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The effect of fly ash composition on the expansion of concrete due to alkali–silica reaction

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Abstract

This paper presents the results from expansion tests on concrete prisms and mortar bars containing reactive aggregate and different types and levels of fly ash. Eighteen fly ashes representing those commercially available in North America were tested. The results show that the bulk chemical composition of the fly ash provides a reasonable indication of its performance in physical expansion tests but cannot be used to accurately predict the degree of expansion or the minimum safe level of fly ash required to suppress expansion to an acceptable limit. Generally, for a given fly ash replacement level (RL), the expansion increases as the calcium or alkali content of the ash increases or its silica content decreases. A corollary to this is that the minimum level of fly ash required to limit the expansion to an acceptable level increases as the calcium or alkali content of the ash increases or its silica content decreases. Most of the variation in fly ash performance can be explained on the basis of pore solution composition; those ashes effective in reducing the alkalinity of the pore solution extracted from cement paste samples were also efficient in controlling expansion. The data from this study provide further support for the use of the accelerated mortar bar test as a means for evaluating the efficacy of pozzolans in controlling expansion due to alkali–silica reaction (ASR).

Keywords: Alkali–aggregate reaction; Concrete; Expansion; Fly ash; Pore solution

1. Introduction

It is now generally accepted that the appropriate use of fly ash can prevent expansion due to alkali–silica reaction (ASR) in concrete. This claim is supported both by extensive laboratory research [1] and by field experience [2]. However, most of the experimental data available relate to the use of fly ashes from bituminous coal sources (e.g. ASTM Class F fly ash), which are characterized by relatively low calcium contents (i.e. <10% CaO). Relatively few detailed studies have been conducted using higher calcium fly ashes from sub-bituminous or lignite coals, especially those with calcium contents in excess of 25% CaO. The available data invariably indicate that such ashes are less efficacious in controlling expansion compared with traditional Class F fly ashes [3–6]. The inferior performance may be largely ascribed to differences in the pore solution chemistry in concretes with low or high-CaO fly ash. It has been shown that high-CaO fly ash is not as effective in reducing the pore solution alkalinity of cement paste systems [3,7] and that a greater proportion of the alkalis in high-CaO fly ash may be "available" for reaction [8].

The aim of the current study was to determine the effect of ash composition on ASR expansion for a wide range of commercially available fly ashes and to establish relationships between the composition of the ash and the minimum level necessary to control deleterious reaction. Eighteen different fly ashes were collected from various sources within North America and these were combined in various proportions with high-alkali cement and reactive aggregate for testing in both concrete prism and accelerated mortar bar tests.

2. Experimental details

Two Portland cements (PC) with alkali contents, of 1.02% Na_2O_e (HAPC) and 0.60% Na_2O_e (LAPC) were used together with 18 fly ashes with a wide range of chemical composition. The chemical compositions of the

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PCs and fly ashes are presented in Table 1. Recently published changes in the Canadian specifications for supplementary cementing materials (CSA A23.5) included a new classification system for fly ash based on the calcium oxide content (CaO) of the ash. The new categories of fly ash are Type F ($\leq 8 \pm 1\%$ CaO), Type CI (>8% and $\leq 20 \pm 2\%$) and Type CH (>20% CaO). As shown in Table 1, two of the fly ashes are type F, eight are Type CI and eight are Type CH. It should be noted that fly ash MN would also meet Type F and ashes PI and C2 would meet Type CI because of the tolerances placed on the calcium oxide limits.

A reactive siliceous limestone (Spratt) was used as the coarse aggregate together with a non-deleteriously reactive natural sand in all the mixes. Concrete prisms were cast and tested in accordance with the Canadian Standards Association Concrete Prism Test, CSA A23.2 Test 14A (equivalent to ASTM C 1293) using 420 kg/m^3 of cementitious material and W/CM ranging from 0.42 to 0.45. Five control mixes (without fly ash) were cast at Na_2O_e contents of 5.25, 4.20, 3.70, 3.15 and 2.89 kg/m^3 of concrete. The first mix, at 5.25 kg/m^3 Na_2O_e, represents concrete made with 420 kg/m^3 of cement with the alkali content raised to 1.25% Na_2O_e (as per CSA) and the other four represent concrete with the same cement content but with 20%, 30%, 40% and 45% alkali dilution. The alkali contents were adjusted by mixing the low and high-alkali cement, and by adding NaOH to the mixing water, if needed.

A total of 42 mixes were cast using various replacement levels (RLs) of different fly ashes. All these mixes were cast using high-alkali cement with, in the majority of cases, the alkali content boosted with NaOH to achieve 1.25% Na_2O_e on the basis of the mass of the PC in the mixture, disregarding the alkalis present in the fly ash. Three of the mixes (with 20% FM, 30% WM, and 45% OK) were cast with an alkali content of 5.25 kg/m^3 Na_2O_e calculated on the basis of alkalis from the cement and added NaOH.

Mortar bars were prepared and tested according to the Accelerated Mortar Bar Test Method, CSA A23.2-25A (equivalent to ASTM C 1260) using the same cementing material combinations used for the concrete prism test. The reactive coarse aggregate (Spratt) was crushed and graded according to the standard test procedure. Mortar samples were cast at an aggregate/cementing materials (CM) ratio of 2.25 and W/CM equal to 0.50. Samples were cured at room temperature, in their moulds, for 24 h. Then, they were stripped, immersed in water and maintained at 80°C for another 24 h. After that, samples were taken out, their initial lengths were measured and they were soaked in 1 M NaOH solution at 80°C throughout the testing period. Length changes were measured at 3, 7, and 14 days. The 14-day expansion results are reported here.

