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Reliability of chemical index model in determining fly ash effectiveness against alkali-silica reaction induced by highly reactive glass aggregates

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HIGHLIGHTS

- Validation of Malvar and Lenke [1] chemical index model for recycled glass aggregate.
- Model revisions predict fly ash dosages necessary to control the alkali-silica reaction.
- Allows concrete material suppliers blueprint for implementation of glasscrete in the field.

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ABSTRACT

This study investigates the ability of six fly ashes to control ASR (alkali-silica reaction) generated by recycled glass sand. Specifically, this study evaluates the chemical index model's (Malvar and Lenke, 2006 [1]) capacity to accurately predict the fly ash dosage necessary to mitigate ASR. Results show the current model is conservative for low lime (CaO <10%) ashes (~9% greater dosage than experimental results) and quite conservative for higher CaO (>10%) ashes (~36% greater dosage than experimental results). Conclusions suggest revising model parameters can provide accurate predictions for low CaO ashes and moderately conservative predictions for higher CaO ashes.

1. Introduction and research significance

Fly ash is known as an effective supplementary cementitious material (SCM) to control the alkali-silica reaction (ASR) in concrete containing potentially reactive aggregates [1–15]. To determine the required dosage of SCMs to control ASR in such concretes, ASTM C 1567 (commonly known as the accelerated mortar bar test, AMBT) is often used. In this test, mortar bars containing the aggregates of interest and a cement-SCM binary binder are made and exposed to an ASR accelerating environment (1N NaOH solution at 80 °C), while their linear expansion is monitored over time. Recent work [15 and references therein] provided a thorough literature review and experimental investigation of the mechanisms that lead to mitigation of ASR by using fly ash during ASTM C 1567 test. It was found that the most likely mechanisms contributing to fly ash's ability to control ASR are alkali binding (by the added pozzolanic C–S–H) and limiting moisture/ion transport within the material.

In 2006, Malvar and Lenke (M+L) [1] compiled close to a decade's worth of experimental data on ASTM C 1567 and created a chemical index model that can predict the dosage of fly ash necessary to reduce ASR expansion below 0.08% in mortar bars containing reactive natural aggregates. It should be noted that ASTM C 1567 cites <0.10% expansion (at 14 days NaOH exposure) as representing an innocuous behavior; but the M+L model is more conservative, aiming for 0.08% expansion. Based on the chemical composition of the cement and fly ash, this model provides empirical nomographs that can be used by concrete suppliers as well as government transportation agencies to create a binary (cement-fly ash) concrete mixture that can be durable against ASR when use reactive aggregates is unavoidable.

Malvar and Lenke used several combinations of Portland cement, fly ash, and reactive aggregates to develop their model. To date, only one subsequent study has been published to validate if the M+L model is accurate when tested against an independent cement, fly ash, or aggregate, other than those used in developing the model [16]. In fact, even though those researchers use a different cement and fly ash, it also uses Spratt reactive aggregates, which is one of the aggregates used by Malvar and Lenke to

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develop their model [16]. Spratt is a siliceous limestone with ASTM C 1567 expansion without fly ash ≈0.40%.

To better evaluate the reliability of the M+L model in predicting the necessary fly ash dosage to mitigate ASR, this study uses a totally independent recycled soda-lime glass aggregate, along with independent sources of Portland cement and six different fly ashes. Recycled glass (e.g., crushed containers and window plates) is a non-conventional aggregate resource, whose application in concrete is becoming widespread due to its local availability, as well as environmental benefits associated with the use of recycled materials [17]. Recycled glass is a highly reactive aggregate (ASTM C 1567 expansion without fly ash = 0.60–0.80%, depending on the method of crushing), which also contains a uniquely high alkali content (∼14%), allowing the glass aggregates to sustain a high pH and a high ASR rate as the aggregates continue to dissolve in the concrete pore solution. Past research showed that concrete containing recycled glass sand can be made to achieve desired strength and durability, by using fly ash or slag as a partial cement replacement [15,18–24]. However, to date, no blueprint for attaining the proper SCM dosage in these materials has been suggested, other than direct ASR testing according to ASTM C1567 or ASTM C1293. Given that not all design engineers and concrete suppliers have access to laboratory facilities to allow direct ASR testing, the availability of a simple and reliable model to determine the necessary SCM dosage is particularly valuable.

