An Extended Chemical Index Model to Predict the Fly Ash Dosage Necessary for Mitigating Alkali-Silica Reaction in Concrete

Asghar Gholizadeh Vayghan ^{a,*}, Jared Robert Wright ^b, Farshad Rajabipour ^c

^a Ph.D. Candidate and Graduate Research Assistant, Department of Civil and Environmental Engineering,
The Pennsylvania State University, 3127 Research Drive, State College, PA, 16801

^b Ph.D. Candidate and Graduate Research Assistant, Department of Civil and Environmental Engineering,
The Pennsylvania State University, 3127 Research Drive, State College, PA, 16801

^c Associate Professor, Department of Civil and Environmental Engineering, The Pennsylvania State
University, 231M Sackett Building, University Park, PA, 16802

* Corresponding author: contact at a.v.gholizadeh@gmail.com

ABSTRACT

Currently, the concrete prism test per ASTM C1293 or RILEM AAR-3 is considered the most reliable accelerated test to determine the dosage of pozzolans to suppress alkali-silica reaction (ASR) in concrete. However, the test takes 2 years, which makes it impractical as a mixture design tool for new concrete construction. In the present work, a multiple nonlinear regression model is developed for predicting the fly ash dosage necessary to mitigate ASR per CPT. The model uses the oxide compositions of portland cement and fly ash, as well as the reactivity of the aggregates. Seventy-six experimental data points on CPT expansion results for plain portland cement and fly ash-blended concrete mixtures were used to develop and evaluate the model. The model successfully predicts the fly ash required to mitigate ASR for different aggregates, cement and fly ash combinations. The prediction errors in most cases meet ASTM C1293 multi-laboratory precision criterion.

Keywords: Alkali-Aggregate Reaction (c); Expansion (c); Fly Ash (d); Modeling (e)

1. INTRODUCTION

ASR expansion continues to cause enormous damage and maintenance costs in many concrete structures [1]. For new construction, ASR could be avoided by adequate replacement of cement with supplementary cementitious materials (SCMs), among which the use of fly ash is the most common for ASR mitigation [2]. Fly ash is effective in suppressing ASR due primarily to its alkali-binding effect (which reduces the alkalinity of concrete pore solution), consuming portlandite, and reducing the permeability and mass transport in concrete [3,4,5]. One very important, yet difficult to answer, question is “How much fly ash should be proportioned in a given mixture to mitigate ASR?” Generally, higher dosages of cement replacement by fly ash lead to better suppression of ASR [3]. However, this could result in a decline in the early-age strength and/or strength development as well as other durability properties (e.g., salt scaling) of concrete [6,7]. Therefore, finding the correct fly ash dosage required to mitigate ASR is crucial.

The available standard test methods provide useful measures for assessing the ASR potential of given aggregates. For example, ASTM has a number of current test methods to evaluate the reactivity of aggregates and to find the proper SCM dosage needed to mitigate ASR. The accelerated mortar bar test (AMBT) described in ASTM C1260 [8] and the RILEM equivalent AAR-2 [9], is a quick method to assess the

47 reactivity of aggregates. ASTM C1567 [10] takes a similar approach to find the
48 adequate cement replacement dosage with SCMs to allay ASR. RILEM AAR-2, ASTM
49 C1260 and C1567 are quick and practical, but they are often criticized because of the
50 low reliability of their results due to exposing samples to an unrealistically harsh ASR
51 environment of high temperature and inexhaustible alkalinity [11,12,13]. In addition,
52 they test mortars, which could perform very differently than the field concrete mixtures.
53 A more reliable test method to predict ASR expansion of ordinary portland cement
54 (OPC) and blended cement concrete mixtures is the concrete prism test (CPT),
55 described in ASTM C1293 [14] and RILEM TC 219-ACS AAR-3 [15]. The U.S. Federal
56 Highway Administration (FHWA) considers CPT as the most reliable test method
57 currently available for assessing the sustainability of ordinary and blended concrete
58 mixtures to resist ASR damage [16]. However, CPT allows for much less acceleration
59 compared to AMBT and needs two years to assess the performance of mixtures
60 containing SCM. Another reliable method of assessing ASR is the outdoor exposure
61 block testing [11], which takes several years to provide information.

62 AASHTO PP-65 [17] is a new standard specification, which is aimed at selecting
63 appropriate measures for preventing ASR in new concrete construction. It offers an
64 elaborate method for classifying the aggregate reactivity (into non-reactive, moderately,
65 highly, or very highly reactive) based on the results of AMBT or CPT for plain OPC
66 mixtures. It also includes prescriptive and performance-based methods for determining
67 the SCM (i.e., fly ash, slag, or silica fume) dosage required to be proportioned in
68 concrete mixtures to prevent ASR. The prescriptive method of AASHTO PP-65 uses
69 the aggregate reactivity class, concrete element size and exposure level to moisture

and alkalis, and importance of the structure (with respect to safety and economic consequences should ASR occur), in determining the minimum SCM level needed. With respect to fly ash, the prescriptive method is only applicable for fly ash with $\text{CaO} < 18\%$, which excludes almost all Class C ashes. The allowable Class F fly ashes are classified only based on their alkali content (into $\text{Na}_2\text{O}_{\text{eq}} < 3.0\%$, and $3.0\% < \text{Na}_2\text{O}_{\text{eq}} < 4.5\%$), with $\text{Na}_2\text{O}_{\text{eq}} > 4.5\%$ not being allowed. While this serves practicality, it does not account for the quantitative values of fly ash constituents (e.g., $\text{SiO}_2\%$, $\text{Al}_2\text{O}_3\%$, $\text{CaO}\%$) that have a strong impact on the efficiency of fly ash against ASR. In general, while very helpful, the prescriptive method of AASHTO PP-65 is conservative and only applicable to certain fly ashes.

Alternatively, AASHTO-PP65 and similar international specifications allow for a performance-based approach to determine the minimum SCM level for ASR mitigation based on the results of the concrete prism test (CPT) [14,15]. The obvious challenge is the 2-year time that is needed to perform this test. It will be of extreme value if a statistical model can be developed based on past test data, to successfully predict the 2-year CPT results. This model should take into account the numerical values of aggregate reactivity (i.e., the 1-year expansion results of ASTM C1293 concrete prism test on a 100% ordinary portland cement concrete mixture containing the reactive aggregates), and elemental compositions of portland cement and fly ash. Such a model can (a) save time and cost associated with performing the long term experiments, and (b) be applicable for both Class F and Class C fly ashes. In the present work, this model is developed and evaluated using the available literature data on CPT results for plain OPC and OPC-fly ash concrete mixtures.

94 2. EARLIER WORK ON ASR PREDICTIVE MODELS FOR FLY ASH 95 CONCRETE

96 In 2006, Malvar and Lenke developed a chemical index model using multiple sets of
97 data available in the literature on the ASTM C1567 (AMBT) results of 31 different fly
98 ashes [18]. They argued that calcium oxide is the most deleterious component of fly
99 ash in promoting ASR. They also introduced other deleterious components such as
100 Na₂O, K₂O, MgO and SO₃ and converted them to a molar equivalent CaO_{eq} index
101 formula that would represent all fly ash components that promote ASR expansion.
102 Similarly, SiO₂ was considered to be the main oxide suppressing expansion, and Al₂O₃
103 and Fe₂O₃ were introduced in the form of their SiO₂ equivalents to determine a SiO_{2eq}
104 index formula. The ASR promoting and suppressing factors of a cement-fly ash blend
105 were then combined into a ratio shown in Eq. 1 [18].

$$C_b = \frac{(CaO_{eq\alpha})_b}{(SiO_{2eq\beta})_b} = \frac{CaO + \alpha(0.905Na_2O + 0.595K_2O + 1.391MgO + 0.700SO_3)}{SiO_2 + \beta(0.589Al_2O_3 + 0.376Fe_2O_3)} \quad \text{Eq. 1}$$

