Feasibility of using recycled glass in architectural cement mortars

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ABSTRACT

The feasibility of using 100% recycled glass (RG) as a fine aggregate replacement in architectural white cement mortar was investigated. All the cement mortar mixtures were proportioned with a fixed water to binder ratio of 0.40. The dosage of superplasticizer was varied to produce highly workable recycled glass self-compacting white cement mortar (RG-SCWM) mixtures. Metakaolin (MK) was used in the RG-SCWM mixtures to suppress alkali-silica reaction (ASR). The test results revealed that increased in the recycled glass (RG) content improved the performance of workability and drying shrinkage. However, there was a gradual reduction in flexural and compressive strengths as the content of RG increased. The incorporation of MK effectively mitigated the ASR expansion and also increasing the resistance towards acid attack. Overall results have proved that it is feasible to produce aesthetically-pleasing architectural cement mortar by using 100% recycled glass as the fine aggregate.

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1. Introduction

Post-consumer waste glass represents one of the major components of the solid waste stream. Today, discarded waste glass has become a substantial burden on the landfills throughout the world. In Hong Kong, about 300 tonnes of waste glass is generated every day. However, only 3% of this waste glass was recovered and recycled [1]. Thus, disposal and recycling of waste glass have become a major concern in Hong Kong due to the lack of a local glass manufacturing industry to serve as a viable recycling outlet. As a result, it is essential to find a sustainable alternative to reuse and recycle the waste glass.

Concrete construction provides a significant market potential for waste glass recycling. Extensive studies have been carried out to utilize crushed recycled glass as partial replacement of aggregates into conventional concrete and mortar [2–6]. Previous studies have found that the use of recycled glass (RG) as an aggregate replacement material in concrete is a viable and effective recycling option. Topçu and Canbaz [2] used crushed green soda glass as partial replacement of coarse aggregate in concrete. The concrete containing waste glass was compared to the normal concrete. Test revealed that as the glass content increased to 30% in concrete, there was a 15% reduction in 28-day compressive strength. As the proportion of glass increased to 45% and 60%, decreases of

31% and 49% in compressive strength were recorded. This may be due to the high brittleness and poor geometry of glass aggregates leading to cracks which affected the adhesion between the glass aggregates and the cement paste. Park et al. [3] investigated the mechanical behaviour of styrene butadiene rubber (SBR) latex modified glass filled concrete. They found that the use of the polymer improved the mechanical strength because the presence of SBR latex formed a thin film at the interface and resulted in better interfacial bonding strength between the RG and the cement mortar.

Apart from strength, the use of RG in concrete may result in expansion due to alkali-silica reaction (ASR). The particle size of glass aggregate was found to have a major influence on ASR expansion since the rate of reaction depends mainly on the surface-areas of reactive silica aggregate. Coarser particles size of glass was reported to exert more negative impact than finer particles size of glass [7–10]. However, there exists a "pessimism" size of the glass aggregate at which the maximum expansion occurs [10]. Furthermore, it is also expected that the ASR expansion increases with increasing glass aggregate content in concrete [9–11].

Owing to the problems associated with the use of coarse glass aggregates in concrete, research interest has been primarily concentrated on the use of fine glass particles/powder (grinding from glass cullet) as sand or cement replacement in concrete or mortar [7,9,12–17]. In contrary to coarse glass aggregates, glass powder (GP) not only was found to cause negligible ASR expansion, but also can function as an effective suppressor to reduce ASR expansion of concrete. It is understood that the particle size of GP less than 38 μm (classified as a pozzolanic material) will react with

calcium hydroxide (the alkali) to form C–S–H in the course of cement hydration [7].

The initial study on the use of GP with particle size less than 10 µm as a pozzolanic material was undertaken by ARRB [9]. A study by Shao et al. [7] found that the smaller GP had better stability and strength of the concrete. Özkan and Yüksel [12] investigated the mechanical and durability properties of cement mortars by utilizing different types and coloured GP. The results showed that incorporating different colours of glass in mortar did not have any notable effect on the compressive strength. Compared to other supplementary cementing materials, GP modified concrete exhibited similar gain in strength compared to fly ash (FA) modified concrete [7,13,14]. Shao et al. [7] also found that 30% replacement of cement by <38 µm GP in concrete exhibited higher strength than the FA in concrete. Furthermore, Shayan and Xu [9,15] observed that the particle size of GP less than 300 µm did not show any ASR expansion in the accelerated mortar bar test (1-N NaOH, 80 °C) [7].

