Pergamon

Cement and Concrete Research 30 (2000) 1139–1150

CEMENT AND CONCRETE RESEARCH

The effect of product form of silica fume on its ability to control alkali–silica reaction

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Received 7 December 1999; accepted 19 April 2000

Abstract

Various alternative product forms of silica fume (SF), such as densified, compacted, and slurried, have been developed and employed to improve transport and handling properties over those of as-produced undensified SF. However, few data exist on the dispersibility of these forms in concrete to ascertain whether there is equivalent performance. The effects that the form of SF have on resistance to alkali–silica reaction (ASR) expansion were investigated by: (1) concrete prism expansion; (2) mortar bar expansion; and (3) paste pore solution analysis. The mixtures tested included 4%, 8%, and 12% SF replacement by mass of cement, and ordinary Portland cement mixtures for control purposes. At low replacement levels of SF (i.e. 4%), performance was found to vary with product form. At higher levels of replacement (i.e. 8% and 12%), there are no discernible differences in the results from the concrete prism expansion (up to 1 year) or paste pore solution analysis of mixtures made with the various forms of SF tested. The accelerated mortar bar test results at all levels of replacement indicate that under these conditions undensified and slurried SFs are significantly better at controlling the expansion of a reactive siliceous limestone aggregate than are densified or pelletized SFs. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Silica fume; Product form; Dispersion; Alkali–silica reaction; Expansion

1. Introduction

Research has continued to prove that silica fume (SF) concrete can be stronger and more durable than concrete made solely with ordinary Portland cement [1]. As such, the market for SF in concrete applications has increased greatly. In fact, the ability of SF to increase both strength and durability properties of concrete has resulted in SF being the most touted concrete addition of the past decade [2].

SF is a by-product resulting from the reduction of high-purity quartz with coal in electric arc furnaces in the manufacture of ferro–silicon alloys and silicon metal [3]. It is a highly reactive pozzolan due to three of its most notable characteristics, namely [4]:

- an average particle diameter of 0.1 μm (approximately 100 times smaller than average Portland cement particles);
- a high amorphous silica composition (typically >90% SiO_2); and
- a very high surface area of 20,000 m^2/kg (as compared to Portland cement values of 300–500 m^2/kg).

In all, SF particles act as nucleation sites for hydration, pozzolanically improve the interfacial transition zone around aggregates, and pozzolanically react to infill and subdivide original pore space, giving fewer capillary pores and more of the finer gel pores [5].

As-produced SF also has a very low bulk density, which typically ranges from 130 to 430 kg/m^3. This fact creates economic difficulties in the transport of SF from silicon alloy furnace sites to cement or concrete plants, and also makes it hard to handle. Commercial suppliers have responded by processing SF using different methods of densification and compaction in order to improve the handling and transport properties of the material. Final bulk densities have been reported to be as high as 600–700 kg/m^3 for some densified products with agglomerated particles being up to 1 mm in diameter [5]. This is not a problem as long as the SF can be redispersed during concrete mixing or when interground to

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PII: S0008-8846(00)00297-0

form a blended cement. However, if this is not the case, two of the characteristics (small particle size and high surface area) which make the SF such a good supplementary cementing material (SCM) will be greatly reduced. It is possible that the full potential of the SF concrete will not be achieved. The performance of the resulting mixtures may also be variable. There also exists the possibility that the presence of undispersed agglomerates could cause additional problems [6,7]. Not much is known about the possible deleterious effects as published data relating delivery form of SF to the resulting performance and durability of the concrete are lacking [4].

The term durability refers to a concrete's ability "to withstand the processes of deterioration to which it can be expected to be exposed" [8]. One such deterioration mechanism is alkali–silica reaction (ASR), a reaction between the thermodynamically unstable silica in some aggregates and the hydroxyl ions in the pore solution of concrete. SCMs, such as SF, have been proven to improve ASR resistance of concrete through the production of a dense and impermeable matrix, which will inhibit the movement of water and alkalis, and by binding free alkalis in calcium silica hydrates or by adsorption on their large specific surface area, thereby reducing the hydroxyl ion concentration of the pore solution [9]. A complete review of the ability of SF to control ASR expansion is available [10]. The question remains whether all product forms of SF can still achieve this improved ASR resistance.

This report will discuss the method, results, and analysis of a research program carried out to investigate the effects of product form on SF's ability to control ASR.

2. Experimental program

2.1. Materials

All specimens tested in this program were made with high alkali, CSA Type 10 Portland cement. The equivalent alkali content of this cement was 0.98% and a complete chemical analysis is provided in Table 1. This cement met all the requirements for use in both the accelerated mortar bar (CSA A23.2-25A) and concrete prism (CSA A23.2-14A) tests.

The five SFs used in the program were chosen to represent the range of product forms currently in use in North America. The chemical analyses of the SFs are presented in Table 1. A list outlining these SFs and certain relevant characteristics is provided in Table 2.

It should be noted that these SFs are not all from the same source. The code CAN refers to a Canadian source and US refers to a US source, while the numbering refers to the five different suppliers from which the SFs were received. These SFs were chosen to reflect the products, which are commercially available, through both source and form. As such, all the SFs employed came directly from plants either as finished products or in the state in which they would be prior to intergrinding as an ingredient in SF blended cement.

There is currently no standard method for measuring the loose bulk density of SF. For this study, this was determined by filling and weighing a calibrated 400-ml brass cup with SF. The cup was always filled in two layers, with four tamps per layer, and extra material was struck off at the top. This procedure was performed five times for each fume to obtain an average loose bulk density for the material, as shown in Table 2.

Deleteriously reactive aggregate from the Spratt quarry near Ottawa, Ontario was used in the mortar and concrete test specimens. It is a crushed, siliceous limestone, which is deleteriously reactive and often employed as a standard aggregate for ASR tests [11]. It should be noted that it is the siliceous component of this aggregate that is reactive.

2.2. Concrete prism expansion test

The concrete prisms test procedure followed the CSA A23.2-14A (similar to ASTM C 1293) standard. For the purpose of this report, the most recent data possible are presented, yet further monitoring of the prisms will continue to a minimum of 2 years. Such long-term expansion measurements are required to ensure that the SF does not merely delay the onset of ASR.

