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Use of waste glass as sand in mortar: Part II – Alkali–silica reaction and mitigation methods

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ABSTRACT

Waste glass may be used in concrete provided that the potential deleterious expansion caused by alkali–silica reaction (ASR) could be mitigated. In this study, the influence of glass content, color and particle size on ASR expansion of mortar was determined by the accelerated mortar bar method. Two approaches to control ASR expansion were investigated for green, brown and clear glass sand mortar. They were: (1) by replacing cement with pozzolans, that is, 30% fly ash, 60% GGBS, 10% silica fume, or 20% glass powder; (2) by adding a suppressor, that is, plain steel fibers, and lithium chloride and lithium carbonate compounds. Test results showed that the ASR expansion increased with higher glass content in the case of clear glass sand mortar, but would decrease with increasing content for green and brown glass sand mortar. The ASR expansion also decreased with smaller glass particle size, regardless of glass color. Fly ash and GGBS were the most effective in mitigating ASR expansion, followed by silica fume, steel fibers and lithium compounds.

1. Introduction

With increasing awareness of significance of environmental protection and natural resource conservation, the sustainability of concrete as a building material has become an issue [1–5]. Utilization of solid waste in concrete seems to have considerable benefits on cutting waste disposal cost, reducing greenhouse gas emission, conserving natural raw materials, satisfying the increasing stringent environment regulations and even enhancing concrete properties. Among the many types of solid waste, glass has been popularly studied as a substitution for coarse and fine aggregates and even cement. Due to its physical characteristics and chemical compositions, waste glass is considered as good substitution as sand, especially important for places lacking in natural resource and dealing with disposal of wastes. Research has been conducted by the authors to study the performance of cement mortar with glass sand, including fresh, mechanical and durability properties, and reported in Part I of this two-part paper [6].

The alkali–silica reaction (ASR) is a critical factor limiting the incorporation of high glass sand content and its wide application [7–9]. The amorphous silica in glass is susceptible to attack by the alkaline environment and would depolymerize to form a monomer $Si(OH)_4$, which could further react with alkalis such as Na^+, K^+ and Ca^{2+} to form the ASR gel. This ASR gel can absorb water and swell inside the microstructure of concrete, resulting in internal stress. Once the internal stress exceeds the strength of concrete, severe cracking and damage may occur.

However, the ASR phenomenon in glass mortar and concrete is still debatable and not conclusive due to inconsistent test results from previous investigations [6–18]. In terms of the influence of glass color on ASR expansion, some literature reported that green glass showed the lowest ASR expansion compared with brown and clear glass due to the existence of Cr_2O_3 [7,11,12]. However, Ozkan and Yuksel [18] observed very small difference among green, brown and clear glasses in ASR reactivity. Dhir et al. [19] on the other hand reported that green glass showed the highest ASR expansion while clear glass showed the lowest.

Several methods have been investigated to mitigate ASR in concrete containing waste glass [10–12], including cement replacement by mineral materials such as fly ash, and addition of fibers and lithium compounds. Those test results show that these methods are all effective in restraining ASR expansion, and further investigations are necessary.

In this study, the effects of glass color, content and particle size on ASR in cement mortar were examined and reported. A comprehensive investigation on ASR mitigation was also carried out, using supplementary cementitious materials (that is, fly ash, ground granulated blast-furnace slag (GGBS), silica fume and glass powder), and additives (that is, steel fibers and lithium compounds).

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2. Materials and methods

2.1. Materials

Type I ordinary Portland cement (OPC), with alkali content of 0.6% (that is, sodium equivalent $Na_2O_{eq} = Na_2O + 0.658K_2O$), was used. The chemical composition and physical properties are shown in Table 2 in Part I paper [6]. Class F fly ash, GGBS and silica fume, with chemical compositions shown in Table 1, were separately used as cement replacement in this study. To mitigate ASR expansion, smooth steel fibers, with length of 5 mm and diameter of 0.16 mm, and solid lithium chloride (LiCl) and lithium carbonate (Li_2CO_3) were used. Three colors of glass, namely green, brown and clear were studied. The recycling and processing of the wasted glass can be found in Part I paper [6]. The chemical compositions of waste glasses of different colors, as well as natural sand, are also shown in Table 1 in Part I paper [6]. To determine the potential pozzolanic characteristics of glass, glass particles were further finely ground to less than 75 μm and used as partial cement replacement.

2.2. Mix proportions

The reference mortar comprised cement, natural sand and water mixed in the ratio of 1:2.25:0.47 by mass, as specified by ASTM C 1260 [20]. Other mixtures with natural sand replaced with green, brown, clear or mixed-color (that is, mixed glass with green-to-brown [G:B] glass in the ratio of 2:1 by mass) waste glass sand at 0, 25%, 50%, 75% and 100% by mass were prepared. The grading requirement for sand is shown in Table 2. In addition, one series of mortar specimens containing 100% glass sand with G:B mix ratio of 3:1, 2:1, 1:1, 1:2, and 1:3 were also studied. For each glass sand mortar mixture, different ASR mitigation methods were investigated. The percentage of cement replacement was 30% for fly ash, 60% for GGBS and 10% for silica fume by mass. Ground glass powder was also used as cement substitution to mitigate ASR, at a replacement content of 20%. The added amount of steel fibers was at 1.5% by volume of mortar. The addition of LiCl and Li_2CO_3 was 1% of cement by mass. The solid lithium compounds were dissolved in water and added to the mortar mix. Mix proportions of mortar are summarized in Table 3.

Table 1
Chemical compositions of fly ash, GGBS and silica fume.

Composition (%)	Fly ash	GGBS	Silica fume
SiO_2	38.90	32.15	95.95
Al_2O_3	29.15	12.87	0.28
Fe_2O_3	19.64	0.36	0.32
CaO	2.50	40.67	0.16
MgO	2.10	6.05	0.37
SO_3	0.19	4.95	0.18
Na_2O	0.26	0.28	0.05
K_2O	0.48	0.51	0.57

Table 2
Grading requirement of sand according to ASTM C 1260 [20].

