USE OF FLY ASH IN DOD AIRFIELD CONCRETE PAVEMENTS

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Abstract

Concrete pavement failures due to alkali-silica reaction (ASR) have emphasized the need to use supplementary cementitious materials, such as fly ash, to prevent deleterious expansions. Previous research by the U.S. Department of Defense (DOD) resulted in the adoption of 25% minimum cement replacements with Class F fly ash (with additional requirements) to prevent ASR. Recent research has shown the effect of fly ash chemical composition on its effectiveness in preventing ASR, and has allowed the determination of minimum cement replacement values to prevent ASR given fly ash composition, cement composition, and aggregate reactivity. This knowledge has allowed for lowering the requirements on the fly ash, allowing more ashes to be used and reducing costs. New minimum replacement values to mitigate ASR expansion are proposed for use even when the aggregate is labeled as innocuous. The impact of these results on DOD unified facilities guide specifications for airfield pavements is discussed.

Keywords: alkali silica reaction, fly ash, chemical composition, aggregate reactivity, ASTM C 1260

1 INTRODUCTION

A state-of-the-art review [1,2] resulted in the development of guidelines to prevent alkali-silica reaction (ASR) now used by the Tri-Services (U.S. Navy, Air Force, and Army) for airfield pavements, and which are being adapted into Department of Defense (DOD) unified facilities guide specifications (UFGS) dealing with concrete in general. However, these guidelines were somewhat conservative for fly ash, allowing only the use of ASTM C 618 [3] Class F fly ashes with additional restrictions. Hence, many ashes very close to, but not meeting those specifications could not be used, in some cases increasing concrete costs by requiring transportation of other ashes from far away. Recent research [4,5] has shown that those specifications could be relaxed while insuring ASR mitigation. This paper presents a summary of the updated fly ash requirements and the current enhancements to the tri-service UFGS for concrete pavements.

2 BACKGROUND

ASR is the reaction between the alkali hydroxide in Portland cement and certain siliceous rocks and minerals present in the aggregates, such as opal, chert, chalcedony, tridymite, strained quartz, cristobalite, etc. The products of this reaction often result in concrete expansion, cracking, and ultimately failure of the structure or pavement, including significant potential for foreign object damage to aircraft. ASR needs several components to occur: alkali (from the cement or external sources), water (or high moisture content), and a reactive aggregate. There are 3 characteristics of a fly ash that determine its efficiency in preventing ASR:

- Fineness – Finer pozzolans are more efficient in preventing ASR [6,7,8]. Malhotra et al. [6] state: "fineness of fly ashes is one of the most important physical properties affecting pozzolanic activity". Ultra fine fly ash (UFFA) [9] and raw silica fume with particle sizes around 3 and 0.1 μm, respectively, are very effective in preventing ASR.
- Mineralogy – While ashes can be characterized by their chemical components, these components can be bound and react differently from ash to ash, e.g., Mehta [10] showed the importance of mineralogy in mitigating sulfate attack.
- Chemistry – Previous models based only on chemistry have resulted in successful determination of the fly ash potential for ASR mitigation [4, 5, 11, 12].

For a given ash, the chemical composition is easily obtained, but not its fineness or mineralogy. If all ashes studied conform to ASTM C 618, the variation in fineness between them will generally be

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limited, and this factor will be not be very useful in differentiating between ashes. In the following correlations, only the chemical composition is used: each chemical constituent of the fly ash and cement is weighted based on its relative percentage (by weight) in the blend, and molar equivalent. In addition, each chemical constituent, or group thereof, can be weighted using an additional factor (e.g., α and β described below), which would also carry information on the reactivity (itself perhaps a partial reflection of mineralogy) of the constituent, or constituent group.

3 PREVIOUS TESTS

Data were gathered from five previous research studies addressing the use of fly ash in mitigating ASR. A correlation was sought between the chemical composition of the ash and the cement, and the 14-day expansion per ASTM C 1260 [13] (also called the accelerated mortar bar test, or AMBT). For cementitious blends of cement and fly ash, ASTM C 1260 was typically modified to represent the blend (this is now addressed in ASTM C 1567 [14]). Fly ash and cement compositions for all five studies are shown in Tables 1 and 2 (except for most of the Class C fly ashes, and the 14-day expansions of the cement alone, E_{14c}, and of the cement and fly ash blends, E_{14b}, which can be found in [4]).

McKeen et al. [15, 16] tested 5 fly ashes with four reactive aggregates and with Type I/II low-alkali cement (0.55% Na_2O_{eq}, where $Na_2O_{eq} = Na_2O + 0.658\ K_2O$). AASHTO T 303 [17] (similar to ASTM C 1260 or CSA A23.2-25A [18]) was used to find the 14-day control expansions (E_{14c}). Shehata and Thomas [11] tested 18 ashes (with 5.6 to 30% CaO content) with one cement (1.02% Na_2O_{eq}) and reactive Spratt aggregate (E_{14c} = 0.371%). Based on Canadian Standards Association (CSA) specifications [19] the ashes were classified as low lime Type F ash (CaO ≤ 8%), medium lime Type CI (8% < CaO ≤ 20%), and high lime Type CH (CaO > 20%). Touma et al. [20, 21] evaluated a Class F ash (CaO = 12.3%) and a Class C ash (CaO = 26.1%) with 6 reactive aggregates and one Type I/II high-alkali cement (1.14% Na_2O_{eq}). Shon et al. [22] studied one Type C fly ash (CaO = 25.9%) with a medium alkali cement (0.65% Na_2O_{eq}) using a reactive sand (E_{14c} = 0.245%). Detwiler [23] cites AMBT data with low, medium, and high CaO fly ashes (5.7%, 18.6%, 25.7%, respectively), a Type I low-alkali cement (0.43% Na_2O_{eq}), and a single reactive quartzite aggregate (E_{14c} = 0.25%).

