



# The role of alkali content of Portland cement on the expansion of concrete prisms containing reactive aggregates and supplementary cementing materials

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## ABSTRACT

This paper presents results covering the effects of alkali content of Portland cement (PC) on expansion of concrete containing reactive aggregates and supplementary cementing materials (SCM). The results showed that the alkali content of PC has a significant effect on expansion of concrete prisms with no SCM. When SCM is used, the expansion was found to be related to both the chemical composition of the SCM and, to a lesser extent, the alkali content of the PC. The concrete expansions were explained, at least partly, on the basis of the alkalinity of a pore solution extracted from hardened cement paste samples containing the same cementing blends. An empirical relation was developed correlating the chemical composition (Ca, Si and total  $\text{Na}_2\text{O}_e$ ) of the cementing blend (PC + SCM) and the alkalinity of the pore solution. Results from accelerated mortar bar test (ASTM C 1260) and a modified version thereof are also presented.

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## 1. Introduction

The level of expansion and disruption in concrete containing reactive aggregate depends on the alkali content of the concrete and the reactivity of the aggregate. It has been reported that the expansion increases as the alkali content of the concrete increases [1–4]. The levels of alkali that trigger the expansion depend, however, on the reactivity of the aggregates. Alkali from Portland cement (PC) is one of the major sources of alkalis in concrete. The use of supplementary cementing materials (SCM) such as fly ash and slag has been found to be an effective preventive measure against alkali silica reaction (ASR) in concrete [4–6]. Reducing the level of pore solution alkalinity is one of the mechanisms by which SCM mitigate the expansion [6].

Fly ash is a type of SCM which performance in mitigating ASR is dependent on its composition [4]. The Canadian Standard CSA A3001-03 [7] classifies fly ash based on its calcium content as follows:

| Type                      | CaO (wt.%)                | Loss on ignition, LOI (wt.%) |
|---------------------------|---------------------------|------------------------------|
| Low calcium (F)           | $\leq 8 \pm 1$            | $\leq 8$                     |
| Intermediate calcium (CI) | $> 8$ and $\leq 20 \pm 2$ | $\leq 6$                     |
| High calcium (CH)         | $> 20$                    | $\leq 6$                     |

When used with low-alkali Portland cement, low-calcium fly ashes of alkali content in the range of 3.0 to 3.9 wt.% have been reported to increase the expansion in concrete containing opaline silica [8] and

cristobalite [9]. Thomas et al. [10] reported similar findings for samples containing siltstone and siliceous limestone, and 25 wt.% fly ashes. On the contrary 25 wt.% of the same three fly ashes (of CaO content ranged from 1.49 wt.% to 3.74 wt.% and  $\text{Na}_2\text{O}_e$  from 2.98 to 3.86 wt.%) were able to reduce the expansion of concrete containing flint sand at all the tested alkali contents which ranged from 4.0 to 6.3 kg  $\text{Na}_2\text{O}_e$  per  $\text{m}^3$  of concrete [10].

Nixon et al. [11] studied the chemistry of the pore solution of pastes containing five PC of  $\text{Na}_2\text{O}_e$  in the range from 0.22 wt.% to 1.06 wt.% and a fly ash of  $\text{CaO} = 1.85$  wt.% and  $\text{Na}_2\text{O}_e = 3.4$  wt.%. For the tested levels of ash replacement (10 to 40 wt.%), they found fly ash to increase the pore solution alkalinity at 28 days compared to that of a control paste sample with a theoretical dilution of the cement content equal to the ash replacement level. At later ages, 365 days, fly ash introduced to all tested PC except the one with 0.22 wt.%  $\text{Na}_2\text{O}_e$  reduced the pore solution alkalinity beyond that of mere dilution. For the PC with  $\text{Na}_2\text{O}_e$  of 0.22 wt.%, the tested fly ash increased the pore solution alkalinity. The work of Nixon et al. [11] explained, at least partly, the expansion trends reported by other researchers [8–11] where higher expansion was obtained for some reactive aggregates when fly ash is added to low-alkali PC. This can be attributable to the increased pore solution alkalinity when the tested fly ashes were used with low-alkali PC.

This paper presents results from a study that investigated the effects of fly ash of a wide range of chemical composition on the expansion of concretes containing two reactive aggregates from North America, and PCs of different alkali contents. The effects of fly ash composition on the alkalinity of the pore solution of pastes containing PC of different alkali contents are also reported. In addition, a modified version of the accelerated mortar bar test (AMBT) is presented. This

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modified version is intended to determine the safe level of  $\text{Na}_2\text{O}_e$  of PC that can be used with a particular reactive aggregate without causing deleterious expansion. The method also evaluates the efficacy of SCM in mitigating the expansion due to ASR when used with PCs of a wide range of alkali contents.