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

Table 3
Mixture proportions of glass sand mortar.

Mix No.	Water (g)	Cement (g)	Pozzolan (g)	Sand (g)	Glass sand (g)	Additive (g)
Ref-0	207	440	–	990	0	–
Ref-25	207	440	–	743	248	–
Ref-50	207	440	–	495	495	–
Ref-75	207	440	–	248	743	–
Ref-100	207	440	–	0	990	–
FA-0	207	308	132	990	0	–
FA-25	207	308	132	743	248	–
FA-50	207	308	132	495	495	–
FA-75	207	308	132	248	743	–
FA-100	207	308	132	0	990	–
GGBS-0	207	176	264	990	0	–
GGBS-25	207	176	264	743	248	–
GGBS-50	207	176	264	495	495	–
GGBS-75	207	176	264	248	743	–
GGBS-100	207	176	264	0	990	–
SF-0	207	396	44	990	0	–
SF-25	207	396	44	743	248	–
SF-50	207	396	44	495	495	–
SF-75	207	396	44	248	743	–
SF-100	207	396	44	0	990	–
GP-0	207	352	88	990	0	–
GP-25	207	352	88	743	248	–
GP-50	207	352	88	495	495	–
GP-75	207	352	88	248	743	–
GP-100	207	352	88	0	990	–
Fiber-0	207	440	–	990	0	85
Fiber-25	207	440	–	743	248	85
Fiber-50	207	440	–	495	495	85
Fiber-75	207	440	–	248	743	85
Fiber-100	207	440	–	0	990	85
LiCl-0	207	440	–	990	0	4.4
LiCl-25	207	440	–	743	248	4.4
LiCl-50	207	440	–	495	495	4.4
LiCl-75	207	440	–	248	743	4.4
LiCl-100	207	440	–	0	990	4.4
LiCO-0	207	440	–	990	0	4.4
LiCO-25	207	440	–	743	248	4.4
LiCO-50	207	440	–	495	495	4.4
LiCO-75	207	440	–	248	743	4.4
LiCO-100	207	440	–	0	990	4.4

FA: Fly ash; GGBS: Ground granulated blast-furnace slag; SF: Silica fume; GP: Glass powder; Fiber: Steel fiber; LiCl: Lithium chloride; and LiCO: Lithium carbonate (Li_2CO_3).

2.3. Methods

The ASR expansion was determined by accelerated mortar bar tests as per ASTM C 1260 [20] or C 1567 [21]. For each mix, three 25 mm × 25 mm × 285 mm mortar bars were prepared. They were demolded 24 h after casting and placed in water at 80 °C for the next 24 h. The initial lengths of the mortar bars were then recorded before they were immersed into 1 N 80 °C NaOH solution for curing. The expanded lengths were subsequently measured after 2, 4, 7, 10, 14, 21 and 28 days. The average value of three mortar bar specimens was reported as the ASR expansion. According to ASTM C 1260 [20], expansion larger than 0.2% at 14 days is considered potentially deleterious while less than 0.1% is innocuous. However, for mortars with pozzolans such as fly ash, ASTM C 1567 [21], which states 0.1% as the threshold value for potentially deleterious expansion, should be followed. All the mortar specimens were however investigated until 28 days, to study the ASR development at a later stage. Scanning electron microscopy

(SEM) was also employed to observe the ASR reaction gel in glass sand mortar.

3. Test results and discussion

3.1. Effect of glass color and content

Some researchers [7,12] pointed out that green color glass would be the least reactive in ASR due to its high content of Cr_2O_3, which is added for greenish color. In this study, this effect was clearly observed, when one compares the results of green and clear glass sand mortars. However, in spite of the lesser content of Cr_2O_3, brown glass sand mortar also exhibited similarly small ASR expansion as green glass sand mortar. As the chemical content differs only slightly, Dhir et al. [19] has attributed the different alkali resistance of colored glasses to the manufacturing process instead.

Shi [22] reviewed the ASR expansion in glass concrete and proposed that the mechanism of expansion of concrete caused by glass sand was different from that in traditional ASR expansion. According to Shi [22], Na^+ and Ca^{2+} are first dissolved from glass when the OH^- in pore solution attacks the glass surface, followed by the depolymerization of silicate network. The reaction, as shown in Eq. (1), then occurs to form ASR gel of C–N–S–H:

$$Ca^{2+} + Na^{+} + [SiO(OH)_3]^{-} \rightarrow C - N - S - H \quad (1)$$

The swelling capacity of the ASR gel depends on its chemical composition, especially on the ratio of $CaO/(SiO_2 + Na_2O)$ [23]. It is speculated that in the produced ASR gel of soda–lime glass the content of calcium is relative higher than other types of glass or natural sand. Therefore, the non-swelling ASR gel in glass sand mortar would lead to a less expansion. The same conclusion was also made by Saccani and Bignozzi [16].

The ASR expansions of mortar with green, brown and clear glass sand obtained in the present study are shown in Fig. 1a–c. With increasing content of glass sand, ASR expansion increased substantially for clear glass sand mortar but this was not so for green and brown glass sand mortars. The different ASR reactivity was probably due to significant micro-cracking in clear glass sand in the crushing process.

