COMBINED EFFECT OF AN AIR-ENTRAINING AGENT AND SILICA FUME ON ALKALI-SILICA REACTION

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The objective of this work was to investigate the effectiveness of combining air-entrainment of cement with partial silica fume (SF) replacement of cement as a means of controlling expansion caused by alkali-silica reaction (ASR). The expansion of mortar bars due to ASR was reduced by the partial replacement of cement with silica fume and was also reduced by the incorporation of an air-entraining agent (AEA). The combination of AEA and silica fume reduced expansion by the maximum amount.

INTRODUCTION

Previous work has shown that expansion due to ASR may be reduced by partial replacement of cement by SF (1) or by air-entrainment (2). It was concluded by Jensen et al (2) that when about 4% air voids were introduced the average expansion could be reduced by about 40%. This was attributed to the accommodation of alkali-silica gel in the air-void system. In the experiments conducted in this research, it was confirmed that SF and AEA used individually can reduce expansion of mortar bars containing 2% opal as alkali-reactive aggregate. The combination of air-entraining agent and SF in the mortar bars caused the greatest reduction in expansion due to ASR but the reduction was not the arithmetic sum of the two reductions found when the agents were used individually.

MATERIALS AND EXPERIMENTAL METHODS

Materials

Opal, from Nevada, U.S.A., in a proportion of 2% by mass of aggregate, was used as an alkali expansive component in mortar bars made with non-alkali expansive limestone aggregates from Exshaw, Alberta. The opal and limestone aggregates were crushed, sieved and blended to meet the size gradation requirements of ASTM C-227. Other constituents used in the mortar bars included type 10 low alkali cement, silica fume slurry and air-entraining agent. The chemical composition and physical properties of the cement and SF are shown in Table 1. Alkali content was boosted to 1.0% (equivalent Na_2O) by addition of reagent grade NaOH to the mixing water. This procedure simplified comparison of results obtained with these high alkali mixes with those obtained in other tests in which the same cement was used as a low alkali control.

TABLE 1 - Chemical Composition(%) and Physical Properties of Cement and Silica Fume (SF)

	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	L.O.I.	S.A.[1]	S.G.
Cement	63.32	22.03	4.13	2.52	2.16	0.17	0.41	3.10	-	-
SF	0.35	95.65	0.37	0.08	0.21	0.08	0.43	3.66	18.19	2.103

Experimental Methods

Expansion Tests. Alkali-expansivity of the mortar bars was assessed by the method of ASTM C-227. Bars were measured in triplicate and average values are shown in the Figs 1 - 3. An extra bar was cast for the examination of microstructure.

Air-Void Measurement. The method of ASTM C-457 was employed for determination of the air-void system in the mortar bars. The equipment was designed to meet the requirements of the modified point count method. The specimen for air-void measurements was taken from the bars after expansion measurements were completed. One bar per specimen was measured. Over 1000 points were counted and total travel distance was about 1500 mm. The total air-void content (both entrained and entrapped air) was used in data analysis.

Petrographic Examination. Pore structure was examined by optical microscopy. The samples for this examination were taken from the extra bar cast at the same time as, and stored together with, the bars used for expansion measurement when the bar reached an age of three months.

RESULTS

Effect of Silica Fume on ASR

Effect of silica fume on ASR in the absence of AEA. The effect of SF on expansion of bars due to ASR is shown in Fig.1. The expansion decreased with increase in the amount of silica fume. At an age of 10 months, the expansion of mortar bars containing 6% and 12% silica fume was reduced by 20% and 40% respectively (Table 2). The bars containing 24% silica fume did not expand. Silica fume also delayed the start of expansion and the delay period increased with increase in the amount of silica fume.

Effect of silica fume on ASR in the presence of AEA. The effect of silica fume on expansion of bars in the presence of AEA is shown in Fig.2. At the ages shown in the figure, expansion decreased with increase in the amount of silica fume. At an age of 10 months, the expansion of bars containing 6% and 12% silica fume was reduced by 6% and 40% respectively (Table 2). The bars containing 24% silica fume did not expand. The start of expansion was delayed for a longer period when SF was used with AEA than when SF was used without AEA.

Effect of AEA on ASR in Bars Made with and without SF

The effect of AEA on expansion of bars due to ASR is shown in Fig.3. In all three cases

[1] Surface area (m^2/g) measured by N_2 adsorption.

of 0%, 6% and 12% silica fume replacement of cement, the addition of AEA reduced expansion to about the same extent (~50%) at an age of 10 months. This shows that AEA consistently reduced expansion whether silica fume was used or not. The AEA also delayed the start of expansion and the length of the delay tended to increase with increase in the amount of silica fume.