4 EFFECT OF EACH CONSTITUENT ON ASTM C 1260 EXPANSION

In the correlations the total content, i.e., the total amount available from both the ash and the cement, was used for each chemical constituent. To allow for direct comparisons, the expansion of the mix with a blend of cement and fly ash, E_{14b}, was normalized by the expansion of the mix with cement only, E_{14c}. The chemical constituents were divided into those that increase expansion (CaO, Na_2O, K_2O, MgO, SO_3) and those that reduce it (SiO_2, Al_2O_3, Fe_2O_3).

4.1 Calcium Oxide (CaO)

Calcium oxide strongly affects the ash efficiency to mitigate ASR [1, 11, 15]. Current DOD guidelines do not allow Class C fly ash and limit the Class F fly ash CaO content to 8% [1] (see also [24]). CSA guidelines classify fly ashes based on CaO content and use the same 8% (±2%) CaO limit for Class F [19]. A good correlation was found here between normalized expansion and total CaO content with a coefficient of determination $R^2 = 0.71$ (Figure 1). CaO content varied from 3 to 30% for the ashes, and from 63 to 65% for the cements (Tables 1, 2). Since the cement CaO content was fairly constant, the total cementitious (cement plus fly ash) CaO variation is mostly due to the ash CaO content.

4.2 Alkalis (Na_2O and K_2O)

Sodium and potassium oxides have often been grouped together and their content limited, both in the cement and the fly ash. For reactive aggregates it is recommended to use low-alkali cement (≤0.6% total alkali), and for fly ash, either the total or the available alkalis are often limited. However, mixes with low-alkali cement and ashes, and with large variation in the other constituents, could be expected to have a low correlation with the C 1260 expansion, in addition to the low sensitivity of this test to alkalis in the mix. For the ashes studied here there was no noticeable correlation between cementitious alkali content and normalized expansion ($R^2 \approx 0$). ASTM C 618 no longer includes the optional 1.5% available alkali limit, however, since reactive aggregates are very sensitive to alkali, some limit is advisable. While several specifications recognize this, there is no consensus: some limit the available alkalis to 1.5% [24], others limit the total alkali in the concrete mix, accounting for either none of the fly ash alkali (if enough fly ash is used to prevent ASR), or a percentage of it (20 to 100%) [25, 26, 27, 28]. Finally, some specifications have limited the total fly ash alkalis, e.g. to 2% [29], 3%

[28], and 5% [30]. It is proposed to limit total alkalis to 3% instead of limiting available alkalis, allowing for simple alkali control, while affecting few fly ashes (less than 20% of those in Table 1).

4.3 Magnesium Oxide (MgO)

A 5% MgO limit in the fly ash was [31], or is still [24], required. Class F fly ashes typically have very little MgO, but Class C ashes are likely to have more [6]. However, Mehta [32] indicated that the MgO in fly ash often occurs either in noncrystalline form, or in the form of nonexpansive melilite phase, so a weak correlation would be expected. For the current data, a very weak correlation between normalized expansion and MgO content was found , with $R^2 = 0.05$ [5].

4.4 Sulfur Trioxide (SO_3)

Sulfur trioxide can increase deleterious expansion and is limited to a maximum of 5% in ASTM C 618 [1]. A moderate correlation ($R^2 = 0.50$) between normalized expansion and cementitious SO_3 content was found here [5].

4.5 Silicon Dioxide (SiO2)

Increased contents of SiO_2 have shown to lower ASR expansion. For the current data, Figure 2 shows a significant inverse correlation ($R^2 = 0.74$) between the cementitious SiO_2 content and the normalized 14-day expansion.

4.6 Aluminum Trioxide (Al_2O_3)

The sum SiO_2+Al_2O_3 has often shown good correlation with pozzolanic activity [6]. For the data herein, a significant inverse correlation ($R^2 = 0.60$) was found between normalized expansion and cementitious Al_2O_3 content [5].

4.7 Iron Oxide (Fe_2O_3)

Malhotra et al. [6] report that for most ashes the iron oxide is present as non-reactive hematite and magnetite, so a weak inverse correlation would be expected, and was indeed found ($R^2 = 0.13$) for the current data [5].

5 EFFECT OF EACH CONSTITUENT ON ASTM C 1260 EXPANSION

5.1 Constituents Promoting Expansion

CaO has been recognized as having one of the most deleterious effects on expansion. Hence, other deleterious constituents, such as the alkalis, MgO, and SO_3 were replaced by their CaO molar equivalents as either:

$$CaO_{eq} = CaO + 0.905\ Na_2O_{eq} + 1.391\ MgO + 0.700\ SO_3 \qquad (1)$$

$$CaO_{eq} = CaO + 0.905\ Na_2O + 0.595\ K_2O + 1.391\ MgO + 0.700\ SO_3 \qquad (2)$$

The correlation found between normalized expansion and cementitious CaO_{eq} ($R^2 = 0.78$) was better than any previous correlation with a single constituent promoting expansion (e.g. Figure 1) or other combinations thereof [4 ,5].

5.2 Constituents Reducing Expansion

SiO_2 is typically considered the most beneficial constituent in preventing expansion. Hence the Al_2O_3 and the Fe_2O_3 were replaced by their SiO_2 molar equivalents:

$$SiO_{2eq} = SiO_2 + 0.589\ Al_2O_3 + 0.376\ Fe_2O_3 \qquad (3)$$

A strong inverse correlation ($R^2 = 0.78$) was found between expansion and cementitious SiO_{2eq}.