3. Results

3.1. Concrete prism test

The 2-year expansion results for 42 concrete mixes are reported in Table 2. Thirty-three of these mixes were cast and tested at the University of Toronto, whereas the results for the other nine mixes were provided by the Corporate Technical Services (CTS) Laboratory of Lafarge Canada. For the purpose of discussion in this paper, it is assumed that expansions in excess of 0.04% are indicative of sig-

Table 1
Chemical composition of the OPC and fly ashes (mass %)

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Na_2O_e[a]	TiO_2	P_2O_5	Na_2O_e[b]	LOI
HAPC	20.83	5.11	2.01	62.98	2.43	3.25	1.12	0.28	1.02	0.24	0.05	–	0.92
LAPC	21.27	4.22	2.98	62.71	2.13	2.82	0.77	0.10	0.60	0.18	0.11	–	2.40
LG	41.96	19.64	20.07	5.57	1.19	0.95	2.44	0.69	2.30	0.84	0.15	1.10	3.71
FM	47.34	22.34	15.08	6.38	0.82	1.43	1.23	0.60	1.41	1.10	0.32	0.47	2.73
MN	61.5	20.52	4.29	8.68	1.70	0.19	0.60	0.17	0.56	1.38	0.05	0.30	0.08
SD I	50.92	23.64	4.62	13.63	0.86	0.23	0.59	3.38	3.77	0.14	0.73	1.42	0.42
BD	45.66	21.42	5.53	12.34	2.76	0.84	0.96	7.82	8.45	0.65	0.14	2.43	0.35
SD II	51.56	22.90	4.58	15.15	1.16	0.28	0.30	2.60	2.80	0.66	0.12	1.80	0.35
TB	40.68	21.19	4.50	15.87	3.54	2.18	0.49	8.14	8.46	0.96	0.65	3.60	0.53
C1	44.29	20.96	5.23	17.51	4.21	2.13	0.84	1.13	1.68	1.12	0.63	0.77	1.14
WM	39.77	21.46	5.69	18.46	3.77	1.86	0.66	3.71	4.14	1.04	0.54	2.52	1.06
BR	32.71	19.02	5.76	18.85	4.30	4.81	0.68	8.28	8.73	1.24	0.52	4.79	1.18
PI	38.42	20.57	5.64	20.50	4.39	1.76	0.62	2.64	3.05	1.00	0.52	1.84	2.01
C2	39.83	19.56	5.54	21.53	4.62	2.14	0.60	1.55	1.94	1.20	0.71	0.99	1.68
EW	38.22	18.43	5.72	24.61	4.72	1.55	0.44	1.39	1.68	1.42	1.04	0.94	0.18
PP	35.20	18.72	6.06	26.61	5.12	2.49	0.36	1.59	1.83	1.50	1.19	1.33	0.39
IN	36.12	18.64	6.07	26.62	5.41	1.80	0.40	1.34	1.60	1.48	1.12	1.02	0.16
OK I	34.60	16.45	7.13	27.71	5.89	2.71	0.21	1.51	1.65	1.30	0.71	1.23	0.28
OK II	31.65	16.65	7.28	29.10	6.57	3.17	0.20	1.72	1.85	1.33	0.74	1.19	0.36
CC	41.12	11.24	5.93	30.00	4.40	2.13	1.76	1.10	2.26	0.47	0.10	1.05	0.78

[a] Acid soluble alkali.
[b] Available alkali, expressed as Na_2O_e, as per ASTM C311.

Table 2
Expansion of concrete prisms after 2 years (%)

Fly Ash		Replacement Levels (RLs)[a]									(RLs)[b]		
Type	Source	0%	15%	20%	25%	30%	40%	45%	50%	60%	20%	30%	45%
Control		0.250		0.241		0.164	0.114	0.044					
F	LG				*0.030*								
F	FM		0.083	0.043							0.099		
F	MN[c]		*0.039*		*0.014*								
CI	SD I		0.100	0.067	0.042								
CI	BD			0.156		0.113	0.087						
CI	SD II[c]		0.062		*0.032*								
CI	TB				0.117								
CI	C1				*0.039*								
CI	WM			0.123		0.100	0.068		0.042			0.112	
CI	BR				0.157								
CH	PI				*0.026*								
CH	C2				0.080								
CH	EW					0.086	0.051		*0.033*				
CH	PP[c]		0.176		0.082								
CH	IN[c]		0.191		0.130								
CH	OK I					0.138		0.054		*0.021*			0.136
CH	OK II[c]				0.176								
CH	CC				0.162								

[a] Standard concrete prism test, alkali level = 1.25% Na_2O_e of mass of PC.
[b] Concrete prism test with augmented alkalis [5.25 kg/m^3 or 1.25% Na_2O_e of the mass of (PC + FA)].
[c] Indicates data supplied by CTS.

nificant or damaging expansion, as this is generally consistent with the onset of visible cracking.

The development of expansion with time for the control samples (i.e. those without fly ash) at various alkali contents is shown in Fig. 1. The expansion of all five concrete mixes exceeded 0.04% after 2 years although the rate of expansion and the magnitude of the ultimate expansion is clearly dependent on the alkali content of the concrete. The relationship between the 2-year expansion data and the alkali content of the control samples is shown in Fig. 2. There is a progressive increase in the prism expansion as the alkali content is raised from 2.89 to 4.20 kg/m^3 Na_2O_e but little significant further increase in expansion as the alkali content increases above 4.20 kg/m^3. Extrapolation of the data in Fig. 2 indicates that the alkali content needs to be kept below approximately 2.8 kg/m^3 Na_2O_e in order to keep the expansion below 0.04% at 2 years. It is interesting to note that little further expansion is observed when the alkali content of the mix is raised above about 4.20 kg/m^3 Na_2O_e. This would indicate that at such high levels of alkali, the reaction (or more appropriately the expansion) is limited by some other factors such as the quantity of reactive silica or perhaps the availability of calcium.