In this test, 75 × 75 × 300 mm concrete prisms are cast with 420 kg/m^3 high-alkali Portland cement and the mix water is dosed with NaOH to raise the cement alkalis to 1.25% Na_2O_{eq}. Mixtures were cast with each of the SFs at 4%, 8%, and 12% levels of cement replacement by mass. The specific concrete mixture proportions used are outlined in Table 3. It should be noted that the amount of sodium hydroxide included in the mix was adjusted to accommodate the level of replacement of Portland cement with SF, as the alkali contribution of SF is not included for calculation

Table 1
Chemical analyses for cementitious materials

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	LSO_3	K_2O	Na_2O	Na_2O_{eq}
OPC	19.82	5.13	2.2	62.72	2.64	3.15	1.08	0.27	0.98
Pelletized (PEL)	88.85	0.25	0.08	0.44	0.18	0.21	0.62	0.07	0.48
Densified #1 (DEN1)	94.83	0.22	0.06	0.94	0.34	0.28	0.66	0.17	0.60
Densified #2 (DEN2)	90.73	0.39	1.11	0.52	3.37	0.27	0.96	0.20	0.83
Undensified (UND)	95.52	0.15	0.04	0.30	0.15	0.22	0.75	0.10	0.59
Slurried (SLU)	94.54	0.23	0.03	0.39	0.08	0.21	0.50	0.08	0.41

purposes. The prisms were stored at 38°C over water in plastic pails lined with a saturated absorbent paper to maintain 100% RH. Length change measurements have been taken periodically over 1 year, and will continue to be monitored to a minimum of 2 years.

A note should be made at this point regarding an error in the batching process resulted in 25% more NaOH being added to the mixtures than was required by the standard procedures. This resulted in a somewhat higher total alkali content in the mixtures than was targeted, as shown in Table 3. Even so, the data from the prisms are still valid for the purposes of comparing the between ability of the various forms of SF to control expansion due to ASR.

2.3. Accelerated mortar bar test

The accelerated mortar bar test was studied in accordance with CSA A23.2-25A-M94 (similar to ASTM C 1260-94). Questions have been raised on whether this test is appropriate for evaluating the effectiveness of SCMs against ASR. Recent work has shown that the specified conditions are suitable to accelerate the pozzolanic reactions of SCMs, ensuring that this test is a reasonable evaluation method [12–14]. As such, the accelerated mortar bar test has been included in the Canadian Standard for Supplementary Cementing Materials, CSA A23.5-98, as an optional requirement to assess the ability of SCMs, such as SF to control expansion due to ASR. The test method requires that the SCM in question be tested at various replacement levels and that the reactive aggregate used must produce an expansion of at least 0.30% in a high-alkali Portland cement mixture. The Spratt aggregate used in this study fits this requirement. It should also be noted that although the test conditions are quite severe, but it has been found that at 14 days, a expansion limit of 0.10% correlates well with 0.040% concrete prism limit after 2 years when studying SCMs [13,15,16].

The grading and proportioning of the Spratt aggregate was carried out according to the standard and all aggregate was washed prior to use. The casting was carried out following ASTM C305-94. A ratio of water to cement to aggregate of 0.50:1.00:2.25 was employed. The specimens were stored in a standard 1 M NaOH host solution, pre-heated to 80°C, for 28 days, during which time length measurements were taken periodically. It should be noted that 2.5 and 3 g of a sulfonate-naphthalene-based superplasticizer were added to the 8% and 12% SF replacement mortar bar mixtures, respectively.

Table 2
SF properties

SF	Source	SiO_2 content	Loose bulk density (kg/m^3)	% Na_2O_e
Undensified (UND)	Can-1	95.52	270	0.59
Pelletized (PEL)	Can-1	88.85	557	0.48
Densified #1 (DEN1)	Can-2	94.83	689	0.60
Densified #2 (DEN2)	US-3	90.73	643	0.83
Slurried (SLU)	US-4	94.54	–	0.41

Table 3
Concrete prism mix designs

Materials	Level of replacement			
	0%	4%	8%	12%
Cement (kg)	3.15	3.02	2.90	2.77
SF (kg)	0.00	0.13	0.25	0.38
C. aggregate 10–20 mm (kg)	5.13	5.11	5.09	5.08
C. aggregate 10–5 mm (kg)	2.56	2.56	2.55	2.54
Sand (kg)	5.13	5.11	5.09	5.08
Water (kg)	1.42	1.42	1.42	1.42
w/cm	0.45	0.45	0.45	0.45
NaOH (g)	14.10	13.53	12.97	12.41
Target alkalis (kg/m^3)	5.25	5.04	4.83	4.62
Actual alkalis (kg/m^3)	5.57	5.34	5.13	4.90

2.4. Pore solution composition

For each SF, pastes were prepared at 4%, 8%, and 12% mass replacement at a water-to-cementitious materials ratio of 0.5. A 100% ordinary Portland cement mixture was also cast for control purposes. The paste specimens were mixed in a high shear blender (Waring stainless steel, 3.81 capacity). No superplasticizers or water-reducers were included in the mixtures. Eight cylinders (50 mm diameter × 100 mm high) were filled in two layers and sealed with parafilm and a plastic lid. After casting, the specimens were slowly rotated about their ends at 12 rpm for 24 h to avoid bleeding and segregation prior to set.

Pore solution was extracted from the specimens at 1, 3, 7, 28, and 90 days and analysed for chemical composition. The pore solution was expressed from the samples using a high-pressure apparatus, originally described by Barneyback and Diamond [17]. It should be noted that Duchesne and Berube [18] have shown that the alkali concentration of pore solution is not affected by the pressure at which a sample is expressed. Further analysis will be performed on specimens at 1 and 2 years of age. The specimens were stored at 23°C and 100% r.h. to prevent moisture loss until they were tested. Once the pore solution was collected, it was immediately tested for OH^- ion concentration using automatic H_2SO_4 titration and was tested later for Na^+ and K^+ ion concentrations using flame photometry.

3. Results and discussion

3.1. Accelerated expansion of concrete prisms due to ASR

Results presented in this report are as recent as possible. Currently, Ref. [11] recommends a testing period of 2 years with an expansion limit criterion of 0.04% for the evaluation of SCMs. Although this study is not complete, some preliminary observations can be made from the results obtained to date.

Concrete prisms were cast at 4%, 8%, and 12% replacement of Portland cement by SF with the varying product form SFs. The expansion of concrete prisms with these levels of replacement are shown in Figs. 1–3, respectively. As previously mentioned, an error was made when preparing mixture designs and too much NaOH was added to all of concrete prism mixtures. As such, the concrete prism data reported in this study should only be used for relative, comparative purposes. However, it is of interest to note that the average expansion of the OPC prisms after 52 weeks (0.189%) falls within one standard deviation of the average expansion after 52 weeks of OPC prisms containing Spratt aggregate (μ=0.170%, σ=0.021%) as determined in a inter-laboratory study reported by Fournier and Malhotra [19].