TABLE 2 - Comparison of Expansion due to ASR with and without SF and AEA

	SF content (%)	Expansion (%) No AEA	Expansion (%) With AEA	Decrease in expansion due to AEA (%)
	0%	1.05	0.48	54
	6%	0.85	0.45	47
	12%	0.62	0.28	54
Decrease in expansion due to SF (%)	0%	-	-	-
	6%	20	6	-
	12%	40	40	-

Combined Effect of AEA and Silica Fume on ASR

The combined use of AEA and silica fume resulted in the minimum expansion of bars due to ASR (Fig.4).

Expansion Data at Longer Ages

In all cases small further expansions were registered to an age of 550 days the increases varying from a maximum of 0.3% to a minimum 0.02% (Table 3).

TABLE 3 - Observed Expansion of Mortar Bars made with and without AEA and SF

Age (Days)	300						550					
AEA	Absent			Present			Absent			Present		
% SF	0	6	12	0	6	12	0	6	12	0	6	12
% Expansion	1.05	0.85	0.62	0.48	0.45	0.28	1.35	0.91	0.67	0.50	0.57	0.45

Air-Void System

The air-void content and spacing factor of mortar bars containing AEA and containing no AEA are shown in Table 4. In the bars containing no AEA, the air-void content was about 1% - 2% and the spacing factors were of the order of about 2 mm. In the bars containing AEA, the air-void content increased to about 6% to 8% and spacing factors decreased to about 0.3 mm to 0.4mm.

TABLE 4 - Air Void Content and Spacing Factor of the Mortar Bars Containing no AEA and Containing AEA

Samples	Bars with no AEA			Bars with AEA		
SF content(%)	0	6	12	0	6	12
Air void content(%)	1.26	1.23	1.79	7.31	6.16	8.45
Spacing factor(mm)	2.97	2.26	1.97	0.26	0.28	0.42

Petrographic Examination

Figs. 5 and 6 show optical microphotographs of mortar bars containing no AEA. There was extensive development of opal-associated cracks in the bar made without silica fume (Fig. 5). When 6% cement was replaced by silica fume, it greatly reduced the extent of attack and opal particles were surrounded by reaction rims (Fig. 6). Figs. 7 and 8 show optical microphotographs of mortar bars containing AEA. In the bars containing 0% silica fume, the opal was severely attacked, but the reaction products near the particles of opal penetrated into the air void system in the cement paste (Fig. 7). Some cracks were observed in the paste surrounding the opal particles, but they were short as stress was relieved by accommodation of reaction products in the air voids. In the bars containing 6% silica fume replacement of cement, opal particles were surrounded by a reaction rim (Fig.8), but no severe cracking was observed. Reaction products found their way into air voids near the opal particles.

DISCUSSION

(1). Mortar bars containing 2% opal as reactive aggregate showed very high expansion. Partial replacement of cement with silica fume reduced the expansion. The reduction in expansion due to silica fume may be attributed to the consumption of alkali and calcium hydroxide by pozzolanic reactions. This follows because calcium hydroxide is the source of both OH^- and Ca^{++} ions. OH^- is necessary for attack on Si-O-Si bonds in opal and Ca^{++} may exchange for Na^+ and K^+ ions regenerating further amounts of expansive alkali-silica complex. This interpretation is supported by other experimental results which showed that when lime was added to mortar bars containing opal expansion increased (3). Silica fume also delayed the start of expansion regardless of whether or not the bars were air-entrained. This effect was probably a result of the pozzolanic reaction which competes with the alkali-silica reaction for the available alkalies. Also lowering of the Ca-ion concentration probably delayed regeneration of Na-silicate and hence expansion was correspondingly delayed.

(2). Air-entrainment of mortar bars reduced expansion caused by ASR regardless of whether or not silica fume was present. Overall, about 6% air voids with a spacing factor of 0.3mm reduced expansion by about 50%. This is in agreement with the results obtained by Jensen et al (2); i.e. when about 4% air voids were introduced the average expansion was reduced by about 40%. The reduction in expansion due to air-entrainment may be attributed to the pressure relief resulting from the accommodation of reaction products in the air-voids (Figs. 5 and 6).

(3). The combination of AEA and silica fume was far more effective in reducing expansion due to alkali-silica reaction than either AEA or silica fume used separately.

(4). At an age of 10 months, the observed reduction in expansion was not a simple sum of the reduction produced by AEA plus that due to SF (Table 5). Simple addition would indicate reductions of 67% for AEA plus 6% SF and 94% for AEA plus 12% SF whereas observed values were 56% and 73% respectively. An alternative calculation may be considered (Table 5). As shown in Table 2 air entrainment alone reduced expansion by 54% so 46% of the possible expansion remained. Also it is shown that 6% SF (without AEA) reduced expansion by 20%. A 20% reduction of the 46% remaining on use of AEA alone is 9%. This suggests a total predicted reduction in expansion of 63% (i.e. 9%+54%). A similar calculation for 12% SF plus AEA gives a 72% predicted reduction in expansion. Observed reductions were 57% and 73% respectively. The results of similar calculations for 550 day values are also shown in Table 5.