The 2-year expansion results for the various combinations of cement and fly ash (presented in Table 2) show that the effect of fly ash on the expansion varies widely. This fact

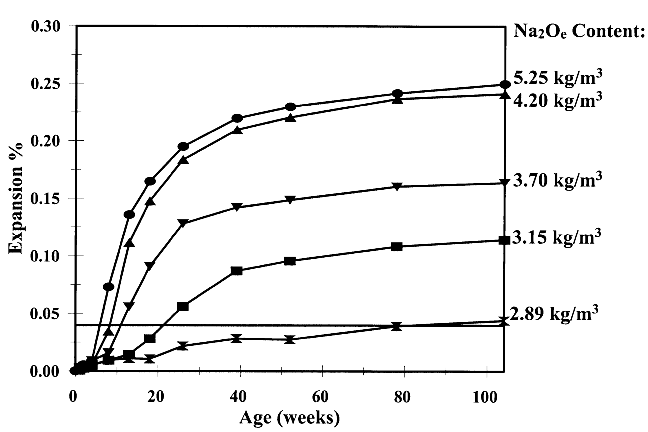

Fig. 1. Effect of alkali content of concrete on expansion due to ASR.

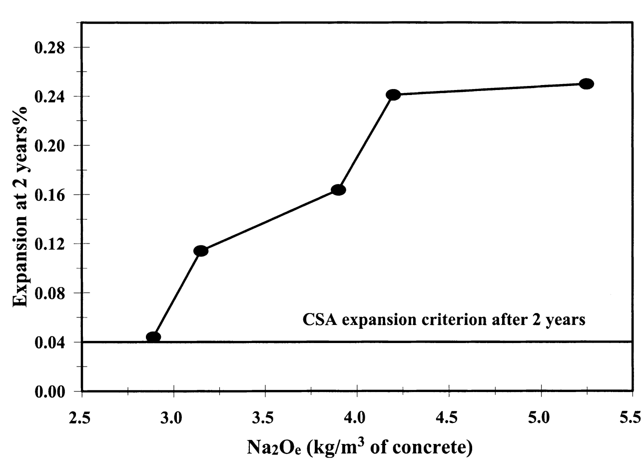

Fig. 2. Effect of alkali content of concrete on the 2-year expansion of concrete prisms.

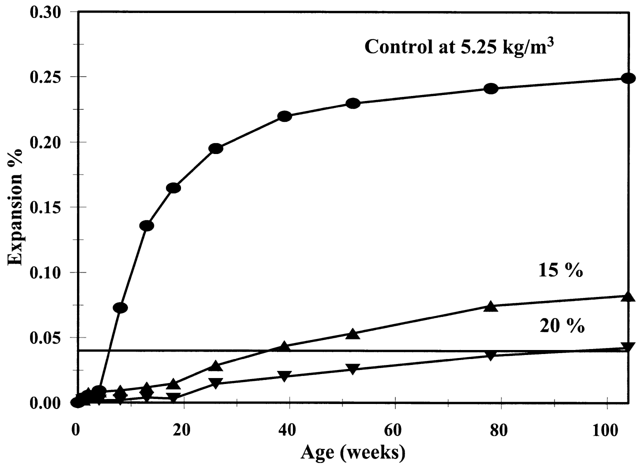

Fig. 3. Effect of low-calcium ash (FM) on expansion due to ASR.

is perhaps best illustrated by comparing the performance of the fly ashes designated FM and OK I as shown in Figs. 3 and 4, respectively. Both ashes have similar alkali contents; however, the FM is a Type F fly ash (with 6.38% CaO) and the OK is a Type CH fly ash (with 27.7% CaO). Both fly ashes meet all the chemical and physical test criteria of both the Canadian and ASTM specifications for fly ash (CSA A23.5 and ASTM C618) and have a history of satisfactory use in concrete. However, they clearly perform very differently with regards to controlling ASR. Fly ash FM is very efficient in controlling expansion with 20% fly ash reducing expansion to just 0.043%; an RL of 25% would have undoubtedly reduced expansion to less than 0.04%. This behaviour is typical of the other low-calcium fly ashes used in this study and reported elsewhere [1]. Fly ash OK on the other hand is far less effective in this role and it can be seen that an RL somewhere in the region of 45% to 60% would be required to limit expansion to less than 0.04% with this material. The other high-calcium ashes exhibited similar behaviour.

Fig. 5 shows the 2-year expansion values of concrete samples containing various fly ashes at different RLs. Also shown in the graph are the 0.04% expansion limit and the expansion values of the control samples at alkali levels corresponding to the dilution levels of the ash. The graph illustrates the variations in the efficiency of different fly ashes in controlling the expansion, i.e. the level of ash required to suppress expansion to less than 0.04% varies considerably between fly ashes. It would appear from Fig. 5 that ashes with either a high-alkali or a high-calcium content are likely to be less effective at a given level of replacement. However, all the fly ashes tested yielded expansion values lower than the control sample with an alkali content of 5.25 kg/m^3 Na_2O_e. In other words, the partial replacement of high-alkali cement for fly ash did not lead to an increase in expansion regardless of the composition of the fly ash. Indeed, in most cases, the expansion of concrete at a particular level of fly ash was less than the control concrete at the same level of dilution. This means that even the less effective fly ashes can be expected to have a beneficial impact on the expansion of the concrete beyond the role of merely diluting the cement alkalis. This phenomenon is further illustrated in Fig. 6 which shows the expansion of the control concrete and three fly ash concretes all at alkali content of 5.25 kg/m^3 Na_2O_e (calculated on the basis of the alkali from the cement plus the added NaOH only). In all cases, the expansion of the fly ash concretes is less than that of the control concrete at the same alkali content. In addition, samples containing fly ash showed less evidences of disruption (e.g. cracking and gel exudation) compared with the control sample cast at Na_2O_e content of 5.25 kg/m^3 of concrete.

