Effect of Blended Fly Ashes in Mitigating Alkali–Silica Reaction

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The role of chemical composition of fly ash in mitigating alkali–silica reaction (ASR) was examined, and findings were used to evaluate blends of high-lime and low-lime fly ashes in their ability to mitigate ASR. In addition, the influence of particle size (fineness) of fly ashes on ASR mitigation was evaluated, so that the relative significance of fineness and chemical composition of fly ash in mitigating ASR could be established. Findings from these studies confirm results from studies on the influence of lime content of ash on ASR mitigation. Blended fly ashes containing content of no more than 16.5% equivalent calcium oxide and no less than 66% equivalent silicon dioxide were found to be effective in mitigating ASR. The performance of blended fly ashes was comparable with that of virgin fly ashes of equivalent chemical composition. Finer fly ashes showed better ASR mitigation in the case of low- and intermediate-lime fly ashes. However, in the case of high-lime fly ashes, the effect of fineness could not be clearly resolved. Findings from this study indicate that both the physical and the chemical properties of fly ash are important in selecting ashes for developing blends that are effective in ASR mitigation.

Alkali–silica reaction (ASR) is a chemical reaction that occurs in concrete between alkali–hydroxides present in the pore solution and certain types of aggregates containing certain reactive siliceous minerals or glass. The deleterious effects of ASR have been observed in a wide variety of concrete structures containing a range of aggregates under different exposure conditions. Some of the common strategies to prevent and mitigate ASR distress in new construction include (*a*) screening potentially reactive aggregates, (*b*) limiting alkali content of concrete, (*c*) use of supplementary cementing materials (SCMs), and (*d*) use of lithium admixtures.

Among the strategies to mitigate ASR, the use of SCMs, particularly fly ash, has been widely employed in the industry. Fly ash is a finely divided coal combustion residue that contains alumino-siliceous glass with varying quantities of lime content (CaO) along with some crystallized mineral constituents.

Well recognized is that fly ashes mitigate ASR distress in concrete through a combination of chemical and physical effects resulting from pozzolanic reaction (*1*). These effects include (*a*) reduction in calcium hydroxide content of hydrated cement paste through formation of a dense and a low calcium oxide to silicon dioxide ($CaO–SiO_2$) ratio calcium–silicate–hydrate (C-S-H) gel, (*b*) eduction in pore solution alkalinity through alkali binding by the pozzolanic reaction product (C-S-H gel), and (*c*) refinement of pore structure and pore-size distribution in hydrated cement paste resulting in reduced permeability. The effectiveness of fly ash in mitigating ASR depends on its chemical and physical characteristics. Fly ashes can vary widely in their chemical composition and particle fineness according to the type of coal from which they are produced, and also on the basis of the operational characteristics of the power plants (*2–5*).

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INFLUENCE OF CHEMICAL COMPOSITION OF FLY ASH ON ASR MITIGATION

Existing specifications (ASTM C618 and AASHTO M295) broadly characterize fly ashes on the basis of their bulk chemical composition into Class F [$SiO_2 + Al_2O_3$ (aluminum oxide) + Fe_2O_3 (iron III oxide) > 70%] and Class C fly ashes ($SiO_2 + Al_2O_3 + Fe_2O_3$ content from 50% to 70%). Canadian specification CSA A23.5 categorizes fly ashes on the basis of their lime content as low-lime content or Type F (≤ 8% ± 1% CaO content), intermediate-lime content, or Type CI (> 8% to ≤ 20% ± 2% CaO) and high-lime content or Type CH (> 20% CaO content).

It has been shown that low-lime fly ashes are more effective in reducing the pore solution alkalinity than high-lime fly ashes; they are consequently better in mitigating ASR (*4, 6, 7*). In a recent study, Rangaraju and Desai showed that the low-lime fly ashes were significantly more effective than high-lime fly ashes in mitigating ASR in the presence of pavement deicing chemicals (*8*).

From findings reported in the literature, recent work by Malvar and Lenke has shown that the efficacy of fly ash in mitigating ASR is better characterized by considering a chemical index that is based on all the principal oxides in fly ash, rather than merely on lime content of the ash (*9*). Findings from this study also indicate that low-lime fly ashes are more effective than high-lime fly ashes at typical replacement levels of 25% by mass of cement.

Although low-lime fly ashes are more effective in mitigating ASR at normal dosage levels, high-lime fly ashes, when used at significantly higher replacement levels, can also mitigate ASR. In their studies, Shehata and Thomas showed that deleterious expansions in concrete prisms with Spratt limestone can be controlled to below 0.04% at 2 years using high-lime ashes (CaO > 24%) at dosage levels in excess of 50% (*7*). However, high levels of cement replacement with fly ash can significantly reduce early-age strength gain and can negatively affect construction operations, although these effects are somewhat less pronounced with high-lime fly ashes. Such concerns are exacerbated during wintertime construction, when the strength gain in concrete is even slower. For these reasons, most construction specifications typically limit the maximum amount of SCM that is allowed in the concrete. Therefore, the use of high-lime fly ash at high dosage levels to mitigate ASR may not be a feasible option.

TABLE 1 Oxide Composition of Cement and Fly Ashes

Sample Number and Material or Mixture ID	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	Total Alkali (as Na_2O equivalent)	Specific Gravity
A. cement (control)	19.78	4.98	3.13	61.84	2.54	4.15	0.82	3.15
B. fly ash								
1. HL1	34.90	19.50	5.70	26.60	5.00	2.00	1.99	2.61
2. HL2	37.60	18.80	6.00	24.20	4.50	2.30	1.81	2.50
3. HL3	39.66	20.42	5.51	22.85	4.22	1.21	1.9	—
4. IL1	41.91	21.08	5.61	18.94	4.21	0.98	2.59	2.57
5. IL2	49.69	15.03	6.6	15.63	4.92	0.9	3.93	2.55
6. IL3	56.26	19.88	4.48	12.25	2.76	0.48	1.21	2.41
7. LL1	54.53	26.29	5.03	7.31	1.6	0.39	0.96	2.17
8. LL2	61.63	24.86	4.56	1.4	0.23	0.21	1.6	2.09
9. LL3	60.30	28.60	3.20	1	0.00	0.00	2.13	2.20

NOTE: — = not applicable.

