modified R<sup>3</sup> pastes was used to evaluate fly ash reactivity and determine if this reactivity can be used to screen for ASR mitigation potential of a fly ash source. For the fly ashes, portlandite consumption varied from 34 to 69 grams per 100 grams of material (Table 3). Standard ash P and beneficiated ash M exhibited the highest amounts per 100 grams of material. Surfactant treated ash K and marginal ash G had the lowest levels of portlandite consumption, approximately half of the portlandite consumption observed for the other fly ashes.

Table 3: Modified R3 portlandite consumption results (grams per 100 grams SCM).

Mix	D	G	J	K	L	M	O	P
CH consumption	61.2	34.6	58.6	33.7	58.9	63.0	56.4	69.2

### 3.3 Accelerated Mortar Bar Test Results

The AMBT expansion plot for the fly ashes including one cement “control” and an inert “limestone” mixture is shown in Figure 1. The AMBT 14-day age is designated by the vertical dashed line, and the 14-day expansion limits (of 0.1% and 0.2%) specified by ASTM C1260 are designated by the two horizontal dashed lines [18]. Expansion data corresponding to 14-day and 28-day ages are also shown in Table 4. OPC (ASTM Type I/II) control mortars indicated an average expansion measurement of 0.355% at 14 days, which indicates the aggregate is susceptible to ASR damage. Only mortar mixtures made with fly ashes M, O and P are below the 0.10% expansion limit at 14 days. Mortar mixtures with standard fly ashes reduced expansion by 50-92% at 14 days and 28-90% at 28 days compared to the

control, while mortar mixes with beneficiated marginal and unconventional fly ashes reduced expansion by 27-91% at 14 days and 26-86% at 28 days compared to control. For non-beneficiated marginal and unconventional fly ashes, mortar mixes with fly ashes J and L reduced expansion by 65-72% at 14 days and 51-44% at 28 days. However, fly ash G increased expansion by 16% at 14 days and 31% at 28 days.

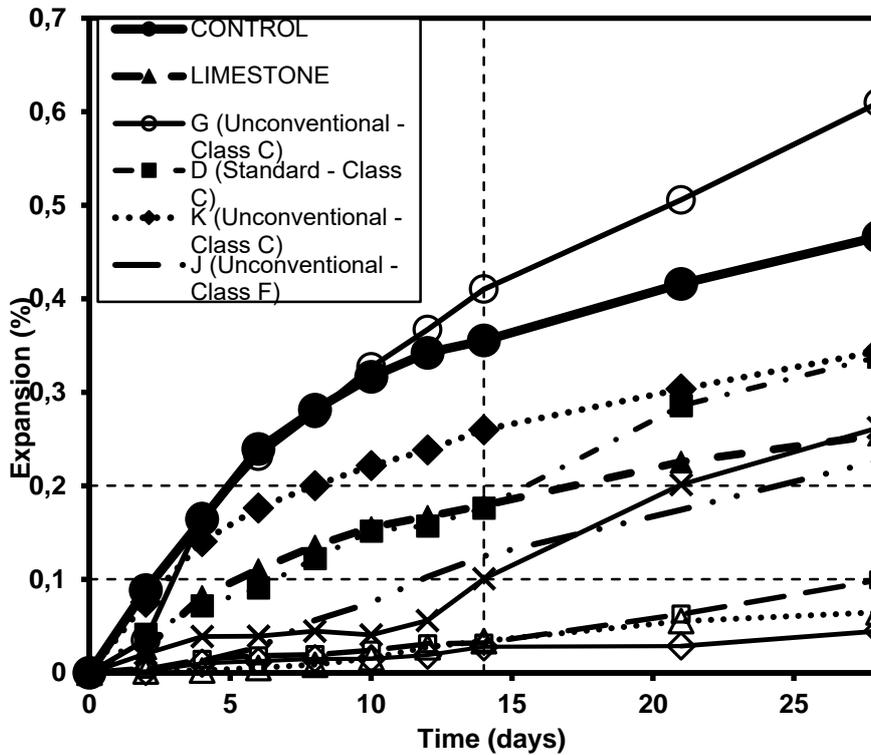


Figure 1: AMBT expansion plots for standard, marginal, and unconventional fly ashes, inert limestone, and control mortar mixtures.

Table 4: AMBT expansion results (in percentage) at 14 and 28-days.