Fig. 7 shows a relation between the CaO content of the ash and the measured or estimated expansion values of the concrete containing 25% ash. Where data were not available for a particular fly ash at an RL of 25%, the expansion value was determined by interpolating or extrapolating the data in Table 2. For example, fly ash WM was tested at RLs of 20%, 30%, 40%, and 50%. The value for a 25% RL was interpolated to be 0.112%. The graph includes the expansion data provided by CTS laboratory. Concrete containing fly ash of alkali content > 4.0% Na_2O_e are represented by the hollow markers while those containing fly ash of alkali content < 4.0% Na_2O_e are represented by solid markers. Also, the Type of the ash (F, CI, or CH) is marked on the graph. There appears to be some relationship between the CaO content of the fly ash and the expansion of concrete prisms for fly ash with a low to moderate alkali level (i.e. < 4.0% Na_2O_e). There is a slight increase in the expansion as the CaO content increases ranging from 5% to 20% with a sudden and remarkable increase above 20–22% CaO. In nearly all cases, fly ashes (with low to moderate alkali) that meet the CSA specification for Type F or Type CI fly ash were effective in limiting the 2-year expansion of concrete prism to $\leq$ 0.04% when used at an RL of 25%. The one exception was fly ash SD I which

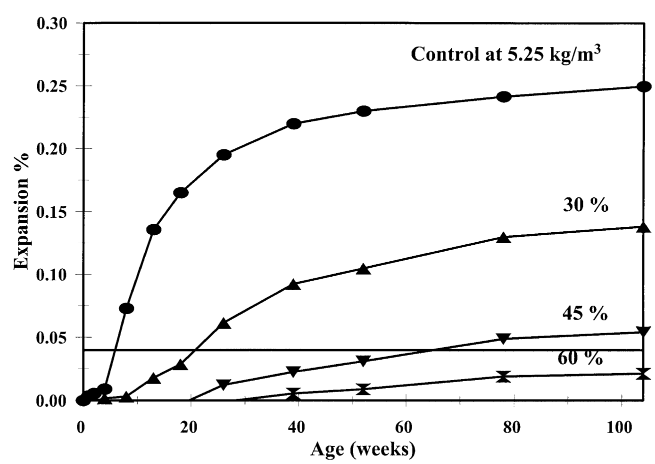

Fig. 4. Effect of high-calcium ash (OK) on expansion due to ASR.

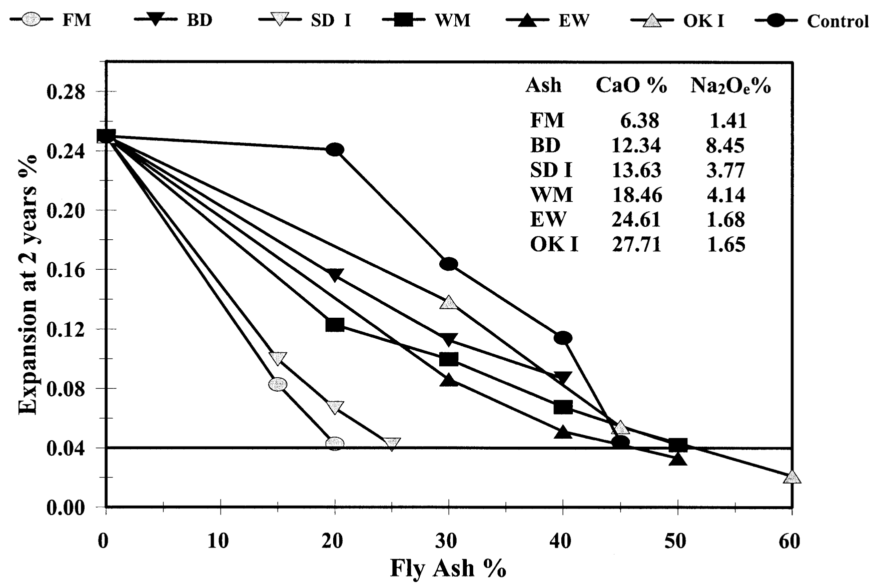

Fig. 5. Effect of ash composition and replacement level on expansion due to ASR.

produced a 2-year expansion of just 0.042% when used at a 25% RL. Fly ashes that are classified as CH ashes generally failed to control expansion to ≤ 0.04% at 25% RL although in all cases, expansion was reduced compared to the control concrete without fly ash. The one exception was fly ash PI which had a CaO content of 20.5% and a measured expansion of 0.026% when tested in concrete at a 25% RL. However, the calcium content of this fly ash is only slightly higher than the 20% limit for Type CI ash. Indeed, this ash could be classified as CI due to the tolerance of ±2% CaO placed on the upper limit for Type CI fly ash.

The expansion results for fly ashes with higher alkali contents (i.e. > 4.0% Na_2O_e) do not fit the general trend shown in Fig. 7. Indeed, in some cases, significant expansion and cracking was observed for concrete containing high-alkali Type CI ashes at RLs of 25% (see Fig. 7) and higher (see Table 2). Fly ashes WM (4.14% Na_2O_e) and BD (8.45% Na_2O_e) resulted in deleterious expansion even when used at an RL of 40%.