The test results are in disagreement with some previous results [9–12,24,25], as shown in Fig. 2, in which the scale for ASR

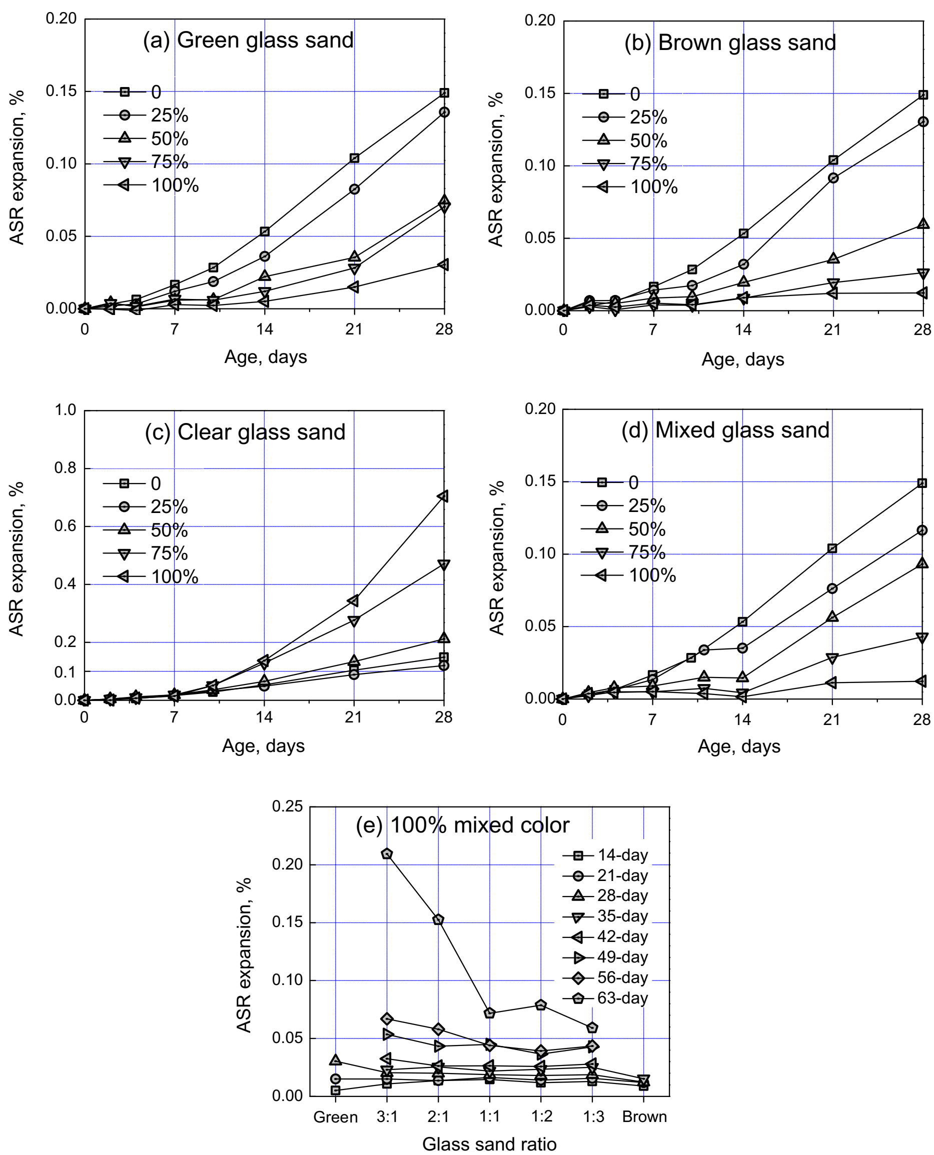


Fig. 1. ASR expansion of mortar with different color glass sands.

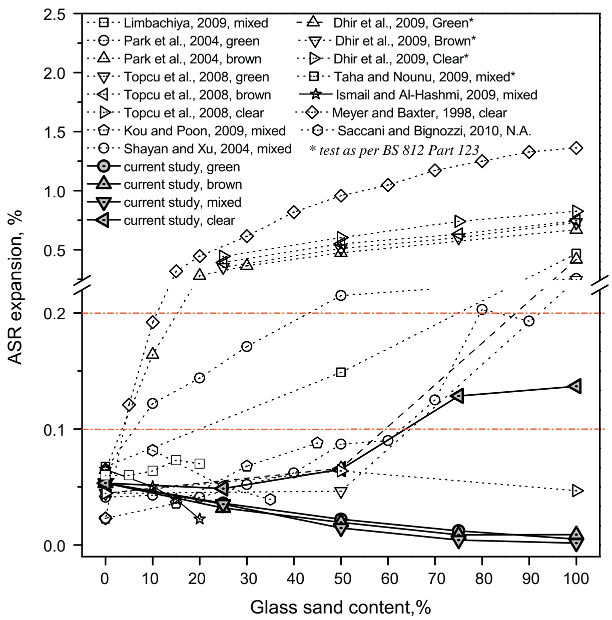


Fig. 2. Effect of glass sand replacement on ASR expansion at 14 days.

expansion less than 0.2% has been magnified for clarity. Most previously reported results showed an increase in ASR expansion with more glass sand content. However, as in the current study, Ismail and Al-Hashmi [15] observed a decrease in ASR expansion for mortar containing glass sand up to 20%. Saccani and Bignozzi [16] also reported that ASR expansion continuously decreased with glass sand content up to 35%.

The large variance among the previous results in Fig. 2 may be related to the micro-cracking in glass particles in the crushing process [25], as mentioned earlier. Unfortunately, detailed information on crushing or micro-cracks in glass particles before ASR test were not provided in the literature except for Rajabipour et al. [25] and the current study, in which micro-cracking was clearly seen in clear glass particles by SEM (Fig. 3a).

3.2. Effect of mixed glass

To determine the glass color effect, ASR expansion of mixed-color glass sand, with G:B = 2:1 by mass, was tested at 25%, 50%, 75% and 100% glass sand content and the results are shown in Fig. 1d. The mixed-color glass sand mortar showed similar ASR expansion as single-color green or brown glass sand mortar, decreasing with higher glass sand content. The effect of mixed-color glass sand was also tested at 100% glass sand content with G:B ratio varying as 3:1, 2:1, 1:1, 1:2 and 1:3, as well as complete green and brown glass sand, as shown in Fig. 1e. From the test results, it is hard to relate the ASR expansion of mixed-color glass sand mortar from those of single-color glass sand mortars.

