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Use of waste glass as sand in mortar: Part I – Fresh, mechanical and durability properties

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ABSTRACT

In this study, mortar made with waste glass as fine aggregates was investigated for its suitability for construction use. A reference mortar mixture was proportioned according to ASTM C 109 and the fine aggregates were replaced by waste glass particles by 0%, 25%, 50%, 75% and 100%, by mass, to study its effect on the properties of mortar. For each mixture, four types of glass sand, namely, brown, green, clear and mixed color glass, were used. Test results indicated that use of waste glass particles as fine aggregates would reduce the flowability and density of mortar, but increase its air content. Except drying shrinkage, the mechanical properties were compromised due to micro-cracking in glass sand and weakened bond with the cement paste. However, durability was enhanced, especially in terms of the resistance to chloride ion penetration. Accelerated mortar bar tests to ASTM C 1260 indicated that green and brown glasses were non-reactive while clear glass was potentially deleterious, with regards to alkali–silica reaction.

1. Introduction

In recent years, the sustainability of construction materials has become an important issue [1]. At the same time, the recycling and reuse of waste is necessary from the viewpoint of environmental protection [2]. Incorporation of recycled solid waste in concrete is a suitable way to preserve natural raw materials, save energy and reduce landfills [3]. Among various urban solid wastes, glass may be considered the most suitable as substitution for sand and cement, due to its physical characteristics and chemical composition [4]. The recycling of waste glass is especially significant as its recycling rate is quite low in many countries, compared to other solid wastes. In the United States, for example, 11,530 kilotons of waste glass was generated 2010 and only 27.1% was recycled, mainly for container and packaging [5]. In Singapore, 72,800 tons of waste glass was disposed in 2011 and 29% was recycled [6].

The effect of replacement of coarse and fine aggregates or even cement by recycled waste glass on the fresh and mechanical properties of concrete or cementitious composites has been reported [7–10]. However, the results appeared to be inconsistent. Air content in concrete, for instance, was reported to increase with the incorporation of glass sand by Park et al. [11] whilst the opposite result was reported by Topcu and Canbaz [12]. Both groups of researchers attributed the change in air content to the poor geometry of crushed waste glass. Inconsistent results were also found in alkali–silica reaction (ASR) expansion of mortar containing glass sand. Some previous work pointed out that serious ASR between glass particles and alkali in cement would be detrimental and this has limited the application of recycled glass in concrete [8]. Several methods were therefore proposed to mitigate the ASR expansion, such as the replacement of cement by pozzolans, addition of fibers, and the addition of lithium compounds [10]. However, some other researchers reported that severe ASR would not occur for glass sand concrete [13]. Also, the influence of glass sand on other durability properties of concrete or other cementitious composites has rarely been reported.

In this Part I paper, the fresh and mechanical properties of mortar with single and mixed-colored glass sand as fine aggregates were investigated. Furthermore, the durability of glass sand mortar, with respect to chloride permeability, ASR and sulfate attack was also examined. As ASR has been a major concern in the use of waste glass particles in concrete, further studies were carried out and reported in Part II paper.

2. Test program

Glass sand was used to replace natural sand as fine aggregates in mortar by 0%, 25%, 50%, 75%, and 100% by mass. Fresh and mechanical properties, including fresh density, air content and flowability; compressive strength, splitting tensile strength, and flexural strength, static and dynamic elastic moduli, as well as drying shrinkage were investigated for glass sand mortar. Durability properties, in terms of resistance to chloride ion penetration, ASR and

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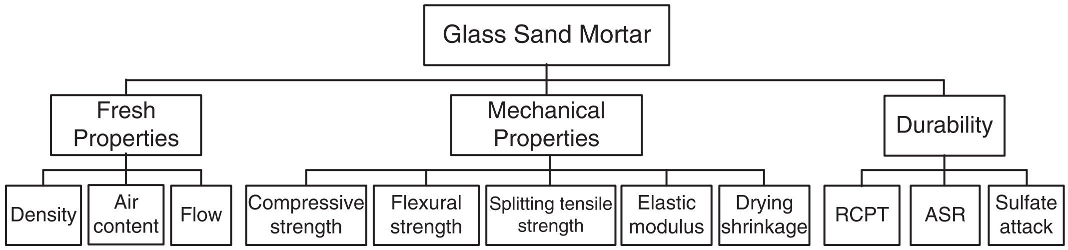


Fig. 1. Test program for mortar with recycled glass sand.

sulfate attack, were also carried out. The overall test program is summarized in Fig. 1. All properties were investigated using brown, green, clear and mixed-colored glass, that is, green and brown glass mixed in the ratio of 2:1 by mass.

2.1. Materials

Waste soda–lime glass bottles, originally used for beer, wine, cooking sauces, and others, were collected from a local recycler. Most of the beer bottles were either brown or green in color, while wine bottles and bottles for other uses were mainly transparent or clear. First, the metal or plastic taps and neck rings were removed from the bottles. After that, the glass bottles were thoroughly cleaned with tap water, to remove paper or plastic labels on the surface and to eliminate contaminations. After washing and drying, the glass bottles were reduced by a jaw crusher into small particles, which satisfied the ASTM C 33 grading requirement for sand [14]. Because of its brittle nature, the crushed glass sand exhibited angular shape, sharp edge, smooth surface texture and a higher aspect ratio than natural sand, as shown in Fig. 2.

Also, some micro-cracks were observed in clear glass particles after the crushing processing, as revealed by optical microscopic (OM) and scanning electron microscopic (SEM) images in Figs. 3a and b. In contrast, very few micro-cracks were found for green glass particle and almost no micro-crack existed in brown glass particle (see Fig. 3c and d). The difference in the amount of micro-cracking might be due to the different manufacturing processes of the glass bottles, as pointed out by Dhir et al. [15].

