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Improving the performance of architectural mortar containing 100% recycled glass aggregates by using SCMs

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Abstract:

An experimental study was carried out to evaluate the mechanical and durability properties of architectural mortar prepared with 100% glass aggregates and using supplementary cementitious materials (SCMs) to replace cement. The mechanical properties were assessed in terms of compressive and flexural strength, whilst the durability characteristics were investigated in terms of drying shrinkage, resistance to high temperature exposure, alkali-silica-reaction (ASR) and acid dissolution.

Experimental results suggested that strengths of glass-based architectural mortar incorporating SCMs (fly ash, ground granulated blast-furnace slag, metakaolin and waste glass powder) were comparable or even superior to that of the pure cement mortar when the cement replacement levels was up to 20%. In particular, waste glass powder (GP) as a pozzolanic material performed better than the other SCMs for flexural strength development of the glass-based mortar. The durability results also indicated that the addition of the SCMs could significantly reduce the drying shrinkage of the glass-based architectural mortar. All the recycled glass architectural mortars prepared with SCMs showed favorable resistance to expansion due to the ASR and less strength loss after heating to 800 °C. GP and ground granulated blast-furnace slag (BS) blended mortars gave better performance below 600 °C as compared to fly ash (FA) and metakaolin (MK) blended mortar. Also, the glass-based mortar containing GP exhibited the best performance of resistance to acid attack. Therefore, there is a potential to produce high performance architectural mortars with excellent mechanical and durability properties by reutilizing recycled glass to fully replace natural aggregates and partially replace cement.

Keywords: Waste glass; Supplementary cementitious materials (SCMs); Glass powder; Durability; Architectural mortar

1 Introduction

With minor variation in composition, soda-lime-silica glass containers are widely used for packaging

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beverage. On the other hand, statistics from the Hong Kong Environmental Protection Department [1] indicate that per capita waste glass containers generation in Hong Kong in 2013 reached up to 13.1 kilograms (obtained by dividing annual waste glass containers generated in kilograms by mid-year estimate of population). And, most of the containers are post-consumer beverage bottles with various sizes, shapes and colors. Currently, due to the lack of a glass manufacturing industry in Hong Kong, most of the waste glass containers are destined for disposal at local landfills. In addition, the mixed colors glass containers with contaminates are difficult to be reused for the manufacture of new glass. Thus, the recovery rate of waste glass in Hong Kong is much lower than that in Europe (about 10% Vs. 73%) [1,2]. For the purposes of recycling valuable resources and relieving environmental stresses on landfill disposal, government and industry have strong interests to develop environmental-friendly technologies which offer new and practical ways to promote glass recycling.

Glass presents several advantages as a packaging material, such as its chemical inertness, low permeability, and high intrinsic strength [3]. For these reasons, a novel channel for the recycling of mixed glass is to reuse it as a replacement of natural aggregates in architectural mortars. A typical glass-based architectural mortar produced with white cement for decorative application is shown in Fig. 1. The aesthetic appearance takes advantages of the appealing colors of the waste glass cullet which is used to fully replace natural fine aggregates (e.g. river sand). However, the main component of soda-lime-silica glass is amorphous SiO_2, so that a major concern about the utilization of glass cullet in cement based materials is alkali-silica (glass) reaction (ASR). When the pH reaches 12, the siloxane bonds in the glass may be hydrolysed by the hydroxide ions [4]. Compared to other aggressive agents, the corrosion caused by alkaline solution is usually more rapid because the attacks could happen to all the components contained in the glass [5]. The ASR between the reactive glass cullet and the alkaline pore solution of the cement paste may develop deleterious expansion. Besides, it has also been reported that the inclusion of waste glass as aggregates in cement based materials might lead to a modest decrease in compressive strength resulting from the relative weaker interface between the cement paste and the smooth glass cullet aggregates [6,7]. Therefore, efforts need to be taken to improve these aspects.