This document will evaluate the accuracy of the M+L model in order to attain this blueprint, and allow production of durable concretes with recycled glass aggregates. Mortars using a type I Portland cement, one of six different fly ashes, and recycled glass as 100% fine aggregates are evaluated. The six fly ashes include four ASTM C 618 Class F and two Class C ashes that contain very different CaO and alkali contents, which are known to influence effectiveness of fly ash against ASR.

2. The chemical index model of Malvar and Lenke [1]

This model equates a normalized ASTM C 1567 14-day mortar bar expansion value (i.e., the 14-day mortar expansion when using fly ash-cement binary blends ($E_{14\mathrm{b}}$), divided by the 14-day mortar expansion when using cement alone ($E_{14\mathrm{c}}$)) to a function containing the chemical indices of the Portland cement alone (C_c) and the fly ash-cement binary blend (C_b). The function containing the chemical indices is represented in Eq. (1), while C_c is created using the formula presented in Eq. (2). The dimensionless parameters a_1–a_4 are included in the model to achieve the best fit between experimental results and model predictions. Eq. (2) includes the weight percentage of different oxides in cement or fly ash (CaO, Na_2O, etc.), commonly measured using X-ray florescence spectroscopy, XRF. Parameters α and β represent independent weighting factors to account for the different reactivity of the chemical compositions. Values of $\alpha = 6.0$ and $\beta = 1.0$ are implemented by the M+L model and by this current research. Furthermore, C_{fa}, the chemical index of the fly ash alone, is calculated similarly, using Eq. (2). Eq. (3) represents a sample calculation for C_b, the chemical index of the fly ash-cement binary blend, where W represents the fly ash content (i.e., mass fraction of the cementitious materials), $\mathrm{CaO}_{\mathrm{eq}\alpha\mathrm{fa}}$ is the modified CaO equivalent of the fly ash, $\mathrm{CaO}_{\mathrm{eq}\alpha c}$ is the modified CaO equivalent of the cement (both $\mathrm{CaO}_{\mathrm{eq}\alpha\mathrm{fa}}$ and $\mathrm{CaO}_{\mathrm{eq}\alpha c}$ are represented by the numerator in Eq. (2)), $\mathrm{SiO}_{2\mathrm{eq}\beta\mathrm{fa}}$ is the SiO_2 equivalent of the fly ash, and $\mathrm{SiO}_{2\mathrm{eq}\beta c}$ is the SiO_2 equivalent of the cement (both are represented by the denominator in Eq. (2)).

$$\frac{E_{14\mathrm{b}}}{E_{14\mathrm{c}}} = \frac{a1}{2}\left[1 - \tan h\frac{\left(\left(\frac{C_b}{C_c}\right) - a_3\right)}{a_4}\right] + \frac{a_2}{2}\left[1 + \tan h\frac{\left(\left(\frac{C_b}{C_c}\right) - a_3\right)}{a_4}\right] \tag{1}$$

$$\begin{aligned} C_{(c\ \text{or}\ \text{fa})} &= \frac{\mathrm{CaO}_{\mathrm{eq}\alpha(c\ \text{or}\ \text{fa})}}{\mathrm{SiO}_{2\mathrm{eq}\beta(c\ \text{or}\ \text{fa})}} \\ &= \frac{\mathrm{CaO} + \alpha(0.905\mathrm{Na_2O} + 0.595\mathrm{K_2O} + 1.391\mathrm{MgO} + 0.700\mathrm{SO_3})}{\mathrm{SiO_2} + \beta(0.589\mathrm{Al_2O_3} + 0.376\mathrm{Fe_2O_3})} \end{aligned} \tag{2}$$

$$C_b = \frac{W(\mathrm{CaO}_{\mathrm{eq}\alpha\mathrm{fa}}) + (1 - W)(\mathrm{CaO}_{\mathrm{eq}\alpha c})}{W(\mathrm{SiO}_{2\mathrm{eq}\beta\mathrm{fa}}) + (1 - W)(\mathrm{SiO}_{2\mathrm{eq}\beta c})} \tag{3}$$