The chemical compositions of glass and natural sand are compared in Table 1 while the size distributions are shown in Fig. 4. The specific gravity (SSD) and water absorption capacity of glass were 2.53% and 0.07%, respectively, compared to 2.65% and 1.0% for natural sand. ASTM Type I Portland cement was used in the study, and the chemical composition and physical properties are listed in Table 2. The equivalent sodium alkali content was 0.6%, calculated from $Na_2O_{eq} = Na_2O + 0.658K_2O$.

Fig. 2. Appearance of natural and glass sand.

2.2. Mix proportion and test methods

Except for the ASR tests, the mix proportion of mortar was selected in accordance with ASTM C 109 [16], with water:cement:sand = 0.485:1:2.75 by mass, for each test property. For each mix, the sand content consisted of natural sand, glass sand or both. The portion of glass sand as a percent of the total sand content by mass was varied from 0% to 100% in steps of 25%. All tests were carried out as per ASTM Standards shown in Table 3 [14,16–26]. For ASR tests, the mixture proportion of mortar consisted of water:cement:sand in the ratio of 0.47:1:2.25, according to ASTM C 1260 [25]. Also, both natural sand and glass sand were used with percentages of 10%, 25%, 25%, 25%, and 15% passing/retained on sieve sizes 4.75/2.36, 2.36/1.18, 1.18/0.6, 0.6/0.3, and 0.3/0.15 mm respectively. No superplasticizer was added.

2.3. Preparation of mortar specimens

The numbers and dimensions of mortar specimens are summarized in Table 3. All the mortar specimens were covered with plastic sheets for 24 h after casting, followed by demolding and curing in water until the age of tests, including RCPT and sulfate attack tests. For the drying shrinkage tests, the mortar specimens were cured in water for 3 days after demolding and then transferred into a controlled room (simulating a tropical climate with a constant temperature of 30 °C and RH of 65%) for measurements up to 56 days. For the ASR tests, all specimens were put in 80 °C water for 1 day and the initial length taken before transferring to 80 °C 1 N NaOH solution. The expanded lengths were subsequently measured after 2, 4, 7, 10, 14, 21, and 28 days. ASR expansion was reported as the average value obtained from three mortar bars.

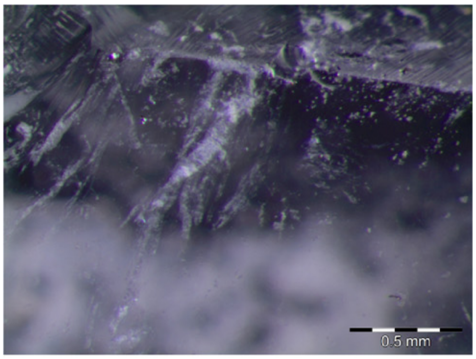
3. Test results and discussion

3.1. Fresh density

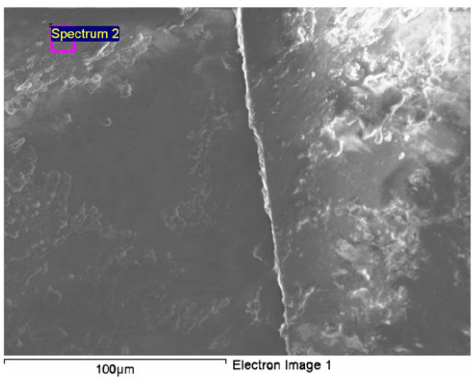
For all mortar mixes, no segregation or bleeding was observed during mixing and casting. The fresh density decreased with a higher content of glass sand, as shown in Fig. 5, due to the smaller specific gravity of glass compared to natural sand. The glass color had no effect on the fresh density, especially when the glass content was less than 75%. The fresh density of mortar with 100% brown, green, clear and mixed colored glass sand was 97%, 96%, 95%, and 97% of that of normal mortar, respectively.

3.2. Air content

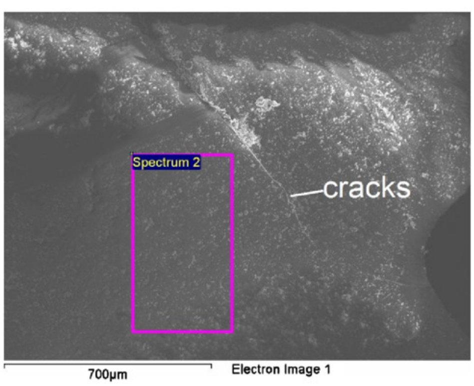
As shown in Fig. 6, the air content of glass sand mortar was between 3% and 3.5%, increasing slightly with higher glass sand content up to 75%. In comparison, Park et al. [11] reported that air content consistently increased 12.2–41.4% for concrete containing glass sand content at 30%, 50%, and 70%. With 100% glass sand, clear glass mortar showed the highest air content of 5.9%, almost



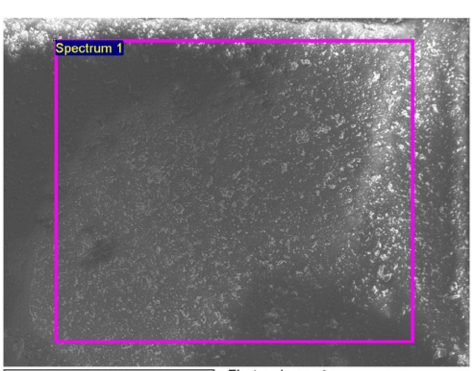
(a) OM image of micro-cracks in clear glass particle.



(b) SEM image of micro-cracks in clear glass particle.



(c) SEM image of micro-cracks in green glass paricle.



(d) SEM image of brown glass particle.

Fig. 3. Appearance of glass sand after crushing.

twice of that of the normal sand mortar. This was due to the sharper edge and higher aspect ratio of glass sand, which enable more air to be retained at the surface of glass particles. Also, as

Table 1
Chemical compositions of glass and natural sand.