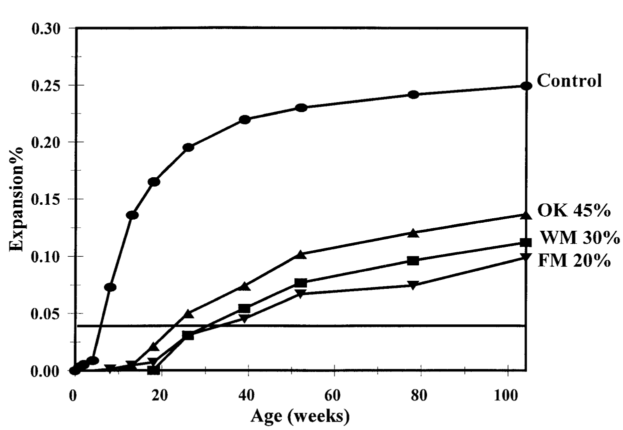

Fig. 6. Effect of ash type and replacement level on expansion of concrete prisms at 5.25 kg/m^3 Na_2O_e.

The relation in Fig. 8 is established in an attempt to correlate the fly ash composition with the expansion of the concrete prisms. The samples and the legend used in Fig. 8 are the same as those used in Fig. 7. Multiple regression analyses were performed between expansion as the dependent variable and the CaO, Na_2O_e, and SiO_2 contents of the fly ash as the independent variables. The best fit (i.e. highest value of R^2 and F ratio) was achieved when the Na_2O_e and CaO were normalized to the SiO_2 content. The graph shows a general trend of increasing expansion as the Na_2O_e and CaO contents of the fly ash increase and as its silica content decreases. The graph also indicates that fly ash with chemical composition that satisfies the condition $(10Na_2O_e + 4.45CaO)/SiO_2 \leq 2$ will likely meet the 0.04% expansion criterion of the concrete prism test after 2 years when used at an RL of 25%.

3.2. Accelerated mortar bar test

The results of the accelerated mortar bar tests showed the same general trends as the concrete prism test data, with higher alkali and higher calcium fly ashes performing less favorably. Fig. 9 shows the 14-day expansion results from the accelerated mortar bar test plotted against the 2-year expansion results from the concrete prism test for the same combination of materials (i.e. same type and level of fly ash). It has been suggested by Berube et al. [9] that material combinations that result in an expansion of less than 0.10% at 14 days in the mortar bar test are likely to meet the 0.04% expansion criterion of the concrete prism test after 2 years. Thomas and Innis [10] found this statement to be applicable to concrete contain various reactive aggregates, pozzolans and slag. The samples tested in the present study show that

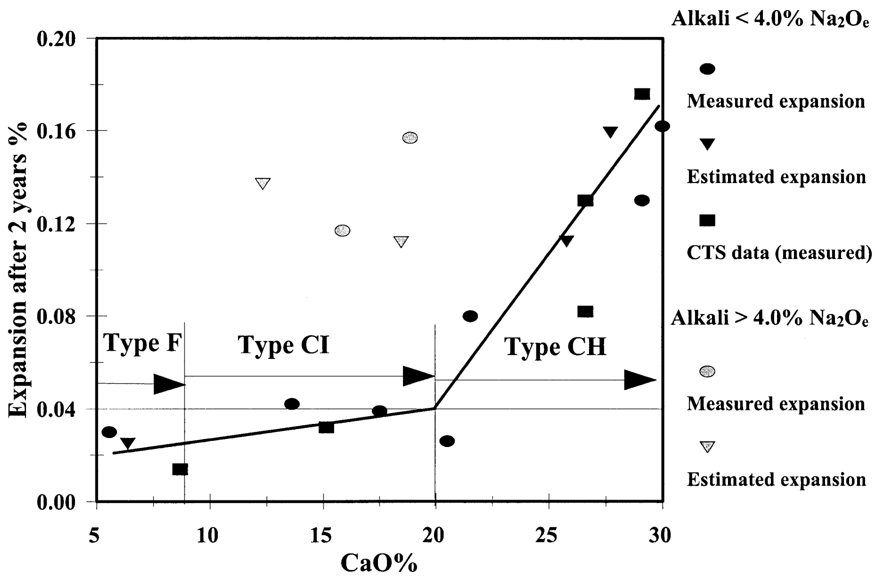

Fig. 7. Effect of CaO content of fly ash on expansion of concrete containing 25% fly ash.

it is reasonable to consider that the material combinations that yield a mortar bar expansion value > 0.1% at 14 days will not meet the 0.04% 2-year expansion criterion from the concrete prism test. However, some material combinations that show mortar bar expansion $\leq$ 0.1% do not necessarily result in a concrete prism expansion $\leq$ 0.04% after 2 years. Although only two combinations (BD at 40% and SD II at 15%) out of a total of 35 tested pass the 0.10% criterion of the mortar bar test and significantly fail the 0.04% limit of the concrete prism test.

In an attempt to establish a better understanding of the factors that influence the mortar bar test results, the pore solution was extracted from the mortar specimens after 14 days immersion in 1 M NaOH solution and analyzed. Fig. 10 shows the hydroxyl (OH^-) ion concentrations plotted against the sum of alkali cations (Na^+ + K^+) in the pore solution. The sum of alkali cations was always higher than the hydroxyl anions, which is attributed mainly to the presence of silica in solution. Sulphate anions may also be present in the pore solution at elevated temperature (80°C) and are expected to contribute, partly, to the difference between the alkali cations and OH anion concentrations. Fig. 11 shows that the difference between the sum of (Na+K) and OH increases as the sum of alkali cations (Na+K) increases, which reflects the presence of higher amounts of other anions (silica and sulphate) in solution at higher alkalinity. Fig. 12 shows that as the alkali content of the pore solution increases so too does the expansion of the mortar bars. The alkali in the pore solution of mortar bars at 14 days is mainly a function of the availability of alkalis in the cementitious system and the quantity of alkalis that penetrate from the external solution of 1 M NaOH at 80°C.