The limit on allowable cement replacement level for a high-lime fly ash can present challenges in situations where ASR mitigation is required and the only available SCM is a high-lime fly ash. In such situations, one way to economically address ASR mitigation is to blend the local high-lime fly ash with an imported low-lime fly ash or other SCMs. This strategy is possible only when the economic benefits of blending SCMs outweigh the use of other SCMs altogether. Alternatively, high-lime fly ash may potentially be used at normal dosage levels in combination with lithium admixture to provide a comprehensive solution to tackle potential ASR issues (*10*).

The behavior of blended fly ashes (i.e., high-lime and low-lime ashes) in mitigating ASR has not been extensively studied, no predictive tools are available to assess the required composition or dosage of the blended ash to achieve adequate ASR mitigation at a given dosage level. In this investigation, a comprehensive evaluation of the efficacy of blended fly ashes in mitigating ASR has been studied.

INFLUENCE OF FINENESS OF FLY ASH ON ASR MITIGATION

Finer fly ashes have significantly higher surface areas than others and therefore tend to be more reactive (*2, 3*). Past research with low-lime fly ashes has shown that finer ashes are more effective in mitigating ASR than coarser ashes are (*11*). However, the effect of fineness of intermediate-lime and high-lime fly ashes on ASR mitigation is not thoroughly established. In this investigation, the effect of fineness of low-lime, intermediate-lime, and high-lime fly ashes on ASR mitigation has been studied.

OBJECTIVES

The primary objectives of this study are to

1. Determine the influence of chemical composition of fly ash on its ability to mitigate ASR and confirm the findings from other research studies,
2. Determine the efficacy of blended fly ash containing high-lime and low-lime fly ashes on their ability to mitigate ASR,
3. Compare the ASR mitigation performance of blended fly ashes with virgin fly ashes of equivalent chemical composition, and
4. Determine the effect of fineness of low-lime, intermediate-lime, and high-lime fly ashes on their ability to mitigate ASR.

EXPERIMENTAL INVESTIGATION

Materials

The materials used in this study include ASTM Type I cement (high-alkali), reactive siliceous limestone from Spratt quarry, and nine fly ashes. Three high-lime fly ashes (HL1, HL2, and HL3), three intermediate-lime fly ashes (IL1, IL2, and IL3), and three low-lime fly ashes (LL1, LL2, and LL3) were used in this study. The oxide compositions of the cement and the fly ashes are shown in Table 1. The particle size distribution of fly ashes was determined using the Malvern laser particle size analyzer. Average particle size and specific surface area of fly ashes are shown in Table 2. Table 2 data show that the average particle size and specific surface area of fly ashes used in this study range from 10.92 to 25.08 μm and 0.66 to 1.8 m^2/g, respectively. Also, it is evident that high-lime fly ashes are generally finer compared with intermediate- and low-lime fly ashes.

Mixture Proportions and Experimental Methods

In this study, standard ASTM C1567 tests were conducted to evaluate the efficacy of fly ashes in mitigating ASR. A standard ASTM C1260 test was conducted to determine the reactivity of Spratt limestone and establish the expansion of control mortar bars (i.e., without fly ash). The mixture proportions used in this study are as

TABLE 2 Average Particle Size and Fineness of Fly Ashes

Fly Ash ID	Average Particle Size, D_{50} (μm)	Specific Surface Area (m^2/g) (laser particle size analyzer)
HL1	14.48	1.610
HL2	12.32	1.550
HL3	10.92	1.800
IL1	13.99	1.490
IL2	20.66	0.969
IL3	21.20	0.961
LL1	20.90	0.807
LL2	25.08	0.660
LL3	17.02	0.887

recommended in ASTM C1260 and ASTM C1567 test procedures. The aggregate-to-cementitious materials ratio and the water-to-cementitious material ratio used are 2.25 and 0.47, respectively. The 14-day expansion of control mixture was found to be 0.398%. An expansion limit of 0.1% at 14 days was considered a measure of effective ASR mitigation. The mortar mixture notations used in this study are the same as the fly ash notations provided in Table 1. All the tests in this research study were conducted by a single operator, and the variability in all of the individual test results was well below 8.3% (the precision limit within-laboratory established in the ASTM C1567 test) from the mean expansion value in that test.

Experimental Program

Effect of Chemical Composition of Fly Ash on ASR Mitigation

To verify and validate the role of fly ash chemistry on ASR mitigation, a series of ASTM C1567 tests was conducted using nine fly ashes with different chemical compositions at a dosage level of 25% replacement by mass of cement. The 14-day mortar bar expansions were correlated with different chemical parameters of the fly ashes with chemical composition of the fly ash as the only variable. To establish these correlations, the following chemical parameters were considered: (*a*) CaO content, (*b*) SiO_2 content, (*c*) sum of SiO_2 + Al_2O_3 + Fe_2O_3 contents, (*d*) equivalent CaO (CaO_{equi}) content, and (*e*) equivalent SiO_2 (SiO_{2equi}) content. The CaO_{equi} and SiO_{2equi} were determined for all the nine fly ashes, as suggested by Malvar and Lenke (*9*). The formulas to calculate CaO_{equi} and SiO_{2equi} are as follows:

$$CaO_{equi} = CaO + 0.905\ Na_2O_{equi} + 1.391\ MgO + 0.7\ SO_3 \quad (1)$$

$$SiO_{2equi} = SiO_2 + 0.589\ Al_2O_3 + 0.376\ Fe_2O_3 \quad (2)$$

where

Na_2O_{equi} = equivalent sodium oxide,
MgO = magnesium oxide, and
SO_3 = sulfur trioxide.