## 2. Materials and experimental methods

### 2.1. Materials

The materials used in this study were three Portland cements (PCs) with different alkali contents (0.36, 0.54 and 0.94 wt.%  $\text{Na}_2\text{O}_e$ ), 9 fly ashes of different chemical compositions and one slag. The chemical compositions of the PCs and SCMs are listed in Table 1. The three reactive aggregates used in the study were: (1) Spratt coarse aggregates (siliceous limestone) from Ottawa, Ontario, (2) Sudbury coarse aggregate (greywacke-argillite) from Sudbury, Ontario, and (3) Jobe sand (chert) from Texas. The 1-year concrete expansion of the Jobe, Spratt and Sudbury aggregates are 0.56%  $\angle/\angle$ , 0.24%  $\angle/\angle$  and 0.17%  $\angle/\angle$ , respectively. These values represent a range of reactivity of the three investigated aggregates with Jobe as the aggregate with the highest reactivity followed by Spratt and Sudbury.

The mixture proportions for concrete and mortar samples were according to the applicable test methods. The paste samples for the pore solution study were prepared at a water-of-cementing materials (w/cm) ratio of 0.5.

### 2.2. Experimental methods

The concrete prism test (CPT) according to ASTM C 1293 [12] was used to investigate the expansion of different mixtures with and without SCM. In addition to samples tested following the standard test method with the alkali content of the PC raised to 1.25 wt.%  $\text{Na}_2\text{O}_e$ , additional samples were tested at different PCs alkali contents. For control samples (without SCM), PC alkali levels ranging from 0.4 wt.% to 1.25 wt.%  $\text{Na}_2\text{O}_e$  were tested. For samples with SCM, Spratt aggregate was tested at PC alkali levels of 1.25 wt.%, 0.94 wt.% and 0.80 wt.%  $\text{Na}_2\text{O}_e$  while Jobe sand was tested at PC alkali levels of 0.94 wt.%, 0.80 wt.% and 0.60 wt.%  $\text{Na}_2\text{O}_e$ . No SCM was used with Sudbury aggregate. These alkali levels were selected to capture, for each aggregate type, the range of alkalis within which a change in the alkali content of the PC is likely to have a significant effect on the produced expansion.

For standard concrete prism test, the PC with  $\text{Na}_2\text{O}_e = 0.94$  wt.% was used and the alkali content was boosted to 1.25 wt.%  $\text{Na}_2\text{O}_e$  by

adding NaOH to the mixing water. For concrete prisms prepared with alkali contents below 0.94 wt.%  $\text{Na}_2\text{O}_e$ , the two PCs with  $\text{Na}_2\text{O}_e$  of 0.94 wt.% and 0.54 wt.% were blended with the right proportion to achieve the required alkali levels.

The different fly ashes were used at a replacement level of 25 wt.% with a Spratt aggregate. For Jobe sand, low and intermediate-calcium fly ashes (F and CI) were used at 20 wt.% while high-calcium fly ashes (CH) were used at 30 wt.%. Slag 100 was used with Jobe sand at 35 wt.%.

The same cementing blends tested using the standard CPT with PC alkali content raised to 1.25 wt.%  $\text{Na}_2\text{O}_e$  were also tested using the standard accelerated mortar bar test (AMBT) according to ASTM C 1260 [13] for samples with no SCM and ASTM C 1567 [14] for samples with SCM.

A modified version of ASTM C 1260 and ASTM C1567 was used to test mixtures containing low-alkali PC. This modified method takes into consideration the effect of the alkali content of PC when evaluating the expansion of aggregates and the efficacy of a cementing system in mitigating the expansion. In this modified version, the alkalinity of a soaking solution was adjusted to reflect the alkali content of the PC used in the mix, following the relation:

$$\text{OH}^- \text{ concentration of the soaking solution (mol/L)} = 0.70 \times \text{Na}_2\text{O}_e \text{ of PC (wt.\%)} \quad (1)$$

The above relation is based on a review of pore solution data from ref. [11], which showed the hydroxyl ion concentration in the pore solution of cement paste with no SCM to be equal to  $0.7 \times \text{wt.\% Na}_2\text{O}_e$  of the PC. The results from the CPT were used as a benchmark to evaluate the efficacy of the modified ASTM C 1260 in predicting the reactivity of the aggregates when used with low-alkali PC.

Paste samples were prepared at a w/cm ratio of 0.50. The samples were cured at room temperature until the age of testing (i.e. 90 days). Four different alkali levels of PC were used, namely 0.36 wt.%, 0.6 wt.%, 0.8 wt.% and 0.94 wt.%  $\text{Na}_2\text{O}_e$ . These levels of alkali content were chosen to represent low, moderate and high-alkali PC in order to investigate the role of PC alkali content on the pore solution alkalinity at the presence of fly ash. The 0.60 and 0.80 wt.%  $\text{Na}_2\text{O}_e$  were achieved by mixing the two PCs of  $\text{Na}_2\text{O}_e$  of 0.94 wt.% and 0.54 wt.%. In addition to control samples with no SCM, selected fly ashes were tested at a replacement level of 25 wt.% with PCs at the four levels of alkali contents.

