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Effect of particle size on alkali–silica reaction in recycled glass mortars

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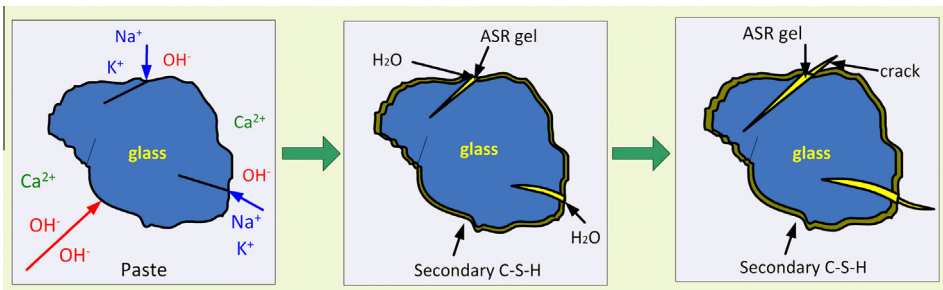
HIGHLIGHTS

- ASR preferentially occurs in internal cracks of glass particles.
- ASR expansion increases with more inherent cracks in glass particles.
- ASR expansion decreases with smaller particle size regardless of glass color.
- The optimal contents for various ASR mitigation methods are determined.
- Fly ash and slag show the highest suppression efficiency on ASR expansion.

GRAPHICAL ABSTRACT



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ABSTRACT

The effect of particle size on alkali–silica reaction (ASR) was investigated to clarify the difference in long-term ASR expansions in mortars using recycled green and brown glass as fine aggregates. Test results revealed that green particles of 1.18 and 2.36 mm showed the highest reactivity while the other sizes resulted in relatively low ASR expansions. Brown glass less than 2.36 mm did not result in large ASR expansion. Furthermore, different ASR suppressors were explored to suppress ASR expansion in mortar using 1.18 mm green glass particles. These included supplementary cementitious materials, steel fiber reinforcement and lithium compounds.

1. Introduction

Waste glass has been explored as a substitute for sand in making concrete in view of sustainability issues related to production and use of concrete [1–3]. For certain type of natural and manufactured materials, such as opal, shale, and silica glass, however, alkali–silica reaction (ASR) has been widely reported to occur [4–6]. The amorphous silica in glass is dissolved under alkali attack to form ASR gel, which can imbibe water and subsequently expand, providing tensile stresses. Once the tensile stress exceeds the tensile strength of the material, cracks will occur. As a result of cracking, corrosive alkalis will be in contact with internal glass structure more easily, accelerating ASR, widening cracks and degrading concrete quality.

ASR is of concern in the re-utilization of waste glass in cementitious mortar and concrete. This study focuses on soda-lime glass since it is the most commonly used and disposed in urban environment. Some researchers have investigated the alkali reactivity of glass particles with different types, colors, sizes and contents [1,7–10]. It is commonly recognized that clear glass shows a higher reactivity than green and brown glass [1,8,10]. Green glass has

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been reported to perform better under alkali attack than brown and clear glass due to the presence of chromium ions, as explained by double-layer theory [1,7,11]. However, there are still debates on the relative reactivity of glass particle with different colors. To name a few, an opposite trend has been reported [12], with flint (clear) glass producing the smallest expansion while green glass producing the largest. It has also been found that mortar bars with brown glass sand expanded less than green glass sand mortar, particularly in the long term [13]. This was attributed to other factors including the nature of the glass product manufacturing processes [12], the availability of alkalis from the glass [9] and the existence of micro-cracks inside the glass particles [14].

Effective ASR mitigation methods have been well documented. They include cementitious material replacement, use of mineral and chemical admixtures, as well as additional reinforcing fibers [7,8,15,16]. The effect of ASR suppressor also depends on the dosage quantity. However, studies reported in the literature are concluded at a certain amount of ASR suppressor. Therefore, the study was aimed at: (a) comparing alkali reactivity of green and brown glass particles; (b) examining the effect of green and brown glass particle size on ASR; and (c) investigating the optimal amount for each mitigation method.

2. Materials and methods

2.1. Materials

Type I Ordinary Portland cement (OPC I) with chemical composition shown in Table 1 was used in this study. It had a sodium oxide equivalent alkali content of 0.6% (determined as $Na_2O_{eq} = \%Na_2O + 0.658 \times \%K_2O$). Green and brown glasses, mainly from beer bottles, were collected from a local recycler and processed in the laboratory. The processing of recycled waste glass involved: (1) pre-soaking and washing by tap water; (2) drying and separating by color; (3) crushing by a jaw crusher; and (4) sieving according to ASTM standard sieve size [17]. With regard to the crusher, its bottom opening can be adjusted, depending on the target size of glass sand. The chemical compositions of green and brown glass are shown in Table 1. The glass sand was determined as fine aggregates as per ASTM C 128 [18]. They had a specific gravity of 2.53 and water absorption of 0.07%, respectively. Compared to natural fine aggregates, the crushed glass sand exhibited sharper edge, more angular shape and smoother surface texture.