All the mortars showed relatively small (<0.04%) and comparable ASR expansion among different mix ratios up to 42 days. However, it is interesting to note that a great difference between green and brown glass sand mortar started emerging at 63 days of testing. A higher fraction of green glass sand could result in much higher ASR expansion, indicating that brown glass exhibited less alkali reactivity in the long term, and this has not been reported before. As shown in Fig. 3b, no cracks were observed in the green glass particles at 28 days while cracks were detected at 63 days (Fig. 3c). On the other hand, no cracks were noted in brown glass sand (Fig. 3d and e).

3.3. Effect of glass particle size

The effect of glass particle size on ASR expansion of green, brown and clear glass sand mortars are shown in Fig. 4. For each color glass, there were five different single sized glass sands, that is, 2.36, 1.18, 0.6, 0.3 and 0.15 mm, to replace 25% of natural sand. All the three colored glass sand mortars showed the same trend, that is, ASR expansion continuously increased with increasing size of glass sand, at each test age. The maximum and minimum ASR expansion occurred at 2.36 mm and 0.15 mm-sized glass sand, respectively, regardless of glass color. Mortar with 25% graded glass sand, as specified by ASTM C 1260, showed intermediate values of ASR expansion (Fig. 1a–c) compared to single sized glass sand mortars. From the test results, single sized green and brown glass sand mortars showed reduced ASR expansion than normal sand mortar (0.053% at 14 days), while single sized clear glass sand mortar showed increased ASR expansion if it was larger than 0.6 mm. These can be explained by the alkali non-reactivity of green and brown glass and alkali reactivity of larger particles of clear glass. Once again, brown glass, particularly of larger size, showed less ASR expansion than green glass at any age, as previously noted.

Test results in this study as well as results from the literature are summarized in Fig. 5. There was no pessimum effect of glass sand size on ASR expansion, which is different from some previous findings [7]. This can be attributed to the pozzolanic reaction between silica in glass sand and cement hydration product, $Ca(OH)_2$ [22,26,27]. However, the pozzolanic reaction would not occur if the glass sand was too large. In this study, it can be noted that if glass sand was smaller than 2.36 mm, pozzolanic reaction would occur since the ASR expansion started decreasing from 2.36 mm till 0.15 mm. The critical particle size for pozzolanic reaction to occur was differently observed as 0.6–1.18 mm [7,27,28], or 0.15–0.30 mm [29].

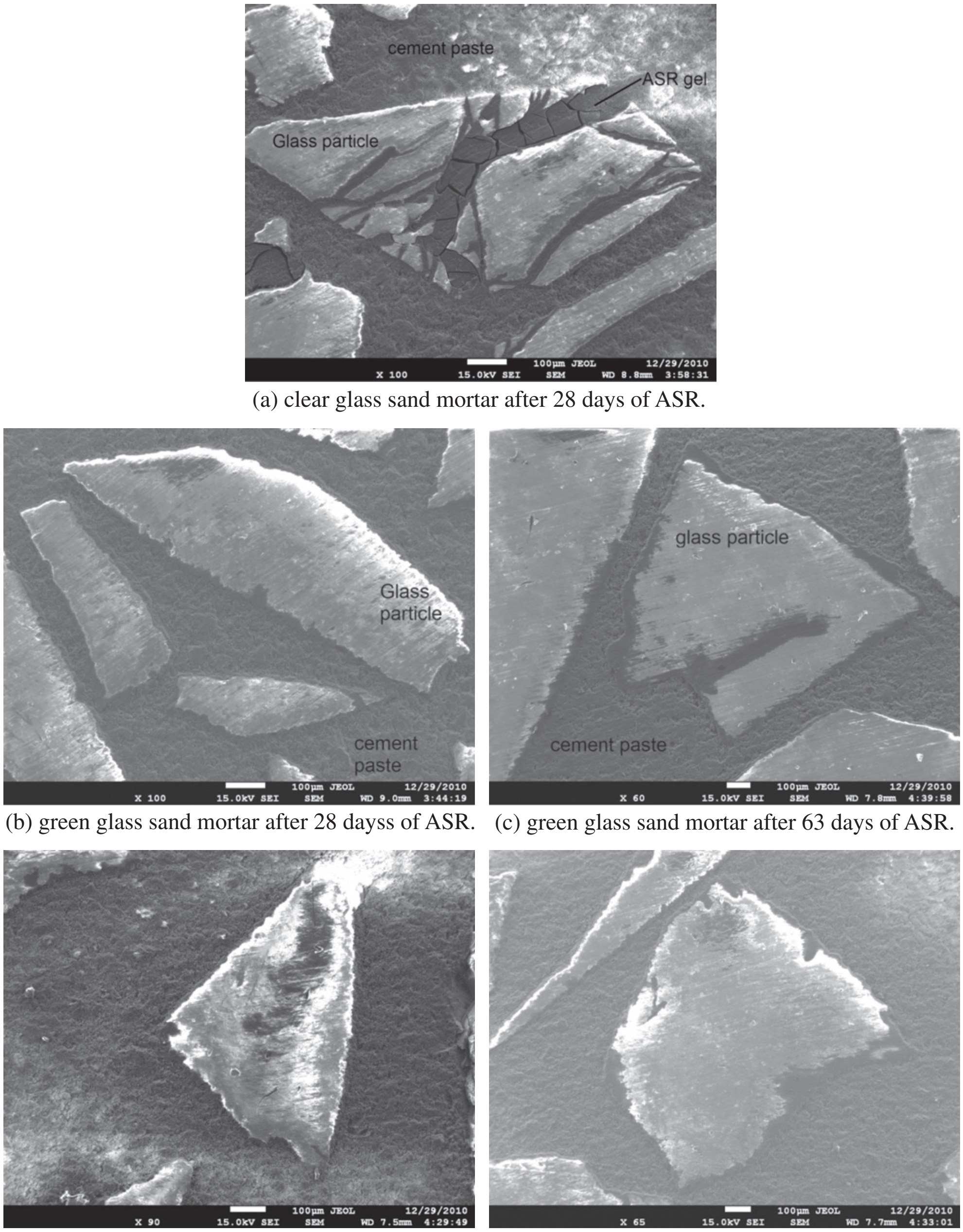
Also, recently, Rajabipour et al. [25] and Maraghechi et al. [30] have stated that the glass surface reaction is not an ASR but a pozzolanic reaction, regardless of glass size. The product of the pozzolanic reaction at the glass particle surface is not swelling, due to the low SiO_2/CaO ratio. On the other hand, it was found that ASR expansion resulting from internal cracks (larger than 2.5 μm) was more prominent, due to the penetration of OH^- ions into and a higher SiO_2/CaO ratio in the glass particles.