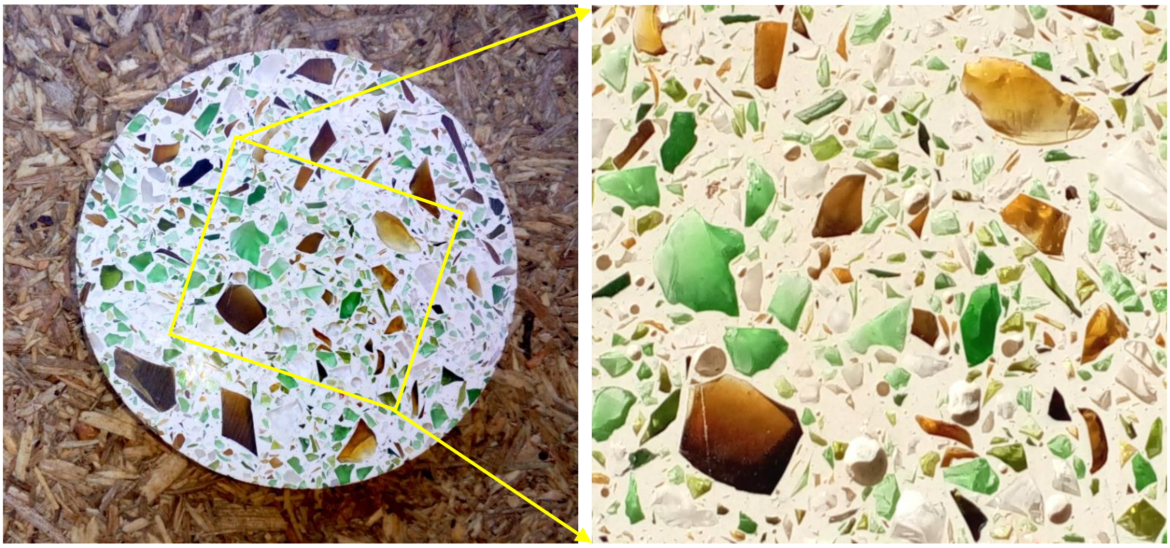


Fig. 1 Architectural mortar produced with waste glass cullet

It is widely accepted that the inclusion of traditional supplementary cementitious materials (SCMs) (i.e. fly ash (FA), ground granulated blast-furnace slag (BS), silica fume, metakaolin (MK)) into concrete can effectively improve its mechanical and durability performance [8-13]. Therefore, for using glass cullet for applications like architectural mortars which usually require good durability and aesthetic appearance, appropriate SCMs should be incorporated. In recent years, use of glass powder (GP) as a pozzolanic material for preparation of mortar and concrete has received considerable interests [14-16]. Experimental results have shown that the incorporation of finer GP in cement based materials has a strong ability to reduce gas permeability [17] and chloride ions diffusivity [17,18], whilst improving the resistance to ASR [18,19], sulfate attack [20], freeze–thaw cycle [16]. More importantly, the color of GP is close to white cement, hence it will not cause any adverse impacts on the aesthetic properties of the architectural mortar. Meanwhile, if the waste GP can be used to partially replace white cement in the architectural mortars, the added-value of waste glass will be further enhanced in terms of reduction in cement consumption

Similarly, taking into account that the color of MK is also nearly white and MK blended concrete exhibits considerable enhancement in durability properties [21,22], the introduction of MK to glass-based architectural mortars is envisioned to compensate for the deficiency of utilization of waste glass in cement based materials although the cost of using MK is high. Compared to the MK, the FA and BS are the primary SCMs in the production of sustainable construction materials because they are less costly. However, the use of FA and BS tends to darken the color of the architectural mortars due to the presence of carbon and iron sulfide [23], respectively.

Previously, there have been many studies focusing on use of the glass aggregates or glass powder in concrete or mortars [24-28]. But few studies have been done to make use of the appealing colors of the mixed glass cullet for the production of architecture mortars [29,30]. Also, the effect of using different SCMs (GP, FA, BS and MK) as partial cement replacements on the performance of the architecture mortar prepared with 100% mixed glass cullet have not been investigated. Thus, a comparative study was carried out with a view to producing desired performance of architecture mortars by using appropriate SCMs. Given the architecture mortars with good aesthetic appearance will have potential to be applied in the indoor areas (e.g. cooking bench, floor tile, countertop), the mechanical (compressive and flexural strengths) and related durability (drying shrinkage, ASR expansion, resistance to acid attack, fire resistance) properties, have been assessed and reported in this paper.

2 Materials and experimental methodology

2.1 Materials

2.1.1 Cement and supplementary cementitious materials (SCMs)

The cement used for the experiment was a white ordinary Portland cement (WC) due to the aesthetic requirement of architectural mortar. The chemical composition of the WC is listed in Table 1. Waste glass powder (GP) was obtained by grinding glass cullet collected from a local glass recycler with a laboratory ball mill for 2 hours. Fly ash (FA) was obtained from a local coal-fired power plant. Ground granulated blast-furnace slag (BS) and metakaolin (MK) were supplied from China. BS was a byproduct of steel production and MK was sourced from a commercial source.

