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An extended chemical index model to predict the fly ash dosage necessary for mitigating alkali–silica reaction in concrete

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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.

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 [3–5]. 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 reactivity of aggregates. ASTM C1567 [10] takes a similar approach to find the adequate cement replacement dosage with SCMs to allay ASR. RILEM AAR-2, ASTM C1260 and C1567 are quick and practical, but they are often criticized because of the low reliability of their results due to exposing samples to an unrealistically harsh ASR environment of high temperature and inexhaustible alkalinity [11–13]. In addition, they test mortars, which could perform very differently than the field concrete mixtures. A more reliable test method to predict ASR expansion of ordinary Portland cement (OPC) and blended cement concrete mixtures is the concrete prism test (CPT), described in ASTM C1293 [14] and RILEM TC 219-ACS AAR-3 [15]. The U.S. Federal Highway Administration (FHWA) considers CPT as the most reliable test method currently available for assessing the sustainability of ordinary and blended concrete mixtures to resist ASR damage [16]. However, CPT allows for much less acceleration compared to AMBT and needs 2 years to assess the performance of mixtures containing SCM. Another reliable method of assessing ASR is the outdoor exposure block testing [11], which takes several years to provide information.

AASHTO PP-65 [17] is a new standard specification, which is aimed at selecting appropriate measures for preventing ASR in new concrete construction. It offers an elaborate method for classifying the aggregate reactivity (into non-reactive, moderately, highly, or very highly reactive) based on the results of AMBT or CPT for plain OPC mixtures. It also includes prescriptive and performance-based methods for determining the SCM (i.e., fly ash, slag, or silica fume) dosage required to be proportioned in concrete mixtures to prevent ASR. The prescriptive method of AASHTO PP-65 uses 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 CaO < 18%, which excludes almost all Class C ashes.

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The allowable Class F fly ashes are classified only based on their alkali content (into $Na_2O_{eq} < 3.0\%$, and $3.0\% < Na_2O_{eq} < 4.5\%$), with $Na_2O_{eq} > 4.5\%$ not being allowed. While this serves practicality, it does not account for the quantitative values of fly ash constituents (e.g., $SiO_2\%$, $Al_2O_3\%$, 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.

2. Earlier work on ASR predictive models for fly ash concrete

In 2006, Malvar and Lenke developed a chemical index model using multiple sets of data available in the literature on the ASTM C1567 (AMBT) results of 31 different fly ashes [18]. They argued that calcium oxide is the most deleterious component of fly ash in promoting ASR. They also introduced other deleterious components such as Na_2O, K_2O, MgO, and SO_3 and converted them to a molar equivalent CaO_{eq} index formula that would represent all fly ash components that promote ASR expansion. Similarly, SiO_2 was considered to be the main oxide suppressing expansion, and Al_2O_3 and Fe_2O_3 were introduced in the form of their SiO_2 equivalents to determine a SiO_{2eq} index formula. The ASR promoting and -suppressing factors of a cement–fly ash blend were then combined into a ratio shown in Eq. (1) [18].

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

where C_b stands for the chemical index of the blend. In the case of no replacement of cement with fly ash, the ratio basically yields the chemical index of the cement (i.e., C_c). The terms α and β were included in the chemical indices to account for "different reactivity" of CaO and SiO_2 in comparison with other oxide components. The normalized expansion of the blend and plain OPC binders at 14 days according to ASTM C1567 (i.e. E_{14b}/E_{14c}) was plotted against their normalized chemical index, C_b/C_c, 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 [21–24]. 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 is 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 2-year expansion of the blended mixture (E_{2Yb}) divided by the 1-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, Na_2O_{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 $(0.9 \times 20\% + 0.1 \times 50\%)/(20\%) = 1.15$.

Fig. 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