5.3 Combination of All Constituents

The normalized expansion was correlated to the ratio CaO_{eq}/SiO_{2eq} (using Equations 1 or 2, and 3), resulting in $R^2 = 0.83$, which is an improvement from the correlations with just CaO_{eq} or SiO_{2eq}. The blend CaO_{eq}/SiO_{2eq} was normalized by the cement only CaO_{eq}/SiO_{2eq} to account for the various cements used. A better fit to this data is trilinear, with two segments of zero slope at low and high replacement levels (as proposed in [12]) resulting in $R^2 = 0.867$ (Figure 3). To account for different reactivity, chemical constituents can be weighted independently, or by groups. Two weighting factors (α and β) were included in the CaO and SiO_2 equivalencies, replacing the previous ratio CaO_{eq}/SiO_{2eq} with a so-called chemical index for the blend, C_b:

$$C_b = \frac{CaO_{eq\alpha b}}{SiO_{2eq\beta b}} = \frac{CaO + \alpha\left(0.905Na_2O + 0.595K_2O + 1.391MgO + 0.700SO_3\right)}{SiO_2 + \beta(0.589Al_2O_3 + 0.376Fe_2O_3)} \qquad (4)$$

where $\alpha = 5.64$ and $\beta = 1.14$ were found to maximize R^2. If the normalized expansion is plotted as a function of the normalized cementitious chemical index, C_b/C_c, a figure similar to Figure 3 is obtained but with a better $R^2 = 0.9026$ [4]. For a blend of ash and cement, the CaO blend content would be W times the ash CaO plus (1-W) times the cement CaO, where W is the weight fraction of the ash constituent. The same chemical index can be defined for a blend with just cement (0% ash), denoted C_c, and for a blend with only fly ash (100% ash), denoted C_{fa}. Finally, the best fit is found using a non-linear model as follows, where $\alpha = 4.42$, $\beta = 0.754$, $a_1 = 1.0550$, $a_2 = 0.7342$, $a_3 = 0.1834$ and $R^2 = 0.9149$:

$$\frac{E_{14b}}{E_{14c}} = \frac{a_1}{2}\left[1 + \tanh\left(\frac{(C_b / C_c) - a_2}{a_3}\right)\right] \tag{5}$$

R^2 does not change significantly for values of α and β near the previous ones, so for simplicity $\alpha = 6$ and $\beta = 1$ were chosen, with $a_1 = 1.0530$, $a_2 = 0.7386$, $a_3 = 0.1778$, and $R^2 = 0.9125$, as shown by the solid line in Figure 4. These values were used to calculate C_{fa}, C_c, and C_b, for the fly ash (Table 1), cement (Table 2), and blends, respectively. Since ASTM C 1260 states in its Precision section "the results of two properly conducted tests in two different laboratories should differ by no more than 27% of the mean expansion," further increases in R^2 may be difficult to achieve.

In Figures 3 and 4, the point (1, 1) represents the 14-day expansion using cement only. As fly ash is used to replace the cement, the x-axis value decreases below 1, and the corresponding normalized expansion eventually decreases. However, for low levels of cement replacement with fly ash, there is little or no decay in the corresponding normalized expansion, and data scatter alone could result in pessimums, two of which are apparent in both figures.

5.4 Fly Ash Chemical Index

Table 1 ranks all the ashes studied by increasing chemical index, C_{fa}. A value of $C_{fa} < 1.4$ usually represents an ASTM C 618 Class F ash, and values $C_{fa} > 1.4$ usually represent a Class C ash. When compared to the CSA standard [19], a value of $C_{fa} < 0.5$ usually represents a CSA Type F ash, $0.5 < C_{fa} < 1.4$ usually represents a Type CI ash, and values $C_{fa} > 1.4$ usually represent a Type CH ash. Hence the chemical index has a good correlation with both standards.

6 MINIMUM REQUIRED FLY ASH

For a given fly ash, a given cement, and a given aggregate reactivity, the objective is to determine the amount of fly ash for the mix to be non-reactive. If in Figure 4 the maximum expansion sought is 0.08% [1], and if E_{14c} is the expansion with cement only, then the maximum normalized expansion sought is $0.08/E_{14c}$. Entering $0.08/E_{14c}$ on the y-axis gives a maximum value of C_b/C_c on the x-axis. Defining the inverse of the hyperbolic tangent function of Figure 4 as function "g" it can be shown [5] that the minimum required percent fly ash substitution by weight, W, is:

$$W = \frac{1 - g(0.08 / E_{14c})}{\left(1 - \frac{CaO_{eq\alpha\, fa}}{CaO_{eq\alpha\, c}}\right) - \left(1 - \frac{SiO_{2eq\beta\, fa}}{SiO_{2eq\beta\, c}}\right) g(0.08 / E_{14c})} \tag{6}$$

This formula gives the minimum required fly ash substitution as a function of the ash chemistry, the cement chemistry, and the AMBT expansion with cement only. Once C_{fa} and C_c are calculated, and assuming that a single cement is used (C_c constant), W can be plotted as a function of E_{14c} and C_{fa}, as shown in Figure 5 for $C_c = 4.0$. In Figure 5, the first 4 curves ($C_{fa} \leq 1.1$) represent ASTM C 618 Class F ashes ($C_{fa} = 0.0$ represents a hypothetical ash with only SiO_2, Al_2O_3, and Fe_2O_3, whose sum is 100% of the ash). The least efficient of these 4 ashes ($C_{fa} = 1.1$, Sum = 70%) could mitigate very reactive aggregates, with 14-day expansions above 0.2% at a 25% replacement level. The least effective Class C ash ($C_{fa} = 3.6$) could not mitigate any reactivity for typical replacement amounts, and could potentially exacerbate the deleterious expansions depending on its composition and the replacement amount. Table 3 shows data points from these curves, for $SiO_2+Al_2O_3+Fe_2O_3 \geq 65\%$. Note that some Class C fly ashes (close to Class F) could be used for ASR mitigation, and that for highly reactive aggregates the needed replacement may be excessive. In the current DOD specifications, Class C ashes are not used, and replacements are limited to 35%. Table 3 also includes minimum replacement levels (for expansion $\leq 0.1\%$) which provide some safety against data scatter and potential pessimums.