Composition (%)	Green glass	Brown glass	Clear glass	Natural sand
SiO_2	71.22	72.08	72.14	88.54
Al_2O_3	1.63	2.19	1.56	1.21
Fe_2O_3	0.32	0.22	0.06	0.76
CaO	10.79	10.45	10.93	5.33
MgO	1.57	0.72	1.48	0.42
Na_2O	13.12	13.71	13.04	0.33
K_2O	0.64	0.16	0.62	0.31
TiO_2	0.07	0.1	0.05	0.05
Cr_2O_3	0.22	0.01	–	–

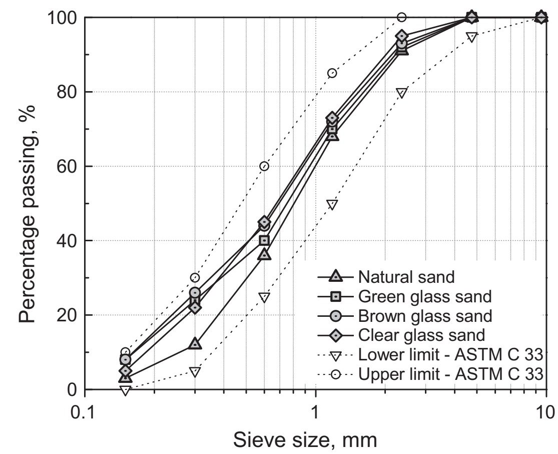


Fig. 4. Grading curve of natural and glass sand.

Table 2
Chemical compositions and physical properties of Portland cement.

Chemical composition (%)		Physical properties	
SiO_2	20.8	Fineness, SSA (m^2/kg)	393
Al_2O_3	4.6	Normal consistency (%)	27.5
Fe_2O_3	2.8	Initial setting (min)	165
CaO	65.4	Final setting (min)	195
MgO	1.3	Soundness (%)	0.5
SO_3	2.2	Penetration (mm)	7.0
Na_2O	0.31	Specific gravity	3.15
K_2O	0.44		

Table 3
Test specimens and standards.

Test	No. of specimens	Dimension[a]	ASTM Standards
Fresh density			C 185
Air content			C 185
Flow			C 1437
Compressive strength	6	50 × 50 × 50	C 109
Flexural strength	6	40 × 40 × 160	C 348
Elastic modulus	3	∅100 × 200	C 469 and 215
Splitting tensile strength	3	∅100 × 200	C 496
Drying shrinkage	3	25 × 25 × 285	C 596
RCPT	3	∅100 × 50	C 1202
ASR	3	25 × 25 × 285	C 1260
Sulfate attack	3	40 × 40 × 160	C 267
	3	50 × 50 × 50	

[a] All dimensions are in mm.

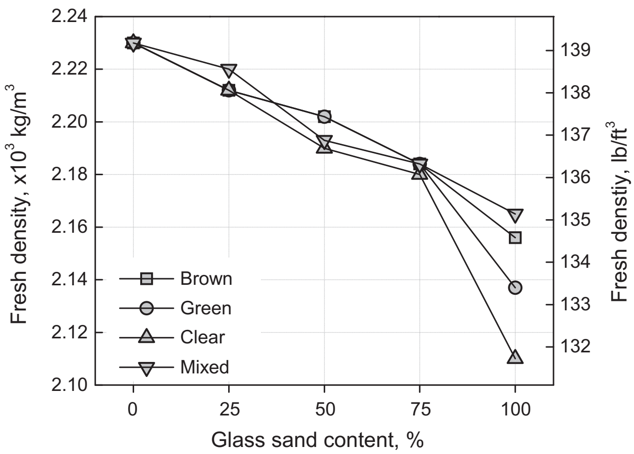


Fig. 5. Fresh density of glass sand mortar.

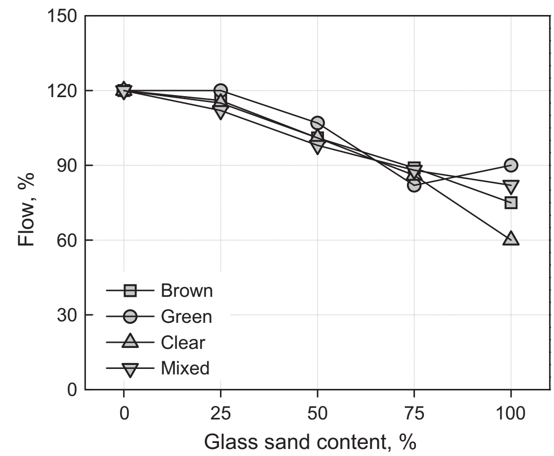


Fig. 7. Flow of glass sand mortar.

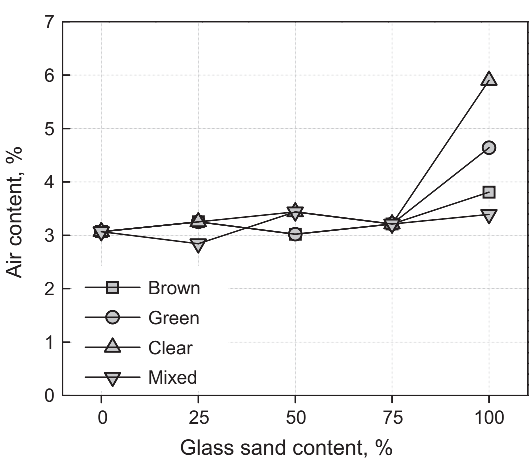


Fig. 6. Air content of glass sand mortar.