Effect of Blended Fly Ashes on ASR Mitigation

The mixtures selected to determine the effect of blending of fly ashes on ASR mitigation were based on the oxide compositions. Accordingly, two high-lime fly ashes (HL1 and HL2) and two low-lime fly ashes (LL2 and LL3) were selected. Each of the selected high-lime fly ashes was blended with each of the low-lime fly ashes, which produced four blending combinations: HL1-LL2, HL1-LL3, HL2-LL2, and HL2-LL3. In each of these blending combinations, the percentage of high-lime fly ash was decreased from 100% to 0% (with decrements of 20%), and the percentage of low-lime fly ash was correspondingly increased from 0% to 100% (with increments of 20%), such that the total quantity of fly ash in the mixture is constant and equal to 25% by mass of cement. By this process, only the oxide compositions of blended fly ashes were varied, keeping all other parameters constant; hence, the oxide equivalents could be correlated to the 14-day expansion. Thus, each of the blended combination consisted of six mixtures, including two virgin fly ash mixtures (100-0 and 0-100) and four blended combination mixtures (80–20, 60–40, 40–60, and 20–80). These combinations and their corresponding net oxide contents are shown in Table 3. The composition of these blended fly ashes and their corresponding mortar bar expansion data will be compared with virgin ashes of similar composition: HL3, IL2, IL3, and LL1.

TABLE 3 Blending Combinations and Their Fly Ash Oxide Composition

		Percentage Fly Ash		Oxide Composition of Blended Fly Ashes						
Blending Combination	Mixture ID	High-Lime	Low-Lime	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	Total Alkali as Na_2O_{equi} (%)
HL1-LL2	100%HL1	100	0	34.90	19.50	5.70	26.60	5.00	2.00	1.99
	80%HL1 + 20%LL2	80	20	40.25	20.57	5.47	21.56	4.05	1.64	1.91
	60%HL1 + 40%LL2	60	40	45.59	21.64	5.24	16.52	3.09	1.28	1.83
	40%HL1 + 60%LL2	40	60	50.94	22.72	5.02	11.48	2.14	0.93	1.76
	20%HL1 + 80%LL2	20	80	56.28	23.79	4.79	6.44	1.18	0.57	1.68
	100%LL2	0	100	61.63	24.86	4.56	1.40	0.23	0.21	1.6
HL1-LL3	100%HL1	100	0	34.90	19.50	5.70	26.60	5.00	2.00	1.99
	80%HL1 + 20%LL3	80	20	39.98	21.32	5.20	21.48	4.00	1.60	2.02
	60%HL1 + 40%LL3	60	40	45.06	23.14	4.70	16.36	3.00	1.20	2.05
	40%HL1 + 60%LL3	40	60	50.14	24.96	4.20	11.24	2.00	0.80	2.07
	20%HL1 + 80%LL3	20	80	55.22	26.78	3.70	6.12	1.00	0.40	2.10
	100%LL3	0	100	60.30	28.60	3.20	1.00	0.00	0.00	2.13
HL2-LL2	100%HL2	100	0	37.60	18.80	6.00	24.20	4.50	2.30	1.81
	80%HL2 + 20%LL2	80	20	42.41	20.01	5.71	19.64	3.65	1.88	1.77
	60%HL2 + 40%LL2	60	40	47.21	21.22	5.42	15.08	2.79	1.46	1.73
	40%HL2 + 60%LL2	40	60	52.02	22.44	5.14	10.52	1.94	1.05	1.68
	20%HL2 + 80%LL2	20	80	56.82	23.65	4.85	5.96	1.08	0.63	1.64
	100%LL2	0	100	61.63	24.86	4.56	1.40	0.23	0.21	1.6
HL2-LL3	100%HL2	100	0	37.60	18.80	6.00	24.20	4.50	2.30	1.81
	80%HL2 + 20%LL3	80	20	42.14	20.76	5.44	19.56	3.60	1.84	1.87
	60%HL2 + 40%LL3	60	40	46.68	22.72	4.88	14.92	2.70	1.38	1.94
	40%HL2 + 60%LL3	40	60	51.22	24.68	4.32	10.28	1.80	0.92	2.00
	20%HL2 + 80%LL3	20	80	55.76	26.64	3.76	5.64	0.90	0.46	2.07
	100%LL3	0	100	60.30	28.60	3.20	1.00	0.00	0.00	2.13

Effect of Fineness of Fly Ash on ASR Mitigation

In this study, three fly ashes, HL1, IL2, and LL3, were considered. Each fly ash was sieved in a Gilsonic auto sieve shaker using four sieves, capable of screening fly ashes into four size fractions: S1 (>45 µm); S2 (25 to 45 µm); S3 (15 to 25 µm); and S4 (5 to 15 µm). Because significant quantities of ash was not retained on sieves S3 and S4 with HL1 and IL2 fly ashes, the individual size fractions from S3 and S4 were combined to form a broader particle size fraction with these two ashes. This combined size fraction is identified as S3S4 (5 to 25 µm) in the results. Thus, three size fractions from HL1 and IL2 fly ashes (S1, S2, and S3S4) and four size fractions from LL3 fly ash (S1, S2, S3, and S4) were considered. After a significant quantity of each of the fly ash size fractions was obtained, mortar bars were prepared by replacing cement with 25% of each of these size fractions. Thus, 14 mixtures were studied, including one control (without fly ash) mixture, four high-lime fly ash mixtures (HL1, HL1-S1, HL1-S2, and HL1-S3S4); four intermediate-lime fly ash mixtures (IL2, IL2-S1, IL2-S2, and IL2-S3S4); and five low-lime fly ash mixtures (LL3, LL3-S1, LL3-S2, LL3-S3, and LL3-S4). Mortar bars of standard size $25 \times 25 \times 285$ mm were used to perform ASTM C1567 test to determine the ability of the size fractions of fly ashes to mitigate ASR.