Figure 5 uses the best fit to the data in Figure 4 (i.e., a 50% reliability level). For design, it is recommended to use a 90% reliability level, represented by the dashed curve in Figure 4. This curve was obtained by shifting the 50% reliability curve to the left until 90% of the AMBT data points were to the right of it. When this curve is used, Figure 6 is obtained, which gives the minimum required replacement with a reliability of 90% that the expansion will be less than the stipulated 0.08%. Data points from Figure 6 are also shown in Table 3. Note that Figures 5 and 6 were developed for a typical cement with $C_c = 4$. For other cements in this study C_c varied only from 3.71 to 4.44 (Table 2), hence, these figures could be used as an approximation to find the minimum replacement for typical cements.

7 CLASSIFICATION USING THE CHEMICAL INDEX

As indicated earlier, the fly ash chemical index C_{fa} has a good correlation with ASTM C 618. Table 1 shows that only ashes DM and BDII appear reversed compared to the ASTM classification, however, BDII has 8.45% Na2Oeq compared to 2.25% for DM. When compared to the CSA standard [19], the chemical index also shows good agreement, with some exceptions. For example, ash MN is a CI (CaO > 8%) but appears within the CSA Type F ashes: this ash has $SiO_2+Al_2O_3+Fe_2O_3$ = 86.3% and almost no SO_3 and no alkalis – it is a very good ash, and arguably should be an F ash. CSA actually allows classifying it as an F ash, since its CaO content of 8.68% can be considered less than 8±2% (CSA states: "For the purpose of classification the tolerance shall be ±2% on the CaO limits"). Similarly, other ashes using the CSA classification appear out of order when compared to the C_{fa} or ASTM ranking for ASR mitigation effectiveness (see also [5] for ranking of CI and CH ashes). Hence this CSA classification is not recommended.

As an additional comparison, the ASTM sum ($SiO_2+Al_2O_3+Fe_2O_3$) is also shown in Table 1 (and Figures 5, 6). This sum closely follows the chemical index in an inverse fashion (with $R^2 = 0.96$ between them), and therefore this sum could be used as a close and simple alternative to the chemical index to assess the efficiency of an ash to mitigate ASR. This sum can easily be implemented in the development of criteria, and was used in Table 3 and Figures 5 and 6.

The chemical index can also be used to assess additional ashes that do not meet typical standards. For example, in Hawaii, cement is imported and is very expensive. If local ashes could be used to replace cement, this would provide considerable savings. Unfortunately the available ash at Barbers Point is neither a Type F nor a Type C per ASTM C 618. For this fly ash the chemical index is 1.11 (based on 2002 composition data), making it equivalent to an ASTM C 618 Class F ash in Table 1. Another interesting ash is an UFFA [9], also shown in Table 1. While the most important characteristic of UFFA is its fineness, its chemical composition includes 11.8% CaO, preventing its usage in some cases. Its fly ash chemical index is 0.57, so that it has the chemistry of a very effective fly ash for ASR mitigation (see Table 1).

8 APPLICATION TO GUIDE SPECIFICATIONS

This method can be used to calculate minimum amounts of fly ash cement replacement to mitigate ASR. It would be advisable to also use absolute minimum replacements depending on the application, whether or not the aggregates are reactive, since the resulting concrete will, in general, be cheaper and more durable (this provides some safety against variations in testing results and aggregate reactivity). For example, the U.S. Navy currently requires a minimum of 25% Class F fly ash (with CaO ≤ 8% and available alkalis ≤ 1.5%) in pavements independently of reactivity [1], and the New Mexico State Highway and Transportation Department [24] requires 20% Class F minimum (with the same limits on CaO and available alkalis, and with $SiO_2+Al_2O_3+Fe_2O_3$ > 85%, or Class C if the aggregate is innocuous).

Current DOD specifications for Class F ash limit the ashes usable to about the top 40% of those in Table 1, and correspond approximately to requiring a sum $SiO_2+Al_2O_3+Fe_2O_3 \geq 80$ to 85%. If the requirements are relaxed to CaO ≤ 13% and total alkalis ≤ 3%, then approximately the top two-thirds of the Class F ashes in Table 1 could be used (this corresponds approximately to requiring a sum ≥ 80%). These are part of the proposed changes for the UFGS update to address reactive aggregates (together with a maximum allowable expansion of 0.08% per ASTM C 1567 for the final mix). Whether the aggregates are reactive or not, the Navy currently requires a minimum of 25% Class F ash with CaO ≤ 8% and available alkalis ≤ 1.5%. Instead, it is proposed to (1) remove the CaO limit for non-reactive aggregates and change it to CaO ≤ 13% for reactive ones, (2) require total alkalis ≤ 3%, and (3) require the following minimum fly ash contents: 25% if $SiO_2+Al_2O_3+Fe_2O_3 \geq$ 70%, 20% if $SiO_2+Al_2O_3+Fe_2O_3 \geq$ 80%, or 15% if $SiO_2+Al_2O_3+Fe_2O_3 \geq$ 90%.