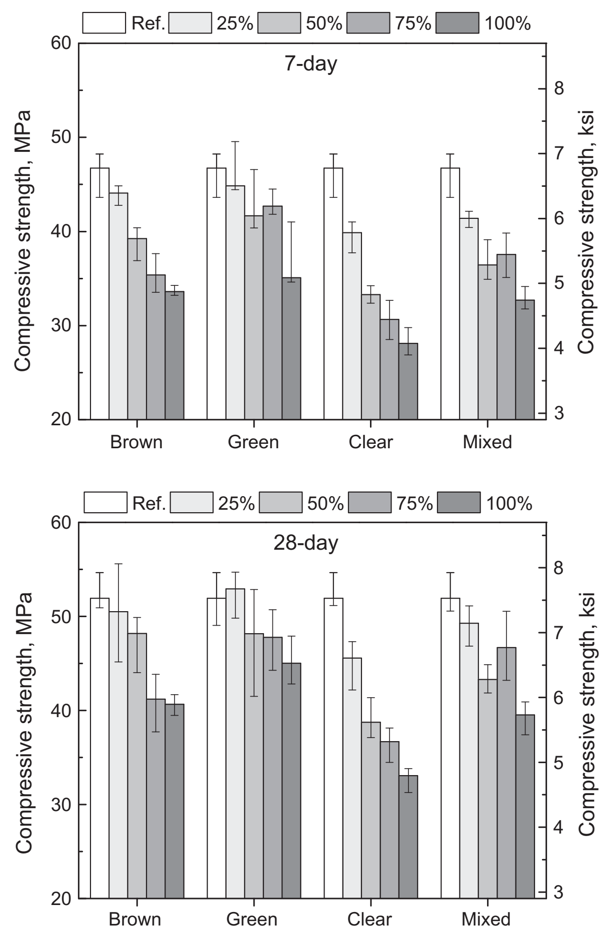


Fig. 8. Compressive strength of glass sand mortar.

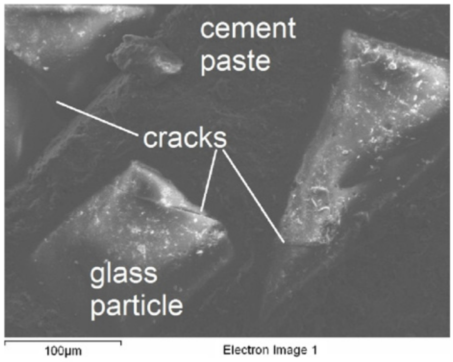
mentioned previously, more micro-cracks were observed in the crushed clear glass particles, which might have affected the packing of aggregates especially at high content.

3.3. Flow

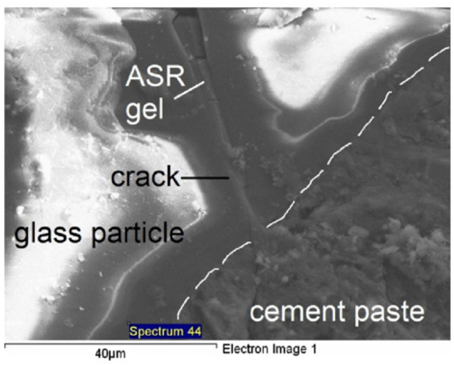
The flow is defined as the percentage increase in mortar base diameter after 15 times of drop on a flow table. The flowability of glass sand mortar was reduced, as shown in Fig. 7. The flow for complete brown, green, clear and mixed color glass sand mortar was 75%, 90%, 60%, and 82% of normal sand mortar, respectively. The sharper edge, more angular shape and higher aspect ratio of glass particles reduced the flowability of mortar by hindering the movement of cement paste and the particles [27]. In addition, the increased surface area of glass sand compared to nearly round natural sand would require more water to wet and more paste to coat and lubricate. The low flowability of mortar also contributed to the increased air content, especially at glass sand replacement of 100%.

3.4. Compressive strength

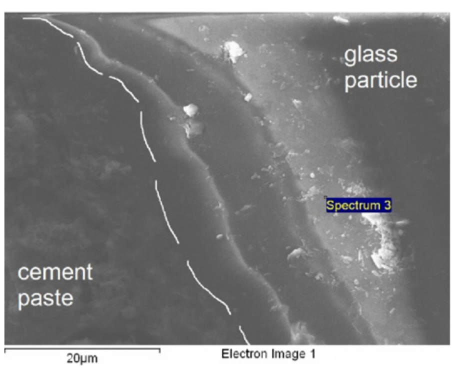
Fig 8 shows the 7- and 28-day compressive strengths of glass sand mortar. The use of glass sand led to a decrease in compressive strength due to the smooth surface and sharper edges of glass particles, which resulted in weaker bond strength at the Interfacial Transition Zone (ITZ) between glass particles and cement paste matrix, that dominates the mechanical and durability properties. Green glass sand mortar showed the least reduction in compressive strength at each glass sand content. Mortars with mixed color glass sand showed comparable strength as those with brown glass sand. Clear glass sand mortar manifested the largest reduction in compressive strength, perhaps due to micro-cracks that formed during the crushing process, as shown further in Fig. 9a. The compressive strength was not significantly affected by glass sand if the content was less than 25%.



(a) Clear glass particle in mortar before ASR test.



(b) Clear glass particle in mortar after 14 days of ASR test.



(c) Brown glass particle in mortar after 14 days of ASR test.

Fig. 9. SEM micrographs of glass particles.

The strength development with glass sand mortar was slightly higher than that of normal sand mortar. At 7 days, mortar with 100% brown, green, clear and mixed glass sand showed 72%, 75%, 60%, and 70% of normal sand mortar respectively. At 28 days, this ratio increased to 78%, 87%, 64%, and 76%. The pozzolanic characteristics of fine glass particles, as reported by Shayan and Xu [9], Shao et al. [28], Shi et al. [29] and Federico and Chidiac [30], might be the reason. This pozzolanic reaction occurs at a later stage and refines the microstructure, thereby reducing the porosity and enhancing the bond strength at the ITZ.

3.5. Flexural strength

Fig. 10 shows the flexural strength of glass sand mortars at 7 and 28 days. The reduction in flexural strength was obvious for glass sand content exceeding 25%, especially in the case of clear glass. For the other types of glasses, the reduction in 28-day strength was smaller than 10% if the glass content was less than 75%. The flexural strengths of mortar with 100% brown, green, clear and mixed glass sand were respectively 76%, 90%, 70%, 76%, that of normal sand mortar at 28 days. Park et al. [11] had similarly reported a 18.1% reduction in flexural strength for concrete containing 70% of glass sand. The reduction in flexural strength was similar to that of compressive strength, and was also due to the decrease in adhesive strength at the glass particle surface, and microcracking in the case of clear glass sand mortar.