The paste samples were mixed using a high-speed, high-shear food blender with 3.8-L stainless steel mixing bowl. After casting, the samples were sealed in  $50 \times 100$  mm polyethylene cylinders and rotated at a speed of 12 rpm for the first 24 h after casting to minimize segregation. The sealed samples were then stored over water at

**Table 1**  
Major oxide composition of the Portland cements and SCMs determined by XRF (wt.%).

| Sample ID Type          | HAPC | LAPC 1 | LAPC 2 | FA # 1<br>F-LA <sup>a</sup> | FA # 8<br>F-LA | FA # 56<br>CI-LA <sup>b</sup> | FA # 106<br>CI-HA <sup>c</sup> | FA # 76<br>CH-LA <sup>d</sup> | FA # 60<br>CH-LA | FA # 82<br>CH-HA <sup>e</sup> | FA # 18<br>CH-LA | FA # 71<br>CH-LA | Slag<br>100 |
|-------------------------|------|--------|--------|-----------------------------|----------------|-------------------------------|--------------------------------|-------------------------------|------------------|-------------------------------|------------------|------------------|-------------|
| $\text{SiO}_2$          | 20.3 | 20.4   | 20.3   | 53.6                        | 57.1           | 49.3                          | 34.1                           | 40.2                          | 35.9             | 32.9                          | 37.5             | 31.4             | 39.5        |
| $\text{Al}_2\text{O}_3$ | 5.06 | 4.73   | 4.59   | 29.0                        | 18.7           | 24.6                          | 20.5                           | 23.3                          | 21.2             | 19.1                          | 19.4             | 18.5             | 9.57        |
| $\text{TiO}_2$          | 0.27 | 0.25   | 0.30   | 1.33                        | 0.85           | 1.64                          | 1.17                           | 1.47                          | 1.68             | 1.39                          | 1.41             | 1.60             | 0.52        |
| $\text{P}_2\text{O}_5$  | 0.13 | 0.09   | 0.09   | 0.14                        | 0.40           | 0.17                          | 0.61                           | 0.95                          | 1.36             | 0.95                          | 1.28             | 1.20             | 0.00        |
| $\text{Fe}_2\text{O}_3$ | 2.55 | 2.89   | 3.15   | 7.62                        | 5.31           | 3.74                          | 5.07                           | 6.01                          | 5.85             | 6.24                          | 5.94             | 5.22             | 0.39        |
| CaO                     | 61.3 | 63.0   | 63.2   | 1.14                        | 8.39           | 15.1                          | 16.4                           | 18.2                          | 24.5             | 23.2                          | 23.9             | 29.8             | 34.3        |
| MgO                     | 2.57 | 3.26   | 2.67   | 0.90                        | 3.01           | 2.56                          | 3.93                           | 4.11                          | 4.46             | 5.14                          | 4.90             | 5.22             | 12.6        |
| $\text{Na}_2\text{O}$   | 0.26 | 0.08   | 0.09   | 0.44                        | 3.02           | 0.34                          | 9.18                           | 1.41                          | 1.70             | 5.52                          | 1.84             | 2.10             | 0.46        |
| $\text{K}_2\text{O}$    | 1.04 | 0.43   | 0.69   | 3.01                        | 1.19           | 0.70                          | 0.72                           | 1.13                          | 0.48             | 0.58                          | 0.56             | 0.31             | 0.56        |
| $\text{SO}_3$           | 3.23 | 2.87   | 2.99   | 0.53                        | 0.52           | 0.72                          | 4.83                           | 1.03                          | 1.29             | 3.02                          | 1.76             | 2.62             | 2.65        |
| $\text{Na}_2\text{O}_e$ | 0.94 | 0.36   | 0.54   | 2.42                        | 3.81           | 0.80                          | 9.66                           | 2.16                          | 2.01             | 5.91                          | 2.21             | 2.30             | 0.83        |

<sup>a</sup> F-LA: Type F fly ash with low-alkali content ( $<4.0$  wt.%  $\text{Na}_2\text{O}_e$ ).

<sup>b</sup> CI-LA: Type CI fly ash with low-alkali content ( $<4.0$  wt.%  $\text{Na}_2\text{O}_e$ ).

<sup>c</sup> CI-HA: Type CI fly ash with high-alkali content ( $>4.0$  wt.%  $\text{Na}_2\text{O}_e$ ).

<sup>d</sup> CH-LA: Type CH fly ash with low-alkali content ( $<4.0$  wt.%  $\text{Na}_2\text{O}_e$ ).

<sup>e</sup> CH-HA: Type F fly ash with high-alkali content ( $>4.0$  wt.%  $\text{Na}_2\text{O}_e$ ).

laboratory temperature ( $23 \pm 2$  °C) until testing. Upon testing, samples were demoulded, broken into fragments (5–20 mm) and squeezed to extract the pore solution following the method described by Barneyback and Diamond [15]. The fragments were exposed to an increasing pressure at a rate of about 2.0 MPa/s until a pressure of 160 MPa was reached. The pressure was then allowed to decrease gradually while the pore solution was collected under vacuum. When the pressure reached zero, the samples were loaded again until a pressure of 320 MPa was reached where the extraction procedure was repeated. The operation of loading and retracting was repeated for a third time with the pressure reaching 480 MPa.