In this study, internal cracks were clearly observed in clear glass sand (Fig. 3a). No crack was found for green or brown glass sand mortar, especially at 100% content (Fig. 3b). In summary, the size effect of glass sand would be attributed to the following reasons: (1) pozzolanic reaction occurs more easily with finer particles; and (2) larger glass particles, especially for clear glass, exhibit more inherent cracks which initiate expansive ASR gel.

The relation between ASR expansion and glass sand size is significant for the study of ASR expansion with random size distribution of crushed glass sand. Based on the results, it can be concluded that ASR expansion decreases with smaller glass particles, provided that it is finer than 2.36 mm. Therefore, an effective method to mitigate ASR expansion of glass concrete is to control the crushing process to ensure a larger portion of glass particles less than 2.36 mm without compromising on the grading requirement.

3.4. Effect of fly ash

The effect of replacing 30% of cement by class F fly ash on ASR expansion of green, brown and clear glass sand mortars at different glass sand contents are shown in Tables 4–6. The suppressing effect of fly ash on ASR expansion is so obvious that the expansion at 14 days was less than 0.02% for all mixtures, which is



(a) clear glass sand mortar after 28 days of ASR.

(b) green glass sand mortar after 28 dayss of ASR.

(c) green glass sand mortar after 63 days of ASR.

(d) brown glass sand mortar after 28 days ofASR.

(e) brown glass sand mortar after 63 days of ASR.

Fig. 3. SEM micrographs of glass sand mortar.

significantly lower than 0.1%, as specified by ASTM C 1567 for innocuous reaction. The ASR expansion was quite small up to 28 days. The most significant effect of fly ash is to decrease the alkali or pH level of the pore solution in cement paste. Also, the microstructure of mortar, especially near the surface, was improved by pozzolanic reaction of fly ash; thus the porosity and permeability of the mortar was reduced. Although the amount of alkali in the 1 N NaOH solution would have been sufficient for ASR, the pathway for alkali and water to penetrate into the interior of mortar specimens was clogged and thus ASR was suppressed.

After 28 days of curing, the surface of all mortar bars remained quite smooth and no cracks were observed. The surface of mortar bars, around 1 mm deep, appeared to be more densified than the interior structure, preventing alkali from penetrating inward. Xu et al. [31] observed the same test results in accelerated mortar bar tests, in which the reaction was confined merely to a few small particles close to the exterior surface of the specimens and no signs of reaction were found in the center portion of mortar bar specimens.

The test results showed that 30% of fly ash is more than sufficient to suppress ASR expansion caused by recycled glass sand.

3.5. Effect of GGBS

The effect of replacing 60% of cement by GGBS on ASR expansion of glass sand mortars are shown in Tables 4–6. The suppressing mechanism for GGBS on ASR expansion was similar as for fly ash; that is, it was mainly because of a reduction in alkali content. As a secondary effect, the porosity of cement paste was reduced due to pozzolanic reaction of GGBS. Lee et al. [32] found that larger porosity of mortar containing glass sand resulted in lesser ASR expansion and fewer cracks by accommodating the formed ASR gel. In this study, the alkalis to react with sand are provided by the external NaOH solution. The reduced porosity of cement paste

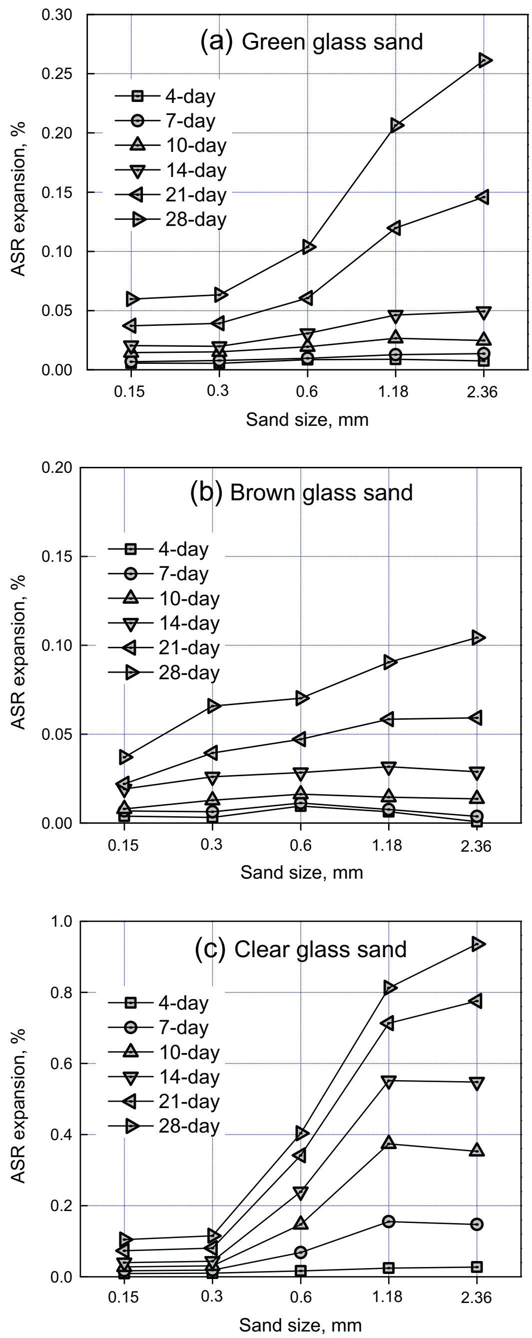


Fig. 4. Effect of glass particle size on ASR expansion (glass sand content of 25%).