There have also been attempts to use RG in self-compacting concrete (SCC) [18,19]. RG was used to replace 30% sand in SCC production. It was shown that the workability of fresh SCC mixes increased with the increase in RG content [18–20]. Chloride ion penetrability and drying shrinkage of the SCC were decreased owing to the low water absorption and porosity of the RG [18,19]. But the compressive strength decreased with the increase of RG content due to the weak bonding between the cement paste and the glass aggregate. The ASR expansion of all the SCC specimens was significantly reduced by the use of fly ash [18]. López et al. [21] reported that it was possible to use a mortar based design approach to produce coloured self-compacting concrete.

The above-mentioned review suggests the potential to utilize coloured RG as sand replacement in the production of recycled glass self-compacting white cement mortar (RG-SCWM) for architectural concrete applications. In this work, a comprehensive experimental study was carried out to investigate the feasibility of using up to 100% RG as sand replacement for the production of architectural cement mortar. In order to create aesthetic pleasing surfaces of the produced products, white Portland cement and metakaolin (both are white in colour) were used respectively as the binder and ASR suppressor for making the mortar.

2. Experimental details

2.1. Materials

White ordinary Portland cement (WC) and metakaolin (MK) were used as the cementitious materials. These materials were chosen in this study due to aesthetic considerations for architectural mortar applications. The chemical composition of these materials is given in Table 1. In this study, recycled glass (RG) containing approximately 23% coarser particles (5–10 mm) with a fineness modulus of 4.19, sourced from a local recycling plant (Laputa

Eco-Construction Material Co. Ltd.) was used. This range of particle sizes chosen aimed to increase the visible and aesthetic of the architectural mortar products [22]. The RG was mainly post-consumer bottles in green colour. The natural fine aggregate used was natural river sand with most of the particles passing through the 2.36 mm sieve. The particle size distributions of RG and river sand are shown in Table 2. A superplasticizer ADVA-109 contained no added chloride and weights approximately 1.045 ± 0.02 kg/l was used as a high range water reducer.

2.2. Mix proportions

The mix proportions of RG-SCWM including the control mixture are presented in Table 3. The total binder content was kept constant at 706 kg/m^3 to provide a high volume fraction of fine materials similar to common self-compacting mortar design. The binder to aggregate ratio was kept at 1:2 throughout the study. All the mixtures were proportioned with a fixed water-to-binder (W/B) ratio of 0.40 and the superplasticizer dosage was varied from 1.0% to 5.5% by weight of binder in order to obtain the targeted mini-slump flow values of 250 ± 10 mm. The control mixture (M10R100) used 90%WC + 10%MK as the binder and 100% river sand as the fine aggregate. As for the M10R25-M10R100 mixes, RG was used as 25%, 50%, 75%, and 100% by mass replacement of the river sand, respectively. For M20R100 and M30R100 mixes, the mix proportion was similar to that of M10R100 except MK was used to replace 20% and 30% of white cement, respectively.

2.3. Mixtures preparation, casting and curing

It is important to use a consistent mixing sequence and duration for the preparation of the RG-SCWM samples. The RG-SCWM mixtures were prepared in a standard rotating drum type mixer with a capacity of 8 kg. Initially, all the dry materials including the binder (WC and MK) and fine aggregate (sand or RG) were mixed for about 90s to attain a uniform mix in dry condition. Then, the required amount of water (superplasticizer thoroughly premixed) was added and the whole mixture was further mixed for another 90s. After that, the mixture was further mixed manually using a steel trowel to ensure a uniformed mixture was attained. Finally, the wet mixture was mixed for an additional 120s by the mixer to complete the mixing sequence. After the whole process of mixing was completed, the fluidity of the freshly prepared mortar was evaluated to ensure the mini-slump flow diameter of 240–260 mm that specified by RFNARC [23] specification was achieved.