In many cases, the prisms exhibited some initial negative expansion, most likely due to autogenous shrinkage. When comparing the mixtures containing SF, it is evident that as the replacement percentage of each SF was increased, the expansion decreased. However, Fig. 1 shows that 4% SF did not reduce long-term expansion when compared to that experienced by the OPC control prisms. The ordinary Portland cement control mixture exceeded the expansion limit criterion of 0.04% shortly after 56 days. After 1 year of testing, the rate of the OPC prism expansion seems to be slowing. The 4% PEL, DEN1, and DEN2 SF prisms exceeded the limit criterion almost exactly at 90 days. These three sets of prisms all experienced minimal expansion up to around 56 days, after which the rate of expansion drastically increased and has continued relatively steadily to date. Although it took longer for these mixtures to surpass the limit than the OPC mixture did, these prisms later achieved higher expansions than the control mixture prisms. Other researchers have reported the occurrence of this pessimum effect where the use of SF at low replacement levels can actually result in higher expansions due to ASR [20]. The trend of expansion of 4% PEL, 4% DEN1, and 4% DEN2 prisms also do not seem to have leveled off, even after 1 year of testing.

Unfortunately, due to a delay in receiving materials, there is not as much long-term data available for the mixtures incorporating the undensified and slurried SFs. However, it is evident from Fig. 1, that the 4% slurried and undensified SF prisms expanded beyond the limit criterion at approximately 126 days. The delay in the onset of expansion for these prism sets was longer than that of the PEL-4%, DEN1-4%, and DEN2-4% mixtures. It was after 90 days that the prisms with 4% of undensified and slurried SF began to expand at a significant rate.

Although all the prisms made with 4% replacement by SF of Portland cement failed the test criterion, there is a noticeable difference in performance between some of the product forms of SF employed. This was not the case, however, at the 8% and 12% levels of replacement, after 1 year of testing. Fig. 2 presents the expansion of prisms with time for concrete with 8% SF, and after 1 year of testing, the prisms made with the pelletized and both of the densified SFs had all surpassed the expansion limit. Again, the data available for the undensified and slurried SF prisms is not as advanced as the others. The latest recorded readings were at 126 days (0.016%) for the slurried SF and 231 days (0.027%) for the undensified SF. At these ages, the prisms were still well below the 0.040% limit criterion, however, the rates and levels of expansion to date seem to

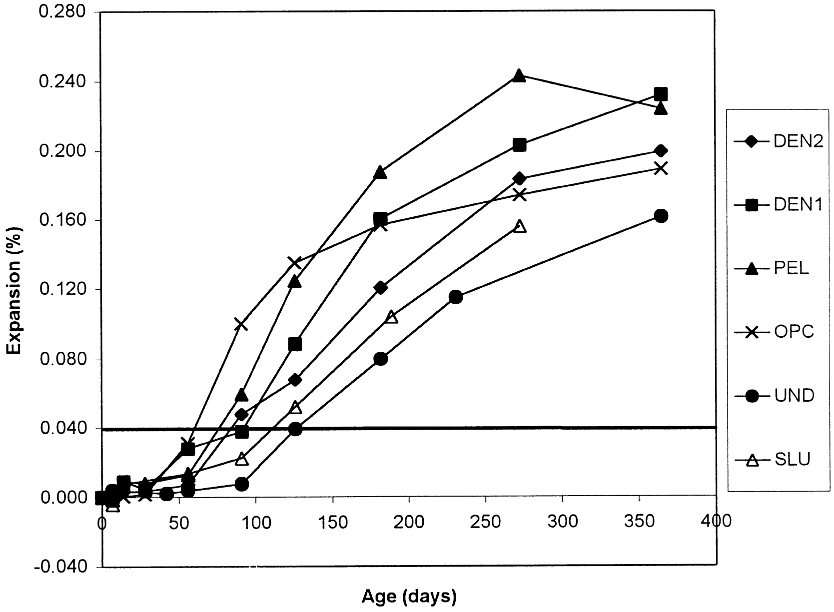

Fig. 1. Expansion of concrete prisms containing 4% SF replacement.

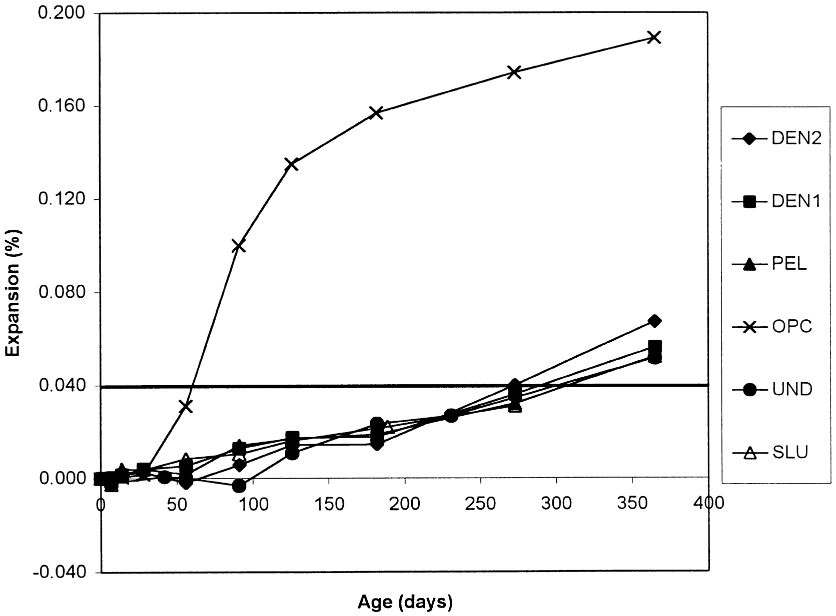

Fig. 2. Expansion of concrete prisms containing 8% SF replacement.

be following the same trend as the prisms made with the other three SFs. In essence, at this point, there is no distinguishable difference in performance of the different product forms in terms of concrete prism expansion at an 8% level of replacement. Also, there is no significant change in the rate of expansion experienced to date by any of the concrete prisms with 8% replacement of cement by SF.

Similar observations can be made for the prisms made with 12% SF. As is evident in Fig. 3, there is no significant difference between the expansion experienced by the prisms made with the different product forms to date. The 12% SF concrete prisms also have not exhibited a significant change in the rate of expansion to date. Fig. 3 also shows that 12% SF is sufficient to maintain expansion below the 0.040% limit after 1 year, no matter what form was employed. It is expected that the prisms will exceed the expansion limit criterion after 2 years since the dosage of NaOH included in these mixtures was 25% higher than specified in the standard.