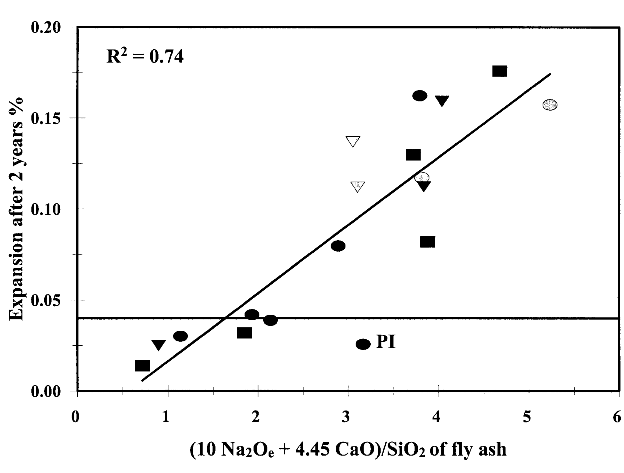

Fig. 8. Effect of ash chemical composition on expansion of concrete prisms containing 25% fly ash (legend, same as Fig. 7).

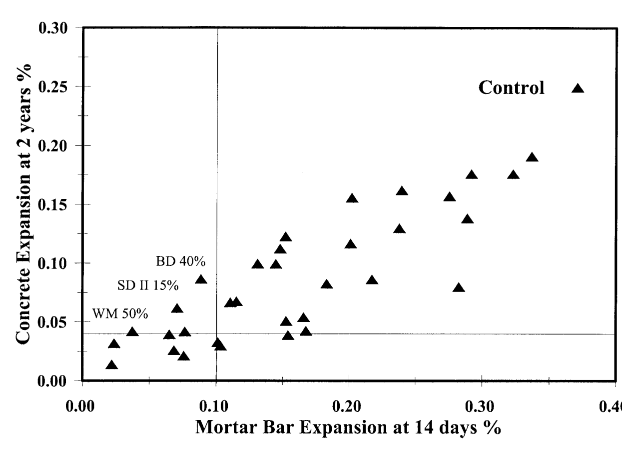

Fig. 9. Relation between the 14-day and 2-year expansions of the accelerated mortar bar and concrete prism tests.

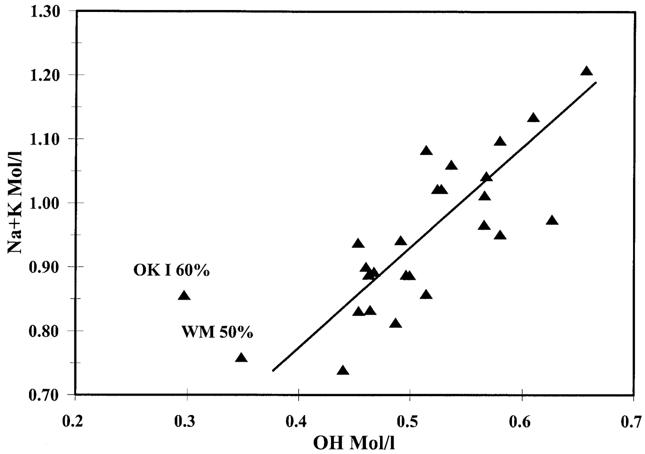

Fig. 10. Relation between OH and (Na + K) ion concentrations in the pore solution extracted from mortar bars at 14 days.

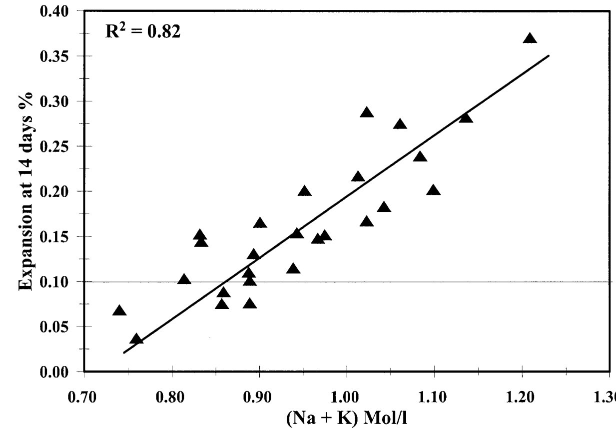

Fig. 12. Effect of (Na + K) ion concentrations in the pore solution on the 14-day expansion of mortar bars.

Thus in the accelerated mortar bar test, one is actually testing the ability of the fly ash to lower the alkalinity of the pore solution (by binding alkalis in the hydrates) and to reduce the diffusivity of the mortar bar making it less accessible to the external alkali solution.

4. Discussion

The results of this study show that the efficacy of fly ash in controlling expansion due to ASR varies within a wide range. For instance, concrete containing 25% fly ash shows 2-year expansion values ranging from 0.014% to 0.176% (Table 2). However, all types of ash at all the RLs reduced expansion compared to the control concrete without fly ash. Moreover, all ashes show reduced expansion as the level of replacement increases. Generally, fly ashes with higher alkali or calcium contents are less effective in controlling expansion due to ASR and consequently have to be used at higher RLs to prevent damaging expansion. While 25% of the low-calcium fly ashes maintained the expansion lower than 0.04% after 2 years, the required level for high-alkali (e.g. BD or WM) or high-calcium ashes (e.g. EW or OK) may be in excess of 40% to 50%.