Hydroxyl ion concentrations of the extracted solutions were determined within 20 min of extraction by potentiometric titration with 0.05 N  $\text{H}_2\text{SO}_4$  solution, while sodium and potassium ion concentrations were determined by flame photometry.

### 3. Results

The effects of PC alkali content on the 1-year expansions of the concrete prisms containing the three reactive aggregates are shown in Fig. 1. As the graph shows, the PC alkali content has a significant effect on the expansion, the higher the alkali content the higher the expansion. The level of PC alkali content required to maintain the expansion below the 0.04% expansion limit at 1 year was 0.70 wt.%  $\text{Na}_2\text{O}_e$  for Spratt and Jobe, and 0.80 wt.% for Sudbury aggregate. Beyond these “safe” alkali levels, however, the expansion values and rates differ from one aggregate to another.

The effect of PC alkali content on prisms containing SCM was not as noticeable as that with prisms without SCM. This can be seen in Fig. 2 which illustrates the expansion of concrete samples with Spratt and 25 wt.% fly ash. It is clear from the graph that the role of PC's alkali content is secondary compared to that of the fly ash composition. In other words, the difference in expansions between samples containing the same ash but a PC of different alkali content is not as significant as that between samples containing different fly ashes but a PC of the same alkali level. In fact, the only fly ash that showed noticeable difference in expansion when used with PC of different alkali content was FA # 18. This fly ash lies at the lower end of CaO content of high-calcium fly ash category (CH), and was not effective in suppressing the expansion when used at 1.25 wt.%  $\text{Na}_2\text{O}_e$ . When used at the alkali content of 0.94 wt.% and 0.8 wt.%, it did marginally meet the 2-year expansion limit. However, there was still no difference between the expansion of concrete prepared with PC of 0.8 wt.% and 0.94 wt.%  $\text{Na}_2\text{O}_e$ .

While high-alkali or high-calcium fly ashes were not able to reduce the 2-year expansion to less than 0.04%, it is noticeable that the use

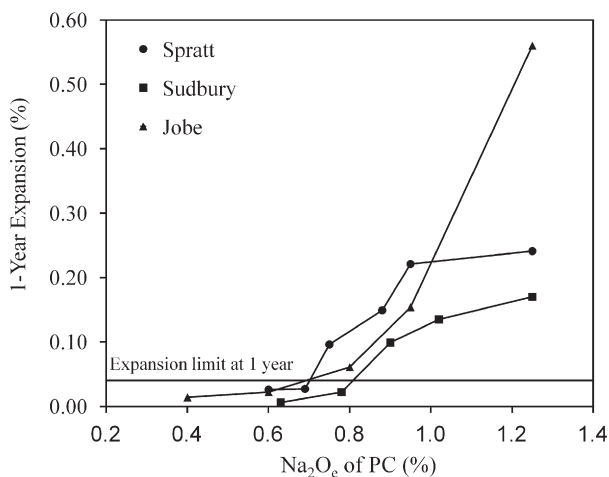


Fig. 1. Effects of PC alkali content on concrete expansion.

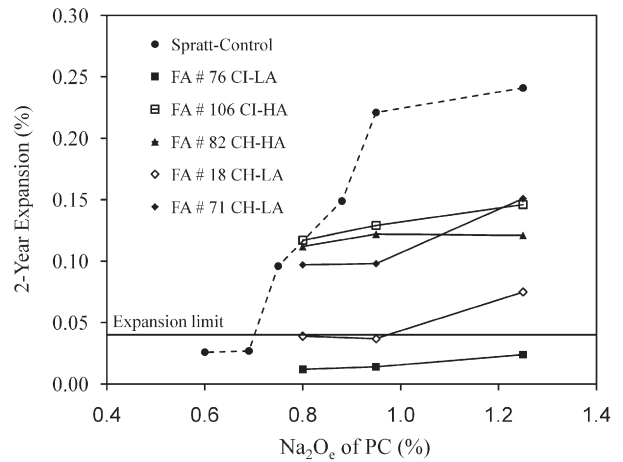


Fig. 2. Expansion of concrete containing Spratt aggregate and 25 wt.% fly ash.

of any of the fly ashes with Spratt aggregates at any of the tested alkali levels (0.80 wt.% to 1.25 wt.%  $\text{Na}_2\text{O}_e$ ) reduced the expansion compared to that of the control samples at the same  $\text{Na}_2\text{O}_e$ . This was not the case with Jobe sand as can be seen in Fig. 3. At PC's alkali levels  $\leq 0.94$  wt.%  $\text{Na}_2\text{O}_e$ , the high-calcium FA # 71 produced higher expansion than that of the control. Also, the high-alkali FA # 82 produces expansion values higher than those of the control samples at all alkali levels. On the other hand, low and moderate-calcium fly ashes of  $\text{Na}_2\text{O}_e$  content  $< 4.0$  wt.% were effective in suppressing the expansion regardless of the alkali content of the PC. The differences between the expansion trends of the two aggregates, Spratt and Jobe, when used with different fly ashes and PCs can be explained based on the reactivity of the two aggregates and the alkalinity of the pore solution. This is presented in the Discussion section of this paper. In terms of the efficacy of the slag, it was found that 35 wt.% was sufficient to suppress the expansion of concrete containing Jobe sand at the three tested alkali levels as shown in Fig. 3.