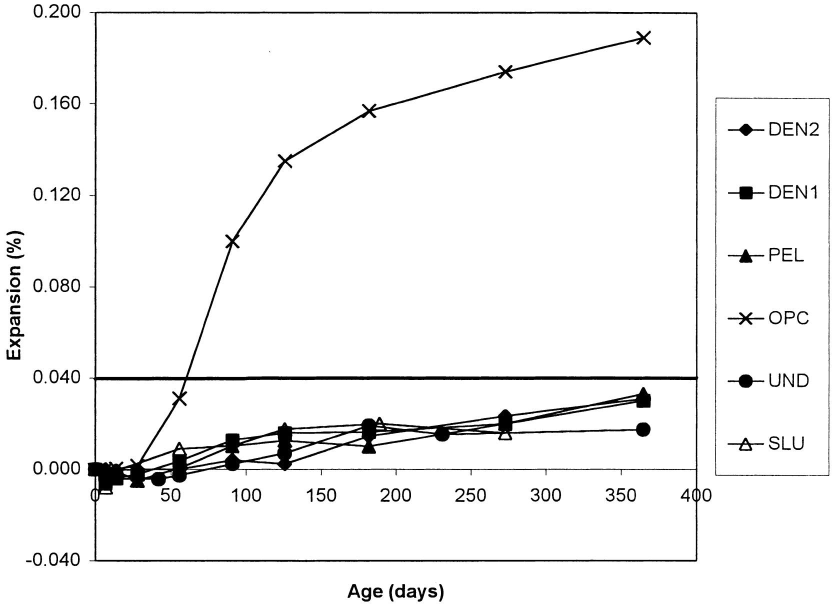

Fig. 3. Expansion of concrete prisms containing 12% SF replacement.

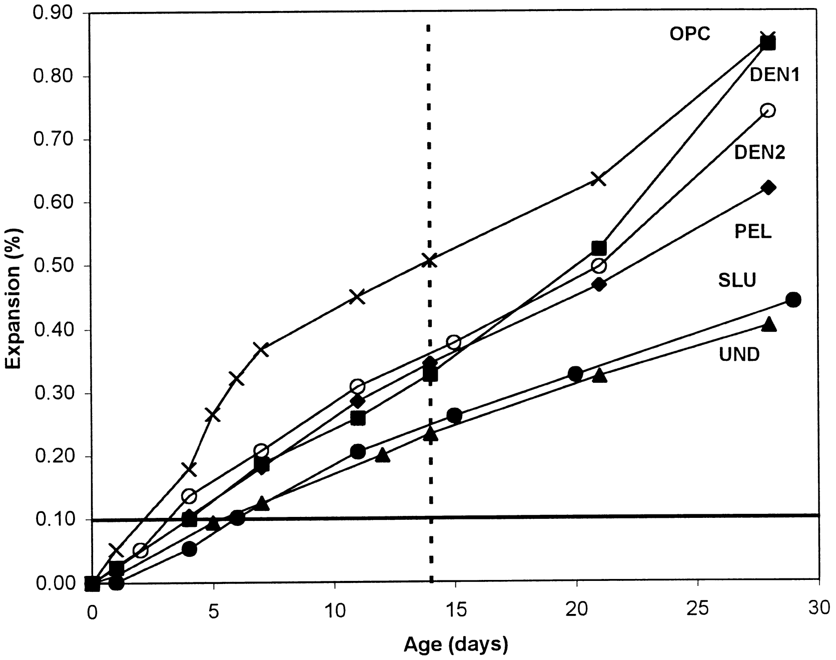

Fig. 4. Expansion of mortar bars containing 4% SF replacement.

3.2. Accelerated expansion of mortar bars due to ASR

Although this is traditionally a 14-day test, all expansions were monitored to 28 days. Figs. 4–6 show the performance of mortar bars with 4%, 8%, and 12% SF, respectively. At 14 days, the expansion of the OPC control specimens seems high at 0.505%. However, this average expansion is within two standard deviations of a mean 14-day expansion of Spratt aggregate (μ=0.416%, σ=0.06%) as determined in a multi-laboratory study of the accelerated mortar bar test (ASTM C1260) and reported by Rogers [21].

The ordinary Portland cement control specimens had exceeded the 0.10% expansion limit criterion after 4 days. All of the 4% SF specimens had expansions of 0.10% or greater by 7 days. After 11 days, all of the 8% SF specimens

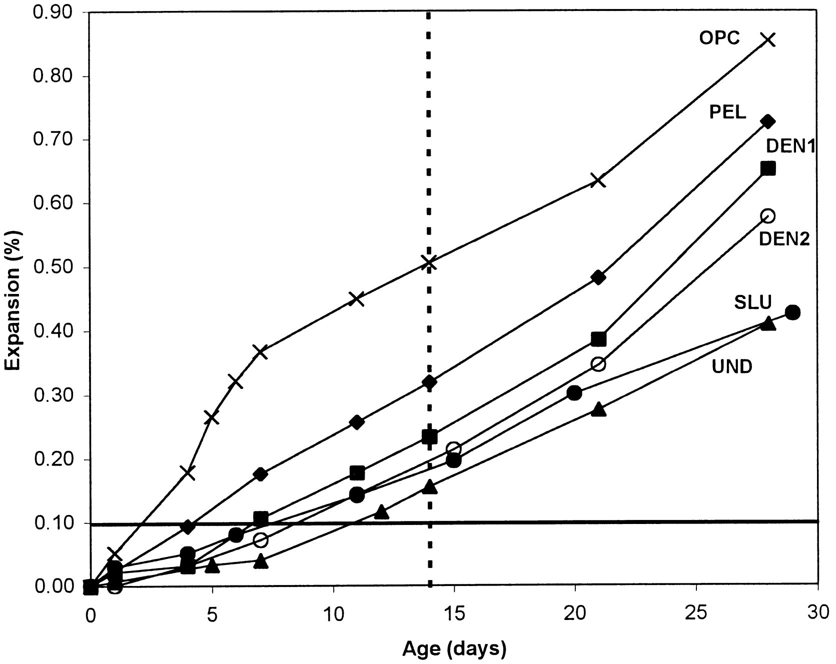

Fig. 5. Expansion of mortar bars containing 8% SF replacement.