and densified ITZ due to pozzolanic reaction of GGBS could decrease the permeability and prevent ingress of alkalis, therefore controlling the ASR reaction inside the mortar bar [31,33].

Also, the mineral admixtures could not only reduce the aggressiveness of the pore solution to the acidic aggregates but also reduce the negative surface charge of the glass particles by lowering the pH value of the pore solution in cement paste. The lower the ionic concentration and the surface charge of the particle, the smaller the expansive pressure that can develop for the ASR product gels [33].

3.6. Effect of silica fume

The effect of replacing 10% of cement by silica fume on ASR expansions is shown in Tables 4–6. All the mortars showed expansion much lesser than 0.1%. The suppressing effect of silica fume on ASR could be primarily attributed to its ultra-fine particle size, which is good for improving the porous microstructure at the ITZ and thus reducing the porosity and increasing the strength of mortar. The size, distribution and continuity of pores inside the paste could significantly affect ASR due to the ingress of water and the ions diffusion [34]. If free water loses the pathway to ingress to the particle surface where active silica is dissolved, the ASR gel formed would not cause any damage since it cannot absorb free water. After 28 days, the specimen surface remained uncracked and was densified due to pozzolanic reaction, the same as observed in fly ash mortar. Moreover, the pozzolanic behavior of silica fume would also contribute to the reduction in pH of cement paste, densification of microstructure, and formation of a CSH with a low CaO/SiO_2 ratio [35].

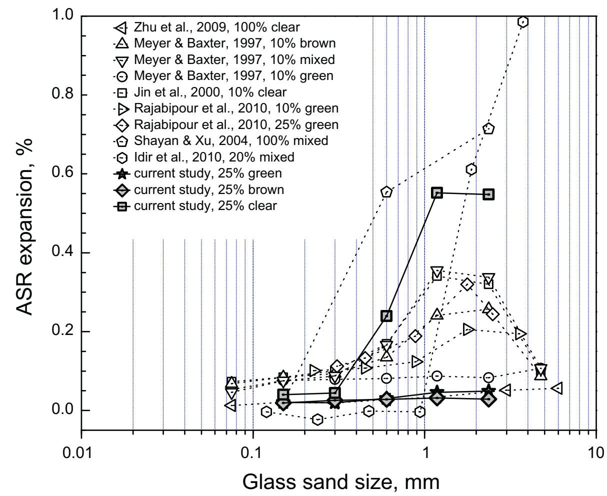


Fig. 5. Comparison of effect of glass particle size on ASR expansion.

3.7. Effect of steel fibers

The effect of adding 1.5%, by volume, of steel fibers on ASR expansions of green and brown glass sand mortars at various glass contents are shown in Tables 4 and 5. The performance of green and brown glass sand mortars, with the addition of steel fibers, was identical at the same glass content. All mortars showed expansion less than 0.1%. The reduction in ASR expansion is more obvious for glass content less than 50%. The function of steel fibers in restraining ASR in glass sand mortar is the same as in normal sand mortar. The internal pressure created by ASR gel causes expansion and cracking and thus could be suppressed by randomly distributing discontinuous single fibers [12]. Crack fiber interactions resist crack propagation and opening due to the chemo-mechanical confinement on the ASR gel. Fibers could not only impose compressive stress on the expanding ASR gel but also prevent the ASR gel from leaving the reaction site [36]. However, it should be noted that the addition of steel fiber would significantly reduce the flowability of mortar mix.

3.8. Effect of glass powder

The effect of replacing 20% cement by ground glass powder on ASR expansion of green and brown glass sand mortars are also shown in Tables 4 and 5. The suppressing effect of green glass powder was relatively more prominent than brown glass. The suppressing effect of glass powder was more obvious at lower glass sand content less than 50%, especially in the reference mortar mix without glass. Moreover, as discussed earlier, the finer the

Table 4
ASR expansions of mortars with green glass sand.

Time (day)	Glass content (%)	Reference	Mitigation methods						
			Fly ash	GGBS	Silica fume	Steel fiber	Powder	LiCl	Li_2CO_3
14	0	0.0533	0.0100	0.0186	0.0202	0.0253	0.0311	0.0594	0.0188
	25	0.0361	0.0044	0.0164	0.0333	0.0194	0.0136	0.0248	0.0122
	50	0.0222	0.0070	0.0072	0.0179	0.0155	0.0100	0.0158	0.0080
	75	0.0121	0.0075	0.0056	0.0126	0.0054	0.0056	0.0102	0.0063
	100	0.0051	0.0061	0.0061	0.0177	−0.0008	0.0037	0.0058	0.0045
21	0	0.1040	0.0135	0.0293	0.0348	0.0493	0.0582	0.1006	0.0283
	25	0.0825	0.0091	0.0248	0.0423	0.0276	0.0300	0.0437	0.0176
	50	0.0354	0.0094	0.0120	0.0245	0.0172	0.0203	0.0228	0.0114
	75	0.0282	0.0112	0.0089	0.0192	0.0058	0.0083	0.0095	0.0071
	100	0.0150	0.0079	0.0100	0.0195	0.0016	0.0055	0.0044	0.0053
28	0	0.1490	0.0230	0.0411	0.0542	0.0844	0.0911	0.1388	0.0608
	25	0.1357	0.0169	0.0335	0.0530	0.0606	0.0533	0.0734	0.0417
	50	0.0742	0.0140	0.0171	0.0350	0.0400	0.0365	0.0427	0.0290
	75	0.0704	0.0144	0.0127	0.0229	0.0230	0.0189	0.0185	0.0220
	100	0.0304	0.0130	0.0087	0.0247	0.0055	0.0126	0.0076	0.0166

Negative sign indicates shrinkage.