The chemical compositions of the SCMs were determined by using X-ray fluorescence spectroscopy (XRF), as given in Table 1. The particle size distributions of the cement and SCMs are shown in Fig. 2, which indicates that the mean diameter of MK is smallest, while the average particle size of GP is larger than that of cement and other SCMs. This is confirmed by the morphologies of SCMs as examined by SEM (Fig. 3). The BS particles with a smooth surface texture, irregular shape and sharp edges are similar to the GP particles, whereas the GP shows higher aspect ratios than BS. The FA is made up of many spherical particles in micrometer range, while the MK is composed of very small agglutinate calcined clay particles.

Table 1

Chemical compositions of cement and SCMs (ms %).

	WC	GP	FA	BS	MK
SiO_2	21.36	73.5	45.70	34.78	55.30
Al_2O_3	5.27	0.73	19.55	14.22	41.36
Fe_2O_3	0.20	0.38	11.72	0.27	0.72
CaO	67.49	10.48	12.27	38.38	0.06
MgO	1.14	1.25	4.10	7.32	-
K_2O	0.077	0.69	1.71	0.77	0.59
Na_2O	0.048	12.74	1.36	-	-
TiO_2	0.14	0.087	1.09	0.71	0.33
SO_3	2.60	-	1.82	3.12	0.24