106 where C_b stands for the chemical index of the blend. In the case of no replacement of
107 cement with fly ash, the ratio basically yields the chemical index of the cement (i.e., C_c).
108 The terms α and β were included in the chemical indices to account for “different
109 reactivity” of CaO and SiO₂ in comparison with other oxide components. The
110 normalized expansion of the blend and plain OPC binders at 14 days according to
111 ASTM C1567 (i.e. E_{14b}/E_{14c}) was plotted against their normalized chemical index, C_b/C_c ,
112 using a hyperbolic tangent function and the factors α and β were optimized to reach the

maximum R^2 value, preserving 90% reliability (i.e., a minimum of 90% of the expansion estimations were conservative). Using the obtained regression function, Malvar and Lenke were able to propose an equation that would predict the necessary dosage of any given fly ash to reduce the AMBT expansion of the blended mixtures below a chosen threshold of 0.08% at 14 days. They compiled this formula into a set of easy-to-use nomographs that yield the necessary fly ash dosage to mitigate ASR, using the chemical index of fly ash (i.e., C_{fa}), and the reactivity of the aggregate presented as the 14-day expansion of plain OPC mixture made without fly ash (E_{14c}). Recently, other researchers have independently verified the effectiveness of Malvar and Lenke's model [19,20].

Malvar and Lenke's model presents a pioneering effort in predicting the needed fly ash dosage to mitigate ASR. However, there are a number of challenges in implementing their model for practical purposes. The model is based on AMBT results, which has reliability concerns, as mentioned before. Most transportation agencies have moved away from AMBT and are now requiring all aggregates to be tested according to CPT. In addition, while their model is accountable for Class F ashes, it becomes ultra-conservative for Class C fly ashes. Therefore, developing a reliable model based on available CPT results that can be used for both Class C and F fly ashes is necessary.

3. THE EXTENDED CHEMICAL INDEX MODEL

In this paper, a new model for predicting the necessary fly ash dosage for mitigating ASR per CPT is developed. New approaches are taken in configuration, optimization

and evaluation of the model compared to the previous works. The current study compiles and utilizes two decades worth of data on CPT [21,22,23,24]. Among the collected data are 26 different fly ashes (Table 1), comprising 13 Class F and 13 Class C ashes, according to ASTM C 618 [25] classification. They contain very diverse CaO and alkali oxide contents. There are also five different Type I portland cements (Table 2), and nine different reactive aggregates (ranging from moderately reactive to very highly reactive, according to AASHTO PP-65 classification) as shown in Table 3.

The main factors that are taken into account in developing this model are the bulk elemental compositions of portland cement and fly ash (i.e., mass percentages of SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , MgO , Na_2O , K_2O , and SO_3) and the reactivity of the aggregates used. The 1-year expansion of 100% OPC concrete prisms in accordance with ASTM C1293 was used as a numerical measure of the aggregate reactivity. Due to lack of literature information, the fineness and crystalline contents of fly ash are not considered in the model.

3.1 Configuration of the model

In order to configure the chemical index formula, the role of each chemical component on ASR expansion per ASTM C1293 needs to be determined first. Higher silica, alumina and iron oxide contents have often lead to better ASR mitigation [18,26,27]. On the other hand, the presence of alkali and alkaline earth oxides (i.e., Na_2O , K_2O , CaO and MgO) in SCMs are known to reduce their efficacy in mitigating ASR [28,29]. In order to confirm these findings for the CPT data obtained from the literature, the

normalized expansion values (i.e., the two-year expansion of the blended mixture (E_{2Yb}) divided by the one-year expansion of the corresponding 100% OPC mixture (E_{1Yc})) are plotted versus the normalized values of each oxide (i.e., SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , $\text{Na}_2\text{O}_{\text{eq}}$, MgO and SO_3) in the binder. The normalized value of each oxide is the total mass percent of that oxide in the blended binder (i.e., OPC + fly ash) divided by the mass percent of that oxide in the corresponding 100% OPC mixture. For example, for a blended mixture with 10% cement replacement with ash, where the SiO_2 contents of cement and fly ash are respectively 20% and 50%, the normalized SiO_2 will be $(0.9 \times 20\% + 0.1 \times 50\%) / (20\%) = 1.15$.

Figure 1 shows that the normalized expansion declines with an increase in normalized values of the ASR suppressing oxides in the blended binder (i.e., normalized SiO_2 , Al_2O_3 and Fe_2O_3). The p-values of the correlation coefficients (i.e., the probability of lack of correlation between the normalized expansion and each of these parameters) are smaller than 0.001, which is an indication of significant correlation. This is in agreement with the findings of Malvar and Lenke about the role of these oxides on ASR expansion based on ASTM C1567 (AMBT) results [18]. It is well established that both SiO_2 and Al_2O_3 in pozzolans reduce ASR expansion [5,30]. While the effect of Fe_2O_3 is not known with certainty, it is likely that Fe_2O_3 would behave somewhat similarly to Al_2O_3 , with one important distinction. While the majority of Al_2O_3 in fly ash is in the form of soluble alumino-silicate glass, most Fe_2O_3 is in crystalline form (e.g., hematite, maghemite), with solubility products much less than that of alumina [31,32]. This partly explains the rather low correlation coefficient between the normalized expansion and Fe_2O_3 (shown in Figure 1). This low correlation is also likely

180 due to the interdependence of Fe_2O_3 with more dominant ASR suppressing species
181 (i.e., SiO_2 and Al_2O_3). Very low Fe_2O_3 values could translate to high SiO_2 and/or Al_2O_3 ,
182 which will in turn lead to lower ASR expansion.

183 Figure 2 shows the effects of the normalized values of CaO , $\text{Na}_2\text{O}_{\text{eq}}$, MgO and
184 SO_3 on the CPT expansion of the specimens. It is observed that higher CaO , MgO and
185 SO_3 in the blended binder promote ASR expansion (with p-values of <0.001 , $=0.023$
186 and <0.001 , respectively). It has been well established that fly ashes with high CaO
187 content are less effective in mitigating ASR, partly due to their inefficiency in lowering
188 the pH of the pore solution [3,4,5]. Although Mg is also a group II element and may
189 affect ASR in a similar way as Ca, the correlation coefficient of MgO in Figure 2 is
190 considerably lower than that of CaO . This is probably due to the fact that magnesium
191 oxide can occur in fly ash both in the form of reactive free MgO (likely to affect ASR)
192 and non-reactive periclase, which does not contribute to ASR [33]. Periclase is
193 especially common in fly ashes with $\text{MgO}>2\%$. It was reported [33] that the proportions
194 of active MgO to periclase can vary considerably, which could explain the low
195 correlation between the total MgO and ASR expansion. Nevertheless, the p-values
196 reported above suggest that the MgO effect is statistically significant.

197 The normalized equivalent alkalis (i.e., $\text{Na}_2\text{O}_{\text{eq}}$) does not apparently have any
198 significant correlation with the expansion (p-value= 0.676 , which translates to 67.6%
199 chance of lack of correlation). A more in depth examination of the effect of $\text{Na}_2\text{O}_{\text{eq}}$ on
200 ASR expansion results (by separating the equivalent alkalis of cement and fly ash) in
201 Figure 3 shows that the alkalis from portland cement considerably promote ASR (p-
202 value <0.001), while the alkalis from fly ash do not have a remarkable effect on the

expansion (p-value=0.071), according to the CPT results. Note that a p-value greater than 0.05 is an indication of not rejecting the null hypothesis (i.e., lack of correlation). It is argued that, alkalis from fly ash dissolve very slowly in the pore solution due to slow reactivity of fly ash in comparison with portland cement [34], and at least a portion of the dissolved fly ash alkalis are immediately bound by the pozzolanic C-S-H. As such, the contribution of fly ash alkalis to ASR may not be measurable during the 2-year time span of the CPT. It has been reported that the alkalinity of pore solution is often reduced by replacing cement with fly ash, even when the $\text{Na}_2\text{O}_{\text{eq}}$ content of fly ash is higher than cement's [34,35]. Similar observation has been made when cement is replaced with highly alkaline soda-lime glass powder as SCM ($\text{Na}_2\text{O}_{\text{eq}} > 13.0\%$) [36].

