



# The capacity of ternary blends containing slag and high-calcium fly ash to mitigate alkali silica reaction



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## ARTICLE INFO

### Article history:

Received 9 March 2012

Received in revised form 23 November 2013

Accepted 14 December 2013

Available online 21 December 2013

### Keywords:

Alkali-silica reaction (ASR)

Alkali leaching test

High-calcium fly ash

Slag

Ternary blends

Concrete prism test

## ABSTRACT

The efficiency of ternary blends containing high-calcium fly ash and slag in mitigating alkali-silica reaction (ASR) was evaluated. The concrete prism expansions showed that the ternary blends did not offer significant advantage over binary blends of portland cement and either of the individual material at the same total SCM content. The ability of a particular blend to mitigate ASR was related to its capacity to retain alkalis in its hydration products, as evaluated by an alkali leaching test. For the slag and fly ash used in this study, the capacity to retain alkalis increased with the ability of the blend to consume  $\text{Ca}(\text{OH})_2$  during its pozzolanic reaction. For the blends investigated here, the alkali leaching test was more realistic than the accelerated mortar bar test in predicting the 2-year expansion of concrete prisms. The adopted alkali leaching test is proposed to be used as a tool to compare the efficacy of different cementing blends to mitigate ASR.

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## 1. Introduction

Alkali-silica reaction (ASR) is a concrete deterioration mode that involves a reaction between the alkalis in pore solution of concrete and some types of aggregates that contain reactive silica. The reaction causes expansion and disruption of concrete. Since the reaction occurs between alkalis in pore solution and reactive silica, most mitigation methods rely on lowering the alkalinity of concrete pore solution through the use of Supplementary Cementing Materials (SCMs) such as fly ash, slag and silica fume [1–7].

The effectiveness of SCMs in mitigating ASR is attributable to pore refinement, alkali dilution due replacing part of the portland cement, and alkali binding by secondary hydration products of the pozzolanic reaction [8]. Duchesne and Bérubé measured the alkali concentration in the pore solutions of various portland cement/SCM pastes [3,4]. They found a threshold of pore solution alkalinity of pastes of about 0.65 mol/L of  $\text{NaOH} + \text{KOH}$  below which no significant ASR deterioration occurs in concrete test specimens containing the same cementing blend as that of the pastes [3,4]. Similar finding was reported by Shehata and Thomas [1,2,5,6] for binary and ternary blends containing silica fume and fly ash. Shehata and Thomas found that the ability of a cementing blend to mitigate ASR was related to the amount of alkalis

available from the same blend to a leaching solution of an alkali ( $\text{Na}^+ + \text{K}^+$ ) concentration of 0.25 mol/L [6]. However, in their study, Shehata and Thomas used silica fume, fly ash and ternary blends thereof. In addition to lowering alkali availability in pore solution, SCMs consume  $\text{Ca}(\text{OH})_2$  through its pozzolanic reaction. Large amount of  $\text{Ca}(\text{OH})_2$  available in the cementing system was reported to aggravate ASR [9,10].

Earlier research work has shown high-calcium fly ash (ASTM Class C or CSA Type CH) to be less effective than low-calcium fly ash (Class F or Type F) in mitigating ASR. Indeed, high-calcium fly ash requires replacement levels in the range of 50% to lower the expansion to the acceptable limit while around 25% of low-calcium fly ash is sufficient [1–2,5–7,11–13]. The lower efficacy of high calcium fly ash is attributed, mainly, to its reduced ability to bind alkalis in its hydration products [6].

Slag was found effective in mitigating ASR. Like other types of SCMs, slag's beneficial effect comes mainly from binding alkalis into its hydration products, and hence, lowering  $\text{OH}^-$  ions in pore solution of concrete [14]. Slag requires relatively high replacement levels, around 35–50%, in order to achieve an acceptable mitigation effect [13–16]. The amount of slag replacement depends on the level of reactivity of aggregates and the alkali content of the portland cement. For aggregates of lower reactivity or for concrete with less alkali content portland cement, lower replacement levels of slag are sufficient. For concrete with highly reactive aggregates or high alkali content, higher replacement is necessary [15]. The hydration products of slag were reported to have a high capacity to bind

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alkalis [17,18]. Richardson and Grove [17] attributed this high capacity of slag to bind alkalis to the low Ca/Si ratio of C–S–H produced in pastes containing portland cement and slag. The same authors [17] reported that an Al–Mg rich phase similar to hydrotalcite is also formed as a product of hydration of slag. Chen and Brouwers [18] suggested that while lower Ca/Si ratio of C–S–H contributes to alkali binding, the hydrotalcite-like phase has higher role in alkali binding in hydrated slag cement paste.

In earlier studies, researchers attempted the use of ternary blends where two types SCMs were used along with portland cement as preventive measures against ASR [1,11]. Shehata and Thomas [1] were able to achieve significant reduction in expansion due to ASR when 5% silica fume was added to 30% high-calcium fly ash. The performance of the two materials when combined was significantly better than the performance of each individual material even when used at much higher replacement levels. This synergy was attributable to the high capacity of the hydration products of ternary blends to bind and retain alkalis into their hydration products [1,6]. The high portlandite consumption was also believed to have a positive effect [1].

This paper presents the results of an investigation that targeted the use of ternary blends of high-calcium fly ash and slag to counteract ASR. The main objective of the research is to find out whether or not a synergy exists between slag and high-calcium fly ash in terms of mitigating ASR.