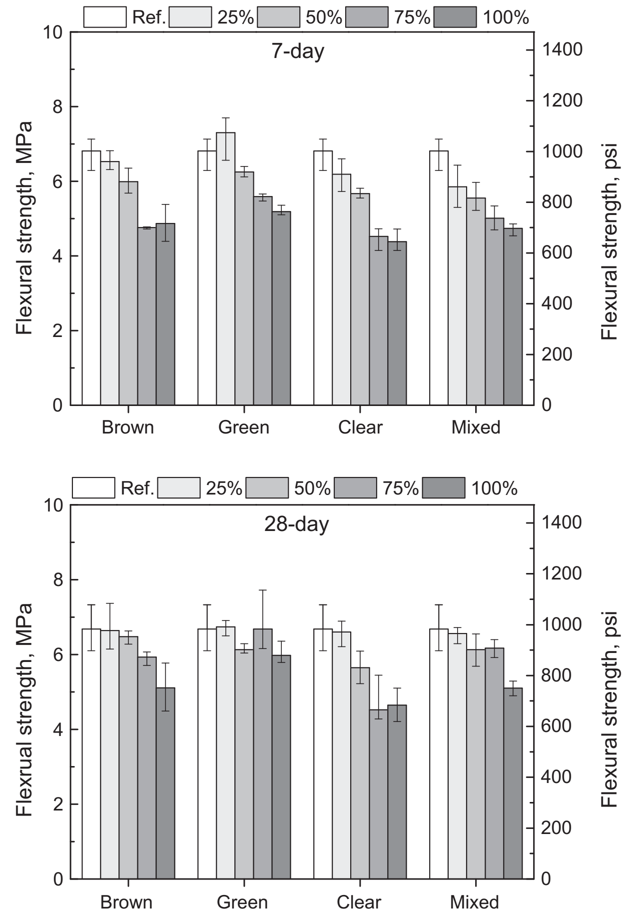


Fig. 10. Flexural strength of glass sand mortar.

3.6. Splitting tensile strength

The splitting tensile strengths of glass sand mortars at 28 days are shown in Fig. 11. The glass sand mortars exhibited splitting tensile strengths varying between 2.85 and 3.95 MPa. With 25% of brown, green, clear and mixed glass sand, the splitting tensile strength of mortar showed a slight increase. However, with higher percentages of glass sand, the splitting tensile strength was reduced, regardless of the glass color. For clear glass sand mortar, the splitting tensile strength decreased consistently with increasing glass content.

The splitting tensile strengths of mortars with 100% brown, green, clear and mixed color glass were 93%, 82%, 77%, and 79%, that of normal sand mortar, respectively. Park et al. [11] on the other hand reported that concrete with 70% glass sand exhibited a splitting tensile strength of 80% of that of the normal concrete because of the reduced adhesive strength. Compared to compressive and flexural strengths, the reduction in splitting tensile strength was less prominent, probably because the sharper edge and higher

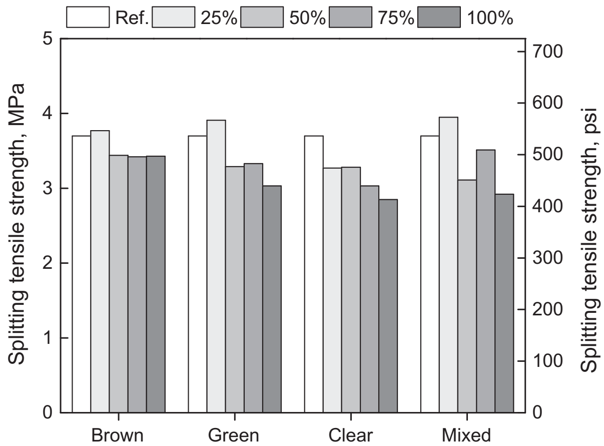


Fig. 11. Splitting tensile strength of glass sand mortar.

aspect ratio of glass sand resulted in a higher degree of internal friction [31].

3.7. Static and dynamic moduli of elasticity

The static and dynamic moduli of elasticity of glass sand mortar, determined at 28 days, are shown in Fig. 12. The static and dynamic moduli of mortar varied from 23 to 30 GPa and 27 to 36 GPa, respectively. The glass sand caused an obvious reduction in the modulus of elasticity in the case of clear glass. With other color glass sand, the reduction was less, especially for glass content of up to 50%. At a glass content of 100%, the static modulus of brown, green, clear and mixed glass mortar was 97%, 93%, 80%, and 88% of that of the normal sand mortar. As for the dynamic modulus, they were 90%, 92%, 77%, and 89%, respectively.

Although the elastic modulus of glass is higher than sand [32], the weaker bond and porous microstructure at ITZ in glass sand mortar would lead to a lower modulus, especially in clear glass sand mortar due to micro-cracking. Compared with other mechanical properties, the elastic modulus was the least affected.

3.8. Drying shrinkage

The drying shrinkages of mortar specimens with mixed color glass are shown in Fig. 13. All mortar mixes showed stable shrinkage after 21 days. The drying shrinkage values were less than 750×10^{-6} mm/mm at 56 days, specified as acceptable for concrete by the Australian Standard AS3600 [33]. The normal sand mortar had the highest drying shrinkage, compared with all glass sand mortars, suggesting that the replacement of sand by glass particles improve the dimension stability of mortar. This is consistent with those reported by Kou and Poon [34], in which the drying shrinkage of concrete decreased with increasing glass sand content up to 45%.