In configuring the chemical index formula of the binder, only the elements shown to be influencing ASR performance of the binder are utilized. Similar to Malvar and Lenke's model [18], the ASR promoting factors of cement and fly ash (P_c and P_{fa} per Eq. 2 and Eq. 3, respectively) and their ASR suppressing factors (S_c and S_{fa} per Eq. 4 and Eq. 5) are defined as a general linear sum (for the sake of simplicity of the model) of the corresponding oxides. The parameters p_i , p'_j , s_k and s'_l are the amplifications coefficients of each constituent oxide of cement and fly ash. Unlike the previous models [18,19,20], these parameters are not predetermined based on their molar equivalents to CaO or SiO_2 . In fact, p_i , p'_j , s_k and s'_l values are optimized such that the overall accuracy of the model in estimating the fly ash dosage is maximized.

$$P_c = p_1 \times \text{CaO} + p_2 \times \text{Na}_2\text{O} + p_3 \times \text{K}_2\text{O} + p_4 \times \text{MgO} + p_5 \times \text{SO}_3 \quad \text{Eq. 2}$$

$$P_{fa} = p'_1 \times \text{CaO} + p'_2 \times \text{Na}_2\text{O} + p'_3 \times \text{K}_2\text{O} + p'_4 \times \text{MgO} + p'_5 \times \text{SO}_3 \quad \text{Eq. 3}$$

$$S_c = s_1 \times \text{SiO}_2 + s_2 \times \text{Al}_2\text{O}_3 + s_3 \times \text{Fe}_2\text{O}_3 \quad \text{Eq. 4}$$

$$S_{fa} = s'_1 \times SiO_2 + s'_2 \times Al_2O_3 + s'_3 \times Fe_2O_3 \quad \text{Eq. 5}$$

The ASR vulnerability index of the blended binder (V_b) is defined as the ratio of the ASR promoting factors to ASR suppressing factors of the binder (i.e., P_b and S_b , respectively), as shown in Eq. 6.

$$V_b = \frac{P_b}{S_b} = \frac{(1-f) \times P_c + f \times P_{fa}}{(1-f) \times S_c + f \times S_{fa}} \quad \text{Eq. 6}$$

where f is the fly ash dosage as cement replacement, P_b is the proportional sum of ASR promoting factors of cement and fly ash (i.e., P_c and P_{fa}), and S_b is that of ASR suppressing factors of cement and fly ash (i.e., S_c and S_{fa}). Although correlating V_b to the two-year expansion of the blended concrete mixture (E_{2Yb}) seems to be intuitively the right approach to take, no single formula can relate V_b to E_{2Yb} , since V_b does not account for the reactivity of the aggregates, which has a profound influence on the expansion of the mixture. To address this problem, the E_{2Yb} value for each blended mixture is normalized to the 1-year expansion value of the corresponding 100% OPC mixture, E_{1Yc} , per Eq. 7. Similarly, for each blended mixture, the V_b value is normalized to that of the corresponding 100% OPC mixture, $V_c [=V_b|_{f=0}]$, as shown in Eq. 8. Therefore, for each control mixture (i.e., 100% OPC), the normalized expansion (E_n) and normalized ASR vulnerability index (V_n) of the binder will be equal to 1. Addition of fly ash will lead to changes in the E_n and V_n values, based upon which the correlation between these two parameters is derived. Among linear, logarithmic, quadratic, hyperbolic tangent and sigmoid functions, the logarithmic function (Eq. 9) showed the highest potential to yield accurate fly ash dosage predictions. Notice that the normalization of expansion and ASR vulnerability values of the blended binders to those of 100% OPC mixtures takes

aggregate reactivity into account. Aggregate reactivity is represented by the 1-year expansion of OPC mixture (i.e., E_{1Yc}). After normalizing E_{2Yb} to aggregate reactivity, E_{2Yb} can be written down as $E_{2Yb}=E_{1Yc} \times (a+b \times \ln(V_n))$ where both the aggregate reactivity (E_{1Yc}), and the fly ash on the blended binder's ASR expansion are represented.

$$E_n = \frac{E_{2Yb}}{E_{1Yc}} \quad \text{Eq. 7}$$

$$V_n = \frac{V_b}{V_c} \quad \text{Eq. 8}$$

$$E_n = f(V_n) = a + b \times \ln(V_n) \quad \text{Eq. 9}$$

Parameters a and b are determined based on the routine procedure of fitting a simple linear regression function between E_n and $\ln(V_n)$, as shown in Eq. 10 and Eq. 11.

$$a = \frac{1}{n} \left(\sum_{i=1}^n E_{n_i} - b \times \sum_{i=1}^n \ln(V_{n_i}) \right) \quad \text{Eq. 10}$$

$$b = \frac{n \times \sum_{i=1}^n (E_{n_i} \times \ln(V_{n_i})) - \sum_{i=1}^n E_{n_i} \times \sum_{i=1}^n \ln(V_{n_i})}{n \times \sum_{i=1}^n (\ln(V_{n_i}))^2 - (\sum_{i=1}^n \ln(V_{n_i}))^2} \quad \text{Eq. 11}$$

The following manipulations leading to Eq. 12 are made in order to parametrically predict the fly ash dosage, f , necessary to achieve a normalized expansion value of E_n . The parameters in this equation (i.e. a , b , P_c , P_{fa} , S_c and S_{fa}) depend on the coefficients introduced in Eq. 2 through Eq. 5 (i.e., p_i , p'_j , s_k and s'_l), and the elemental composition of fly ash and cement.

$$V_n = \frac{V_b}{V_c} = f^{-1}(E_n) = e^{(E_n - a)/b}$$

$$\frac{V_b}{V_c} = \frac{\frac{f \times P_{fa} + (1-f) \times P_c}{f \times S_{fa} + (1-f) \times S_c}}{\frac{P_c}{S_c}} = \frac{f \times \left(\frac{P_{fa}}{P_c} - 1\right) + 1}{f \times \left(\frac{S_{fa}}{S_c} - 1\right) + 1}$$

$$\frac{f \times \left(\frac{P_{fa}}{P_c} - 1\right) + 1}{f \times \left(\frac{S_{fa}}{S_c} - 1\right) + 1} = e^{(E_n - a)/b} \rightarrow f = \frac{1 - e^{(E_n - a)/b}}{\left(1 - \frac{P_{fa}}{P_c}\right) - \left(1 - \frac{S_{fa}}{S_c}\right) \times e^{(E_n - a)/b}} \quad \text{Eq. 12}$$

257 After compiling the model based on many correlation functions for Eq. 9 with high
 258 R^2 values and observing significant prediction errors in Eq. 12, it was concluded that
 259 maximizing R^2 value of Eq. 9 is not the best approach to develop an accurate model. In
 260 other words, maximizing R^2 of a regression fit, where the error is defined as the
 261 difference between the predicted and actual expansion values, does not necessarily
 262 lead to minimizing the prediction errors in estimating the fly ash dosage. Therefore,
 263 unlike the previous models [18,19,20], the coefficients p_i , p'_j , s_k and s'_l are not optimized
 264 on the basis of maximizing the R^2 value of E_n vs. V_n fit (i.e., Eq. 9). These parameters
 265 need to be optimized by targeting the minimization of the fly ash dosage prediction error
 266 defined per Eq. 13, where f_i and E_{ni} respectively stand for the actual fly ash dosage
 267 used and the normalized 2-year expansion for the i^{th} mixture. The parameter $\overline{|E|}$ is the
 268 sum of the absolute fly ash dosage prediction errors. P_{ci} , P_{fai} , S_{ci} and S_{fai} are also the
 269 ASR promoting and suppressing factors of cement and fly ash used in the i^{th} mixture.
 270 Another optimization criterion was to maintain a minimum reliability level of 65-70% (i.e.,
 271 limiting the total number of fly ash dosage underestimations to 30-35%). Although the
 272 rate of underestimations may not seem conservative enough, it should be noted that

this is for the entire range of expansion results, and is not necessarily indicative of an unconservative model. As it will be shown later, the reliability of the model's predictions increases to 85% for the expansions in the range of the mitigation threshold (i.e., 0.04%). Further increase in the reliability could be provided by reducing the mitigation threshold to lower levels (e.g. 0.02%, etc.)