TABLE 5 - Observed and Calculated % Reduction in ASR Expansion due to AEA + SF

Ages (Days)	300		550	
% SF	6	12	6	12
Observed	57	73	58	67
Arithmetic sum	67	94	69	83
Alternative summation	63	72	75	82

CONCLUSIONS

(1). Expansion of mortar bars due to alkali-silica reaction was reduced by air-entrainment and by partial replacement of cement with silica fume.

(2). Onset of expansion was also delayed.

(3). A combination of air-entrainment with replacement of cement by silica fume further decreased expansion when compared with the expansion of bars containing air-entraining agent and silica fume used separately.

(4). Expansion due to alkali-silica reaction does not decrease by simple arithmetic addition when control is sought by combining air-entrainment with partial cement replacement by silica fume.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge financial support from the Natural Sciences and Engineering Research Council of Canada and supply of materials from Canadian Cement Companies, W.R. Grace and Steele Bros. Ltd. Thanks are due to Rene Kadach for secretarial assistance.

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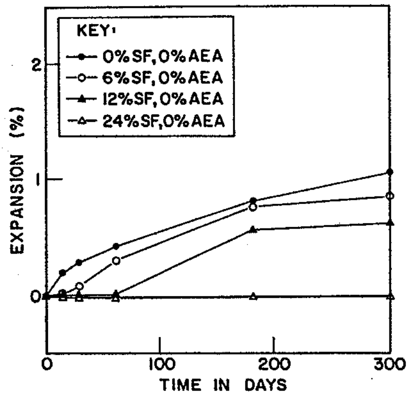

Figure 1 Effect of SF on ASR expansion of mortar bars in the absence of AEA

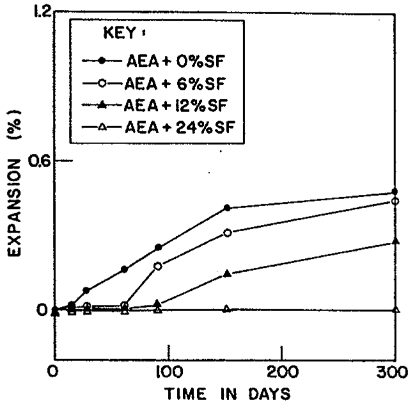

Figure 2 Effect of SF on ASR expansion of mortar bars in the presence of AEA

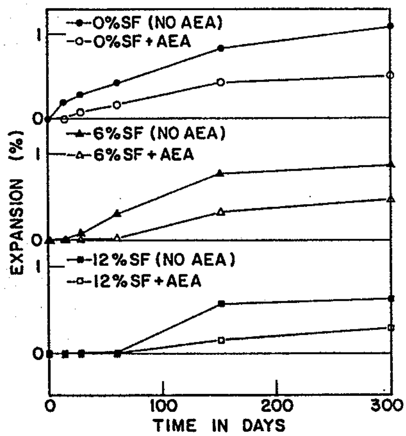

Figure 3 Effect of AEA on ASR expansion of mortar bars

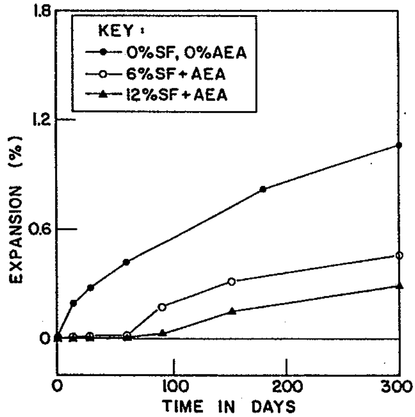

Figure 4 Effect of combined AEA and SF on ASR expansion of mortar bars

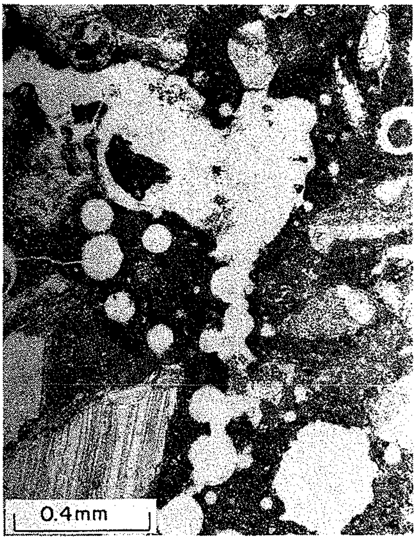

Figure 5 Optical micrograph of opal in mortar bars with no AEA and no SF

Figure 6 Optical micrograph of opal in mortar bars with 6% SF but no AEA

Figure 7 Optical micrograph of opal in mortar bars with AEA but no SF

Figure 8 Optical micrograph of opal in mortar bars with AEA and 6% SF