DISCUSSION OF RESULTS

Effect of Chemical Composition of Fly Ash on ASR Mitigation

The performance of nine virgin fly ash mixtures in ASTM C1567 test is shown in Figure 1*a*. Figure 1*b* shows the 14-day mortar bar expansion values for the nine fly ash mixtures. Figures 1*c* through 1*f* show the 14-day mortar bar expansion as a function of CaO, SiO_2, CaO + $SiO_2 + Al_2O_3$, CaO_{equi}, and SiO_{2equi} (calculated by using the formulas given earlier) in the fly ash mixtures, respectively.

Figure 1*b* shows that all of the high-lime fly ashes are not effective in reducing the mortar bar expansion below 0.1% (at 14 days) whereas all of the low-lime ashes are effective in controlling the expansions below 0.1%. Similar results are also obtained in the past by other researchers (*8, 10*). Figures 1*c* through 1*f* show that the 14-day ASR expansion is directly proportional to CaO and its equivalent but inversely proportional to SiO_2, its equivalent, and $SiO_2 + Al_2O_3 + Fe_2O_3$ content. Also, the $SiO_2 + Al_2O_3 + Fe_2O_3$ content had the best fit among all with $R^2 = .933$. Also, ASR expansion below 0.1% was achievable with fly ashes that contained CaO and its equivalent less than 12.5% and 16.25%, respectively, and also contained $SiO_2 + Al_2O_3 + Fe_2O_3$, SiO_2, and SiO_2 equivalent greater than 78.5%, 51%, and 66%, respectively, which indicates that their roles are significantly important. Thus, these oxides and their equivalents may be suitably altered in blended fly ashes to achieve ASR expansion within 0.1%. This concept of using specific oxide and oxide equivalents of fly ash to mitigate ASR expansion is used as a basis for the detailed studies carried out on blending of fly ashes, detailed in the next section.

Effect of Blended Fly Ashes on ASR Mitigation

Performance of Blended Combinations of High-Lime and Low-Lime Fly Ashes

The performance of the four fly ash blends (HL1-LL2, HL1-LL3, HL2-LL2, and HL2-LL3) in the standard ASTM C1567 test is shown in Figures 2*a* through 2*d*. Figures 2*e* through 2*h* shows the 14-day mortar bar expansion as a function of the CaO, SiO_2, $SiO_2 + Al_2O_3 + Fe_2O_3$, CaO_{equi}, and SiO_{2equi} contents in the four blends.

Figures 2*a* through 2*d* show that as the percentage of high-lime fly ash in the blend decreases from 100% to 0%, the mortar bar expansion decreases. Conversely, as the percentage of low-lime fly ash increases in the blend from 0% to 100%, the mortar bar expansion decreases. Also, the expansions of mortar bars with blended ashes (80%HL–20%LL, 60%HL–40%LL, 40%HL–60%LL, and 20%HL–80%LL) were found to be within the expansions of 100% HL and 100% LL mixtures. Also, a definite linear trend seems to exist in all the blended combinations. Figures 2*e* and 2*f*, show that a linear trend exists in all the oxides and their equivalents of blended combination of fly ash and 14-day mortar bar expansion. Also, mortar bar expansions below 0.1% were achievable with all blended fly ashes, whose CaO and CaO_{equi} were less than 11% and 16%, respectively. Similarly, linear trends were also seen between SiO_{2equi} content of the blended fly ashes and 14-day mortar expansion, and, in this case, ASR mitigation below 0.1% was achievable with blended fly ashes, whose $SiO_2 + Al_2O_3 + Fe_2O_3$, SiO_2, and SiO_{2equi} were greater than 78%, 51%, and 66%, respectively. These values are in close agreements with values of the CaO, CaO_{equi}, $SiO_2 + Al_2O_3 + Fe_2O_3$, SiO_2, and SiO_{2equi} obtained earlier (for virgin fly ashes).

Comparison of Performance of Virgin and Blended Fly Ash Mixtures with Equivalent Chemical Composition

The purpose of comparing the performance of virgin and blended fly ash mixtures having similar oxide composition is to understand if significant variations are introduced into ASR mitigation.

Data in Table 3 show that all blended fly ash mixtures of 80%HL +20%LL—80%HL1+20%LL2, 80%HL1+20%LL3, 80%HL2+20% LL2, and 80%HL2+20%LL3—have approximately similar oxide composition, and they can be compared with a virgin fly ash mixture (HL3) of approximately similar composition. A similar comparison can be made for 60%HL+40%LL, 40%HL+60%LL, and 20%HL+ 80%LL fly ash blending combination mixtures with IL2, IL3, and LL1 virgin fly ash mixtures, respectively. Thus, Figures 2*a* through 2*d* can be replotted by comparing the expansion behavior of the aforementioned fly ash blended combinations with virgin fly ash mixtures. This is shown in Figures 3*a* through 3*d*. Also, the CaO_{equi} of both blended fly ash and virgin fly ash mixtures are found and compared, as shown in Figure 4*a*. The 14-day expansion of the fly ash blended combinations and virgin fly ash mixtures having similar oxide composition is shown in Figure 4*b*. Figures 3*a* through 3*d* show that the expansion behavior of both blended fly ash and virgin fly ash mixtures are similar. Figures 4*a* and 4*b* show that the mixtures 80%HL+ 20%LL, 60%HL+40%LL, HL3, and IL2 had CaO_{equi} significantly above 16%; correspondingly, their expansions were above 0.1%. However, 40%HL+60%LL, 20%HL+80%LL, IL3, and LL1 had CaO_{equi} at about approximately 16% or below; correspondingly, their expansions were below 0.1%. Thus, a blended combination of 50%HL+50%LL may seem an optimum for ASR mitigation from the data presented.