$$\overline{|E|} = \sum_{i=1}^{63} \left| \frac{1 - e^{(E_{n_i} - a)/b}}{\left(1 - \frac{P_{fa_i}}{P_{ci}}\right) - \left(1 - \frac{S_{fa_i}}{S_{ci}}\right) \times e^{(E_{n_i} - a)/b}} - f_i \right| \quad \text{Eq. 13}$$

3.2 Training the model

The data obtained from the literature on the CPT expansion results are summarized in Table 4. Among the total of 76 data points, 63 data points were randomly selected from the database to train the model. The remaining 13 data points (highlighted in gray in Table 4) were used for evaluating the model. Generalized Reduced Gradient (GRG) algorithm using Microsoft Excel Solver add-on was selected for minimizing $\overline{|E|}$ per Eq. 13 (which leads to optimization of p_i , p'_j , s_k and s'_l), allowing for a maximum of 22 underestimations (65% reliability).

The optimized p_i , p'_j , s_k and s'_l are shown in Table 5, leading to optimum P_c , P_{fa} , S_c and S_{fa} as shown in equations Eq. 14 through Eq. 17. These coefficients are not the same as those obtained by Malvar and Lenke [18] (see Eq. 1), for the following reasons. The coefficients in Malvar and Lenke's model are simply molar mass ratios of each oxide to CaO in the numerator, or to that of SiO₂ in the denominator. This inherently assumes that the reactivity and effect of all ASR promoting oxides (numerator) is the

same and only the molar ratios of these oxides need to be accounted for. The same assumption is made for the ASR suppressing oxides in the denominator. The factors α and β were flexible and determined by curve fitting. In the present work, no such presumptions were made and all oxide coefficients p_i , p'_j , s_k , and s'_l were allowed to be optimized in order to improve the flexibility of the model and its match to the experimental data. In addition, it should be also noted that, in the present model, the ASR promoting and suppressing factors of fly ash and portland cement are separated. Moreover, this model is optimized based on CPT test results as opposed to AMBT results used by Malvar and Lenke.

$$P_c = 0.13 \times CaO + 0.7 \times Na_2O + 0.18 \times K_2O + 0.19 \times MgO \quad \text{Eq. 14}$$

$$P_{fa} = 0.2 \times CaO + 0.44 \times MgO + 0.34 \times SO_3 \quad \text{Eq. 15}$$

$$S_c = 0.17 \times SiO_2 + 1.22 \times Fe_2O_3 \quad \text{Eq. 16}$$

$$S_{fa} = 0.67 \times SiO_2 + 0.12 \times Al_2O_3 + 0.17 \times Fe_2O_3 \quad \text{Eq. 17}$$

The effects of individual oxide components of fly ash on its efficacy for ASR mitigation was discussed in section 3.1 (“Configuration of the model”) above. Here, the relative magnitudes of these oxide coefficients are discussed in more details. The promoting effect of CaO on ASR has been well documented in the past. The CaO coefficient in cement is slightly smaller than that in fly ash likely because a majority of cement CaO is consumed during hydration of portland cement to form C-S-H and other stable calcium containing phases. The effect of MgO, in theory, may be similar to CaO. In Eq. 14, the difference between the coefficients for CaO and MgO corresponds well with their difference in molar mass. In portland cement, MgO is often present in the form of non-reactive periclase or in solid solution with C_3S [37]. The noticeably greater

MgO coefficient in Eq. 15 for fly ash (in comparison with that of cement in Eq. 14) may be due to the fact that a large portion of fly ash MgO could be in the reactive free form [33]. This free MgO by itself can generate expansion as it hydrates to form Mg(OH)_2 , as opposed to periclase and the solid solution MgO found in portland cement. The significance of alkalis in cement and their lack of significance in fly ash was discussed before (section 3.1). In Eq. 14, Na_2O appears with a considerably greater coefficient compared to K_2O , which may be justified in terms of the smaller ionic size, and therefore, easier mobility of Na, which makes it more deleterious in comparison with K. The exact effect of SO_3 on ASR is unknown. In cement, SO_3 is in the form of gypsum or alkali sulfates. Sulfates from both sources could promote expansion through formation of ettringite; however, majority of ettringite is usually formed before the first measurement in CPT (7 days). This could explain why SO_3 term does not appear in the outcome of the regression analysis in Eq. 14. On the contrary, SO_3 in fly ash may be released slower, resulting in delayed expansions, thus contributing to CPT measurements.

As for the ASR suppressing oxides, the greater magnitude of $\text{SiO}_{2,\text{fa}}$ coefficient compared to that of $\text{SiO}_{2,\text{c}}$ is probably due to the consumption of cement silicates during the hydration reactions, which reduces their availability for ASR mitigation. Nevertheless, cement silicates can affect ASR expansion via reducing the available portlandite content. SiO_2 from fly ash, on the other hand, is freely available to mitigate ASR. The case for alumina is similar to SiO_2 . While alumina in cement is consumed to form ettringite and AFm phases, alumina in fly ash is freely available to impact ASR (primarily through reduction of aggregate dissolution [38]). The greater coefficient of

$\text{Fe}_2\text{O}_{3,c}$ compared to $\text{Fe}_2\text{O}_{3,fa}$ could be justified by noticing the different phases where iron exists in cement and fly ash. Fe_2O_3 in cement is present in reactive/soluble C_4AF phases and, as such, can affect the hydration reactions and ASR expansion. In fly ash, however, Fe_2O_3 is mainly in the form of non-reactive phases (e.g., hematite and maghemite) [31].

Figure 4 shows the correlation between the normalized ASR vulnerability index (V_n per Eq. 8) of binders (calculated for the optimized p_i , p'_j , s_k and s'_l) to their normalized concrete expansions (E_n per Eq. 7), when tested according to ASTM C1293. The regression equation correlating E_n and V_n is shown in this figure, in which the terms a and b are calculated per Eq. 10 and Eq. 11.

The mean absolute error (MAE) of fly ash dosage predictions per Eq. 18 (with A_i and P_i being the actual and predicted fly ash replacement dosages) is $8.31 \pm 1.79\%$, which seems to be acceptable. The $\pm$ indicates the 95% confidence interval, and is calculated using Minitab software. The reliability of the predictions was laid on the lower bound (i.e., 65%). Providing higher reliability for all ashes, leads to large overestimations and reduces the accuracy of the model.

$$MAE = \frac{1}{N} \times \sum_{i=1}^N |A_i - P_i| \quad \text{Eq. 18}$$

3.3 Evaluation of the model

Evaluating the model with the 13 highlighted data points showed promising results with an MAE of $5.20 \pm 3.02\%$. According to ASTM C1293 [14] multi-laboratory precision

criterion, when the average expansion of two properly conducted CPT experiments exceeds 0.014% (i.e., 140 micro strains), the two results on the same aggregates should not differ by more than 65% of their average (Eq. 19), in 95% of the times. Assuming the developed model to represent a CPT test physically performed in a “different laboratory”, the predicted expansion values should be in conformance with ASTM precision criterion. The average precision of CPT expansion prediction for the 13 data points according to Eq. 19 is 42.50%. Except for one occasion (data row 13), this criterion is satisfied for all other data points. It should be noticed that there are occasions of unacceptable differences among the data points used to develop the model (Table 4). Data rows 4 and 5 (78.9% difference from the mean), 34 and 36 (83.1% difference from the mean), and 41 and 42 are the examples of discrepancies among identical experiments existing in the data. The proposed model cannot possibly be more accurate than the available database used to train the model.

$$\frac{|E_1 - E_2|}{\frac{E_1 + E_2}{2}} \times 100\% \leq 65\% \quad \text{Eq. 19}$$

For the cases where the average expansion is below 0.014%, the precision criterion cannot be satisfied, because slight overestimations as low as 5% result in high relative differences. The model always yields conservative predictions in very low expansion values, due primarily to the logarithmic form of the E_n versus V_n fit. However, this does not seem to be critical, since the ultimate application of the model is for mitigating the expansion just below 0.04%.