Table 5
ASR expansions of mortars with brown glass sand.

Time (day)	Glass content (%)	Reference	Mitigation methods						
			Fly ash	GGBS	Silica fume	Steel fiber	Powder	LiCl	Li_2CO_3
14	0	0.0533	0.0100	0.0186	0.0202	0.0253	0.0402	0.0594	0.0288
	25	0.0320	0.0097	0.0020	0.0210	0.0213	0.0247	0.0520	0.0257
	50	0.0196	0.0112	−0.0017	0.0175	0.0081	0.0139	0.0225	0.0126
	75	0.0087	0.0014	−0.0008	0.0148	0.0043	0.0115	0.0115	0.0050
	100	0.0090	0.0066	−0.0011	0.0126	0.0049	0.0056	0.0133	0.0029
21	0	0.1040	0.0135	0.0293	0.0348	0.0493	0.0802	0.1006	0.0506
	25	0.0916	0.0095	0.0086	0.0326	0.0420	0.0595	0.0919	0.0476
	50	0.0355	0.0086	0.0078	0.0224	0.0190	0.0403	0.0371	0.0235
	75	0.0194	0.0008	0.0034	0.0209	0.0120	0.0267	0.0196	0.0125
	100	0.0120	0.0065	0.0005	0.0141	0.0082	0.0142	0.0164	0.0075
28	0	0.1490	0.0230	0.0411	0.0542	0.0844	0.1117	0.1388	0.0839
	25	0.1305	0.0105	0.0225	0.0554	0.0640	0.0750	0.1278	0.0781
	50	0.0594	0.0109	0.0260	0.0280	0.0430	0.0493	0.0590	0.0383
	75	0.0262	0.0007	0.0086	0.0234	0.0373	0.0339	0.0343	0.0212
	100	0.0123	0.0049	0.0094	0.0110	0.0184	0.0134	0.0233	0.0111

Negative sign indicates shrinkage.

Table 6
ASR expansions of mortars with clear glass sand.

Time (day)	Glass content (%)	Reference	Mitigation methods		
			Fly ash	GGBS	Silica fume
14	0	0.0533	0.0100	0.0186	0.0202
	25	0.0486	0.0098	0.0071	0.0213
	50	0.0654	0.0057	0.0143	0.0252
	75	0.1284	0.0073	0.0043	0.0206
	100	0.1368	0.0080	0.0057	0.0171
21	0	0.1040	0.0135	0.0293	0.0348
	25	0.0888	0.0127	0.0162	0.0299
	50	0.1334	0.0084	0.0201	0.0304
	75	0.2768	0.0101	0.0124	0.0274
	100	0.3435	0.0093	0.0104	0.0267
28	0	0.1490	0.0230	0.0411	0.0542
	25	0.1198	0.0168	0.0199	0.0425
	50	0.2118	0.0149	0.0224	0.0549
	75	0.4710	0.0121	0.0134	0.0384
	100	0.7046	0.0108	0.0120	0.0389

glass sand, the less ASR expansion. If the glass sand particle is fine enough, such as less than 75 μm, the ASR expansion would be totally eliminated while pozzolanic reaction would occur instead. That is why fine glass powder could replace cement and suppress ASR. Taha and Nounu [10] attributed the ASR suppressing effect of glass powder to the non-availability of both alkali in concrete and reactive silica in glass particles. Dyer and Dhir [26] have explained the chemical reactions of glass powder used as cement