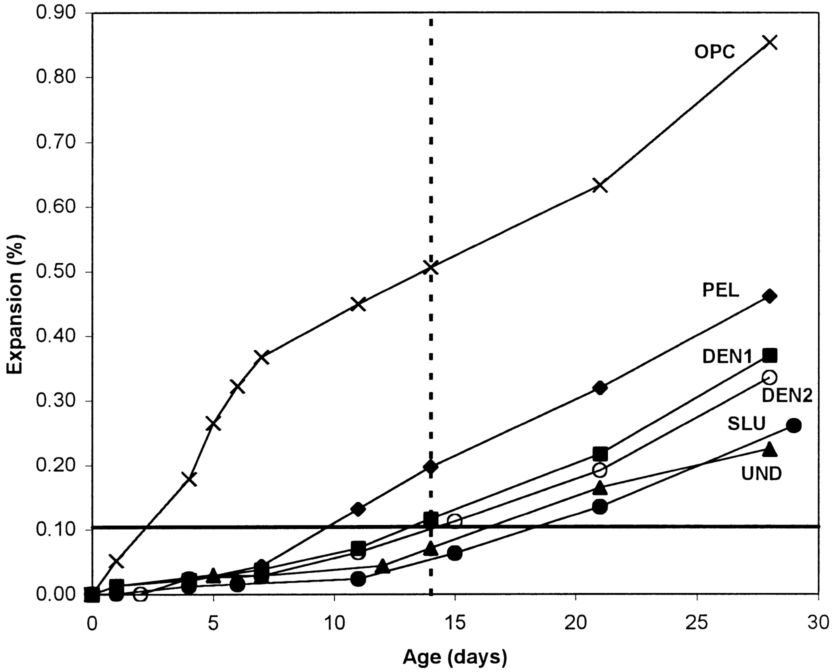

Fig. 6. Expansion of mortar bars containing 12% SF replacement.

had also failed the test limit. With 12% SF, only the specimens containing either the undensified or slurried form of SF had average expansions below 0.10% after 14 days of testing. The specimens made with the two densified SFs just barely exceeded the 0.10% limit; however, the 12% pelletized SF specimens still performed poorly with an expansion of almost 0.20% at 14 days.

There was no delay of the onset of expansion with any of the sets of mortar bars containing 4% SF. Of the mortar mixtures with 8% SF, only PEL-8% expanded significantly immediately and increased steadily. The expansion of UND-8% began after 7 days, while the other three SFs tested (DEN1, DEN2, and SLU) exhibited a large increase in the rate of expansion at approximately 4 days. All of the 12% SF specimens experienced a delay in the onset of expansion. For PEL-12%, DEN1-12%, and DEN2-12%, the onset of expansion occurred at approximately 7 days, while with SLU-12% and UND-12%, significant expansion began after 11 days. These trends are actually quite different from those observed with the concrete prisms.

The above discussion of the accelerated mortar bar test results makes it evident that differences were observed in performance between the various product forms of SF tested, even with the 12% replacement of cement mortar mixtures. At all three levels of replacement of cement, the slurried and undensified SF mixtures performed fairly similarly in terms of ultimate expansion and rates at which this expansion was achieved; these two forms of SF were consistently better at controlling mortar bar expansion than the other three forms tested. There was no significant difference in the expansion results observed for mortars with the 4% replacement of cement by the pelletized or either of the two densified SF mixtures, up to 21 days. With 8% and 12% SF content, the pelletized SF mortar bars expanded the most, followed by the DEN1 mortar bars and then the DEN2 mortar bars.

3.3. Paste specimen pore solution composition

This section highlights key findings of the paste specimen pore solution study. Fig. 7 shows that generally a good balance was found between the alkali ion concentration and the OH^- concentration. Therefore, further analyses were

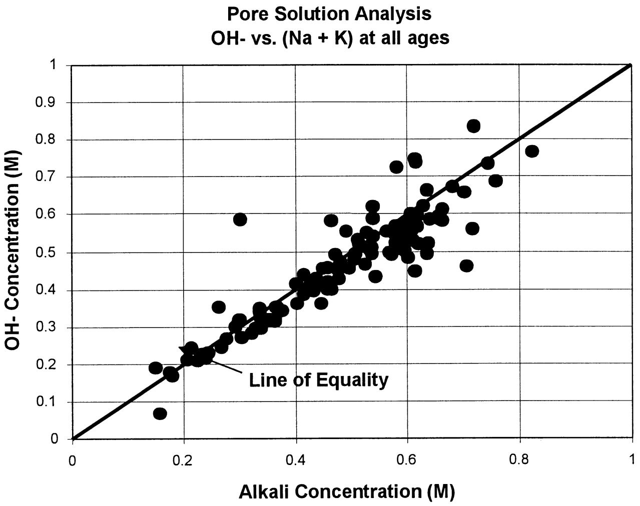

Fig. 7. Balance between ionic species in pore solution.

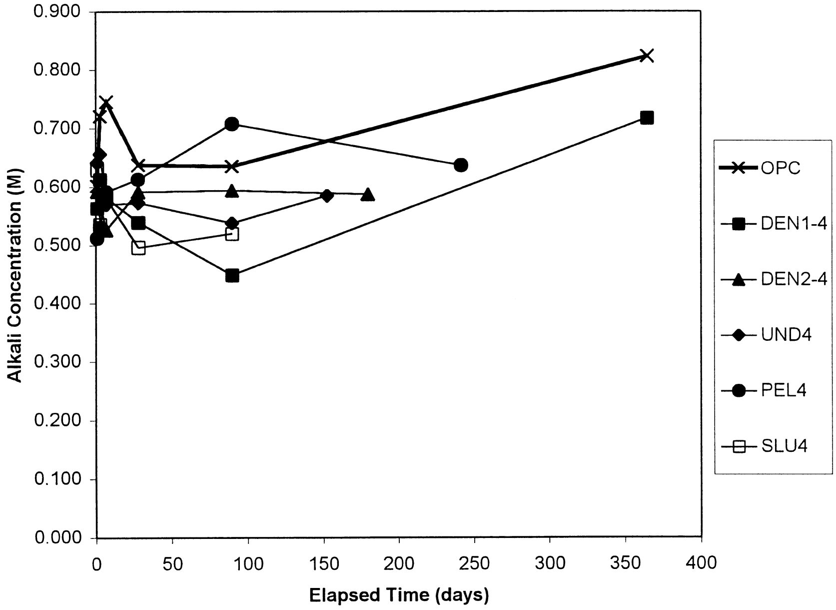

Fig. 8. Effect of product form of SF on pore solution alkalinity with time at 4% level of replacement.

simply performed using the alkali ion concentration data as determined by flame photometry.

Several broad observations can be made from the pore solution analysis results. Generally, SF addition at all replacement levels, for all product forms and ages tested, reduced the alkali concentration when compared to that of the neat cement paste. The only exception to this trend was found with the 4% pelletized SF mixture where the alkali concentration at 90 days was higher than that of the OPC at 90 days. Also, an increase in the replacement level of SF resulted in a larger decrease in the alkali concentration at 7, 28, and 90 days for all SFs. This trend did not hold for the data at 1 and 3 days.