3.4 Fly ash dosage prediction charts

375 As demonstrated before, Eq. 12 yields the fly ash dosage required to reduce ASR
 376 expansion of a mixture from its original level (E_{1Yc}) down to E_{2Yb} . In order to predict the
 377 fly ash dosage needed to mitigate ASR down to ASTM C1293 threshold (i.e. 0.04%),
 378 Eq. 20 can be used.

$$f_{req.}\% = \frac{1 - e^{(0.04/E_{1Yc} - 0.864)/0.6}}{\left(1 - \frac{P_{fa}}{P_c}\right) - \left(1 - \frac{S_{fa}}{S_c}\right) \times e^{(0.04/E_{1Yc} - 0.864)/0.6}} \times 100\% \quad \text{Eq. 20}$$

379 According to this equation, for a concrete mixture (incorporating portland cement
 380 with ASR promoting and suppressing factors of P_c and S_c) which has shown a 1-year
 381 expansion of E_{1Yc} per ASTM C1293, in order to mitigate ASR using a fly ash having P_{fa}
 382 and S_{fa} , $f_{req.}\%$ of OPC replacement with that fly ash is need. In order to facilitate the use
 383 of this formula, a set of charts have been developed. Due to variations in chemical
 384 composition of both cement and fly ash, no single chart can predict proper fly ash
 385 dosage. As Eq. 20 suggests, for different levels of P_{fa}/P_c and S_{fa}/S_c different graphs
 386 correlating E_{1Yc} to $f_{req.}\%$ need to be generated. $P_r = P_{fa}/P_c$ ranges from 0.124 to 1.063,
 387 based on which four levels (i.e., 0.10, 0.45, 0.75 and 1.1) were selected to develop four
 388 charts. $S_r = S_{fa}/S_c$ also ranges from 3.51 to 7.41. Five levels of S_{fa}/S_c (i.e., 3.5, 4.5, 5.5,
 389 6.5 and 7.5) were selected within this range to generate 5 curves within each chart.
 390 Figure 5 shows the fly ash dosage needed to mitigate ASR in a concrete mixture made
 391 with a given cement and reactive aggregate.

392 Further assessments are performed on the proposed model using seven special
 393 data points (shown in Table 6), in which the fly ash replacement percent in the
 394 experiments has led to mitigation of ASR down to $0.04\% \pm 0.004\%$ (i.e., ASTM C1293
 395 threshold with 10% tolerance). Therefore, these data points can be directly applied to

the charts in order to further evaluate the prediction accuracy of the model. Table 6 shows the results of evaluating the accuracy of the model for these data points. All predictions, except for one data point are reasonably conservative (Reliability=86%).

3.5 Online application for estimation of fly ash dosage necessary to mitigate ASR

The developed model has been implemented into an easy-to-use spreadsheet and published online for use [39]. The users are able to obtain the necessary replacement level by inputting the chemical composition of fly ash and cement, the aggregate reactivity level, and selecting either ASR mitigation level or structure type. The aggregate reactivity can be entered either as the one-year CPT expansion result of the aggregate, or the aggregate reactivity level based on AASHTO PP-65 classification (i.e., R_0 : non-reactive ($E_{1Yc} < 0.04\%$), R_1 : moderately reactive ($0.04\% < E_{1Yc} < 0.12\%$), R_2 : highly reactive ($0.12\% < E_{1Yc} < 0.24\%$), or R_3 : very highly reactive ($E_{1Yc} > 0.24\%$)).

The target E_{Y2b} is entered either in the form of ASR mitigation level or the structure type. There are four levels of ASR mitigation available in the spreadsheet adopted from AASHTO PP-65; 1- some deterioration from ASR may be tolerated ($E_{Y2b} = 0.06\%$), 2- moderate risk of ASR is acceptable ($E_{Y2b} = 0.05\%$), 3- minor risk of ASR is acceptable ($E_{Y2b} = 0.045\%$), and 4- ASR cannot be tolerated ($E_{Y2b} = 0.04\%$). The users can alternatively select the structure type in which ASR mitigation is intended. The offered structure types follow the fourfold classification of AASHTO PP-65 as follows: 1- Non-load bearing elements inside buildings; temporary structures (service-life < 5 years), 2- Sidewalks; curbs; gutters; service life < 40 years, 3- Pavements; culverts;

highway barriers; rural, low-volume bridges; service life 40 to 75 years, 4- Major bridges; tunnels; critical elements difficult to inspect or repair; service life > 75 years. The four levels of ASR mitigation correspond to the four categories of structures, respectively. By entering the composition of the portland cement and fly ash (or following the instructions given on the website, if the fly ash composition is not available), selecting either ASR mitigation level or structure type, and finally entering the aggregate reactivity or selecting the reactivity class, the necessary fly ash dosage to mitigate ASR is reported by the spreadsheet.

4. SUMMARY AND CONCLUSIONS

The chemical compositions of portland cement and fly ash have a profound effect on the concrete performance against ASR for any given reactive aggregate. The regression analyses suggest that CaO and MgO of portland cement and fly ash, and also SO₃ of fly ash promote ASR, while SiO₂, Al₂O₃, and Fe₂O₃ components suppress ASR. While the alkalis (Na₂O_{eq}) from portland cement clearly promote ASR, fly ash alkalis show no significant contribution on ASR expansion results of the concrete prism test.

A novel extended chemical index model was developed in this study, which uses the chemical compositions of fly ash and cement, and the 1-year expansion results of concrete prism test to predict the amount of fly ash (as cement replacement) required to mitigate ASR. The generated model offers acceptable prediction accuracies for both Class C and F fly ashes and can be used for both of them. According to the statistical

analyses of the prediction errors, the model has a good potential to be a useful and reliable tool for concrete practitioners and infrastructure owners for ASR mitigation purposes.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support from the National Science Foundation (NSF) under CMMI CAREER Award# 1254333, awarded to the third author. Any opinions, findings, conclusions, or recommendations expressed in this manuscript are those of the authors solely and do not necessarily reflect the views of NSF. We like to dedicate this article to the memory of Dr. Javier Malvar who was an admired and inspirational concrete engineer. The contributions of Mr. Ali Kazemian in collecting and compiling the literature are greatly appreciated. The first author would like to thank his dear mother and wife for their endless support and love.