For each mix, the freshly prepared RG-SCWM mixture were used to produce twelve $40 \times 40 \times 160$ mm prisms for flexural and compressive strength tests. Another six prism samples were cast for the determination of water absorption and resistance to acid attack. Besides, six $25 \times 25 \times 285$ mm prisms were prepared to measure drying shrinkage and alkali-silica reaction (ASR)

Table 1
Chemical composition of cementitious materials.

	White Portland cement	Metakaolin
Chemical composition (%)		
Silicon dioxide (SiO$_2$)	21.36	51.39
Aluminium oxide (Al$_2$O$_3$)	5.27	32.91
Ferric oxide (Fe$_2$O$_3$)	0.2	0.58
Calcium oxide (CaO)	67.49	0.01
Magnesium oxide (MgO)	1.14	0.01
Sodium oxide (Na$_2$O)	0.048	0.39
Potassium oxide (K$_2$O)	0.077	0.98
Sulphur trioxide (SO$_3$)	2.6	–
Loss on ignition	1.58	13.57

Table 2
Physical properties of river sand and RG.

Sieve size (mm)	River sand (% passing)	Recycled glass (% passing)
5	99.8	76.7
2.36	98.2	47.0
1.18	93.4	28.0
0.6	80.3	15.6
0.3	34.4	8.8
0.15	2.0	4.4
Fineness modulus	1.92	4.19
Relative density (g/cm^3)	2.62	2.49

Table 3
Mix proportion of RG-SCWM mixtures.

Notation	W/B (kg/m^3)	Binder		Aggregate		SP (%)	Mini slump (mm)
		WC (kg/m^3)	MK (kg/m^3)	Sand (kg/m^3)	RG (kg/m^3)		
M10R0	0.4	282	635	71	1412	0	5.5	243
M10R25	0.4	282	635	71	1059	353	4.0	258
M10R50	0.4	282	635	71	706	706	2.5	257
M10R75	0.4	282	635	71	353	1059	1.5	259
M10R100	0.4	282	635	71	0	1412	1.0	240
M20R100	0.4	282	565	141	0	1412	1.8	250
M30R100	0.4	282	494	212	0	1412	2.8	245

expansion. Also, 70 × 70 × 70 mm cube sample was prepared for the determination of abrasion resistance.

After casting, all the samples were kept in their moulds in the laboratory environment at 25 ± 3 °C for the first 24 ± 2 h. After demoulding, three 25 × 25 × 285 mm prisms, were immediately used to determine the initial lengths and then they were transferred to a drying chamber with a temperature of 23 °C and relative humility of 50%. The remaining samples were stored in a water tank at temperature of 25 ± 3 °C until the age of testing.

2.4. Test methods

2.4.1. Fresh properties
The mini-slump flow cone with an internal diameter of 100 mm was used to evaluate the fluidity of RG-SCWM as described by EFN-ARC [23] (Fig. 1). Before the test, the truncated cone mould was placed on a clean metal plate and the freshly prepared RG-SCWM mixture was poured into the cone without any compaction. Once the cone was fully filled with the mortar, the cone was lifted vertically and the spread diameters of the freshly prepared mortar in two perpendicular directions were measured. Occurrence of segregation and/or bleeding, if any, was visually observed and noted during the mini-slump flow test.

2.4.2. Permeable voids and water absorption
The permeable voids and water absorption test were conducted to assess the water permeability characteristics of RG-SCWM as per ASTM 642 [24]. For this test, three 40 × 40 × 160 mm prism specimens were cured in water until age of 90 days. Surface dry the saturated specimens by removing surface moisture with a towel and the weight was determined (W_{90}). Afterwards, the saturated surface dry specimens were dried in an oven with a constant temperature of 105 ± 5 °C until constant weight achieved (W_{od}). The permeable voids in percentage are given below:

$$\text{Permeable voids} = [(W_{90} - W_{od})/V] \times 100 \tag{1}$$

where V = volume of prism specimen

Subsequently, the initial surface absorption (ISA) and final water absorption (FWA) tests was carried out by completely immersing the oven dried specimens in water. The specimens were removed from the water immersion and weighed at different intervals, 30 min and 96 h to evaluate the mass gained for ISA and FWA, respectively. The ISA and FWA values were determined by following formulae:

$$\text{Water absorption} = [(W_t - W_{od})/W_{od}] \times 100 \tag{2}$$

where W_t = weight of surface dried specimen after t immersion period

2.4.3. Flexural strength
A three point flexural strength test in conformity with ASTM C348 [25] was performed at 1, 7, 28 and 90 days after casting. The RG-SCWM specimens with a size of 40 × 40 × 160 mm were tested under a central line load while simply supported over a span of 120 mm. For this test, a universal test machine with a load capacity of 50 kN was used with a displacement rate of 0.10 mm/min set.

2.4.4. Equivalent compressive strength
The equivalent compressive strength test was carried out within 30 min after the flexural strength test according to ASTM C349 [26]. The equivalent compressive strength test used the same specimens previously used for the flexural strength test. The compressive strength was determined using a Denison compression machine with a load capacity of 3000 kN on the broken pieces (portions of the prisms broken in flexure). The reported test results were the average of six measurements.

2.4.5. Drying shrinkage
A modified British standard (BS ISO, Part 8: 1920) method was used for the drying shrinkage test in this study [27]. After demoul-

Fig. 1. Mini-slump flow test for RG-SCWM.

ding, the initial length of three 25 × 25 × 285 mm mortar bar specimens was measured. After the reading, the specimens were conveyed to a drying chamber with a temperature of 23 °C and a relative humidity of 50% until further measurements at 1st, 4th, 7th, 28th, 56th, 90th and the final length measurement was recorded at 112th day. The length of each specimen was measured within 15 min after it was removed from the drying camber.

2.4.6. Expansion due to alkali-silica reaction

For each mix, three 25 × 25 × 285 mm mortar bar specimens were used for the ASR test in accordance with ASTM C1260 [28]-the accelerated mortar bar method. A zero reading was taken after storing the prisms in distilled water at 80 °C for 24 h. The bars were then transferred and immersed in 1 N NaOH solution at 80 °C until the testing time. The expansion of the mortar bars was measured within 15 ± 5 s after they were removed from the 80 °C water or alkali storage condition by using a length comparator. The measurements were conducted at 1st, 4th, 7th, 14th, 21st and 28th days.

2.4.7. Abrasion resistance

The abrasion resistance test was determined by abrading the surface of the 70 × 70 × 70 mm cube specimens after 28 days of water curing as specified by BS 6717 [29]. The test began by contacting the test specimen with an abrasion wheel rotating at the rate of 75 revolutions in 60 ± 3 s. The dimension of the groove resulting from the abrasive action was measured to evaluate the abrasion resistance of the mortar. A smaller groove indicated a better resistance to abrasion.

2.4.8. Chemical resistance

The chemical resistance was studied by immersing the specimens in a sulphuric acid solution in accordance to ASTM C 267 [30]. After the 28 days period of curing, three 40 × 40 × 160 mm prisms were removed from the water tank and each specimen was marked and tied with a nylon string around them. After the initial weight was recorded, the specimen was immersed in a 3% H_2SO_4 solution. The solution was replaced at 4 weeks regular intervals to ensure consistent acid concentration throughout the test period. The specimens were extracted from the solution weekly and the surfaces of the specimens were cleaned with a soft nylon brush before their weights were measured. The weights of the specimens were measured up to 12 weeks, and the percentages of mass losses were determined. The cumulative mass loss of each specimen expressed in percentage is given below:

$$Cumulative\ mass\ loss = [(M_t - M_{int})/M_{int}] \times 100 \qquad (3)$$

where M_t = mass at time t

M_{int} = initial mass before immerse to sulphuric acid.