As mentioned previously, much of the reduced efficacy of high-calcium fly ashes in controlling ASR may be explained on the basis of pore solution chemistry. A study of the effects of fly ash composition on the evolution of the pore solution of cement paste was also conducted by the authors [7] using materials from some of the same sources used for this study. Fig. 13 shows the expansion at 2 years of concrete prisms containing 25% fly ash plotted against the hydroxyl ion concentration of the pore solution extracted from cement pastes of the same age and containing 25% of the same fly ash. The data show that the fly ashes that are capable of lowering the hydroxyl ion concentration of the pore solution of pastes to less than approximately 0.60 mol/l are also generally effective in reducing expan-

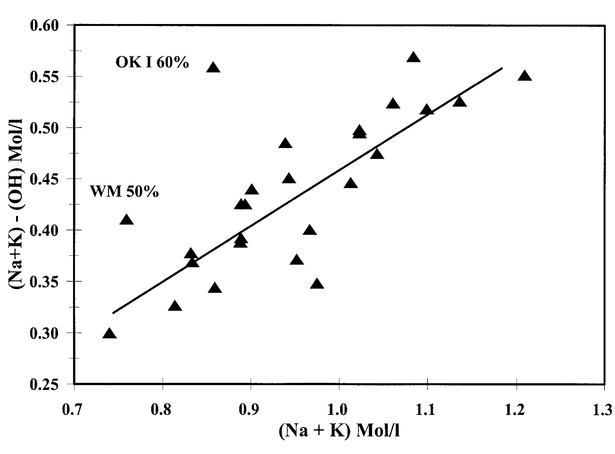

Fig. 11. OH−(Na + K) vs. (Na + K) ion concentrations in the pore solution extracted from mortar bars at 14 days.

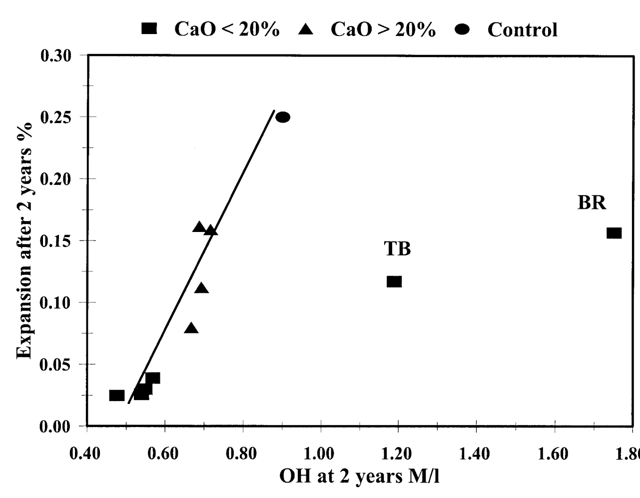

Fig. 13. Effect of OH ion concentration on expansion of concrete containing 25% fly ash.

sion to less than 0.04% at 2 years. A slightly higher value (0.65 mol/l) was suggested by other authors [11]. If the two high-alkali ashes are excluded from the analysis, then there is a broad correlation between the pore solution alkalinity of the pastes and the expansion of the concrete. High-calcium fly ashes reduce both the pore solution alkalinity and expansion compared to the control, but the reductions are not sufficient to prevent damaging expansion.

The behaviour of the high-alkali fly ashes in Fig. 13 is interesting. These ashes produce dramatic increases in the pore solution alkalinity compared with the high-alkali cement control, but the same ashes do not lead to increased expansion; indeed, they significantly reduce expansion compared with the control. This suggests that the effect of fly ash on expansion is not solely the result of its influence on the pore solution chemistry. The authors believe that fly ash plays a further role in the ASR by reducing the availability of calcium in the system. This has been discussed elsewhere [12,13].

For the purpose of using fly ash to control ASR, the question that needs to be answered is not whether a particular fly ash is suitable or not but how much of a particular fly ash is required to limit the risk of expansion to an acceptable level. This minimum or "safe" level will vary depending on the nature of the reactive aggregate, availability of alkali in the concrete (i.e. from PC), the intended exposure conditions of the concrete and, as demonstrated in the present study, the composition of the fly ash itself.

To examine the relationship between the composition of the fly ash and the minimum amount required to control expansion, the concrete prism expansion data in Table 2 were used to estimate the level of fly ash that produced an expansion of 0.04%. In many cases, this level of expansion was bracketed by the results for the RLs selected for study (e.g. MN, SD I, SD II, EW, OK II) and the "safe level" was simply determined by interpolation of the experimental data. In other cases, it was necessary to extrapolate the data to determine the safe level at which an expansion of 0.04% expansion occurs by assuming a linear relationship between expansion and RL. The authors are aware of the limitations of this approach but still consider the exercise useful for the purposes of discussion. The safe levels, estimated to the nearest 5% RL, for the different fly ashes are given in Table 3.

Table 3
Estimated safe level (%) of fly ash required to limit concrete expansion

Group I		Group II		Group III		Group IV	
Ash	Safe level	Ash	Safe level	Ash	Safe level	Ash	Safe level
LG	25	TB	40	PI	25	EW	45
FM	20	BD	50	C2	30	PP	35
MN	20	WM	45			IN	45
SD I	25	BR	55			OK I	55
SD II	20					OK II	60
C1	25					CC	60

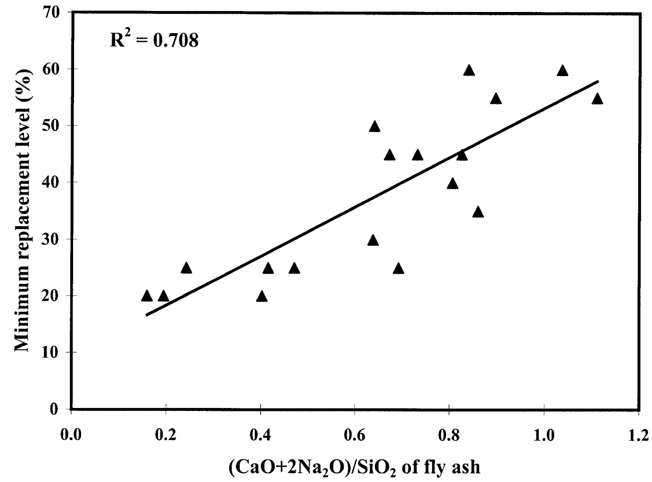

Fig. 14. Relationship between fly ash composition and minimum replacement level.