Mix	Control	D	G	J	K	L	M	O	P	Limestone
14-day	0.355	0.176	0.410	0.125	0.260	0.100	0.034	0.032	0.028	0.179
(Stdev)	0.008	0.003	0.007	0.003	0.007	0.013	0.026	0.007	0.006	0.010
28-day	0.466	0.338	0.610	0.227	0.344	0.262	0.065	0.099	0.045	0.254
(Stdev)	0.013	0.011	0.014	0.003	0.014	0.012	0.046	0.002	0.004	0.019

### 3.4 ASR Expansion Correlations

The ASR expansion at 14-days correlates to several elemental oxides, most notably the calcium oxide (CaO) content and the calcium oxide to iron oxide (CaO:Fe<sub>2</sub>O<sub>3</sub>) ratio. The CaO:Fe<sub>2</sub>O<sub>3</sub> ratio is similar to the sulfate resistance factor, R, currently used in the United States Bureau of Reclamation concrete specification [30]. These relationships are shown in Figure 2 with strong positive exponential correlations ( $R^2 = 0.90$  and  $R^2 = 0.93$ , respectively). The 14-day ASR expansion also correlated to the alumina (Al<sub>2</sub>O<sub>3</sub>) content, with a strong negative linear relationship ( $R^2 = 0.82$ ) (graph not shown). The 14-day ASR expansion also correlates with CH consumption (a moderate negative linear correlation ( $R^2 = 0.75$ )) (Figure 3). ASR expansion results indicate that regardless of source, fly ashes with higher calcium oxide contents have higher expansions. That is, fly ashes classified as Class C based on CaO contents indicate higher susceptibility to ASR expansion. This is consistent with standard ash D and marginal

and unconventional ashes K and G (all classified as Class C fly ashes by CaO contents) showing higher expansions throughout the testing period than the remaining ashes classified as Class F ashes. The fly ashes with high CaO contents or marginal to off-specification primary oxide contents (K and G) are also characterized by low portlandite consumption (pozzolanic reactivity). Finally, for this investigation, particle size does not predict ASR expansion ( $R^2 = 0.60$  at 14-days and  $R^2 = 0.41$  at 28-days, graphs not shown).

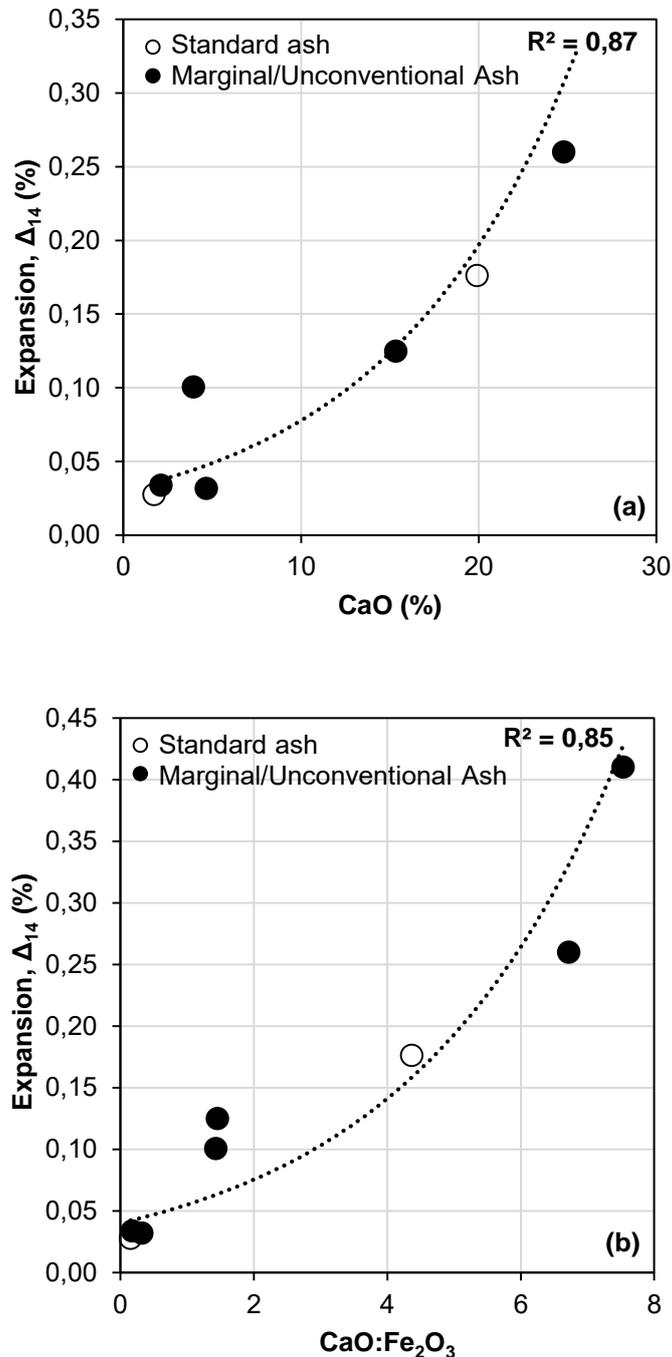


Figure 2: Correlations between (a) 14-day ASR expansion and calcium oxide content and (b) 14-day ASR expansion and calcium oxide to iron oxide ratio.