3. Results and discussion

3.1. Fresh properties

The test results of RG-SCWM mini-slump flow diameter is presented in Table 3. As shown in the table, all the fresh properties of RG-SCWM including the control mixture produced in this study achieved the mini-slump flow diameter of 240–260 mm specified by EFNARC [23]. The superplasticizer (SP) contents in M10R0, M10R25, M10R50, M10R75, and M10R100 were 5.5%, 4.0%, 2.5%, 1.5%, and 1.0%, respectively. In other words, the fluidity of RG-SCWM mixtures increased as the RC contents was increased from 0% to 100%. The reason of this behaviour can be attributed to the particle sizes of RG, since they were coarser than the sand particles. The lower water absorption of RG also led to a lower water demand of the mixes compared [18,20]. The fluidity of the mortar was re-
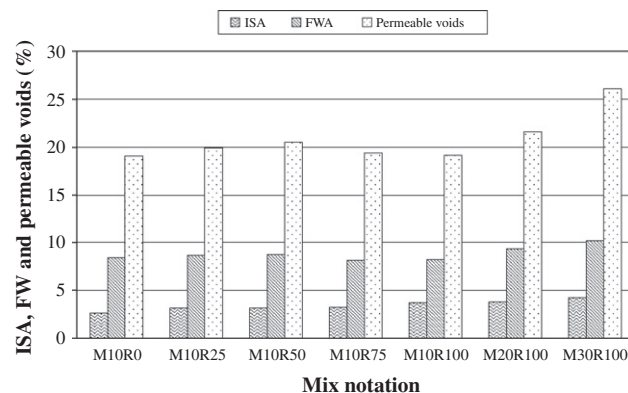

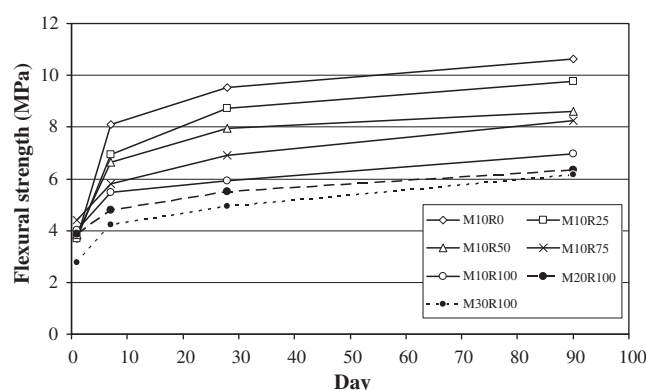**Fig. 2.** Effect of RG and MK content on permeable voids, ISA and FWA.

Fig. 3. Effect of RG and MK content on flexural strength development.
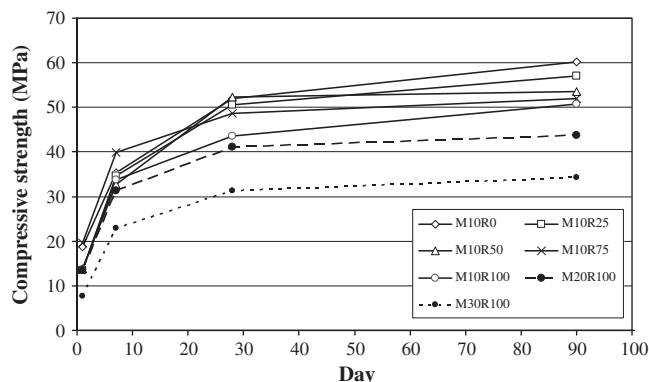

Fig. 4. Effect of RG and MK content on compressive strength development.

duced with the increase in MK content. Guneyisi and Gesoglu [31] also reported similar observations that replacement of cement by MK increased the SP dosage to compensate for the loss in workability. No bleeding or segregation was detected for all the RG-SCWM mixtures.