Effect of Particle Size of Fly Ash on ASR Mitigation

A comparative plot of the 14-day mortar bar expansions of fly ash mixtures containing different size fractions of HL1, IL2, and LL3 fly ashes is shown in Figure 2.

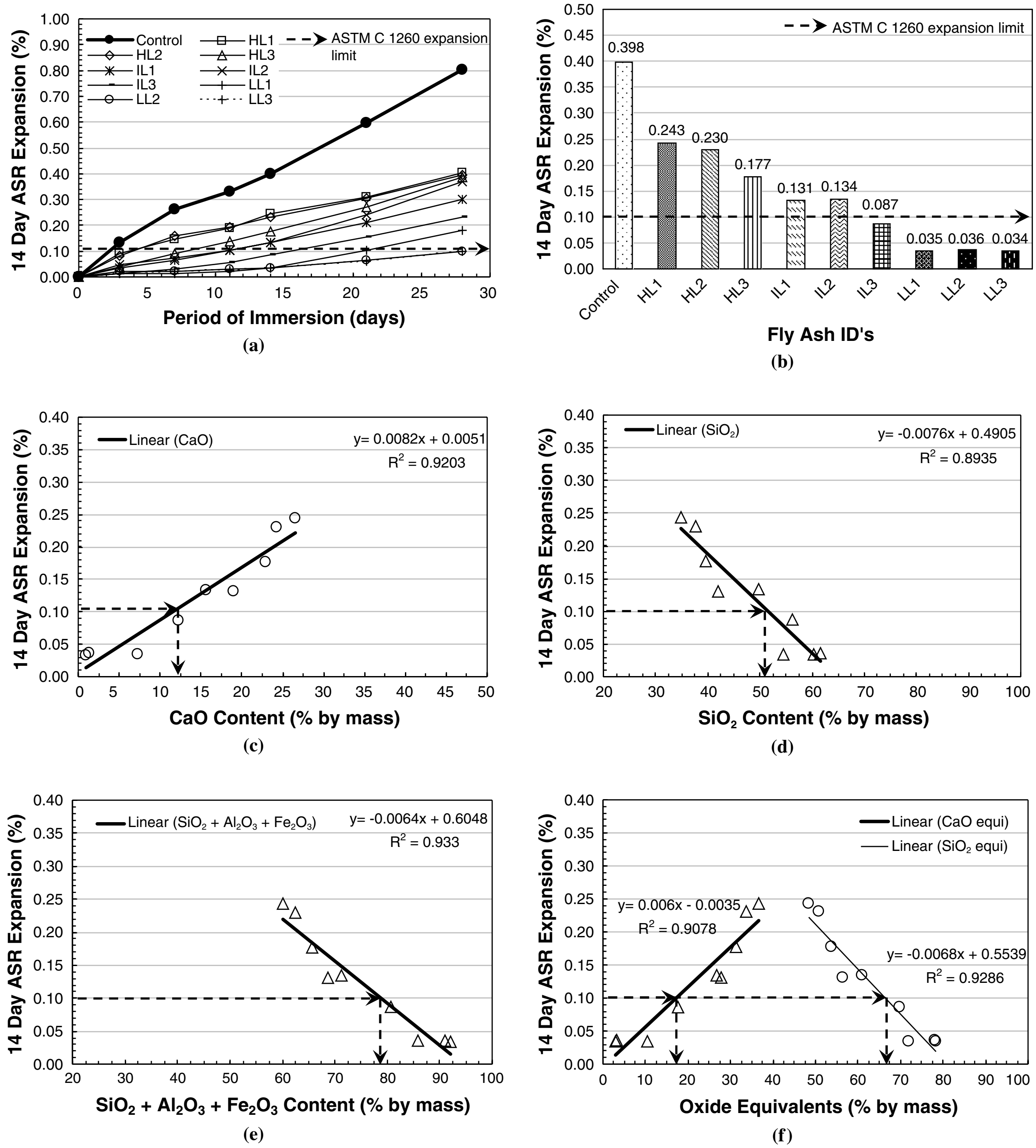

FIGURE 1 Effect of chemical composition of fly ashes: (*a*) performance of virgin fly ashes on ASR expansion, (*b*) 14-day ASR expansion of nine fly ash mixtures, (*c*) CaO versus 14-day ASR expansion, (*d*) SiO_2 versus 14-day ASR expansion, (*e*) $SiO_2 + Al_2O_3 + Fe_2O_3$ versus 14-day ASR expansion, and (*f*) CaO_{equi} and SiO_{2equi} versus 14-day ASR expansion.