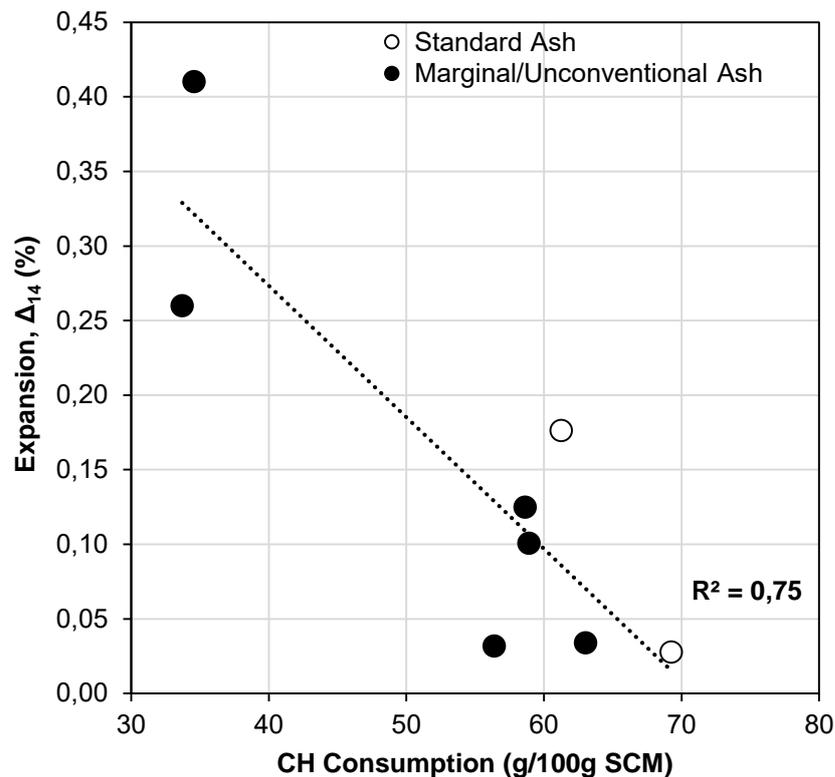


Figure 3: Correlation between 14-day ASR expansion and CH consumption.

#### 4. DISCUSSION

AMBT results indicate the partial replacement of cement with standard, marginal, and unconventional source fly ashes reduced expansion except for one off-specification ash. For the alkali-reactive aggregate used, standard fly ashes D and P mitigated ASR expansion during the entirety of AMBT when compared to the control. Compared to the inert limestone mortar mixture, the Class F ash (P) performed better while the Class C fly ash (D) performed worse at 30% cement replacement.

Beneficiated marginal and unconventional fly ashes O, K, and M also reduced ASR expansion when compared to the control. Fly ashes O and M mitigated expansion to an R0 “non-reactive” classification throughout the entire 28-day measurement duration [11]. These two ashes were also more effective in mitigating ASR expansion than the mortar mixture containing inert limestone. Conversely, the surfactant-beneficiated ash K performed worse than limestone. It should be noted that fly ash K, characterized by marginally low primary oxide contents or high CaO content, had greater expansion than all the fly ashes (except for G) throughout the measurement duration. Still, fly ash K mitigated 14-day expansion to an R1 or “moderately reactive” aggregate classification [11].

Replacement of cement with non-beneficiated marginal and unconventional source fly ashes J, G, and L showed varied results. Inclusions of fly ashes J and L in the mortar mixtures reduced expansion compared to the control. The cyclone collector ash J also performed better than the limestone in mitigating ASR expansion. Fly ash L, characterized by both off-specification fineness and total alkali equivalent, had slightly higher expansion compared to J. Likely its higher CaO, lower pozzolanic reactivity (due to its large particle size), and high alkali equivalent content contributed to increased later age expansion. Despite marginal properties, fly ashes J and L still reduced the aggregate reactivity to R1 or “moderately reactive” rating at 14-day expansion limit [11]. Finally, fly ash G was ineffective in controlling ASR expansion and increased relative expansion compared to the control. Fly ash G’s ineffectiveness in mitigating ASR expansion could be potentially linked to its unusually low off-

specification primary oxide content (or subsequently high CaO content) and high sodium content, which lowered its potential to reduce pore solution alkalinity and subsequently increased ASR expansion.