Malvar and Lenke [1] compiled experimental data using different combinations of various reactive aggregates, Portland cements and fly ashes; and used statistical regression to determine the best values for dimensionless model parameters a_1, a_2, a_3, and a_4. The goal was to develop the model that can predict the experimental results of ASTM C 1567 (i.e., 14-day mortar bar expansion, $E_{14\mathrm{b}}$), with both a 50% reliability level and a 90% reliability level. Their model yielded a_1, a_2, a_3, and a_4 values for 50% reliability as 0.0000, 1.0550, 0.7320, and 0.1834, respectively. For 90% reliability, the model yielded a_1, a_2, a_3, and a_4 values as 0.0000, 1.0244, 0.6696, and 0.1778, respectively. Through algebra, Malvar and Lenke [1] were able to propose Eq. (4) that would predict the necessary dosage of any given fly ash (of known chemical composition) to yield 14-day mortar bar expansions below 0.08%. Eq. (4) predictions are based on the chemical composition of the cement and fly ash and the value $E_{14\mathrm{c}}$.

$$W = \frac{1 - \left(a_4 \tan h^{-1}\left(\frac{\left(2\left(\frac{0.08}{E_{14c}}\right) - (a_1 + a_2)\right)}{a_2 - a_1}\right) + a_3\right)}{\left(1 - \left(\frac{\mathrm{CaO}_{\mathrm{eq}\alpha\mathrm{fa}}}{\mathrm{CaO}_{\mathrm{eq}\alpha c}}\right)\right) - \left(1 - \left(\frac{\mathrm{SiO}_{2\mathrm{eq}\beta fa}}{\mathrm{SiO}_{2\mathrm{eq}\beta c}}\right)\right)\left(a_4 \tan h^{-1}\left(\frac{\left(2\left(\frac{0.08}{E_{14c}}\right) - (a_1 + a_2)\right)}{a_2 - a_1}\right) + a_3\right)} \tag{4}$$

3. Materials and testing protocol

3.1. Cementitious materials and mortar preparation

ASTM C 150-12 type I Portland cement was used throughout our experimentation. Six different ASTM C 618-08a fly ashes were studied including four class F ashes (referred to as F1, F2, F3, and F4) and two class C ashes (referred to as C1 and C2). Three of the Class F fly ashes (F1, F2, and F3) had a low lime content (CaO < 10%) while fly ash F4 had an intermediate lime content (10% < CaO < 20%) and the two Class C fly ashes (C1 and C2) had a high lime content (%CaO > 20). The fly ashes were used at varying cement mass replacement levels to evaluate their efficiency in controlling ASR during ASTM C 1567 test. F1 was tested at fly ash dosages from 10% to 30%, F2 from 15% to 30%, F3 from 15% to 30%, F4 from 15% to 30%, C1 from 20% to 30%, and C2 from 20% to 35%. A control mortar mixture containing 100% Portland cement was also tested and used to create normalized expansion values. The oxide compositions, specific gravities, and median particle sizes of the OPC and the six different fly ashes are provided in Table 1.

3.2. Accelerated Mortar Bar Test (AMBT: ASTM C 1567-11)

This test was used to determine the dosage of each fly ash that was necessary to control ASR in mortar bars containing 100% recycled glass sand. The 14-day mortar bar expansion values ($E_{14\mathrm{c}}$ and $E_{14\mathrm{b}}$) were determined as a function of fly ash dosage for the six types of fly ash. Recycled glass aggregates were composed of three main colors: amber (∼30%), clear (∼30), and green (∼40%). To obtain the aggregates, glass bottles were washed and crushed using a ball mill. All mortar mixtures were mixed according to ASTM C 305-06 and prepared with a w/cm of 0.47 and a 53% volume fraction of sand having a gradation in the range of