3.2. Permeable voids and water absorption

The effect of RG and MK on the permeable voids, initial surface absorption (in first 30 min), and final water absorption (96 h) of all SCWM mixtures is presented in Fig. 2. It can be observed that M10R0 samples which contained no glass showed the lowest ISA value of 2.61%. As the RG content was increased to 100%, the aver-
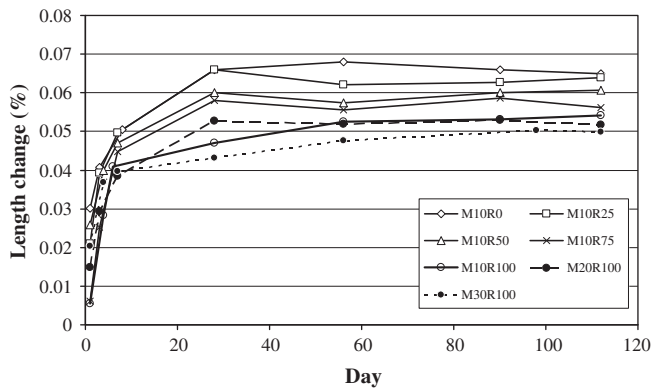
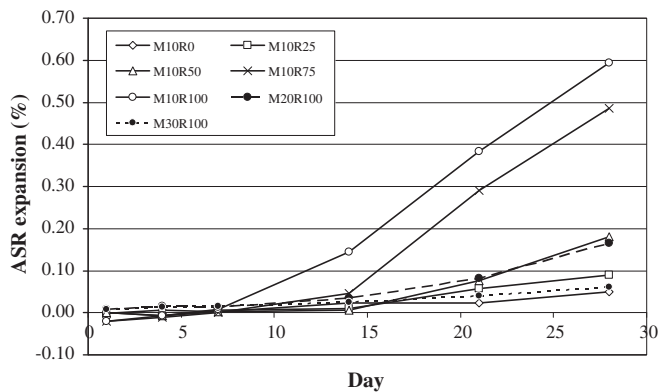**Fig. 5.** Effect of RG and MK content on drying shrinkage.

Fig. 6. Effect of RG and MK content on ASR reactivity.

3.3. Flexural and compressive strengths

Fig. 3 shows the development of flexural strength with time (1, 7, 28 and 90 days). The results indicated that as RG were used as sand replacement at 25%, 50%, 75% and 100%, reduction of 8.2%, 19.1%, 22.5% and 34.5% in 90-day flexural strength, respectively were observed. This can be explained by the weaker bonding between surface of the RG and the cement paste. Also, the average values of flexural strength were inversely proportional to the percentage of MK replacement. As expected, the flexural strength decreased with an increase in MK replacement level. Previous studies by Li and Ding [34] suggested that concrete achieved the best strength performance with 10% MK replacement. Yet, the 28 day-flexural strength values of all samples tested were higher than 5 MPa.

As in the case of flexural strength, the relationship between compressive strength and RG content with respect to the curing age are shown in Fig. 4. The percentage decrease in compressive strength of the RG-SCWM specimens at 28 days were 5.1%, 10.9%, 13.5%, and 16.7% at RG content of 25%, 50%, 75%, and 100%, respectively, when compared to the control. Similar results had been reported that incorporating glass in concrete reduced the compressive strength [3,6,11]. Apparently the compressive strength decreased with increasing MK content in a similar manner to that observed for the flexural strength.

3.4. Drying shrinkage

Fig. 5 shows the drying shrinkage development of the RG-SCWM samples with time up to 112 days. From the test results, the increase in RG content resulted in a reduction in drying shrinkage values of the mortar bars. It is important to note that the ultimate long term drying shrinkage of the mortar bar containing 100% RG (M10R100) was 17% lower than that of the control (M10R0). This may be due to the lower absorption capacity of RG cullet [18,19]. As shown in Fig. 5, it can be seen that the drying shrinkage of the SCWM incorporating 100% RG (M10R1005-M30R100) at all test ages decreased with the increase in MK content. The slightly decrease in drying shrinkage by adding MK is evidently supported by literature [35]. Inclusion of MK reduced the drying shrinkage could lower the amount of evaporable water due to slower rate of hydration of MK. The test results of 56-day drying shrinkage for all RG-SCWM mixes were less than 0.075%, which satisfied the Australian Standard AS 3600 [36] for concrete mixes.

age ISA value of M10R100 was 3.75%. This could be attributed to the larger particle size and angular shape of RG, resulting in larger pore volumes [11] in the mortars. It was also noted that with the increasing use of MK to replace WC, the ISA values of RG-SCWM increased. The increase of porosity can be attributed to the slower rate of hydration of MK when compared to WC [32]. Similar observations concerning the effect of MK on the water absorption of concrete were also reported by other researchers [33].