In terms of ASTM C618 classification of fly ash based on CaO content, regardless of whether the ashes were in-specification or off-specification, it is observed that at 30% replacement, the Class C ashes tested in this study increased 14-day ASR expansion by roughly 61% compared to Class F ashes [20]. Class C fly ashes with high CaO contents have been shown to be less effective in reducing the pore solution alkalinity of the mixture, and thus are less efficacious in controlling ASR expansion [3,31]. For a Class C fly ash with both high CaO and alkali contents, such as marginal ash G, the high alkali content may be available for reaction prompting further expansion [32]. In addition, this investigation has established strong correlations between CaO content and CaO:Fe<sub>2</sub>O<sub>3</sub> ratio to ASR expansion ( $R^2 = 0.90$  and  $R^2 = 0.93$ , respectively). These correlations are consistent with the literature [4,30].

For ASR mitigation based solely on alumina (Al<sub>2</sub>O<sub>3</sub>) content, it is observed that fly ashes with low alumina contents (e.g., K and G) have high 14-day ASR expansion while fly ashes with high alumina contents (e.g., M and P) appear more efficacious in controlling ASR expansion. However, the strong correlation between alumina content and expansion ( $R^2 = 0.82$ ) is not consistent for the remaining fly ashes (e.g., D, J, L, and O). It has been suggested that alumina mitigates or restricts ASR expansion by limiting the dissolution of amorphous silica in the reactive aggregates and by reducing the alkalinity of the pore solution through C-A-S-H formation (which enhances alkali sorption into the solid hydrate phases) [33-37]. The role of alumina and silica in glassy phases of the ashes in ASR mitigation has also been attributed to their contribution to pozzolanic reactivity [38].

Much like the bulk oxide contents (the summation of SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and Fe<sub>2</sub>O<sub>3</sub>), alumina content is an inverse indicator of CaO content. However, correlating ASR expansion with any bulk oxides content has its limitations since they are not always correlated to amorphous phases given the variable amounts of SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> in crystalline phases. This oxide limitation is seen with the previously mentioned fly ashes D, J, L, and O showing inconsistencies between 14-day ASR expansion and alumina content. In this investigation, classification based on CaO content for ASR mitigation is more consistent than alumina.

Furthermore, a moderate correlation between portlandite consumption and expansion ( $R^2 = 0.75$ ) was also observed for the investigated fly ashes. Fly ashes with low CH consumption (e.g., K and G) will likely not be useful for ASR mitigation. However, usage of pozzolanic reactivity as a sole predictor of ASR expansion is not advised due to the complex nature of the ASR reaction [16,17]. Even if a pozzolan is reactive, further study should be conducted on its ASR mitigation potential. Pozzolanic reactivity testing is better used as a rapid test to screen out inert materials that do not mitigate ASR.

Further AMBT experimentation using a larger range of fly ashes consisting of marginal and unconventional fly ashes, in addition to ASTM C1293 concrete prism tests, may be needed to clarify these findings and provide a better understanding of their behavior.

## 5. CONCLUSIONS

The performance of a suite of fly ashes including standard, marginal, and unconventional fly ashes was compared to a Type I/II portland cement control and an inert limestone mortar made with the same reactive aggregate to assess their capability to mitigate ASR-induced expansion during AMBT. Key findings are summarized as follows:

- Most of the investigated ashes reduced AMBT mortar bar expansion when compared to the control. However, the marginal high-sulfate fly ash (G), with its low primary oxide content and high CaO content was ineffective in mitigating ASR expansion when compared to the control.
- ASR expansion for all ashes regardless of source was strongly, positively correlated to CaO content and CaO:Fe<sub>2</sub>O<sub>3</sub> ratio and moderately, negatively correlated to Al<sub>2</sub>O<sub>3</sub> content and CH consumption. This indicates that a primary controlling parameter (i.e., calcium oxide content) affecting the ability of conventional fly ash to mitigate ASR also applies to marginal and unconventional source fly ashes. Further, pozzolanic reactivity may be used as a screening tool to determine pozzolans that will be poor at ASR mitigation (i.e., very low reactivity), but additional characterization and ASR testing for fly ashes is strongly recommended.

Overall, the marginal and unconventional source fly ashes used in this investigation were shown to mitigate ASR-induced expansion with varying levels of success. Thus, these ashes will need to be tested to determine their ability to reduce expansion, just like conventional fly ashes.

## 6. ACKNOWLEDGEMENTS

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