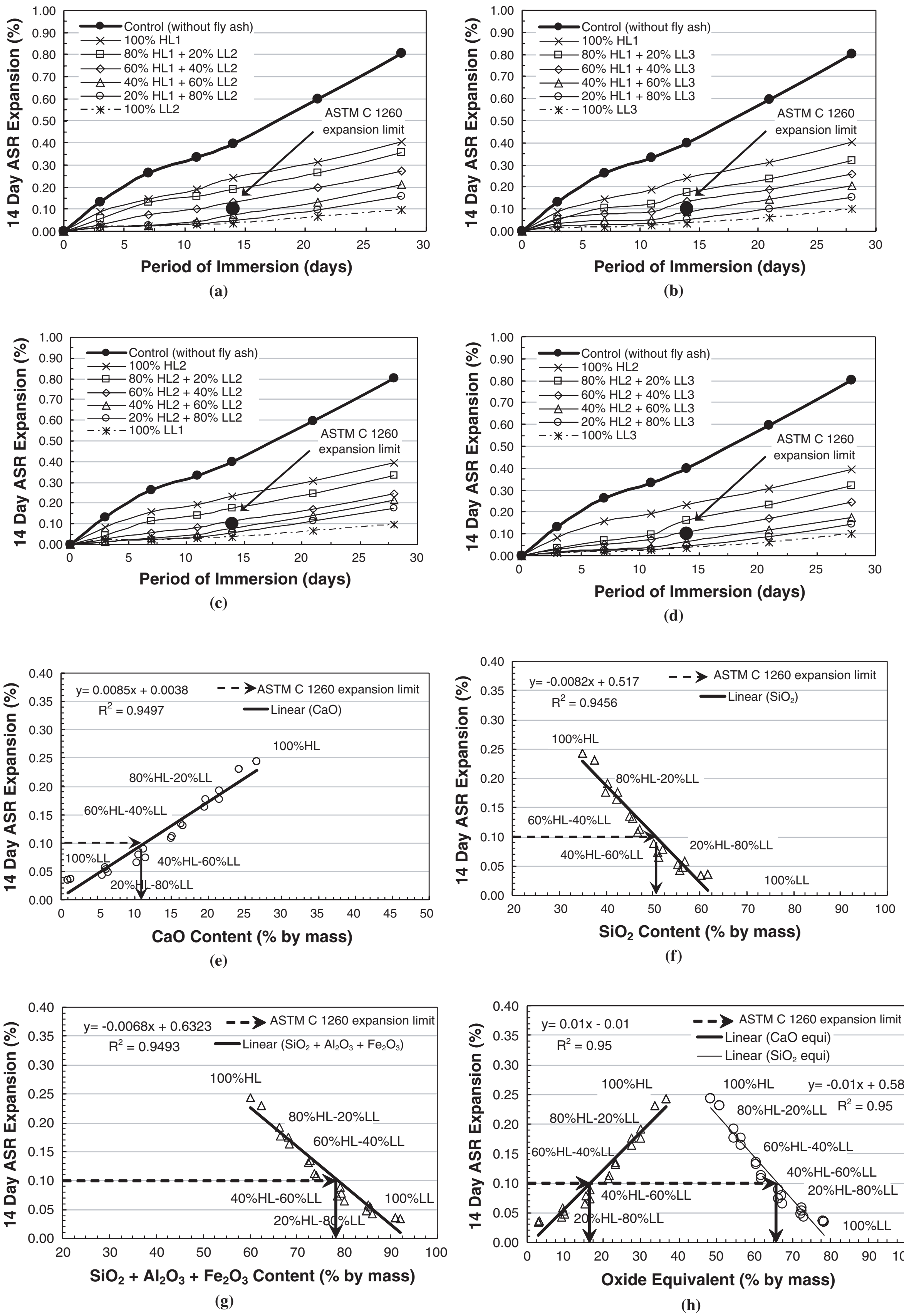

FIGURE 2 Effect of blending of high-lime and low-lime fly ashes on ASR mitigation: (*a*) HL1 and LL2, (*b*) HL1 and LL3, (*c*) HL2 and LL2, (*d*) HL2 and LL3, (*e*) CaO versus 14-day ASR expansion, (*f*) SiO_2 versus 14-day ASR expansion, (*g*) $SiO_2 + Al_2O_3 + Fe_2O_3$ versus 14-day ASR expansion, and (*h*) CaO_{equi} and SiO_{2equi} versus 14-day ASR expansion.