The pore solution alkalinity of pastes containing different blends of cementing materials is shown in Fig. 4. The alkalinity is represented by the hydroxyl ion concentration ( $\text{OH}^-$ ) which, as expected, equaled the sum of  $\text{Na}^+ + \text{K}^+$  ions for all the tested samples. The  $\text{OH}^-$  of the sample containing FA # 71 was higher than that of the control sample (with no SCM) at all alkali levels. The same was observed for FA # 82 although its pore solution alkalinity was much higher than that of the sample with FA # 71.

On the contrary, low and moderate-calcium fly ashes of  $\text{Na}_2\text{O}_e < 4.0$  wt.% reduce the alkalinity of the pore solution compared to that of samples with no FA. It is also clear from Fig. 4 that the effect

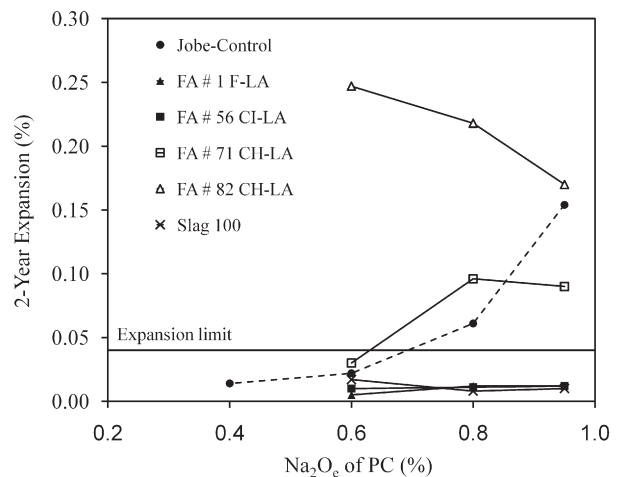


Fig. 3. Expansion of concrete containing Jobe sand and SCM.

of PC alkali content on pore solution alkalinity is secondary compared to that of the fly ash composition.

The empirical relation shown in Fig. 5 illustrates the relation between the main oxide composition of the cementing blend (PC + FA) and the alkalinity of the pore solution extracted from paste samples at the age of 90 days. The oxide composition of a blend is calculated as the sum of the products of the oxide content of each cementing component (PC or FA) multiplied by the proportion of this particular component in the total cementing materials. For example, the CaO content of the paste containing a cementing blend of 25 wt.% FA # 1 and 75 wt.% HAPC =  $0.25 \times 1.14$  wt.% (CaO content of the FA) +  $0.75 \times 61.25$  wt.% (CaO of the PC) = 46.04 wt.%. It is clear from the graph that the pore solution alkalinity increases as the total  $\text{Na}_2\text{O}_e$  and CaO contents of the cementing blend increase and its  $\text{SiO}_2$  decreases.

Figs. 6 through 8 illustrate the efficacy of the modified accelerated mortar bar test (modified AMBT) in evaluating the expansion of reactive aggregates when used with PC of different alkali contents. Using expansion limits of 0.10%  $\angle/\angle$  at 14 days for the modified mortar bar test (represented by the dotted horizontal line in the graphs) and 0.04%  $\angle/\angle$  at 1 year for the concrete prism test (represented by the solid horizontal line), the following “safe” levels of PC’s alkali contents can be determined from the data in Figs. 6, 7 and 8:

| Aggregate | Modified mortar bar test | Concrete prism test |
|-----------|--------------------------|---------------------|
| Spratt    | 0.65 wt.%                | 0.70 wt.%           |
| Sudbury   | 0.75 wt.%                | 0.80 wt.%           |
| Jobe      | 0.35 wt.%                | 0.70 wt.%           |

These results suggest that ASTM C 1260 [13] may be used to determine the effect of PC’s alkalis by appropriate modification of the host solution composition for Sudbury and Spratt aggregate. However, for aggregates like Jobe sand, the safe alkali level determined by the modified C 1260 is much lower than that determined by the concrete prism test.