454 **Table 1: Fly ash properties obtained from literature [21-24] and used in the model. Oxides are**
455 **reported in % by mass.**

Literature	Fly Ash label (class)	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	MgO	SO ₃	LOI	Na ₂ O _{eq}	P _{fa} ^a	S _{fa} ^b
ST [23]	LG (F)	5.57	41.96	19.64	20.07	0.69	2.44	1.19	0.95	3.71	2.30	1.96	33.88
ST [23]	FM (F)	6.38	47.34	22.34	15.08	0.60	1.23	0.82	1.43	2.73	1.41	2.12	36.96
ST [23]	MN (F)	8.68	61.50	20.52	4.29	0.17	0.60	1.70	0.19	0.08	0.56	2.55	44.40
ST [23]	SD I (F)	13.63	50.92	23.64	4.62	3.38	0.59	0.86	0.23	0.42	3.77	3.18	37.74
ST [23]	BD (F)	12.34	45.66	21.42	5.53	7.82	0.96	2.76	0.84	0.35	8.45	3.97	34.10
ST [23]	SD II (F)	15.15	51.56	22.90	4.58	2.60	0.30	1.16	0.28	0.35	2.80	3.64	38.08
ST [23]	TB (C)	15.87	40.68	21.19	4.50	8.14	0.49	3.54	2.18	0.53	8.46	5.47	30.56
ST [23]	C1 (F)	17.51	44.29	20.96	5.23	1.13	0.84	4.21	2.13	1.14	1.68	6.08	30.08
ST [23]	WM (C)	18.46	39.77	21.46	5.69	3.71	0.66	3.77	1.86	1.06	4.14	5.98	30.19
ST [23]	BR (C)	18.85	32.71	19.02	5.76	8.28	0.68	4.30	4.81	1.18	8.73	7.30	25.18
ST [23]	PI (C)	20.50	38.42	20.57	5.64	2.64	0.62	4.39	1.76	2.01	3.05	6.63	29.17
ST [23]	C2 (C)	21.53	39.83	19.56	5.54	1.55	0.60	4.62	2.14	1.68	1.94	7.07	29.98
ST [23]	EW (C)	24.61	38.22	18.43	5.72	1.39	0.44	4.72	1.55	0.18	1.68	7.53	28.79
ST [23]	PP (C)	26.61	35.20	18.72	6.06	1.59	0.36	5.12	2.49	0.39	1.83	8.42	26.86
ST [23]	IN (C)	26.62	36.12	18.64	6.07	1.34	0.40	5.41	1.80	0.16	1.60	8.32	27.47
ST [23]	OK I (C)	27.71	34.60	16.45	7.13	1.51	0.21	5.89	2.71	0.28	1.65	9.06	26.37
ST [23]	OK II (C)	29.10	31.65	16.65	7.28	1.72	0.20	6.57	3.17	0.36	1.85	9.79	24.44
ST [23]	CC (C)	30.00	41.12	11.24	5.93	1.10	1.76	4.40	2.13	0.78	2.26	8.66	29.91
Fournier [22]	FFS FA1 (F)	2.06	41.72	19.70	26.03	0.79	2.12	0.87	1.08	3.38	2.18	1.16	34.74
Fournier [22]	FFS FA2 (F)	2.39	50.16	26.84	12.75	0.26	2.24	0.89	0.78	2.80	1.73	1.13	39.00
Fournier [22]	FFS FA3 (F)	9.07	55.62	20.33	4.08	4.22	1.86	0.94	3.43	0.50	5.44	3.39	40.40
Fournier [22]	FFS FA6 (F)	7.45	59.15	19.13	5.27	2.50	1.06	2.47	0.18	0.18	3.20	2.64	42.82
DB [21]	PFA-A (F)	1.87	42.20	21.60	27.60	0.66	2.55	0.92	1.10	1.85	2.34	1.15	35.56
DB [21]	PFA-B (F)	12.00	53.90	20.90	0.00	2.74	0.50	1.11	0.09	0.57	3.07	2.92	38.62
DB [21]	PFA-C (C)	20.70	32.59	17.93	0.00	8.08	0.72	4.12	1.48	0.96	8.55	6.46	23.99
Moser [24]	Moser FA (C)	24.82	36.89	18.11	6.08	1.88	0.51	5.85	1.69	0.10	2.22	8.11	27.92

^a Calculated per Eq. 15

^b Calculated per Eq. 17

459 **Table 2: Portland cement properties obtained from literature [21-24] and used in the model.**
460 **Oxides are reported in % by mass.**

Literature	Cement	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	K ₂ O	MgO	SO ₃	Na ₂ O _{eq}	P _c ^a	S _c ^b
ST [23]	HAPC	62.98	20.83	5.11	2.01	0.51	1.12	2.43	3.25	1.25	9.21	5.99
Fournier [22]	OPC3	61.72	20.15	5.52	2.59	0.53	1.09	2.19	4.98	1.25	9.01	6.59
Fournier [22]	OPC4	62.39	20.42	5.08	2.37	0.57	1.03	2.55	3.11	1.25	9.18	6.36
DB [21]	CEMENT-A	63.12	20.47	5.51	2.45	0.49	1.16	2.82	2.60	1.25	9.29	6.47
Moser [24]	Moser OPC	62.80	20.66	5.22	3.64	0.95	0.45	1.56	2.88	1.25	9.21	7.95

^a Calculated per Eq. 15

^b Calculated per Eq. 17

464
465

Table 3: Aggregates and their 1 year CPT expansion (E_{1Yc}) results [21-24], and AASHTO PP-65 [17] designation.

Literature	Aggregate Type	1-year % expansion E_{1Yc}	AASHTO PP-65 designation
ST [23]	Spratt*	0.25	Very Highly Reactive
Fournier [22]	Sandstone, quartzwacke, arkose, greywacke, and argillite (Su)	0.075	Moderately Reactive
Fournier [22]	Sandstone, limestone, quartzite, and fine grained volcanics (Al)	0.09	Moderately Reactive
Fournier [22]	Wyoming gravel (Wy)	0.09	Moderately Reactive
Fournier [22]	Siliceous sandstone (Po)	0.13	Highly Reactive
Fournier [22]	Spratt*	0.184	Highly Reactive
Fournier [22]	Metagreywacke (Con)	0.196	Highly Reactive
Fournier [22]	Greywacke (Sl)	0.221	Highly Reactive
DB [21]	Spratt*	0.286	Very Highly Reactive
DB [21]	Rhyolitic Tuff	0.248	Very Highly Reactive
Moser [24]	Chert fine agg	0.43	Very Highly Reactive

466
467
468
469

* Aggregates from same quarries could show different E_{1Yc} due to (a) possible change in aggregate properties with time, (b) difference in the portland cement used, (c) inherent variability of ASTM C1293 test.

470
471

Table 4: E_{1Yc} and E_{2Yb} values based on the cement, fly ash, fly ash dosage, and aggregate type obtained from the literature.

Row ^a	Literature	Cement	%	Fly Ash (type)	%	Aggregate	E_{1Yc} (%)	E_{2Yb} (%)
1	ST [23]	HAPC	100			Spratt	0.250	
2	ST [23]	HAPC	75	LG (F)	25	Spratt		0.030
3	ST [23]	HAPC	85	FM (F)	15	Spratt		0.083
4	ST [23]	HAPC	80	FM (F)	20	Spratt		0.043
5	ST [23]	HAPC	80	FM (F)	20	Spratt		0.099
6	ST [23]	HAPC	85	MN (F)	15	Spratt		0.039
7	ST [23]	HAPC	75	MN (F)	25	Spratt		0.014
8	ST [23]	HAPC	85	SD I (F)	15	Spratt		0.100
9	ST [23]	HAPC	80	SD I (F)	20	Spratt		0.067
10	ST [23]	HAPC	75	SD I (F)	25	Spratt		0.042
11	ST [23]	HAPC	80	BD (F)	20	Spratt		0.156
12	ST [23]	HAPC	70	BD (F)	30	Spratt		0.113
13	ST [23]	HAPC	60	BD (F)	40	Spratt		0.087
14	ST [23]	HAPC	85	SD II (F)	15	Spratt		0.062
15	ST [23]	HAPC	75	SD II (F)	25	Spratt		0.032
16	ST [23]	HAPC	75	TB (C)	25	Spratt		0.117
17	ST [23]	HAPC	75	C1 (F)	25	Spratt		0.039
18	ST [23]	HAPC	80	WM (C)	20	Spratt		0.123
19	ST [23]	HAPC	70	WM (C)	30	Spratt		0.100
20	ST [23]	HAPC	60	WM (C)	40	Spratt		0.068
21	ST [23]	HAPC	50	WM (C)	50	Spratt		0.042
22	ST [23]	HAPC	70	WM (C)	30	Spratt		0.112
23	ST [23]	HAPC	75	BR (C)	25	Spratt		0.157
24	ST [23]	HAPC	75	PI (C)	25	Spratt		0.026
25	ST [23]	HAPC	75	C2 (C)	25	Spratt		0.080
26	ST [23]	HAPC	70	EW (C)	30	Spratt		0.086
27	ST [23]	HAPC	60	EW (C)	40	Spratt		0.051
28	ST [23]	HAPC	50	EW (C)	50	Spratt		0.033
29	ST [23]	HAPC	85	PP (C)	15	Spratt		0.176
30	ST [23]	HAPC	75	PP (C)	25	Spratt		0.082
31	ST [23]	HAPC	85	IN (C)	15	Spratt		0.191
32	ST [23]	HAPC	75	IN (C)	25	Spratt		0.130
33	ST [23]	HAPC	75	OK I (C)	30	Spratt		0.138