The calculated "safe levels" presented in Table 3 are grouped into four categories. Group I contains all the Type F and Type CI fly ashes of low to moderate alkali content (i.e. < 4.0 Na_2O_e). For all of these ashes, the safe level falls somewhere between 20% and 25% replacement. Group II contains all the CI fly ashes of high-alkali content for which the safe RL varies between 40% and 55%. Group III represents two fly ashes of low alkali content which by virtue of their calcium contents may be categorized as either Type CI or CH ashes (i.e. 20% < CaO < 22%). These fly ashes are required to be used at levels of 25% to 30% to control expansion to 0.04% in the conditions used in this study. Group IV includes the fly ashes with calcium contents greater than 25% CaO and with generally low alkali contents (1.60% to 2.26% Na_2O_e). The safe levels estimated for these ashes fall in the range, 35% to 60%. Although it is possible to loosely group the behaviour of the fly ashes by composition, there is no clear relationship between the composition of the ash and the safe level of expansion within a group. For example, in Group II, the improved performance of ash TB compared with BD ash cannot be explained on the basis of composition. A similar statement can be made for the marked improvement in the performance of fly ash PP when compared with OK I, which has a very similar chemical composition.

The chemical composition of the fly ash can be used to explain some but not all of the performance of the fly ashes in the concrete prism test (and, for that matter, the accelerated mortar bar test). Fig. 14 shows the "best fit" relationship between the chemical composition of the fly ash (based on calcium, silica, and alkali contents) and the safe level required to limit expansion to 0.04%. This relationship is almost identical to the relationship linking the chemical composition and the 2-year expansion of prisms with 25% fly ash (Fig. 8). It is clear from Figs. 8 and 14 that the chemical composition may be used to provide an indication of the performance of the fly ash, but cannot be reliably used to predict expansion or determine the minimum replacement required for a particular fly ash. Various mineralogical and physical properties of the fly ash, particularly the quantity of glass present and the fineness of the ash, will also influence the performance. For example, the efficacy of fly ash in controlling expansion was found to increase as its total silica content increases, however, it is obvious that only the amorphous silica will have a beneficial effect on ASR as any crystalline phases (e.g. quartz) can be expected to be inert in concrete. This will be discussed further in a subsequent paper.

The inability to make accurate predictions of performance based solely on the composition of the fly ash highlights the need for a performance indicator. Concrete prism tests, while being reasonably representative of field concrete, suffer from requiring a long testing period. The accelerated mortar bar test provides a test result just 16 days after casting the specimen (or after 14 days in 1 M NaOH at 80°C). The data presented here and elsewhere [9,10] indicate that this test provides a reasonably reliable indication of the performance of pozzolans and slag in the concrete prism test. A recent paper by Thomas and Innis [14] reports concrete prism and mortar bar test results for 70 different combinations of various pozzolans, slag and reactive aggregates, and concludes that combinations that pass the accelerated test (i.e. $\leq$ 0.10% expansion at 14 days) can be used in the field with a very low (and acceptable) risk of deleterious expansion due to ASR. The data presented here generally support that statement. This test has an advantage over accelerated tests with Pyrex glass (ASTM C 441) in that it allows pozzolans or slags to be evaluated in combination with the particular reactive aggregate under question. The nature of the reactive aggregate will influence the level of prevention required (e.g. the safe level of fly ash). A further refinement of the accelerated mortar bar test is required to allow the test to be used to evaluate combinations of pozzolans or slag with cements of varying alkalinity.

Although a wide range of fly ashes was selected for the study, it is apparent that some compositions were not adequately represented. For instance, all the low and high-calcium fly ashes used were characterized by being of low alkali content (i.e. generally below 2.0% Na_2O_e). Also, with one exception, the high-alkali Type CI fly ashes were characterized by having very high-alkali levels (i.e. >8.0% Na_2O_e) and ashes with alkali contents in the range, 4.5% to 8.0% Na_2O_e were not included in this study. Further work is required to fully determine the role of the alkalis in fly ash on its performance in the presence of reactive aggregates.

5. Conclusions

(1) All the fly ashes included in this study reduced the expansion of concrete prisms compared with control concretes without fly ash. In all cases, increasing the level of replacement of a particular fly ash further reduced expansion.

(2) At a given level of fly ash replacement, the expansion of concrete prisms generally increased as the calcium or alkali content of the fly ash increased or as its silica content decreased.

(3) The minimum level of replacement required to control expansion to $\leq$ 0.04% at 2 years generally increased as the calcium or alkali content of the fly ash increased or as its silica content decreased.

(4) Much of the variation in performance of different fly ashes can be explained on the basis of pore solution composition. The fly ashes that were found to be most effective in reducing the alkalinity of the pore solution expressed from paste samples were also found to be the best for controlling ASR expansion.

(5) The accelerated mortar bar test provides a reasonable indication of the performance of a particular fly ash in the concrete prism test.

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