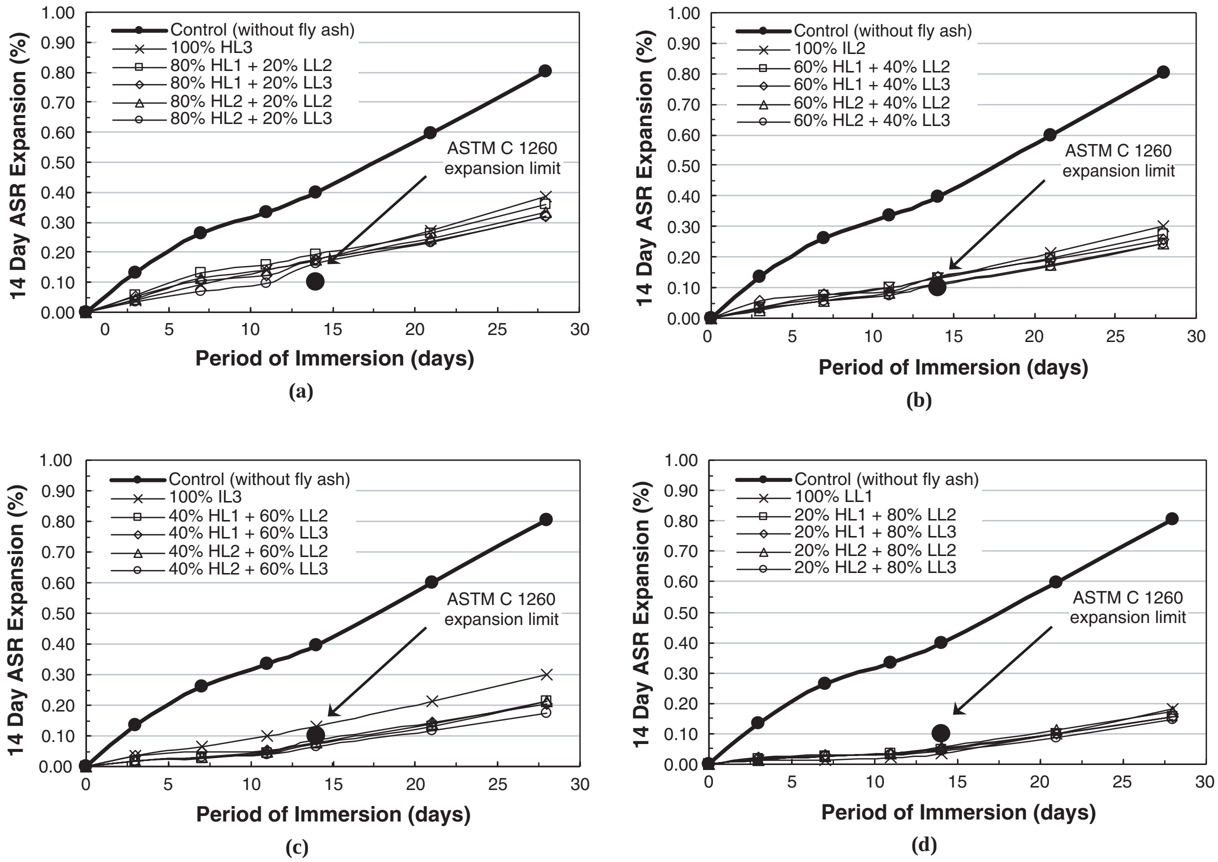

FIGURE 3 Blending of fly ashes having similar composition: (*a*) 80–20 combination, (*b*) 60–40 combination, (*c*) 40–60 combination, and (*d*) 20–80 combination.

Data in Figure 5 show that as the particle size is reduced from S1 to S4 (for LL3 mixtures) and from S1 to S3S4 (for IL2 mixtures), the mortar bar expansion also is reduced. The particle size of fly ash seems to have a marked influence on ASR expansion for the LL3 and IL2 mixtures both. The reduction in mortar expansions for low-lime fly ash mixtures with decreasing particle size from LL3-S1 to LL3-S4 was found to be 73.33%. For intermediate-lime fly ash mixtures, the percentage of reduction in mortar bar expansion was found to be 71.2% for smaller particle size fraction of fly ash (IL2-S3S4) compared with the coarser size fraction of the fly ash (IL2-S1). However, for HL1 mixtures, the decrease in the particle size is beneficial only up to a certain limit (from S1 to S2), beyond which (from S2 to S3S4) the particle size seems to have negative effects. However, expansions of HL1-S2S3 are less than for the virgin HL1 mixture. In none of the tests with HL1 size fractions were the mortar bar expansions below 0.1%. Therefore, the fineness of high-lime fly ashes may not have a significant influence in mitigating ASR.

CONCLUSIONS

On the basis of the boundary conditions established in this study, the following general conclusions can be drawn:

- The chemical composition of a fly ash has a significant influence on the efficiency of the fly ash to mitigate ASR. All the chemical parameters investigated in the study, including CaO, CaO_{equi}, SiO_2, SiO_{2equi}, and $SiO_2 + Al_2O_3 + Fe_2O_3$ content, seem to have a good correlation with the effectiveness of fly ash in mitigating ASR.
- On the basis of the 14-day expansion values, fly ashes with CaO and CaO_{equi} of less than 11% and 16% and with $SiO_2 + Al_2O_3 + Fe_2O_3$, SiO_2, and $SiO_{2\,equi}$ of more than 78.5%, 51%, and 66%, respectively, may be expected to be effective in mitigating ASR at a normal fly ash dosage of 25% by mass replacement of cement with aggregates having a reactivity similar to Spratt limestone or less.
- These oxide limits were found to be applicable for both virgin and blended fly ashes.
- Performance of blended fly ashes in mitigating ASR was found to strongly depend on the chemical composition of the blended fly ash. Performance of the blended fly ash was on par with a virgin fly ash of a similar chemical composition. Performance of blended fly ashes can be predicted in a way similar to that of virgin fly ashes on the basis of the percentage of oxide limits established in this study.
- Fineness of a fly ash showed a significant influence on the ability of a fly ash to mitigate ASR, particularly in the case of low-lime and intermediate-lime fly ashes. However, with high-lime fly ash mixtures, the role of fly ash fineness seems limited.

This study was carried out using a single aggregate and a limited number of fly ashes at a single dosage level of 25% replacement by mass of cement. Hence, the recommended limits on percentage of oxide contents may vary slightly in accordance with the aggregate composition or reactivity, or both. However, because Spratt limestone is a moderate to highly reactive aggregate, and the majority of aggregates