The efficacy of the modified AMBT in predicting the 2-year expansion of concrete prisms containing SCM was investigated for Spratt and Jobe aggregates. Different blends of cementing materials with PC of different alkali contents were tested and the results are shown in Fig. 9. The results from the standard tests (CPT and AMBT) of mixtures containing Spratt aggregate and SCM are also shown on the graph represented by the series labeled “Spratt at 1.25 wt.%  $\text{Na}_2\text{O}_e$ ”. No standard CPT (at 1.25 wt.%  $\text{Na}_2\text{O}_e$ ) was available for Jobe sand with SCM. The horizontal line on the graph represent the 2-year expansion limit of the CPT (0.04%  $\angle/\angle$ ) while the vertical line represents the 14-day expansion limit of the AMBT (0.10%  $\angle/\angle$ ). Out of the 30 test points conducted at alkali contents lower than that of the standard tests, 7 test results (3 for Jobe and 4 for Spratt) failed the modified AMBT but passed the CPT. None of the tested samples

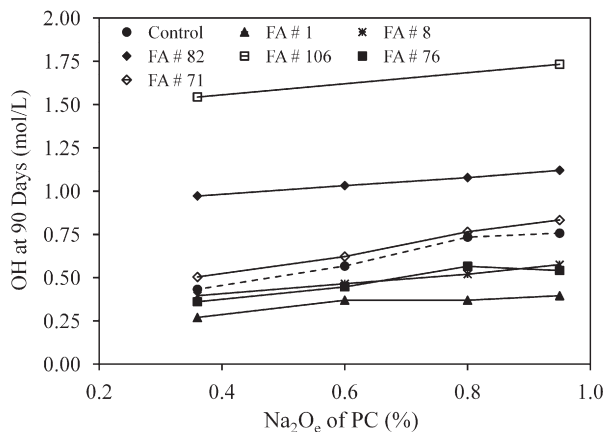


Fig. 4. Pore solution alkalinity of mature paste samples.

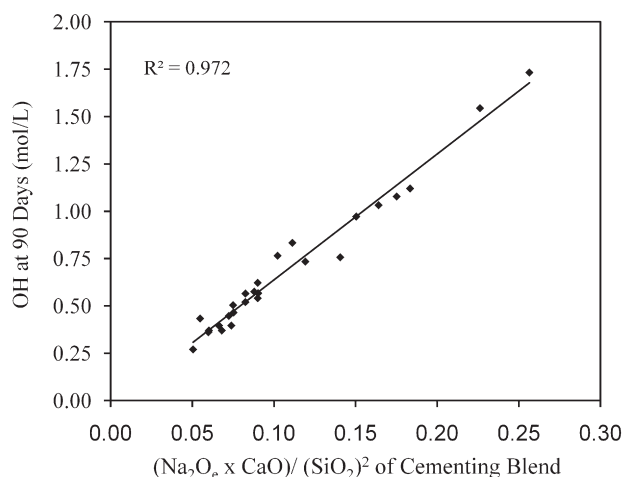


Fig. 5. Relation between main oxide compositions of cementing blends and the pore solution alkalinity of mature paste samples.

passed the modified AMBT and failed the CPT. The remaining 20 test points showed agreement between the two tests (either passed–passed or failed–failed). The three test points that lie on the 0.04%  $\angle/\angle$  expansion limit of the CPT (2 for Jobe and 1 for Spratt at 1.25 wt.%  $\text{Na}_2\text{O}_e$ ) failed the Modified AMBT (or the standard AMBT in case of the Spratt sample) and had CPT expansion values of 0.039, 0.041 and 0.041%  $\angle/\angle$ . The three test points can be considered as agreement between the two tests since the CPT expansions are either above or marginally meet the 0.04%  $\angle/\angle$  expansion limit.

#### 4. Discussion

The results shown in Figs. 1, 2 and 3 demonstrate that different reactive aggregates respond differently to the alkali level of PC and the use of SCM. As Fig. 2 shows, the use of any type of SCM with PC of any alkali content, within those investigated here, reduces the expansion of concrete prisms containing Spratt aggregate compared to that of the control samples at the same PC alkali level. It should be noted, however, that high-calcium and high-alkali fly ashes were not able to reduce the expansions to below 0.04%  $\angle/\angle$ , as shown in Fig. 2. On the other hand, only Types F and CI fly ashes of  $\text{Na}_2\text{O}_e < 4.0$  wt.% and slag 100 were able to reduce the expansion of concrete sample containing Jobe sand as shown in Fig. 3. This can be explained based on the pore solution alkalinity and the response of each aggregate to alkalis as illustrated in Fig. 1. The expansion value of the Jobe at high-alkali

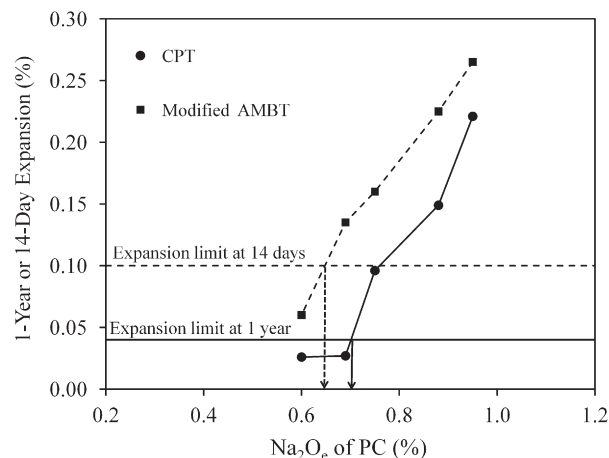


Fig. 6. Results of modified AMBT and CPT for control samples containing Spratt.