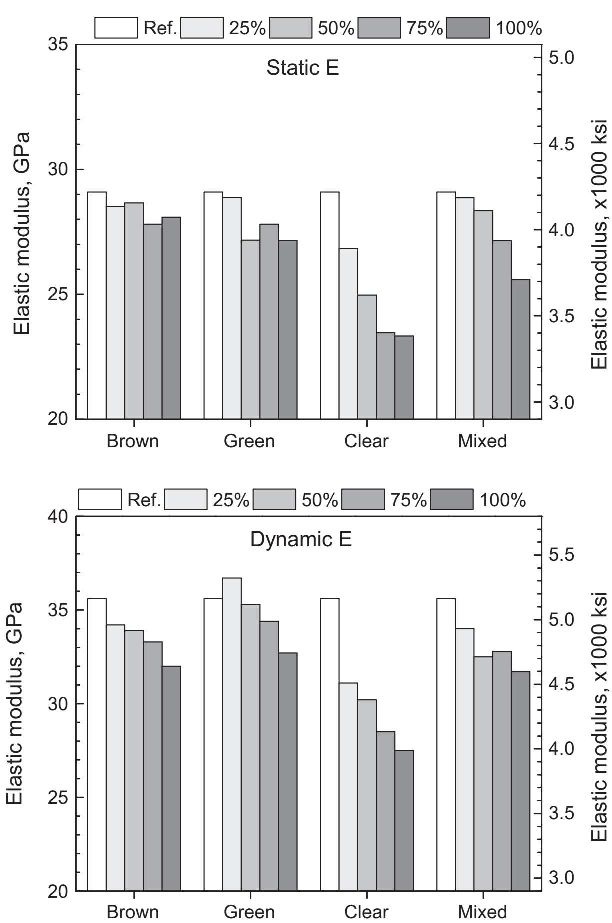


Fig. 12. Static and dynamic moduli of elasticity of glass sand mortar.

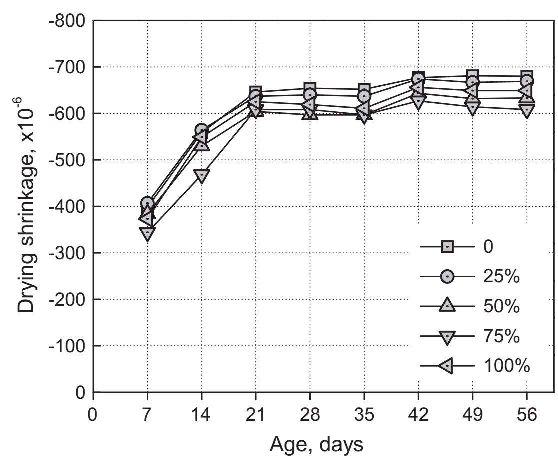


Fig. 13. Drying shrinkage of mixed color glass sand mortar.

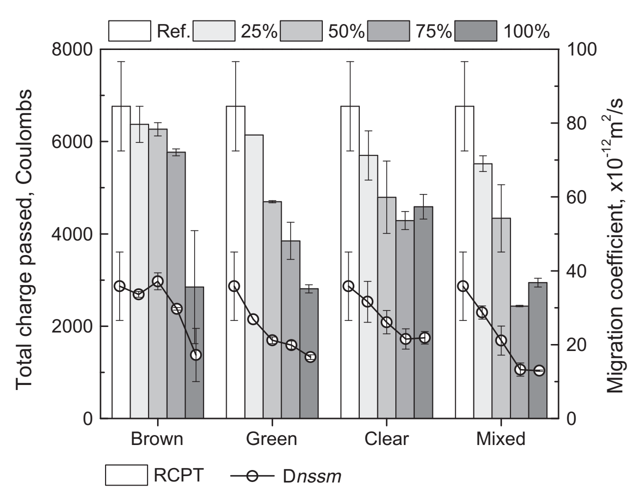


Fig. 14. RCPT results of glass sand mortar.

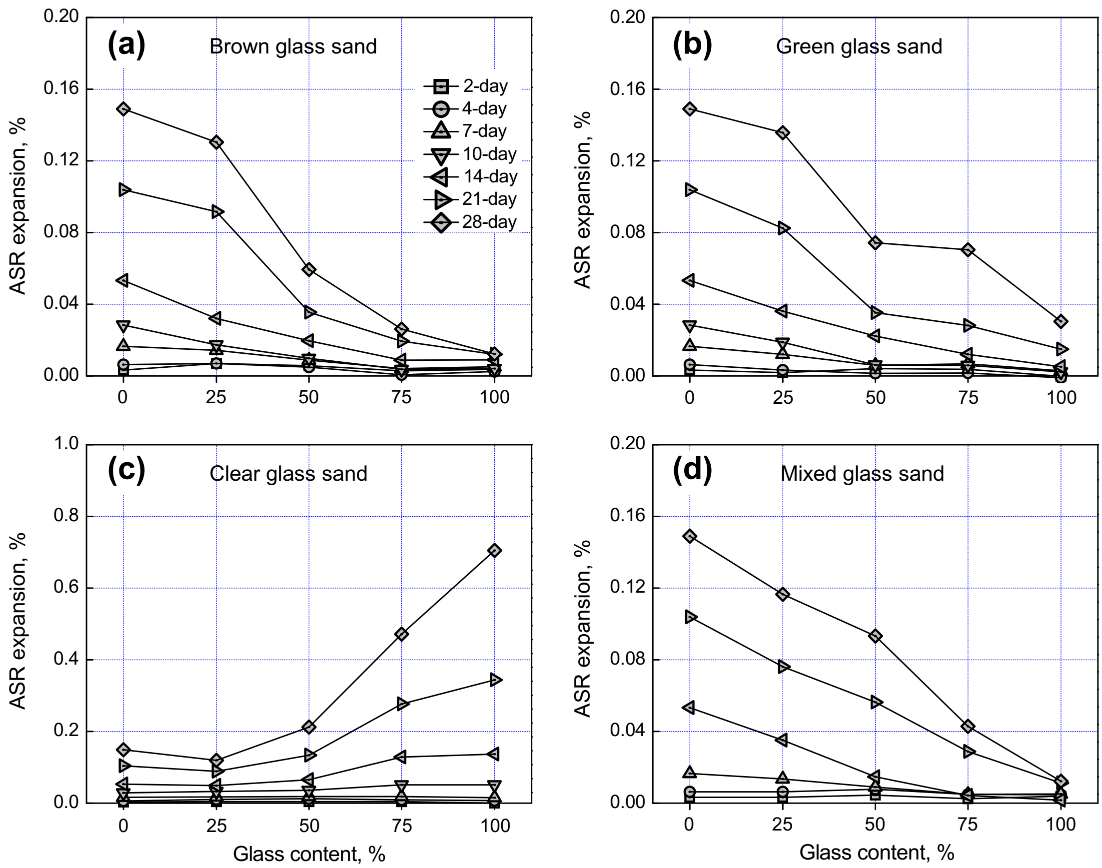


Fig. 15. ASR expansions of glass sand mortar.