34	ST [23]	HAPC	55	OK I (C)	45	Spratt	0.054
35	ST [23]	HAPC	40	OK I (C)	60	Spratt	0.021
36	ST [23]	HAPC	55	OK I (C)	45	Spratt	0.136
37	ST [23]	HAPC	75	OK II (C)	25	Spratt	0.176
38	ST [23]	HAPC	75	CC (C)	25	Spratt	0.162
39	Fournier [22]	OPC 3	100			Ontario Hybrid (Su)	0.075
40	Fournier [22]	OPC 3	80	FA 2 (F)	20	Ontario Hybrid (Su)	0.008
41	Fournier [22]	OPC 3	70	FA 2 (F)	30	Ontario Hybrid (Su)	0
42	Fournier [22]	OPC 3	44	FA 2 (F)	56	Ontario Hybrid (Su)	0.008
43	Fournier [22]	OPC 3	100			Alberta Hybrid (Al)	0.090
44	Fournier [22]	OPC 3	80	FA 3 (F)	20	Alberta Hybrid (Al)	0.016
45	Fournier [22]	OPC 3	70	FA 3 (F)	30	Alberta Hybrid (Al)	0.011
46	Fournier [22]	OPC 4	100			Wyoming gravel (Wy)	0.090
47	Fournier [22]	OPC 4	80	FA 6 (F)	20	Wyoming gravel (Wy)	0.03
48	Fournier [22]	OPC 4	70	FA 6 (F)	30	Wyoming gravel (Wy)	0.013
49	Fournier [22]	OPC 3	100			Siliceous Sandstone (Po)	0.130
50	Fournier [22]	OPC 3	70	FA 1 (F)	30	Siliceous Sandstone (Po)	0.015
51	Fournier [22]	OPC 3	100			Spratt (Sp)	0.184
52	Fournier [22]	OPC 3	70	FA 2 (F)	30	Spratt (Sp)	0.007
53	Fournier [22]	OPC 4	100			Metagreywacke (Con)	0.196
54	Fournier [22]	OPC 4	80	FA 1 (F)	20	Metagreywacke (Con)	0.04
55	Fournier [22]	OPC 4	70	FA 1 (F)	30	Metagreywacke (Con)	0.02
56	Fournier [22]	OPC 4	44	FA 1 (F)	56	Metagreywacke (Con)	0.005
57	Fournier [22]	OPC 3	100			Greywacke (Sl)	0.221
58	Fournier [22]	OPC 3	80	FA 1 (F)	20	Greywacke (Sl)	0.05
59	Fournier [22]	OPC 3	70	FA 1 (F)	30	Greywacke (Sl)	0.021
60	Fournier [22]	OPC 3	44	FA 1 (F)	56	Greywacke (Sl)	0.006
61	DB [21]	Cement-A	100			Rhyolitic Tuff	0.248
62	DB [21]	Cement-A	80	PFA-A (F)	20	Rhyolitic Tuff	0.04
63	DB [21]	Cement-A	60	PFA-A (F)	40	Rhyolitic Tuff	0
64	DB [21]	Cement-A	80	PFA-B (F)	20	Rhyolitic Tuff	0.02
65	DB [21]	Cement-A	60	PFA-B (F)	40	Rhyolitic Tuff	0
66	DB [21]	Cement-A	80	PFA-C (C)	20	Rhyolitic Tuff	0.26
67	DB [21]	Cement-A	60	PFA-C (C)	40	Rhyolitic Tuff	0.15
68	DB [21]	Cement-A	100			Spratt	0.286
69	DB [21]	Cement-A	80	PFA-A (F)	20	Spratt	0.035

70	DB [21]	Cement-A	60	PFA-A (F)	40	Spratt	0
71	DB [21]	Cement-A	80	PFA-B (F)	20	Spratt	0
72	DB [21]	Cement-A	60	PFA-B (F)	40	Spratt	0
73	DB [21]	Cement-A	80	PFA-C (C)	20	Spratt	0.16
74	DB [21]	Cement-A	60	PFA-C (C)	40	Spratt	0.11
75	Moser [24]	Moser OPC	100			Chert sand	0.430
76	Moser [24]	Moser OPC	92	Moser FA (C)	8	Chert sand	0.294

^a The rows highlighted in gray are the ones used for evaluating the model.

474 **Table 5. The optimized values of the coefficients in the ASR promoting and suppressing factors**

Parameter	Optimized value	Parameter	Optimized value	Parameter	Optimized value	Parameter	Optimized value
p_1	0.13	p'_1	0.2	s_1	0.17	s'_1	0.67
p_2	0.7	p'_2	0.44	s_2	0	s'_2	0.12
p_3	0.18	p'_3	0	s_3	1.22	s'_3	0.17
p_4	0.19	p'_4	0				
p_5	0	p'_5	0.34				

475

476

477 **Table 6. Results on prediction accuracy of the charts for the seven data points with**
478 **$E_{2Yb}=0.04\pm0.004\%$**

Row	Cement	Fly ash (class)	E_{1Yc} (%)	P_c	S_c	P_{fa}	S_{fa}	P_r	S_r	Actual replacement (%)	Estimated replacement (%)
4	HAPC	FM (F)	0.25	9.21	5.99	2.12	36.96	0.23	6.17	20	28.4
6	HAPC	MN (F)	0.25	9.21	5.99	2.55	44.40	0.28	7.41	15	25.6
10	HAPC	SD I (F)	0.25	9.21	5.99	3.18	37.74	0.35	6.30	25	29.6
17	HAPC	C1 (F)	0.25	9.21	5.99	6.08	30.08	0.66	5.02	25	39.9
21	HAPC	WM (C)	0.25	9.21	5.99	5.98	30.19	0.65	5.04	50	42.3
54	OPC 4	FA 1 (F)	0.196	9.18	6.36	1.16	34.74	0.13	5.46	20	28.2
62	Cement-A	PFA-A (F)	0.248	9.29	6.47	1.15	35.56	0.12	5.50	20	30.3

479

480

Figure 1. Normalized expansion of the concrete prisms versus normalized values of the ASR suppressing components

485

486

487

Figure 2. Normalized expansion of the concrete prisms versus normalized values of the ASR promoting components

488

489

490

Figure 3. Normalized expansion of the concrete prisms versus $\text{Na}_2\text{O}_{\text{eq}}$ content of cement and fly ash

Figure 4. The optimum correlation between the normalized ASR vulnerability index of binders and their CPT expansions. 65% of the expansions fall below the trend line.

Figure 5. Fly ash dosage required to mitigate ASR per ASTM C1293 concrete prism test ($E_{2Y0}=0.04\%$)

Note: For any given fly ash and cement used, the 1-yr expansion is linked to the applicable curve, and the corresponding value on the y-axis is the fly ash% required to mitigate ASR below ASTM C1293 threshold.