Among the ASR suppressors investigated, fly ash, ground granulated blast-furnace slag (GGBS) and undensified silica fume, were used as supplementary cementitious materials (SCM) to substitute cement, and their chemical compositions are shown in Table 1. Smooth steel fibers, with an average diameter of 0.16 mm and length of 5 mm (that is, aspect ratio of 31), were added as fiber reinforcements. Lithium chloride and lithium carbonate were added as chemical admixtures first by dissolving the solid powder in the mixing water and then pouring it into the dry mixture of cement and sand. It should be noted that the solid lithium carbonate cannot be completely dissolved due to its low solubility. Therefore, all the solid particles should be poured into the mixer, without residue attached on the container wall.

2.2. Mix proportions

To compare the alkali reactivity of green and brown glass sand, three mortar mixtures were obtained from three different concrete mixtures by excluding the coarse aggregates. The three concrete mixtures had design strength of 30, 45 and 60 MPa and were mix-proportioned according to ACI 211 [19]. For each mortar mixture, natural sand was replaced by glass sand by 0%, 25%, 50%, 75% and 100%. Therefore, there were in total 15 mixes each for green and brown glass mortars. The mix proportions are shown in Table 2. The size distribution of both natural and glass sand followed the requirement of ASTM C 1260 [20] as shown in Table 3. The natural sand used in this study exhibited an ASR expansion less than 0.2% at 28 days [13], and is classified as non-reactive aggregate by ASTM C 1260.

Table 2
ASTM standard and modified mortar mixture proportion.

Mix no.	Water	Cement	Sand	Coarse aggregate
C30	0.49	1	1.96	2.77
C45	0.38	1	1.33	2.15
C60	0.32	1	0.99	1.81
ASTM C1260	0.47	1	2.25	–
Modified mix	0.47	1	1.6	–

Table 3
Grading requirement of sand as per ASTM C 1260.

Sieve size		Mass (%)
Passing	Retained on	
4.75 mm	2.36 mm	10
2.36 mm	1.18 mm	25
1.18 mm	600 μm	25
600 μm	300 μm	25
300 μm	150 μm	15

The effect of glass particle size was investigated using 100% single-graded glass sand with two different mix ratios, that is, an ASTM standard mix and a slightly modified mix proportion (see Table 2). In this study, the single-graded glasses include 0.15 mm (that is, those passing/retained on 0.15/0.30 mm sieves), 0.30 mm (0.30/0.6 mm sieves), 0.6 mm (0.6/1.18 mm sieves), 1.18 mm (1.18/2.26 mm sieves) and 2.36 mm (2.36/4.75 mm sieves). It is well known that monosize particles would result in larger void content than well-graded particles of the same shape and surface textures. Therefore, more cement paste will be required to fill the increased voids. To produce good quality mortar, the sand/cement ratio was reduced from the standard value of 2.25 to the modified value of 1.6 in modified mix, while the water-to-cement (w/c) ratio was kept unchanged as 0.47. All mortar mixtures showed sufficient paste to fill aggregates voids and provide lubrication layer for sufficient workability. For comparison purpose, the effect of particle size for natural sand was also determined using the modified mix proportion.

The ASR mitigation methods were carried out for the modified mix proportion with 100% of 1.18 mm green glass sand for which ASR was found to be relatively prominent. Fly ash, GGBS, and silica fume was used to substitute cement from 10% to 50% (at 10% increments); 15% to 60% (at 15% increments), and 5.0% to 12.5% (at 2.5% increments), respectively by mass. Steel fibers were added, by volume of the mortar mixture, at 0.5–2.0% (in steps of 0.5%). The content of lithium chloride and lithium carbonate was 0.5–2.0% (in steps of 0.5%) by mass of cement.

2.3. Test methods

Accelerated mortar-bar test (AMBT) was carried out as per ASTM C 1260 [20]. Three mortar bars, 25 × 25 × 285 mm, were prepared for each mix. The mixing and molding procedure was in accordance with ASTM C 305 [21] and C 1260 [20], respectively. The mortar specimens were demolded 24 h after casting and immersed in water at room temperature in a container, which was transferred into an oven at a temperature of 80 °C for the next 24 h. The initial lengths were then

Table 1
Chemical compositions of materials.

Composition (%)	Cement	Fly ash	GGBS	Silica fume	Natural sand	Green glass	Brown glass
SiO_2	20.8	38.9	32.15	95.95	88.54	71.22	72.08
Al_2O_3	4.6	29.15	12.87	0.28	1.21	1.63	1.21
Fe_2O_3	2.8	19.64	0.36	0.32	0.76	0.32	0.76
CaO	65.4	2.5	40.67	0.16	5.33	10.79	10.45
MgO	1.3	2.1	6.05	0.37	0.42	1.57	0.72
SO_3	2.2	0.19	4.95	0.18	–	–	–
Na_2O	0.31	0.26	0.28	0.05	0.33	13.12	13.71
K_2O	0.44	0.48	0.51	0.57	0.31	0.64	0.16
TiO_2	–	–	–	–	0.05	0.07	0.1
Cr_2O_3	–	–	–	–	–	0.22	0.01