Figure 5 shows that these proposed minimum replacements could mitigate a reactivity of about 0.2% or more with 50% reliability, providing some safety for variations in aggregates labelled non-reactive (E_{14c} < 0.08%). Figure 5 and Table 3 also show that using a 30% content of a Class C ash with $SiO_2+Al_2O_3+Fe_2O_3 \geq$ 65% would also provide a similar benefit (there are 2 such ashes at the bottom of Table 1). Since these recommendations are based on ASTM C 1260, care should be exercised for some aggregates that are less sensitive to this test, as stated in its Appendix X1.

9 CONCLUSIONS

Data from previous research studies were used to assess the effectiveness of fly ashes in preventing ASR, based on their chemical composition, the composition of the cement, and the reactivity of the aggregates. A chemical index was derived based on the fly ash (or cement) constituents, which was optimized to maximize the correlations with test data. For the fly ashes, this index, Cfa, correlated well with ASTM C 618 and CSA A3001 fly ash classifications, and in particular with the sum of ASTM specified oxides ($SiO_2+Al_2O_3+Fe_2O_3$), the latter being recommended for criteria development. This index was also used to assess the efficiency of other ashes that did not meet either specification. For a given aggregate reactivity, a given cement, and a given ash, it was possible to derive the minimum cement replacement that is needed to insure with 90% reliability that the 14-day AMBT expansion would remain below 0.08%.

It is proposed that current fly ash guidelines for use in DOD airfield concrete pavements be modified as follows:

- For non-reactive aggregates, use Class F fly ash with total alkalis ≤ 3%, and require the following minimum fly ash contents (also reflected in Table 3):
  - 25% if $SiO_2+Al_2O_3+Fe_2O_3 \geq 70\%$
  - 20% if $SiO_2+Al_2O_3+Fe_2O_3 \geq 80\%$
  - 15% if $SiO_2+Al_2O_3+Fe_2O_3 \geq 90\%$
- For reactive aggregates, use Class F fly ash with the additional requirements of CaO ≤ 13% and total alkalis ≤ 3% (together with a maximum allowable expansion of 0.08% per ASTM C 1567 for the final mix). Required replacements to mitigate reactivity with 90% reliability can be estimated with Figure 6 and Table 3, and should exceed the minimum requirements for non-reactive aggregates.

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TABLE 1. Fly ash composition and chemical index, C_{fa}.

Fly Ash	Study[a]	SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	MgO	Na_2O_{eq}[b]	ASTM	SUM	CSA	C_{fa}[c]
Winyah St.	[d]	53.54	27.24	8.85	1.34	0.10	0.99	0.63	F	89.6	F	0.18
ENX	[d]	67.40	20.20	4.59	5.29	0.02	1.00	1.36	F	92.2	F	0.26
Escalante(EF)	NM	61.34	25.11	4.42	4.94	0.08	1.09	1.25	F	90.9	F	0.27
4-Corners(4F)	NM	62.56	25.10	4.68	2.81	0.00	0.81	2.40	F	92.3	F	0.29
34-3	M&R[d]	35.50	12.50	44.70	1.89	0.75	0.63	1.25	F	92.7	F	0.29
87-156	M&R[d]	55.50	18.60	4.30	7.00	0.30	0.80	1.19	F	78.4	F/CI	0.31
34-4	M&R[d]	38.30	12.80	39.70	4.49	1.34	0.43	1.15	F	90.8	F	0.33
Coronado(CF)	NM	63.37	22.26	5.34	3.60	0.02	1.06	2.53	F	91.0	F	0.33
MN	S&T	61.50	20.52	4.29	8.68	0.19	1.70	0.56	F	86.3	F/CI	0.36
34-6	M&R[d]	48.00	21.50	10.60	6.72	0.52	0.96	1.13	F	80.1	F/CI	0.36
87-219	M&R[d]	62.00	20.10	2.00	6.90	0.60	1.20	1.49	F	84.1	F/CI	0.37
34-2	M&R[d]	44.10	21.40	26.80	1.95	0.96	0.99	2.09	F	92.3	F	0.38
34-5	M&R[d]	45.10	22.20	15.70	3.77	1.40	0.91	1.58	F	83.0	F	0.40
34-9	M&R[d]	62.10	21.40	2.99	11.00	0.16	1.76	0.77	F	86.5	CI	0.40
87-147	M&R[d]	57.90	26.30	3.90	9.60	0.40	2.10	0.26	F	88.1	F/CI	0.40
FM	S&T	47.34	22.34	15.08	6.38	1.43	0.82	1.41	F	84.8	F/CI	0.41
34-1	M&R[d]	47.10	23.00	20.40	1.21	0.67	1.17	2.62	F	90.5	F	0.41
34-8	M&R[d]	55.60	23.10	3.48	12.30	0.30	1.21	2.00	F	82.2	CI	0.49
LowCaO(DL)	Det.	44.80	23.54	16.98	5.66	1.22	1.26	2.07	F	85.3	F	0.50
LG	S&T	41.96	19.64	20.07	5.57	0.95	1.19	2.30	F	81.7	F	0.52
87-239	M&R[d]	48.90	18.50	21.80	7.30	0.50	2.60	0.99	F	89.2	F/CI	0.54
87-159	M&R[d]	57.50	20.60	7.00	9.10	0.20	2.60	1.32	F	85.1	F/CI	0.54
F-Ash (IF)	Touma	56.50	19.30	4.70	12.30	1.50	2.30	0.30	F	80.5	CI	0.57
UFFA [e]	[d]	50.66	27.24	3.06	11.80	1.03	2.51	0.35	F	81.0	CI	0.57
87-154	M&R[d]	62.30	20.90	2.20	6.10	0.50	0.70	5.48	F	85.4	F/CI	0.58
87-157	M&R[d]	52.80	23.60	8.90	9.50	0.40	2.70	1.63	F	85.3	F/CI	0.61
87-155	M&R[d]	52.20	18.00	10.50	11.90	1.30	2.50	0.46	F	80.7	CI	0.61
SD II	S&T	51.56	22.90	4.58	15.15	0.28	1.16	2.80	F	79.0	CI	0.62
SD I	S&T	50.92	23.64	4.62	13.63	0.23	0.86	3.77	F	79.2	CI	0.63
34-7	M&R[d]	55.70	20.40	4.61	10.70	0.38	1.53	5.22	F	80.7	CI	0.77
Esc/Tolk(ET) [f]	NM	50.19	22.25	4.68	14.73	0.59	3.23	1.67	F	77.1	CI	0.82
87-146	M&R[d]	50.30	20.20	5.50	14.40	0.70	4.00	1.69	F	76.0	CI	0.93
86-805	M&R[d]	46.40	24.50	4.90	13.70	0.60	4.00	1.95	F	75.8	CI	0.96
BarbersPoint [g]	[d]	43.47	18.42	6.30	15.72	6.56	1.45	1.40	[h]	68.2	CI	1.11
C1	S&T	44.29	20.96	5.23	17.51	2.13	4.21	1.68	F	70.5	CI	1.21
85-147	M&R[d]	50.40	21.40	3.50	11.60	0.50	3.00	7.19	F	75.3	CI	1.21
87-144	M&R[d]	47.90	21.90	4.90	13.30	1.10	2.90	6.76	F	74.7	CI	1.26
MedCaO(DM)	Det.	41.00	21.50	6.03	18.62	1.10	4.62	2.25	C	68.5	CI/CH	1.32
BD II	S&T	45.66	21.42	5.53	12.34	0.84	2.76	8.45	F	72.6	CI	1.40
34-10	M&R[d]	46.30	22.10	3.10	13.30	0.80	3.11	7.81	F	71.5	CI	1.41
83-275	M&R[d]	45.60	15.50	7.30	20.30	1.90	5.00	2.12	C	68.4	CI/CH	1.42