Figs. 8 and 9 present the results for the 4% and 8% levels of replacement, respectively. Examination of Fig. 8 indicates that at a 4% level of replacement, the product form of SF does cause differences in the resulting pore solution alkalinity of paste specimens, which confirms the concrete prism expansion results. In contrast, Fig. 9 shows no significant difference in the concentration of alkalis in the specimens made with the various product forms of SF with 8% replacement. Similar results were

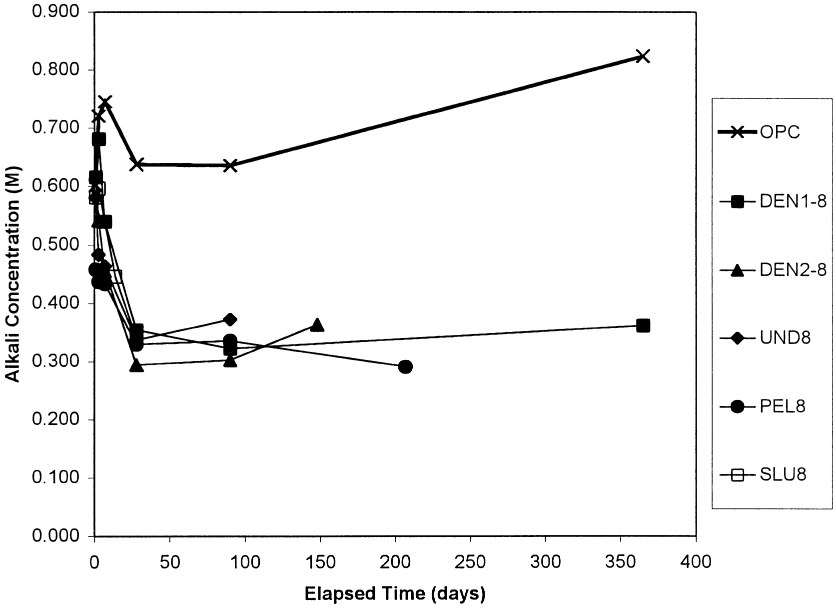

Fig. 9. Effect of product form of SF on pore solution alkalinity with time at 8% level of replacement.

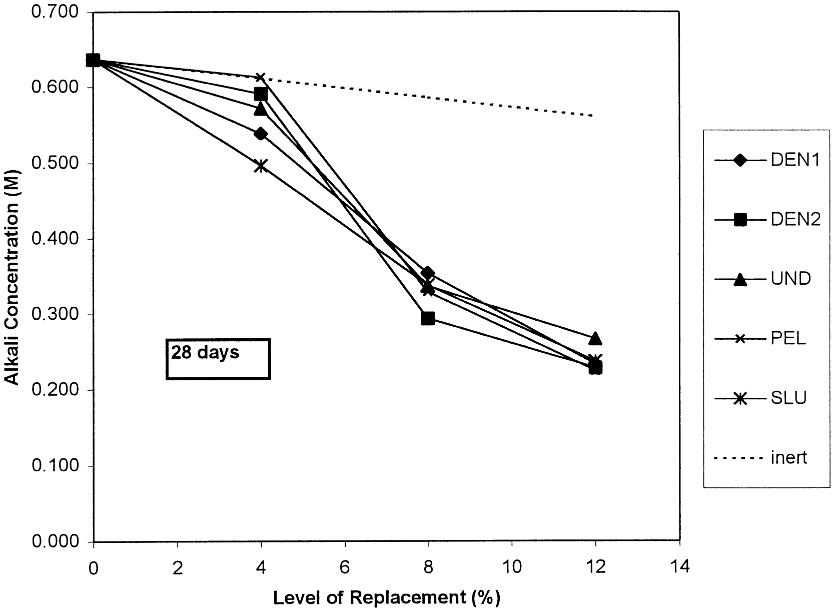

Fig. 10. Effect of SF level of replacement and product form on pore solution alkalinity at 28 days.

observed for the 12% replacement by SF of Portland cement mixtures.

Potentially, at higher levels of replacement such as 8% and 12%, the system is essentially swamped with SF to a degree that the difference in the quantity of exposed, reactive surface area that exists between the different forms of SF no longer matters, at least up to 1 year. This implies that there could be similar performance obtained by different forms of SF at lower replacement levels. For example, a 4% undensified SF concrete mixture may be able to control ASR expansion, as well as a 6% pelletized or densified concrete mixture. Further work correlating a form of SF's performance to the average reactive surface area would definitely be useful.

Figs. 10 and 11 present plots of alkalinity vs. level of replacement for the various product forms of SF at 28 and 90 days of age, respectively. The theoretical effect of an inert diluent has also been plotted on these figures. All the product forms tested at all replacement levels cause a significantly greater decrease in pore solution alkalinity than would an inert diluent except in the case of the 4% pelletized SF paste.

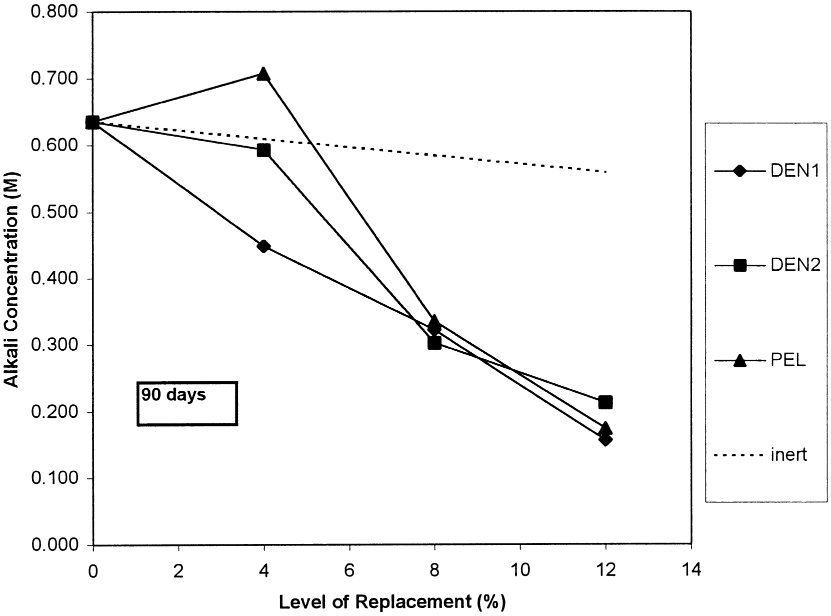

Fig. 11. Effect of SF level of replacement and product form on pore solution alkalinity at 90 days.

4. Summary of results

In Table 4, the performance of the various product forms of SF is ranked in terms of the three studies performed in this research program. The number 1 indicates the best performance and number 6 indicates the worst performance comparatively. The numbers in italics simply mean that the results available are not as advanced as the others, so those rankings are based on trends to date.