-
- 1 Fournier, B., Berube, M. A., Folliard, K. J., & Thomas, M.D.A. (2010). Report on the diagnosis, prognosis, and mitigation of alkali-silica reaction (ASR) in transportation structures (No. FHWA-HIF-09-001).
  - 2 Malvar, L. J., Cline, G. D., Burke, D. F., Rollings, R., Greene, J., & Sherman, T. W. (2001). Alkali-Silica Reaction Mitigation: State-of-the-Art (No. NFESC-TR-2195-SHR). NAVAL Facilities Engineering Command Port Hueneme CA Engineering Service Center.
  - 3 Thomas, M.D.A. (2011). The effect of supplementary cementing materials on alkali-silica reaction: A review. *Cement and Concrete Research*, 41(12), 1224-1231.
  - 4 Shafaatian, S., Akhavan, A., Maraghechi, H., & Rajabipour, F. (2013). How does fly ash mitigate alkali-silica reaction (ASR) in accelerated mortar bar test (ASTM C1567)? *Cement and Concrete Composites*, 37, 143-153.
  - 5 Rajabipour, F., Giannini E., Dunant, C., Ideker, J. H., & Thomas, M. D. A. (2015). Alkali-silica reaction: Current understanding of the reaction mechanisms and the knowledge gaps. *Cement and Concrete Research*, 76, 130–146.
  - 6 Kazemian, A., Gholizadeh Vayghan, A., & Rajabipour, F. (2015). Quantitative assessment of parameters that affect strength development in alkali activated fly ash binders. *Construction and Building Materials*, 93, 869–876.
  - 7 Gopalan, M. K., & Haque, M. N. (1986). Strength development of fly ash concretes. *Materials and Structures*, 19(1), 33-37.
  - 8 ASTM C1260-14, Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method), ASTM International, West Conshohocken, PA, 2014, www.astm.org
  - 9 RILEM Recommended Test Method AAR-2, Detection of potential alkali reactivity of aggregates – The ultra-accelerated mortar-bar test. *Materials and Structures*, 33(229), 2000, 283-289.
  - 10 ASTM C1567-13, Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method), ASTM International, West Conshohocken, PA, 2013, www.astm.org
  - 11 Thomas, M.D.A., Fournier, B., Folliard, K., Ideker, J., & Shehata, M. (2006). Test methods for evaluating preventive measures for controlling expansion due to alkali-silica reaction in concrete. *Cement and Concrete Research*, 36(10), 1842-1856.
  - 12 Ideker, J. H., Bentivegna, A. F., Folliard, K. J., & Juenger, M. C. (2012). Do current laboratory test methods accurately predict alkali-silica reactivity?. *ACI Materials Journal*, 109(4).
  - 13 Lindgård, J., Andiç-Çakır, Ö., Fernandes, I., Rønning, T. F., & Thomas, M. D. A. (2012). Alkali-silica reactions (ASR): Literature review on parameters influencing laboratory performance testing. *Cement and Concrete Research*, 42(2), 223-243.
  - 14 ASTM C1293-08b, Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction, ASTM International, West Conshohocken, PA, 2008, www.astm.org
  - 15 RILEM recommended test method AAR-3: Detection of potential alkali-reactivity - 38°C test method for aggregate combinations using concrete prisms. *Materials and Structures*, 33(229), 2000, 290-293.
  - 16 Accelerated Determination of ASR Susceptibility During Concrete Prism Testing Through Nonlinear Resonance Acoustic Spectroscopy - Report - October 2013, FHWA-HRT-13-085
  - 17 American Association of State Highway and Transportation Officials (AASHTO), Standard practice for determining the reactivity of concrete aggregates and selecting appropriate measures for preventing deleterious expansion in new concrete construction, PP-65-11, 2013.

-
- 18 Malvar, L. J., & Lenke, L. R. (2006). Efficiency of fly ash in mitigating alkali-silica reaction based on chemical composition. *ACI materials journal*, 103(5).
  - 19 Wright, J. R., Shafaatian, S., & Rajabipour, F. (2014). Reliability of chemical index model in determining fly ash effectiveness against alkali-silica reaction induced by highly reactive glass aggregates. *Construction and Building Materials*, 64, 166-171.
  - 20 Schumacher, K. A., & Ideker, J. H. (2014). New Considerations in Predicting Mitigation of Alkali-Silica Reaction Based on Fly Ash Chemistry. *Journal of Materials in Civil Engineering*, 27(4), 04014144.
  - 21 Duchesne, J., & Bérubé, M. A. (1994). The effectiveness of supplementary cementing materials in suppressing expansion due to ASR: another look at the reaction mechanisms part 2: pore solution chemistry. *Cement and Concrete Research*, 24(2), 221-230.
  - 22 Fournier, B., Ferro, A., and Sivasundaram, V. (2001) CANMET/Industry Research Consortium on Alkali Aggregate Reactivity in Concrete, Technical Report, 1004031.
  - 23 Shehata, M. H., & Thomas, M. D. (2000). The effect of fly ash composition on the expansion of concrete due to alkali-silica reaction. *Cement and Concrete Research*, 30(7), 1063-1072.
  - 24 Moser, R. D., Jayapalan, A. R., Garas, V. Y., & Kurtis, K. E. (2010). Assessment of binary and ternary blends of metakaolin and Class C fly ash for alkali-silica reaction mitigation in concrete. *Cement and Concrete Research*, 40(12), 1664-1672.
  - 25 ASTM C618-12a, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, ASTM International, West Conshohocken, PA, 2012, www.astm.org
  - 26 Mehta, P. K. (1986). Standard Specifications for Mineral Admixtures-An Overview. ACI Special Publication, 91.
  - 27 Malhotra, V. M., and Ramezaniapour, A. A. (1994). Fly Ash in Concrete. MSL 94-45(IR), CANMET, Canada Center for Mineral and Energy Technology, Natural Resources Canada, Ottawa, Ontario, Canada, 307 pp.
  - 28 Malvar, L. J., Cline, G. D., Burke, D. F., Rollings, R., Sherman, T. W., & Greene, J. L. (2002). Alkali-silica reaction mitigation: state of the art and recommendations. *ACI Materials Journal*, 99(5).
  - 29 Hawkins, M.R. (1987). Alkali silica reaction: Minimizing the risk of damage to concrete. Guidance notes and model specification clauses, Technical Report No. 30. The U.K. Concrete Society, 34pp.
  - 30 Ramlochan, T., Thomas, M. D. A., Gruber, K. A. (2000). The effect of metakaolin on alkali-silica reaction in concrete. *Cement and Concrete Research*, 30, 339-344.
  - 31 ACI Committee 232. (2002). Use of Fly Ash in Concrete: (ACI 232.2R-96). Farmington Hills, MI: American Concrete Institute.
  - 32 Stumm, W., Morgan, J.J. (1995). *Aquatic Chemistry: Chemical Equilibria and Rates in Natural Waters*. Wiley-Interscience, New York.
  - 33 Locher, F. W. (1960). Hydraulic properties and hydration of glasses of the system $\text{CaO-Al}_2\text{O}_3\text{-SiO}_2$. Proceedings of the Fourth International Symposium on the Chemistry of Cement, V. 1, NBS Monograph 43, Washington, DC, pp. 267-276.
  - 34 Diamond, S. (1981). Effects of two Danish fly ashes on alkali contents of pore solutions of cement-fly ash pastes. *Cement and Concrete Research*, 11(3), 383-394.
  - 35 Hobbs, D.W. (1982). Influence of pulverized-fuel ash and granulated blast furnace slag upon expansion caused by the alkali-silica reaction. *Magazine of Concrete Research*, 34(1), 83-94.
  - 36 Shafaatian, S. (2012). Innovative methods to mitigate alkali-silica reaction in concrete materials containing recycled glass aggregates. Ph.D. dissertation. Pennsylvania State University, U.S.A.
  - 37 Barnes, P., & Bensted, J. (2002). *Structure and performance of cements*. CRC Press.

-
- 38 Chappex, T., & Scrivener, K. L. (2013). The effect of aluminum in solution on the dissolution of amorphous silica and its relation to cementitious systems. *Journal of the American Ceramic Society*, 96(2), 592-597.
  - 39 Gholizadeh Vayghan, A., Rajabipour, F. (2015). Fly ash dosage predictor. Retrieved June 23, 2015, from <http://gholizadeh.weebly.com/fly-ash-dosage-predictor.html>