[a] S&T: Shehata&Thomas [11]; NM: McKeen. [15]; Det: Detwiler [23]; Touma [21]; Shon [22]; M&R: Malhotra [6].

[b] Total alkalis

[c] $$C_{fa} = \frac{CaO_{eq\alpha\,fa}}{SiO_{2eq\beta\,fa}} = \frac{CaO + 6.0\left(0.905Na_2O + 0.595K_2O + 1.391MgO + 0.700SO_3\right)}{SiO_2 + 1.0(0.589Al_2O_3 + 0.376Fe_2O_3)}$$

[d] These ashes were not used in model development but in demonstrating model usage.

[e] Ultra fine fly ash (UFFA) composition provided by Boral Material Technologies.

[f] 50/50 blend of two ashes: Escalante Type F and Tolk Type C.

[g] Barber's Point fly ash composition provided by Hawaiian Cement.

[h] Meets neither C nor F fly ash specifications.

TABLE 2. Portland cement composition and chemical index, C_c.

Cement Type	Study [a]	SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	MgO	Na_2O_{eq}	C_c [b]
High Alkali	S&T	20.83	5.11	2.01	62.98	3.25	2.43	1.02	4.17
Low Alkali	NM	21.10	4.30	3.20	63.90	3.00	2.00	0.55	3.87
Low Alkali	Detwiler	20.87	4.53	2.28	63.99	2.34	3.86	0.43	4.44
High Alkali	Touma	20.90	4.43	3.01	62.65	3.06	2.97	1.15	4.32
Med Alkali	Shon	19.12	5.07	3.40	64.73	3.13	0.64	0.65	3.71

[a] S&T: Shehata and Thomas [11]; NM: McKeen, et al. [15]; Detwiler [23]; Touma [21]; Shon [22].

[b] $$C_c = \frac{CaO_{eq\alpha c}}{SiO_{2eq\beta c}} = \frac{CaO + 6.0\left(0.905Na_2O + 0.595K_2O + 1.391MgO + 0.700SO_3\right)}{SiO_2 + 1.0(0.589Al_2O_3 + 0.376Fe_2O_3)}$$

TABLE 3. Estimated necessary cement replacement with fly ash to prevent ASR (%).

ASTM C1260 expansion	Fly Ash Minimum $SiO_2+Al_2O_3+Fe_2O_3$ (%) (50% reliability)				Fly Ash Minimum $SiO_2+Al_2O_3+Fe_2O_3$ (%) (90% reliability)			
%	90	80	70	65	90	80	70	65
<0.1	15	20	25	30	15	20	25	30
0.2	15	20	25	30	18	21	30	39
0.3	18	21	29	38	22	26	37	48
0.4	20	24	33	43	25	30	41	NR*
0.5	22	26	36	47	27	32	45	NR*
0.6	23	28	39	NR*	29	34	48	NR*
0.7	24	29	41	NR*	30	36	NR*	NR*
0.8	25	30	43	NR*	31	38	NR*	NR*
0.9	26	32	44	NR*	32	39	NR*	NR*
1	27	33	46	NR*	33	40	NR*	NR*

*NR = Not recommended due to difficulties in finishing and strength gain.