Some issues warrant further discussion in terms of a combination of the results of all three studies performed in this program. No significant difference in performance was observed in terms of concrete prism testing or pore solution alkalinity between the various product forms used at 8% and 12% replacement, while differences were observed at 4% replacement. However, for the mortar bar testing, noticeable differences in performance were found between the various forms at all levels of replacement. One possible contributing factor to these occurrences could be the difference in mixers used to cast the paste specimens, mortar bars, and concrete prisms. The paste specimens were cast in a high-speed, high-shear, blender mixer, which possibly had the ability to break apart and better disperse the SF, no matter what form was used. Also, when casting the concrete prisms, there is a very short dry-blend period (i.e. 20 s) where the SF and cement are being intermixed with the sand and two sizes of coarse aggregate. This blending could help break up any SF agglomerations present and better disperse the SF so that performance may be more similar. There is no such dry-blend period for the mortar bar casting and there is no large coarse aggregate to provide as strong of a grinding action during mixing.

Comparison of Figs. 12 and 13 lead to further possible explanations. The other factor that could have influenced these results is the severe test conditions (80°C, 1.0 M NaOH), which are employed in the mortar bar test. These extreme conditions could force an observable difference in performance between different mixtures, even when comparing different high-performance mixtures. This is in contrast to the conditions used in the concrete prism test (38°C, moist storage). The potential does exist, however, that differences may be noticed at 8% and 12% replacement levels with the concrete prism results at much later ages, i.e. approaching 2 years or more. In other words, possibly the trends observed in the accelerated mortar bar test results have not yet had time to manifest in the concrete prism test. Alternatively, it could be that product form may never cause differences in the concrete prism test results at 8% or 12% replacement. In the concrete prism test, there is a finite, internal supply of alkalis available for ASR to occur. In contrast, the mortar bar test conditions give a nearly unlimited, external source of alkalis available for reaction. It could be that there are SF agglomerations present in both the mortar bars and the concrete prisms, and the degree to which these clusters are present is linked to the form of SF used. In the case of the mortar bars, there is a sufficient alkali dosage present to cause these agglomerations to react and cause ASR expansion to varying degrees for the various product forms studied. For the concrete prism test, the alkalis may have been exhausted, and as such, no difference in performance at 8% and 12% replacement for the varying product forms was observed. A final possible explanation could be the influence of cross-section size. Agglomerations present in a mortar bar, which is significantly smaller in dimensions than a concrete prism, would have relatively more significant effects on expansion results than any present in concrete prisms.

It is interesting to compare the performance of the two densified fumes in the three studies. DEN2 was better at controlling mortar bar and prism expansion than DEN1, but DEN1 consistently had lower pore solution alkalinity than DEN2. DEN1 had a higher bulk density than DEN2. As such, it could be harder to disperse evenly through a mixture, and thus not be able to control expansion as well as DEN2. In the paste pore solution study, a high-speed, high-shear mixer was used, which would help better disperse a SF of high density. Also, DEN1 has a much lower Na_2O_{eq} than DEN2. It is most likely that the higher alkali content of DEN2 explains why the paste samples made with DEN2 had higher pore solution alkalinities than those made with DEN1, even though DEN2 was better at controlling the ASR expansion of Spratt aggregate.

Table 4
Summary of results

	Concrete prism expansion (after 180 days)			Mortar bar expansion (after 28 days)			Paste pore solution study (after 90 days)		
Form of SF	4%	8%	12%	4%	8%	12%	4%	8%	12%
UND	1	1	1	1	1	1	3	1	2
PEL	6	1	1	3	5	5	6	1	1
DEN1	5	1	1	5	4	4	2	1	1
DEN2	3	1	1	4	3	3	4	1	1
SLU	*2*	*1*	*1*	2	2	2	*1*	*1*	*1*
OPC	4	6	6	6	6	6	5	6	6

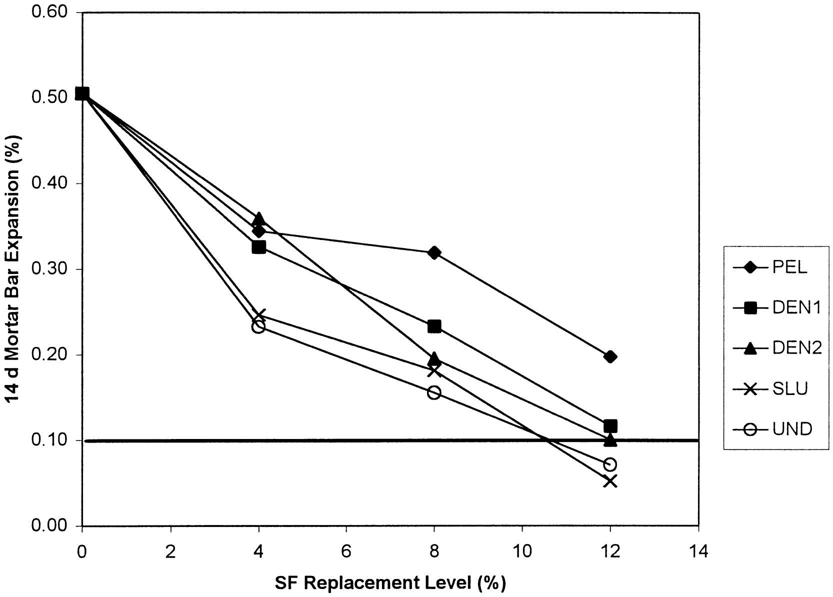

Fig. 12. Effect of SF level of replacement and product form on 14-day mortar bar expansion.

As expected, the pelletized SF consistently performed poorly. At times, its inclusion in a mixture gave results equivalent to or worse than those found with the OPC control samples (Figs. 1, 8, 10, and 11). It should be again reiterated that pure pelletized SF is not marketed for use in industry, nor is it recommended for use as an SCM in concrete in ACI C234R-96. It was simply included to evaluate an extreme case. However, it is used to intergrind with cement clinker to form blended SF cements. These results do emphasize though the importance of stringent grinding techniques and quality control monitoring of the resulting grain sizes. If many pellets of SF go through the intergrinding process without getting broken down, the properties of the concrete that the blended SF is used could very well be equal or even worse than those of an OPC concrete. This results in an inefficient use of materials, since SF could be added without the expected improvement in performance.