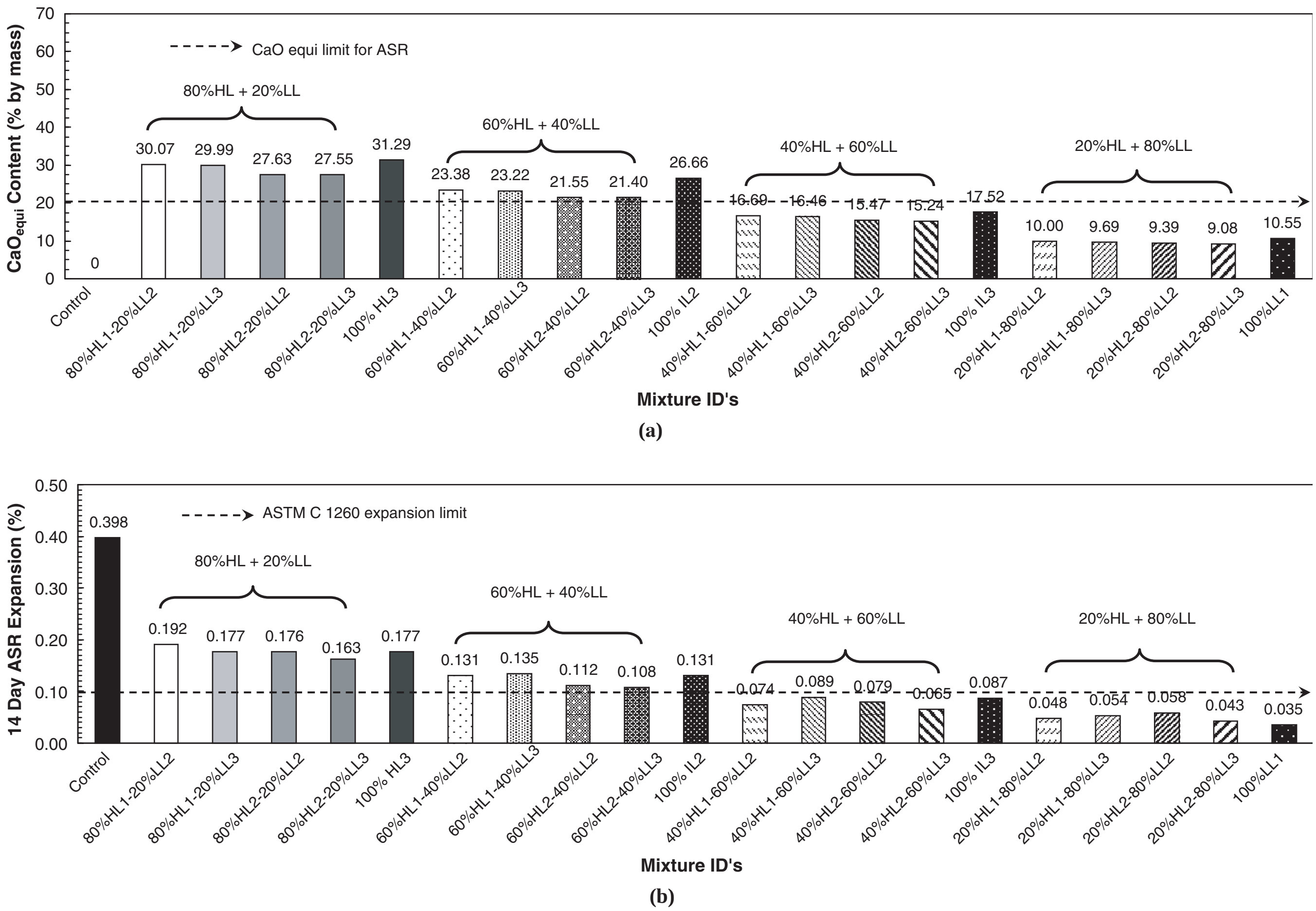

FIGURE 4 Comparison of expansions of virgin and blended fly ash mixtures with similar oxide composition: (*a*) CaO_{equi} of blended and virgin fly ash mixtures and (*b*) 14-day ASR expansion for blended and virgin fly ash mixtures.

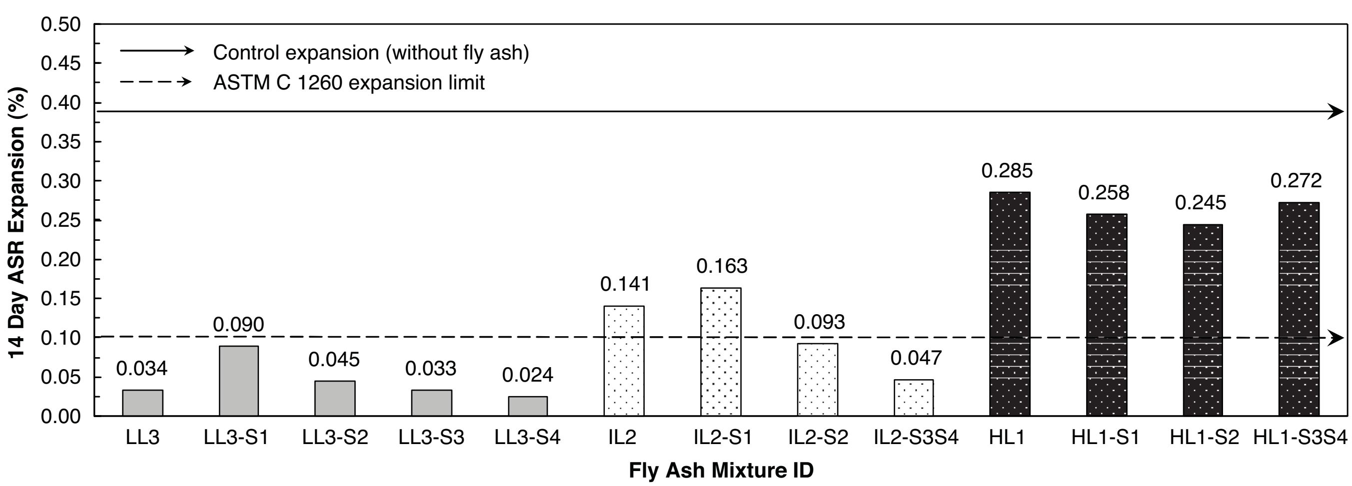

FIGURE 5 Effect of particle size fractions of high-, intermediate-, and low-lime fly ashes on 14-day mortar-bar expansion in ASTM C1567 tests.

used in the field are likely to be of lower reactivity, the findings from this study should be valid for the majority of aggregates and fly ashes commonly employed.

Overall, it can be concluded that blending of fly ashes was helpful in controlling mortar bar expansions to less than 0.1% at 14 days in the standard ASTM C1567 tests. This can be used as a strategy in locations where supplies of low-lime Class F fly ashes are limited but supplies of high-lime Class C fly ashes are abundant.

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