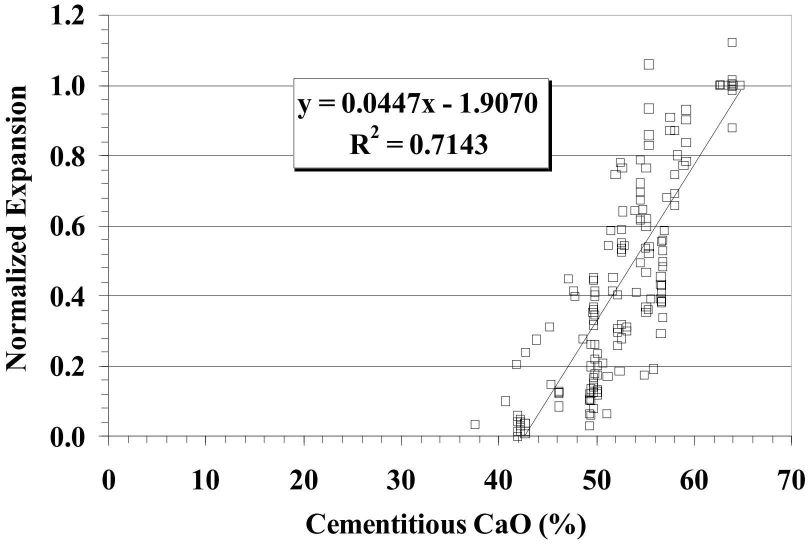

Figure 1. Effect of total CaO content (in cement and fly ash) on 14-day AMBT expansion.

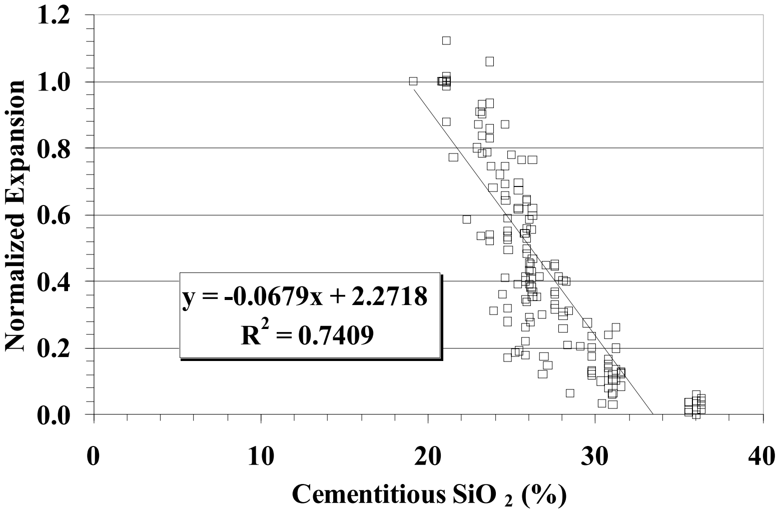

Figure 2. Effect of total SiO_2 content (in cement and fly ash) on 14-day AMBT expansion

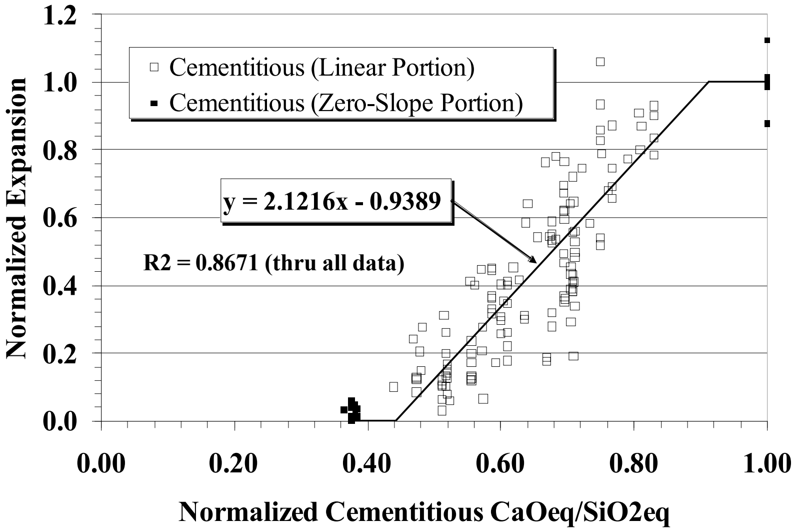

Figure 3. Effect of normalized CaO_{eq}/SiO_{2eq} ratio on 14-day AMBT expansion.

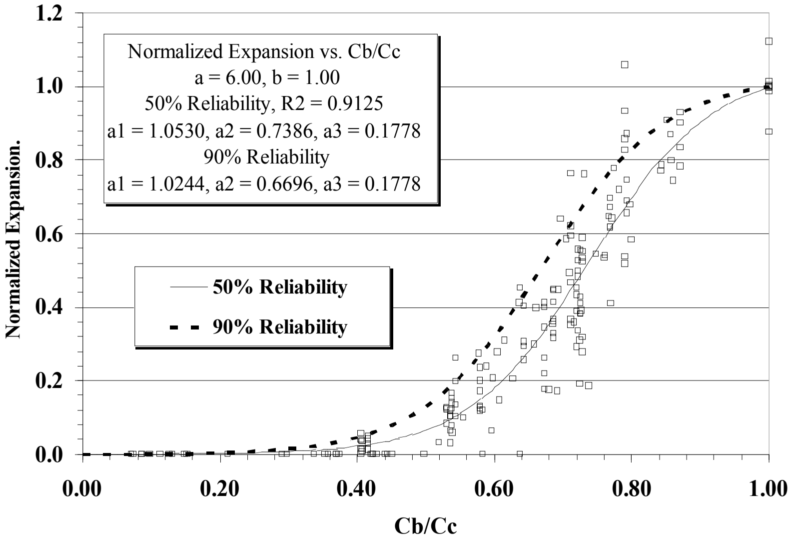

Figure 4. Effect of C_b/C_c ratio on AMBT expansion (hyperbolic tangent model).