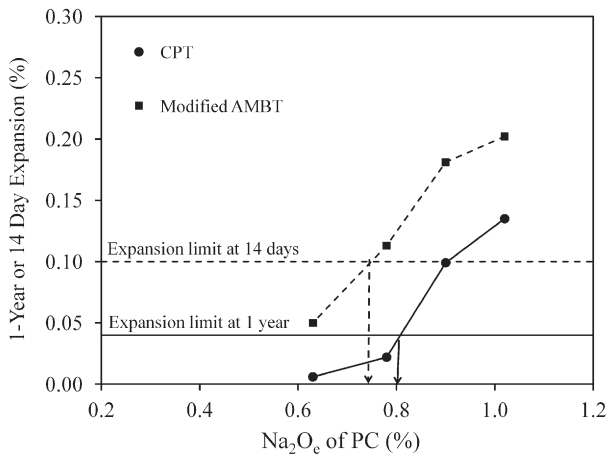


Fig. 7. Results of modified AMBT and CPT for control samples with Sudbury.

content is way higher than that of the Spratt. In addition, the expansion of concrete with Spratt increases with the increase in alkali content until a certain alkali level beyond which the increase in alkali content does not cause significant expansion. At such high level of alkali content, factors other than pore solution alkalinity, such as reduced ion diffusivity or reduction in  $\text{Ca}(\text{OH})_2$ , help reduce the expansion [4]. This seems to be the case with the high-calcium or high-alkali fly ashes investigated with Spratt aggregate in this paper. Although, these ashes increase pore solution alkalinity beyond that of the control samples as shown in Fig. 4, the Spratt aggregate was not adversely affected by the increased level of alkalinity, but was positively affected by the reduced  $\text{Ca}(\text{OH})_2$  or ion diffusivity associated with using SCM. On the contrary, the expansion of the highly reactive Jobe sand continues to increase at a higher rate with the increase in alkali content as shown in Fig. 1. For this type of aggregate, and unlike Spratt, pore solution alkalinity continues to have the major role on expansion at high-alkali levels. This was the reason for the high-calcium/high-alkali fly ash (FA # 82) and, to lesser extent, the high-calcium fly ash (FA # 71) to increase the expansion in concrete with Jobe as shown in Fig. 3. It should be noted that the high-alkali fly ash (FA # 82) produced a significant increase in pore solution alkalinity compared to that produced by FA # 71, as shown in Fig. 4.

The expansions of concrete prisms containing Jobe sand and FA # 82 decreases with the increase in alkali content of the PC (Fig. 3). However, the expansions at the three tested PC's alkali contents were significantly higher than the 0.04% expansion limit. The reason behind this trend is not clearly understood. The alkalities of the pore

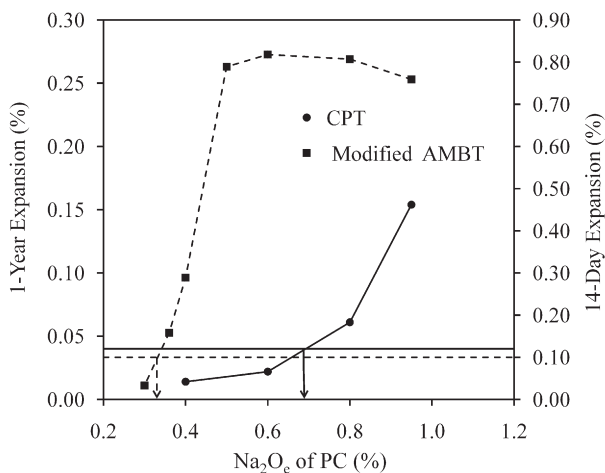


Fig. 8. Results of modified AMBT and CPT for control samples with Jobe sand.

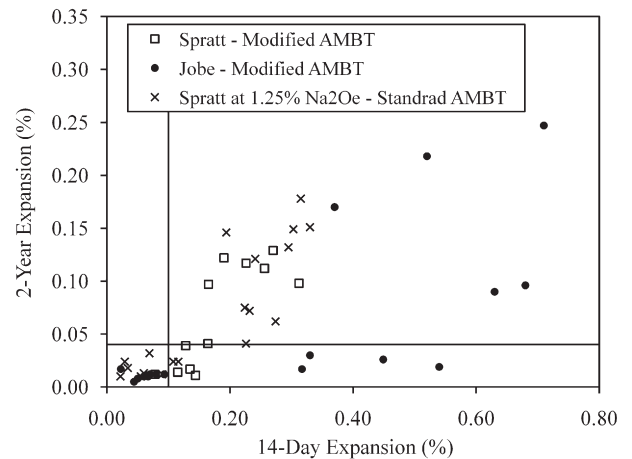


Fig. 9. Two-year expansion of concrete containing SCM versus 14-day expansion from the modified or standard AMBT.

solution of mature paste samples at the three tested alkali levels were very close. There is a possibility, however, that at low-alkali content of PC, more alkalis were contributed from the fly ash. In the case of concrete, these contributed alkalis were rapidly consumed by the highly reactive sand causing more expansion, instead of being bound by the hydration products of the cementing materials as the case may have been with paste samples. An earlier work by Shehata and Thomas [16] demonstrated that more alkalis are contributed from SCM to solutions of lower alkalinity.