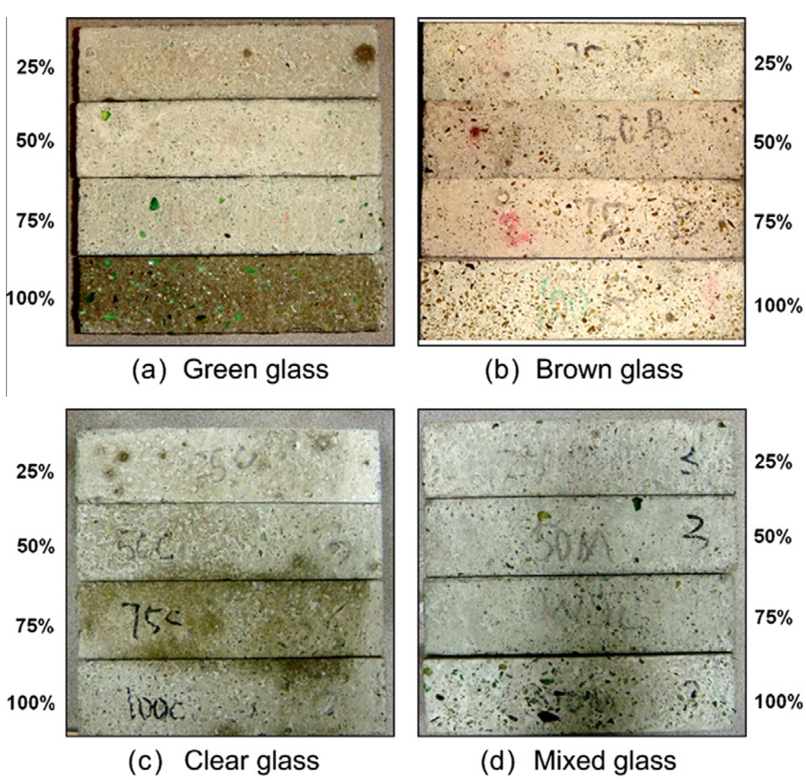


Fig. 16. Appearance of glass sand mortar specimens after sulfate attack tests.

The reduced shrinkage could be due to the negligible water absorption capacity of glass particles, the higher aspect ratio and the irregular shape of glass particles, and the relatively higher volume fraction of fine aggregates in glass sand mortar. Mortar with 75% glass sand showed the lowest drying shrinkage while 100% showed intermediate values. The reason for the latter could be that a significant higher portion of finer particles could facilitate the movement of moisture in glass sand, leading to higher shrinkage.

3.9. Rapid chloride permeability test (RCPT)

The RCPT results at 28 days are shown in Fig. 14. All the mortar specimens exhibited high values of total charge passed, with the normal sand mortar showing the highest value of 6764 (±966) Coulombs, due to the porous structure of cement paste and the lack of coarse aggregates. The total charges passed in 50% brown, green, clear and mixed glass sand mortar were 93%, 69%, 71%, and 64%, respectively, that of the normal sand mortar. The reduction in values was consistent with a previous study by Kou and Poon [34], who reported a decrease of 60% in the charge passed for concrete with 45% of the natural sand replaced by glass sand.

The resistance of mortar to chloride ion penetration seemed to increase due to the lower porosity and permeability of glass particles [35], in spite of a more porous ITZ microstructure. Another possible reason is the finer size distribution of crushed glass sand, leading to better packing efficiency of mortar [34], and pozzolanic reaction which consumed OH^- and improved impermeability. Contrary to mechanical properties, mortar with clear glass sand did not show the poorest performance in RCPT, especially at 25%, 50%, and 75% glass content. Instead, brown glass sand mortar showed the least resistance at such glass contents. Mixed color glass sand mortar exhibited the highest resistance while green glass sand mortar showed intermediate resistance to chloride ion penetration.

According to NT build 429 [36], the non-steady-state migration coefficient D_{nssm} of chloride is calculated as

$$D_{nssm} = \frac{0.0239(273+T)L}{(U-2)t}\left(x_d - 0.0238\sqrt{\frac{(273+T)Lx_d}{U-2}}\right) \quad (1)$$

where D_{nssm} is the non-steady-state migration coefficient, $\times 10^{-12}$ m^2/s; U the absolute value of the applied voltage, V; T the average value of the initial and final temperatures in the anolyte solution, °C; L the thickness of the specimen, mm; x_d the average value of the penetration depth, mm; and t is the test duration, h.

In this study, a voltage of 60 V was applied for 6 h. At the end of the test, the specimens were axially split to measure the depth of chloride penetration, x_d, by spraying with 0.1 N $AgNO_3$ solution. The reported non-steady-migration coefficients were each the average of three specimens and are shown in Fig. 14. The chloride migration coefficients for brown, green, clear and mixed color glass sand mortars, at 100% glass content, were 80%, 59%, 37%, and 36%, respectively, that of the normal sand mortar. The calculated migration coefficients confirmed the RCPT results that glass sand increased the resistance to chloride ion penetration.

Also, the effect of glass color was confirmed. That is, mixed color glass sand mortar had the lowest chloride migration coefficients while clear glass sand mortar exhibited intermediate values, at contents of 25%, 50%, and 75%. The detrimental effect of internal micro-cracks in clear glasses was not obvious. This is because unlike mechanical properties, the chloride conductivity would not be affected if the crack is less than 200 μm wide [37].