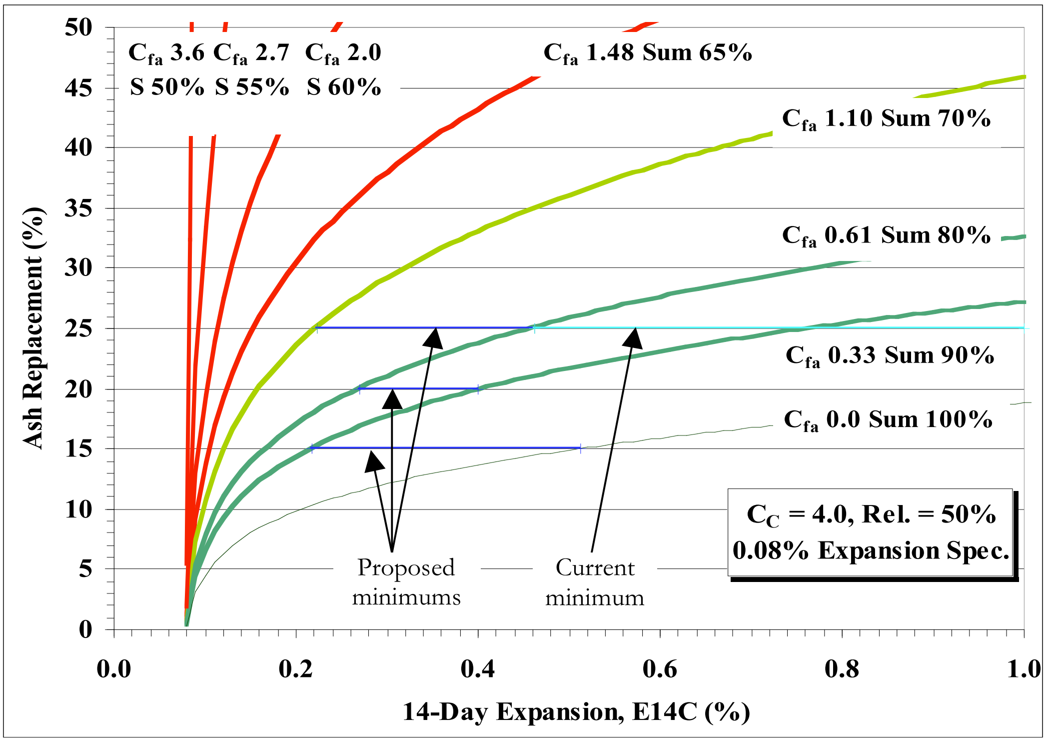

Figure 5. Minimum fly ash replacement to mitigate ASR with 50% reliability.

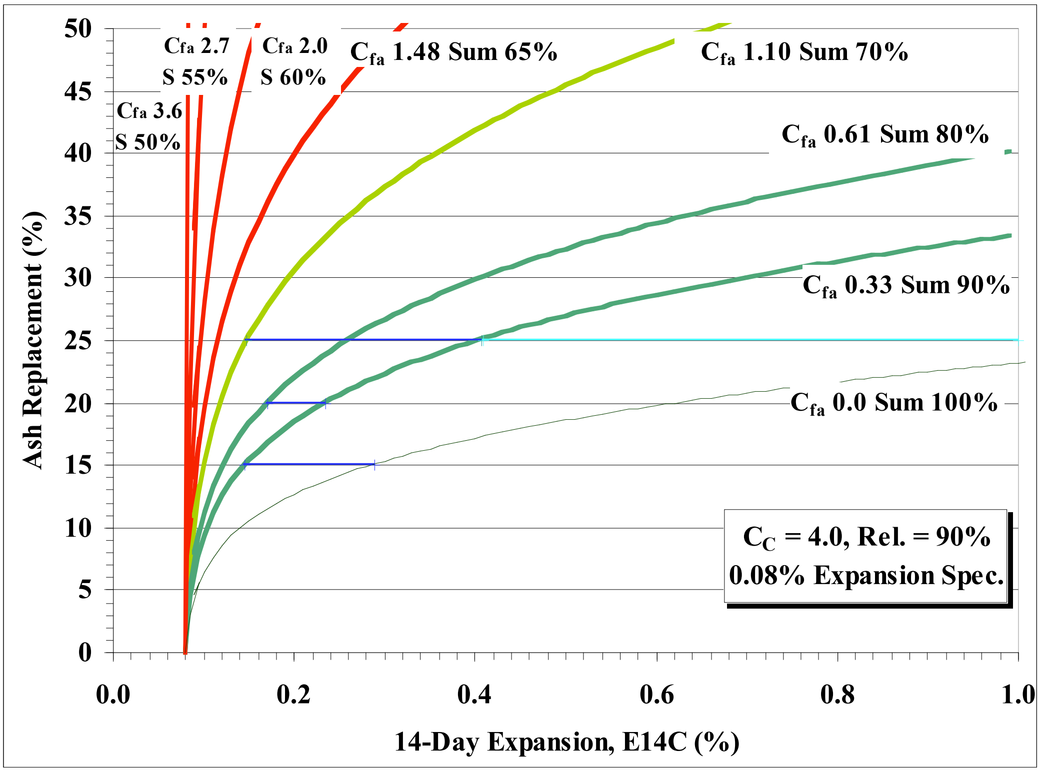

Figure 6. Minimum fly ash replacement to mitigate ASR with 90% reliability.