In general, the role of alkali content of PC on the expansion of concrete prisms containing SCM is not as significant as that of the type of SCM used. In other words, for the reactive aggregates tested in this study, ASR can be mitigated provided that the right type and level of SCM are used, regardless of the alkali content of the PC. The role of PC alkalis on pore solution alkalinity is similar to that on concrete expansion. This was demonstrated in Fig. 4 and can also be concluded from the relation developed in Fig. 5 which shows a strong relation between pore solution alkalinity and the parameter  $(\text{Na}_2\text{O}_e \times \text{CaO})/(\text{SiO}_2)^2$  of the cementing blend. The effect of PC alkali content on this parameter is not as significant as that of the fly ash composition. This can be demonstrated by examining the values of the parameter  $(\text{Na}_2\text{O}_e \times \text{CaO})/(\text{SiO}_2)^2$  for different fly ashes used at different PC's alkali contents:

| Fly ash       | $(\text{Na}_2\text{O}_e \times \text{CaO})/(\text{SiO}_2)^2$ |                                         |
|---------------|--------------------------------------------------------------|-----------------------------------------|
|               | PC of 0.60 wt.% $\text{Na}_2\text{O}_e$                      | PC of 0.94 wt.% $\text{Na}_2\text{O}_e$ |
| FA # 1 F-LA   | 0.06                                                         | 0.07                                    |
| FA # 71 CH-LA | 0.09                                                         | 0.11                                    |
| FA # 82 CH-HA | 0.16                                                         | 0.18                                    |

It is clear that changing the alkali content of PC does not result in significant change in the value of the parameter  $(\text{Na}_2\text{O}_e \times \text{CaO})/(\text{SiO}_2)^2$ , compared to the case when a different fly ash is used. Indeed, for the three different fly ashes used in the above example, the increase in the parameter was in the range of 0.01 to 0.02 when the same fly ash was used with a PC of  $\text{Na}_2\text{O}_e = 0.94$  wt.% instead of PC of  $\text{Na}_2\text{O}_e = 0.60$  wt.%. On the contrary, using a high-calcium fly ash (FA # 71) instead of low-calcium fly ash (FA # 1) increased the parameter by 0.03 and 0.04 when the ash was used with PC of 0.60 wt.%  $\text{Na}_2\text{O}_e$  and 0.94 wt.%  $\text{Na}_2\text{O}_e$ , respectively. The effect of using the high-alkali fly ash (FA # 82) was even more significant.

The results of the modified AMBT showed the test to be a promising tool for testing cementing blends with PC of different alkali levels. For determining the safe level of alkali required to mitigate expansion in concrete with no SCM, the test was effective with Spratt and Sudbury aggregates. However, it overestimated the expansion of concrete with

Jobe sand. This is attributable to the sensitivity of this reactive aggregate to alkalis. The large amount of soaking solution provides enough alkalis to promote a reaction of this highly reactive aggregate, regardless of the alkali concentration of the solution (Fig. 8).

Also, the use of the modified AMBT to evaluate the expansion of cementing blends containing SCM and low-alkali PC showed promising results. The test can be utilized as a screening test for evaluating the efficacy of SCM in mitigating ASR expansion in concrete contacting PC of different alkali levels. Samples that pass the modified AMBT at 14 days would most likely pass the CPT at 2 years. Samples that fail the modified AMBT would require further testing, either using the CPT or testing under site exposure. This is the same criterion governing the current use of the standard AMBT. However, more research is needed to cover a wider range of aggregates. It should also be born in mind that testing large blocks in exposure sites provide more reliable expansion results [17]. Hence, results from test blocks should also be considered when evaluating the efficacy of the modified AMBT.

## 5. Conclusions

For the range of aggregate reactivity and chemical composition of the cementing materials used in this study, the following conclusions are drawn:

- The effect of the alkali content of Portland cement on the ASR expansion of concrete containing SCM is secondary compared to that of the composition of SCM.
- The expansion of concrete containing reactive aggregate and SCM can be explained, to a large extent, based on the effect of SCM on the pore solution alkalinity.
- The alkalinity of the pore solution of mature cement pastes containing SCM and PC of different alkali contents could be predicted based on the silica, calcium oxide and total alkalis of the cementing blend (PC + SCM).
- Using soaking solutions of various alkalinities, a modified version of the AMBT was introduced and showed promising results in terms of predicting the 2-year expansions of concrete prisms containing SCM and PC of different alkali levels. The test was also effective in determining the safe PC's alkali levels for concrete with no SCM, for two of the three tested aggregates.

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