Fig. 7. ASR cracks of RG-SCWM bars after 28 days storage in 1 N NaOH at 80 °C.
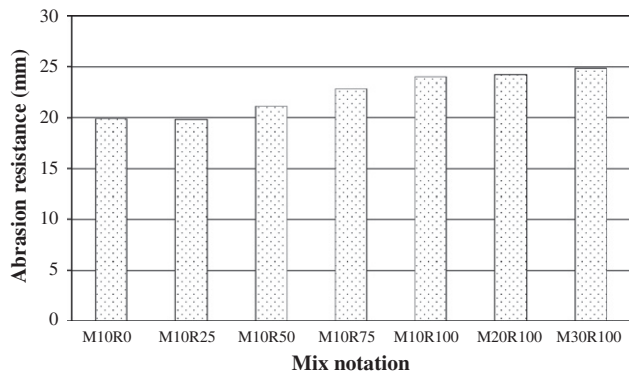
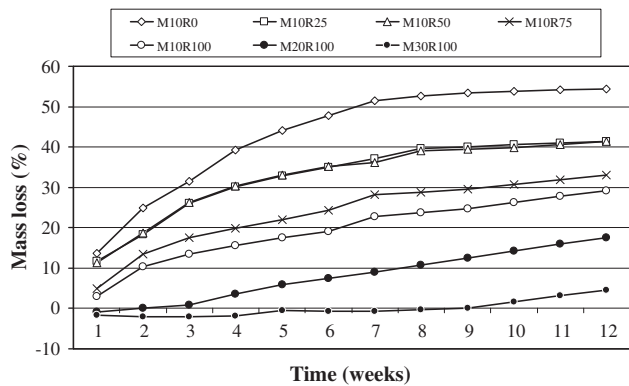**Fig. 8.** Effect of RG and MK content on abrasion resistance.

Fig. 9. Effect of RG and MK content on chemical resistance.

3.5. Expansion due to alkali-silica reaction

Fig. 6 shows the ASR expansion results of the mortar bas. The ASR expansion noticeably increased with an increase in RG content from 0% to 100%. At the age of 14 days, all the mortar bars mixes showed ASR expansion below the permissible limits (0.10%), except for the M10R100 mix even when 10% MK had already been used to replace cement. As expected, the highest ASR expansion value of M10R100 of about 0.60% was recorded at 28 days. Fig. 7 shows that the scattered ASR cracks formed extensively in the surface mortar bar of M10R75 and M10R100. But when the MK content was increased to 20% and 30%, a marked reduction of 72% and 90% in ASR expansion was recorded, respectively. Similar to previous studies [10,37], MK had been proven as an effective ASR suppressor even for the 100% RG in the mix.

3.6. Abrasion resistance

The effect of RG and MK content on the abrasion resistance of RG-SCWM is shown in Fig. 8. As seen from the figure, the abrasion resistance was reduced with an increase in the RC and MK content. The obtained results show similar qualitative trend to a previous study [38] in which the ability of concrete to withstand abrasion was shown to decrease with a decrease in concrete strength. Turgut and Yahlizade [39] also showed that concrete paving blocks containing 30% of coarse glass cullet resulted in a 18% reduction of the abrasion resistance as compared with the control sample.

3.7. Chemical resistance

The loss of mass upon acid attack is shown in Fig. 9. Up to 12 weeks of storing in a 3% solution of H_2SO_4, the control
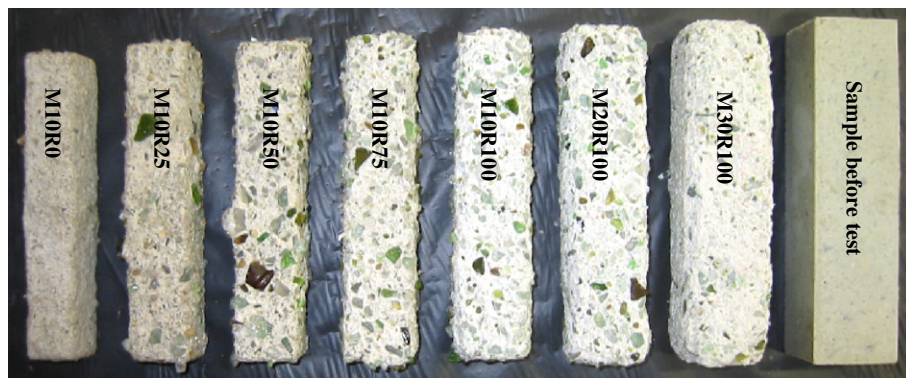