## 2. Materials and experimental details

The cementing materials used in this study are three General Use portland cements (PC-1, PC-2, and PC-3), high-calcium fly ash (FA), and slag. The chemical compositions of the cementing materials are listed in Table 1. The three portland cements are of high alkali contents and from the same source; however, they represent three different deliveries used at different stages of the experimental program.

The reactive aggregates used in this study were highly expansive alkali-reactive siliceous limestone coarse aggregates from the Spratt quarry in Ottawa, Ontario. Non-reactive natural sand was used as the fine aggregate in the concrete samples.

The experimental work was designed to study the resistance of high-calcium fly ash/slag ternary blends against ASR. In addition to ternary blends, binary blends were examined for comparative purposes. The effectiveness of the ternary and binary blends of high calcium fly ash and slag were evaluated using the concrete prism test (CPT) and the accelerated mortar bar test (AMBT). To understand the mechanisms that determine the efficacy of different blends in mitigating ASR, the portlandite,  $\text{Ca}(\text{OH})_2$ , consumption and alkali-binding capacity of pastes containing different blends were evaluated using thermal gravimetric analysis and an alkali leaching test, respectively. The experimental procedures are

presented in the following paragraphs. Table 2 lists the cementing blends investigated in each of the tests.

### 2.1. Concrete prisms and accelerated mortar bars

Concrete prisms were prepared using reactive (Spratt) aggregates and non-reactive natural sand according to the Canadian standard, CSA A23.2–14A/28A. For all concrete samples, the alkali content was boosted to 1.25%  $\text{Na}_2\text{O}_e$  by mass of portland cement in the cementing blend. Accelerated mortar bar test was carried out as per CSA A23.2–25A. Mortars bars were prepared using the Spratt aggregates where the aggregates were crushed and screened to meet the required gradation.

### 2.2. Thermal gravimetric analysis

Paste samples were prepared using a high-speed, high-shear food blender at a water-to-cementing materials ratio (W/CM) of 0.5. The prepared paste blends were poured into plastic molds of 50 mm diameter and 100 mm height and cured above water and 35 °C for the first 24 h. Then, the samples were de-molded and soaked in saturated lime solution at 23 °C for another 27 days. After that, the samples were taken out of limewater and broken into pieces and soaked into alcohol for 1 week. Then, the samples were stored in an oven at 80 °C until they reached constant mass. On the day of analysis, the fragments were crushed to pass 1.18 mm sieve, and further crushed to pass 80  $\mu\text{m}$ -sieve immediately prior to testing. The analysis was carried out using AutoTGA 2950HR V6.1A thermal analyser .

### 2.3. Alkali leaching test

The ability of a cementing blend to bind alkalis from pore solution and retain them in its hydration product was analysed using the alkali leaching method described by Shehata and Thomas [6] with minor modifications – mainly in terms of leaching period and the particle size of the leached paste samples. Basically, paste samples were prepared at a w/cm of 0.5 and cured over water at 23 °C for 28 days. After 28 days, the paste samples were demoulded, broken into fragments of 5.0–20.0 mm and placed in an oven at 100 °C for 1 week. Then, the fragments from each sample were broken and screened to sizes between 2.36 mm and 1.18 mm. The screened sample (1.18–2.36 mm) were then soaked into solutions of pre-determined alkalinity of 0.0 mol/L and 0.25 mol/L of  $(\text{Na}^+ + \text{K}^+)$ . Distilled water was used as the 0.0 mol/L solution whereas KOH and NaOH were combined to prepare the 0.25 mol/L alkali solution. The ratio of potassium to sodium cations in the 0.25 mol/L solution was similar to that in the portland cement used in the samples. Small plastic vials of 20 mL capacity were used to store the paste samples and alkali solution. The mass ratio between paste (solids) and the solution were kept at 1–10. The samples and vials were sealed to avoid evaporation and carbonation. In addition, samples from the 0.25 mol/L solution were collected in 20-mL vials and stored under the same conditions as the vials containing the paste and solution.

At the end of the one-month leaching period, the mass of each vial was determined and compared to its mass before the leaching period. This was carried out to make sure that evaporation had not occurred. Then, the alkali concentrations in the solutions were determined using an ATS 200S model flame photometer. The measured alkali concentration of the 0.25 mol/L solution with no paste sample was taken as the datum or initial alkali concentration of the host solution. The initial alkali concentration of the 0.0 mol/L solution (distilled water) was taken as zero. For each paste sample, the difference between the alkali concentration of the leaching solution and the datum – or initial – alkali concentration of the same

**Table 1**  
Chemical composition of the cementing materials (Mass%).

	PC-1	PC-2	PC-3	FA	Slag
$\text{SiO}_2$	19.58	19.40	19.92	33.26	34.4
$\text{Al}_2\text{O}_3$	5.35	5.16	5.57	18.24	7.40
$\text{Fe}_2\text{O}_3$	2.29	2.50	2.10	6.45	0.94
CaO	62.84	61.50	63.02	28.73	43.2
MgO	2.43	2.15	2.55	5.32	9.30
$\text{SO}_3$	4.10	4.23	3.86	2.59	0.83
$\text{K}_2\text{O}$	1.13	1.17	1.05	0.33	0.58
$\text{Na}_2\text{O}$	0.21	0.25	0.20	1.94	0.57
$\text{TiO}_2$	0.31	–	0.31	1.45	0.44
$\text{P}_2\text{O}_5$	0.11	–	0.12	0.88	175 ppm
$\text{Na}_2\text{O}_e$	0.95	1.02	0.89	2.16	0.95
S.G.	–	–	–	n.a.	2.94

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