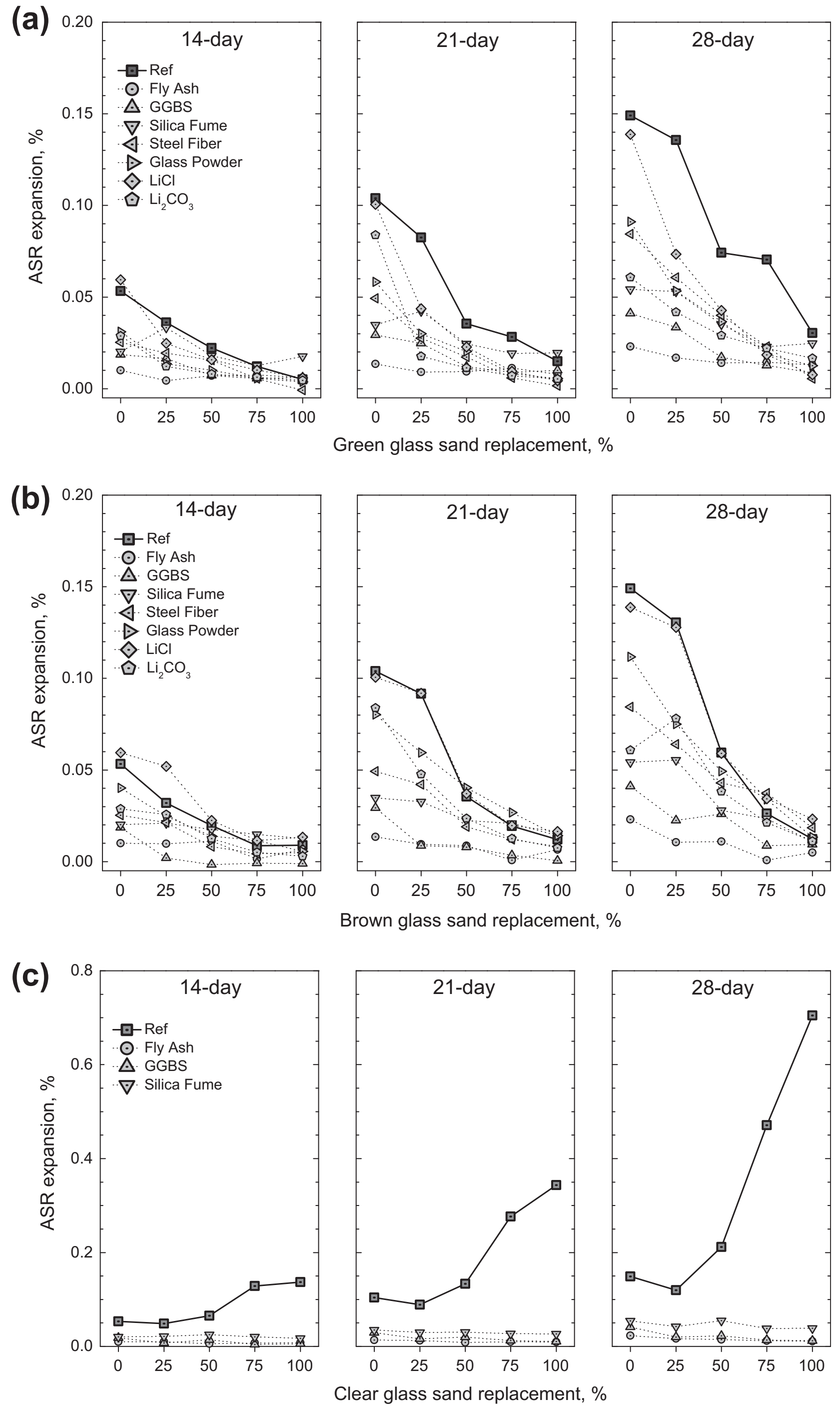


Fig. 6. Comparison of different mitigation methods on ASR expansion of mortar with (a) Green, (b) Brown, and (c) Clear glass sand.

component in detail. In the chemical terms, the ASR of glass powder is identical to pozzolanic reaction, except for the time at which each reaction occurs. The fine glass powder has a high surface area and hence favors the rapid pozzolanic reaction over the deleterious ASR. The ASR mitigating use of glass powder as cement replacement could thus widen the application of waste glasses [9], resulting in a value-added utilization.

3.9. Effect of lithium chloride and lithium carbonate

The effect of adding 1% LiCl or Li_2CO_3 compound by weight of cement on ASR expansion are shown in Tables 4 and 5. Green glass sand showed reduced ASR expansion at all glass contents, and the effectiveness was more obvious at low glass content. The suppressing effect of Li_2CO_3 was more prominent than LiCl, because of the higher ratio of [Li]/[Na], which has been found to be the key factor in restraining ASR expansion [37]. The ratio of [Li]/[Na] for 1% LiCl and Li_2CO_3 was 0.74 and 0.84 in this study, respectively. For brown glass, the effect of Li_2CO_3 on ASR was similar as for green glass. However, the LiCl did not show any suppression effect in ASR, especially for normal sand mortar. There is a minimum content of lithium compounds required to effectively suppress ASR [38]. From the results, the content of lithium compounds used in this study, that is, 1% of cement by mass, is high enough to suppress ASR for green glass but not for brown glass.

So far, the ASR suppressing mechanism of lithium is not well known [10]. It is expected that lithium compounds could change the nature and chemical composition of the ASR gel [38]; reducing the solubility of the reactive silica; and the ability of dissolved silica to be repolymerised; thus leading to smaller repulsive forces between the particles of the ASR gel and smaller expansive ability of the ASR gel [10].

3.10. Comparison of different ASR mitigation methods

Different ASR suppressing methods are compared in Fig. 6, for green, brown and clear glass sand mortars with different glass contents at 14, 21 and 28 days. Fly ash apparently showed the highest effect, followed by GGBS. The restraining effect of silica fume was more obvious in clear glass sand mortar than in green and brown glass sand mortar. Both green and brown glass powder showed ASR suppressing effect in glass sand mortar, although the effect was less than fly ash and GGBS.

Compared with the substitution of cement, addition of steel fibers or lithium compounds was less effective in reducing ASR expansion. It is therefore suggested that concrete with recycled glass sand should incorporate mineral materials, such as fly ash and GGBS, in preventing potential deleterious ASR expansion, particularly in the case of clear glass.

The negative effect of such ASR mitigation methods must also be noted. The addition of lithium compound would add to production costs of concrete, although the amount used in this study is low enough to avoid a substantial difference. In addition, the use of fly ash and GGBS could reduce concrete strength at the early age. Also, the utilization of steel fibers or silica fume could result in significant decrease in workability, for which superplasticizer would become necessary to maintain the same workability.

4. Conclusions

Based on the results of the study, the following conclusions can be drawn:

1. Due to micro-cracking in clear glass particles during the crushing process, mortars with clear glass sand exhibited higher ASR expansion. The effect was found to be potentially deleterious if clear glass particles were used to replace more than 50% of the natural sand in mortar. On the other hand, green and brown glass sand mortars proved to be innocuous regardless of the replacement level due to insignificant or absence of micro-cracking. Also, ASR expansion decreased with smaller glass sand size, due to pozzolanic reaction of fine glass particles.
2. Fly ash and GGBS were the most effective ASR suppressing methods since they could reduce the alkalinity in the pore solution and decrease the porosity and permeability of the cement paste, thus controlling the ASR mechanism. Addition of steel fibers or lithium compounds was less effective.
3. By using supplementary cementitious materials, ASR expansion in clear glass sand mortar could be reduced to below acceptable limits, i.e., 0.1% at 14 days.

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