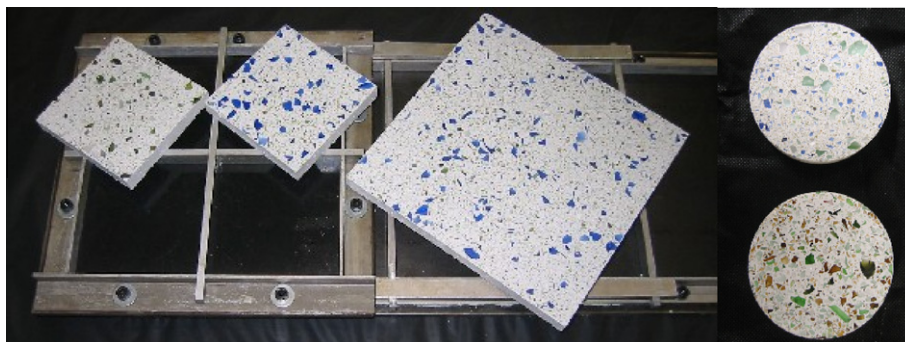**Fig. 10.** Degradation of RG-SCWM specimens after exposure to sulphuric acid for 12 weeks.

Fig. 11. Architectural mortar with different colour of glass, size and shape.

(M10R0) specimens showed the most significant deterioration with respect to loss in mass. The loss of mass is probably related to the removal of material from the surface by the degradation of the cementitious matrix. However, the rate of mass loss was somewhat negligible after 7 weeks of immersion. Evidently, the M10R75 and M10R100 samples with higher amounts of RG contents showed better resistance to acid attack as shown in Fig. 10. This was due to RG had a higher degree of resistance to acid attack than that of river sand [40].

By comparing the effect of MK content, M20R100 and M30R100 with higher contents of MK showed better resistance to acid attack. It is important to note that for the SCWM samples incorporating 100% RG, the mass loss was decreased to 17.6% for 20% MK and to 4.6% for 30% MK. This can be explained by the ability of MK to reduce the amount of $Ca(OH)_2$ in the hydrated cement matrix [41].

4. Conclusions

The salient conclusions from this study on assessing the feasibility of using recycled glass to produce recycled glass self-compacting white cement mortar (RG-SCWM) are drawn in following:

- For a given W/B ratio, increase in RG content improved the fluidity of fresh RG-SCWM mixtures. However, incorporating MK in the mixtures increased the SP dosage to compensate for the loss in workability.
- The presence of RG and MK in the RG-SCWM increased the initial surface and final water absorption in all cases.
- The presence of MK and RG content caused a reduction in both flexural and compressive strengths. The flexural strength was found to be about one-sixth of the compressive strength.
- The drying shrinkage of RG-SCWM decreased with increasing RG and MK content.
- The ASR expansion of RG-SCWM was directly proportional to the RG content. MK was found to be an effective suppressor to mitigate the ASR expansion of mortar containing 100% RG.
- The abrasion resistance of the RG-SCWM decreased with an increase in RG and MK content.
- The resistance to acid attack increased when RG was incorporated into RG-SCWM. Mortar specimen with 30% MK and 100% RG exhibited little loss of mass even after immersion in a 3% solution of H_2SO_4 for 12 weeks.

Finally, a number of architectural mortar using different colours and particle sizes of recycled glass aggregates were produced at the laboratory. Some of these samples are shown in Fig. 11. The results demonstrate that it is feasible to produce different types of 100% recycled glass architectural mortar with the self-compacting method.

Acknowledgements

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