3.10. Alkali–silica reaction (ASR)

The ASR expansions with time for different color glass sand mortars are shown in Fig. 15. The expansion of brown and green glass sand mortars was lower than 0.1% at 14 days and lower than 0.2% at 28 days. For green, brown and mixed color glass sand mortar, the ASR expansion decreased with increasing glass sand content, indicating that the green and brown glasses were less reactive with alkali than natural sand, at least for the monitored period. The ASR expansion of brown and green glass sand mortars was comparable and quite small, up to 28 days.

However, the clear glass sand mortars exhibited a totally different characteristics from green and brown glass sand mortars. The ASR expansion significantly increased with higher clear glass sand content, especially beyond 25%. Through visual observation, there existed mapping cracks on the surface of clear glass sand mortar specimens after 28 days of curing. The width, length and density of such cracks increased with higher clear glass content. For brown and green glass sand mortars, no such crack was observed. This could have led to different ASR reactivity of different colored glass particles [38]. That is, the presence of micro-cracks in clear glass particles would lead to obvious ASR expansion (Fig. 9b) while the rare existence of micro-cracks in green and brown glasses resulted in slight ASR expansion (Fig. 9c).

It appears that the green and brown glass sand would pose no risk in ASR expansion. This could be further assured by incorporating mitigation methods, such as the use of cementitious supplementary materials; or the addition of fibers or lithium compounds. A thorough experiment has therefore been conducted to determine the long term ASR expansion and the effectiveness of various ASR

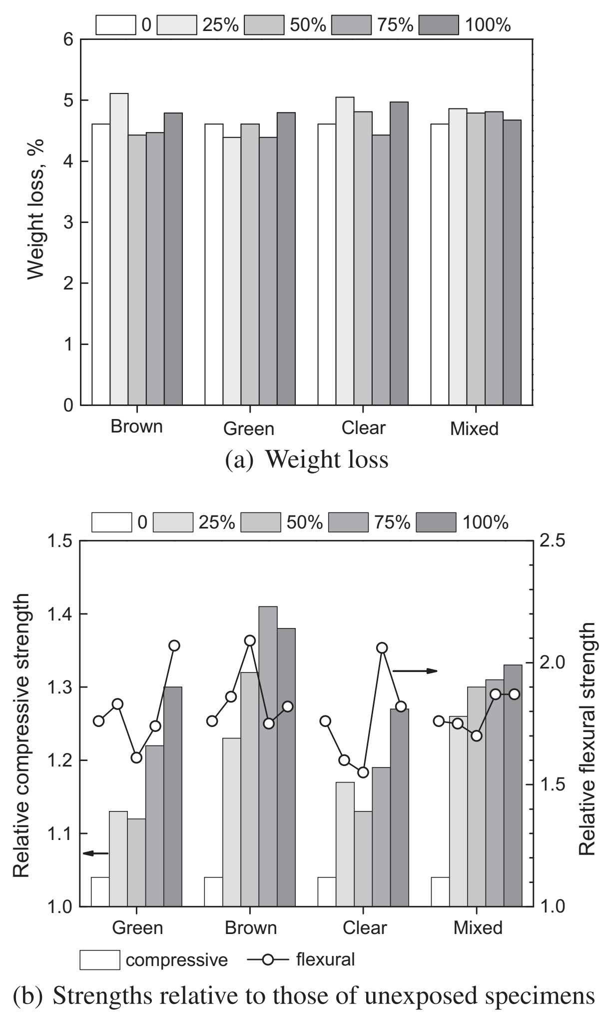


Fig. 17. Sulfate attack test results of glass sand mortar.

mitigation methods for green and brown sand mortars, and the results are reported in Part II paper.

3.11. Sulfate attack

After curing in water for 28 days, three mortar prisms and three cubes of each mix were weighed (SSD) before immersion in saturated $MgSO_4$ solution for 24 h, followed by oven-drying at 105 °C for the next 24 h. This wet-and-dry procedure was repeated for 10 cycles and the weight loss, compressive strength and flexural strength were recorded. Visual observation (Fig. 16) revealed that the exterior cement paste of the specimens was dissolved, exposing the glass sand. All glass sand mortars showed comparable weight loss regardless of glass color and glass content, as shown in Fig. 17a. In comparison, several investigators [39–41] have reported decreasing weight loss in concrete with increasing percentage of glass sand.

The compressive and flexural strength of glass sand mortars after 10 wet-and-dry cycles, relative to the strength of mortars cured in water for 28 days only, are shown in Fig. 17b. The results revealed that all mortars showed increased mechanical strength after the sulfate attack, particularly for flexural strength. Chen et al. [40] have also reported less strength reduction in concrete with higher percentage of glass sand. A possible reason is that only the surface of mortar specimens was attacked by sulfate while the inner core of specimens was intact from the sulfate attack. The strength increase could also be due to pozzolanic reaction of fine glass particles at high temperature during the test.

4. Conclusions

Based on the test results obtained in this study, the following conclusions may be deduced:

1. The irregular shape and smaller density of glass particles resulted in higher air content and lower density and flow of glass sand mortar regardless of glass color.
2. The use of glass sand in mortar resulted in lower compressive, flexural and splitting tensile strengths, and elastic modulus because of a weakened bond at the interfacial transition zone between the glass particles and cement paste. However, the negligible water absorption capacity of glass particles led to improved dimensional stability and hence lower drying shrinkage of glass sand mortar. Also, due to the existence of micro-cracks as a result of the crushing process, clear glass sand mortar showed the poorest mechanical performance.
3. Replacement of natural sand by waste glass particles led to a higher resistance to chloride ion penetration. With regards to ASR expansion, micro-cracking in the glass particles appeared to play an important role. Clear glass was more susceptible to micro-cracking during the crushing process, and is potentially deleterious while brown glass particles were relatively free of micro-cracks and could be considered as a non-reactive aggregate even in the long-term. With respect to resistance to sulfate attack, glass sand mortar exhibited similar weight loss as normal sand mortar; however the mechanical properties were not affected if not enhanced.

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