Specimens containing the undensified or slurried SFs consistently performed better in the accelerated mortar bar

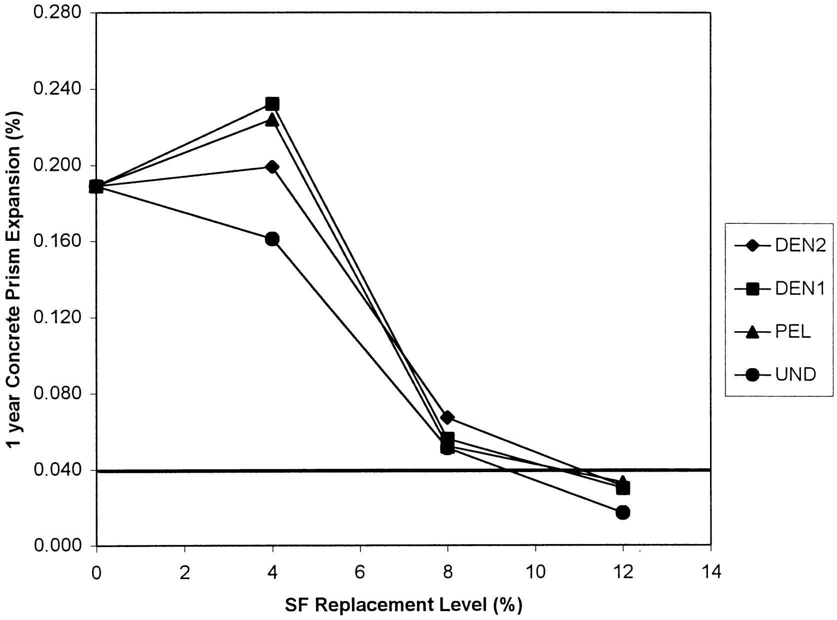

Fig. 13. Effect of SF level of replacement and product form on 1-year concrete prism expansion.

test, as well as at a 4% replacement level in both the concrete prism and pore solution studies. These forms of SF are simply more conducive to adequate dispersion throughout a mixture and make it easier for all the benefits of SF to be realized.

5. Conclusions

(1) With all forms of SF tested, 4% replacement was not sufficient to control ASR expansion of Spratt aggregate. At a 4% level of replacement, the product form of SF does cause differences in the concrete prism expansion up to 1 year, the accelerated mortar bar test results, and the resulting pore solution alkalinity of paste specimens. At this level of replacement, the undensified and slurried forms of SF consistently performed the best, while the pelletized form of SF performed poorer than the other mixtures.

(2) Concrete prisms containing 8% or 12% SF expand similarly up to 1 year, regardless of the product form of SF. In addition, the alkalinity of paste pore solutions containing 8% or 12% SF replacement by mass were similar, regardless of the product form of SF.

(3) The product form of SF caused differences in results of the accelerated mortar bar test at all levels of replacement. The undensified and slurried forms of SF were best at mitigating the expansion due to ASR. The pelletized form of SF performed poorer than all other mixtures, as was expected.

(4) All mortar bar mixtures failed to control deleterious ASR expansion of Spratt aggregate, with the exceptions of the 12% replacement with undensified and slurried SF mixtures.

References

[1] R.D. Hooton, Influence of silica fume replacement of cement on physical properties and resistance to sulfate attack, freezing and thawing, and alkali–silica reactivity, ACI Mater J 90 (2) (1993) 143–161.

[2] D. Marsh, An alternative to silica fume? Concr Prod 97 (11) (November) (1994) 24.

[3] V.M. Malhotra, Fly ash, slag, silica fume, and rice-husk ash in concrete: A review, Concr Int 15 (1993) 23–28.

[4] ACI Committee 234, Guide for the Use of Silica Fume in Concrete, American Concrete Institute, Detroit, 1994.

[5] R.D. Hooton, R.F. Bleszynski, A.M. Boddy, Issues related to silica fume dispersion in concrete, in: M. Cohen, S. Mindess, J. Skalny (Eds.), Material Science of Concrete: The Sidney Diamond Symposium, 1998, pp. 435–446.

[6] D. Bonen, S. Diamond, Occurrence of large silica fume-derived particles in hydrated cement paste, Cem Concr Res 22 (1992) 1059–1066.

[7] K. Pettersson, Effects of silica fume on alkali–silica expansion in mortar specimens, Cem Concr Res 22 (1) (1992) 15–22.

[8] A. Neville, Properties of Concrete, 4th edn. Wiley, 1996.

[9] J. Kropp, Relations between transport characteristics and durability, RILEM Rep 12 (1995) 138.

[10] M.D.A. Thomas, R.F. Bleszynski, The use of silica fume to control expansion due to alkali–aggregate reactivity in concrete — a review, in: S. Mindess, J. Skalny (Eds.), Materials Science of Concrete, vol. VI, American Ceramic Society, Westerville, OH, 2000.

[11] CSA A23.1-94, Appendix B: Alkali–aggregate reaction, Concrete materials and methods of concrete construction, (1994) 112–135.

[12] M. Berra, G. De Casa, T. Mangialardi, Evolution of chemical and physical parameters of blended cement mortars subjected to the NaOH Bath Test, in: A. Shayan (Ed.), Proceedings of the 10th International Conference on Alkali–Aggregate Reaction in Concrete, Melbourne, Australia, 1996, pp. 483–491.

[13] M.A. Berube, J. Duchesne, D. Chouinard, Why the accelerated mortar bar method ASTM C1260 is reliable for evaluating the effectiveness of supplementary cementing materials in suppressing expansion due to alkali–silica reactivity, Cem Concr Aggregates 17 (1) (1995) 26–34.

[14] M. Berra, T. Mangialardi, A.E. Paolini, Application of the NaOH bath test method for assessing the effectiveness of mineral admixtures against reaction of alkali with artificial siliceous aggregate, Cem Concr Compos 16 (3) (1994) 207–218.

[15] M.D.A. Thomas, F.A. Innis, Use of the accelerated mortar bar test for evaluating the efficacy of mineral admixtures for controlling expansion due to alkali–silica reaction, Cem Concr Aggregates 21 (2) (1999) 157–164.

[16] M.D.A. Thomas, F.A. Innis, Effect of slag on expansion due to alkali–aggregate reaction in concrete, ACI Mater J 95 (6) (1998) 716–724.

[17] R.S. Barneyback Jr., S. Diamond, Expression and analysis of pore fluids from hardened cement paste and mortars, Cem Concr Res 11 (1981) 279–285.

[18] J. Duchesne, M.A. Berube, Evaluation of the validity of the pore solution expression method from hardened cement pastes and mortars, Cem Concr Res 24 (3) (1994) 456–462.

[19] B. Fournier, V.M. Malhotra, Inter-laboratory study on the CSA A23.2-14A concrete prism test for alkali–silica reactivity in concrete, in: A. Shayan (Ed.), Proceedings of the 10th International Conference on Alkali–Aggregate Reaction in Concrete, Melbourne, Australia, 1996, pp. 302–309.

[20] J. Duchesne, M.A. Berube, The effectiveness of supplementary cementing materials in suppressing expansion due to ASR: another look at the reaction mechanisms: Part 1. Concrete expansion and portlandite depletion, Cem Concr Res 24 (1994) 73–82.

[21] C.A. Rogers, Multi-laboratory study of the accelerated mortar bar test (ASTM C1260) for alkali–silica reaction, Cem Concr Aggregates 21 (2) (1999) 185–194.