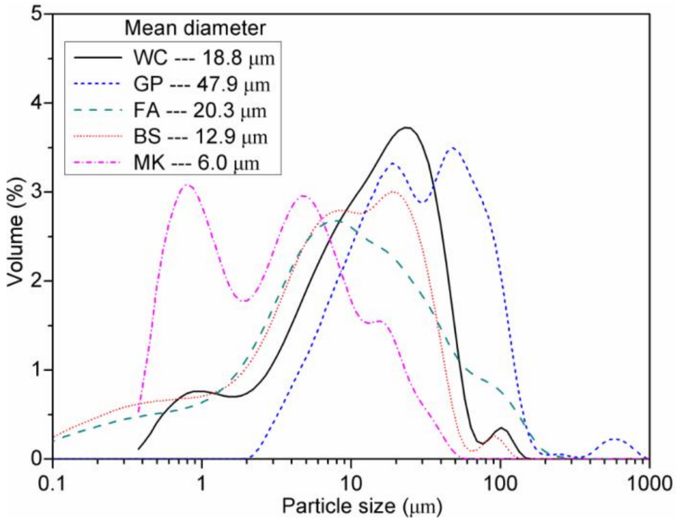


Fig. 2 Particle size distributions of cement and SCMs

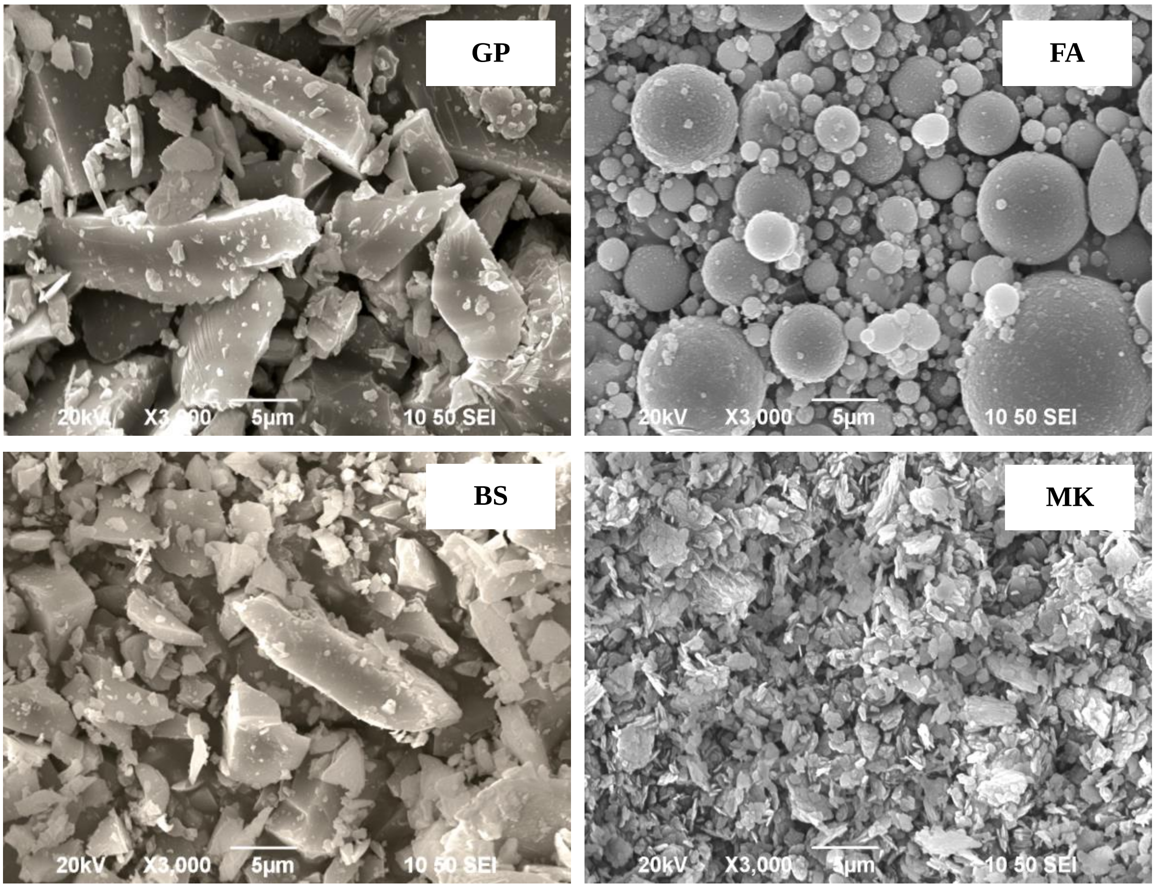
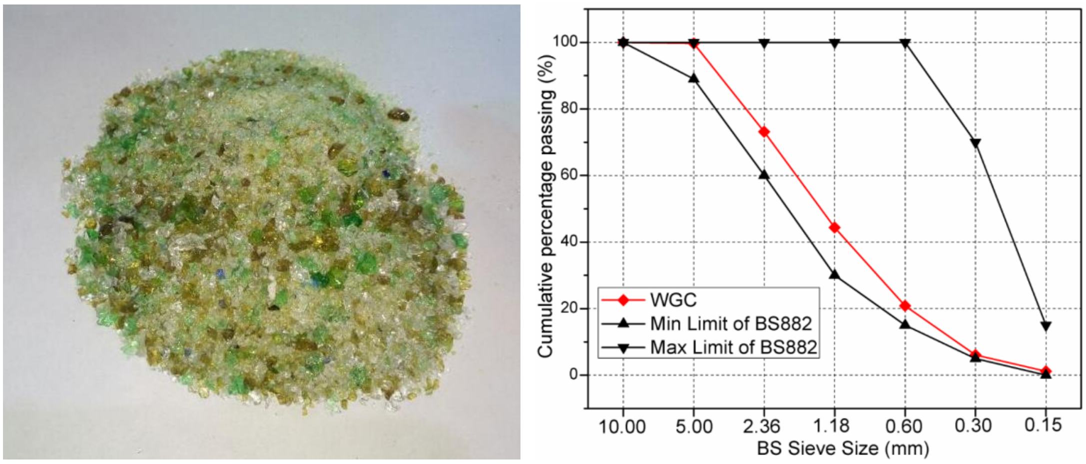


Fig. 3 Morphologies of SCMs

2.1.2 Waste glass cullet (WGC)

The recycled glass used in this study was a blend of post-consumer beverage bottles with different colors collected from a waste glass recycler in Hong Kong. The waste glass bottles were crushed to obtain the cullet with particle size of smaller than 5 mm. After that, the glass cullet was rinsed with tap water first and then oven-dried for a minimum of 24 hours at 105 ^{o}C. The appearance and gradation curve of WGC are presented in Fig. 4.



(a) Appearance of WGC (b) Gradation curve of WGC

Fig. 4 Characteristics of WGC

2.2 Research Framework and mix design

This study focused on evaluation of the mechanical and durability properties of architectural mortars incorporating different SCMs. The test variables included the types and contents of SCMs (FA, BS, MK and GP). For the mechanical properties, the architectural mortars were prepared with WC replaced by GP, FA, BS at 20% and 50% (respectively indicated by GP20, GP50, FA20, FA50, BS20 and BS50, where CON indicates the control prepared with only WC). Due to the high specific surface area of MK, only 5% and 15% of WC were replaced by MK (named as MK5 and MK15). The durability properties studied included drying shrinkage, ASR, high temperature exposure resistance and resistance to acid attack and were evaluated on the mortars prepared partial replacement of 20% of cement by BS, FA, and except for MK used at 5% or 15%. The framework of this study is shown in Fig. 5.

The cement mortar mixes containing the SCMs were prepared at a water-to-binder of 0.4 and aggregate-to-binder ratio of 2.0. The mix proportions of the prepared cement mortars are given in Table 2. A superplasticizer (SP) without the presence of chloride was used to achieve the desired workability with flow values more than 230 mm. All the mixtures were mixed thoroughly before the fresh mortars were cast into steel molds. Each mold was put on a vibrating table for 15s for compaction. The specimens were demolded after 24 hours.

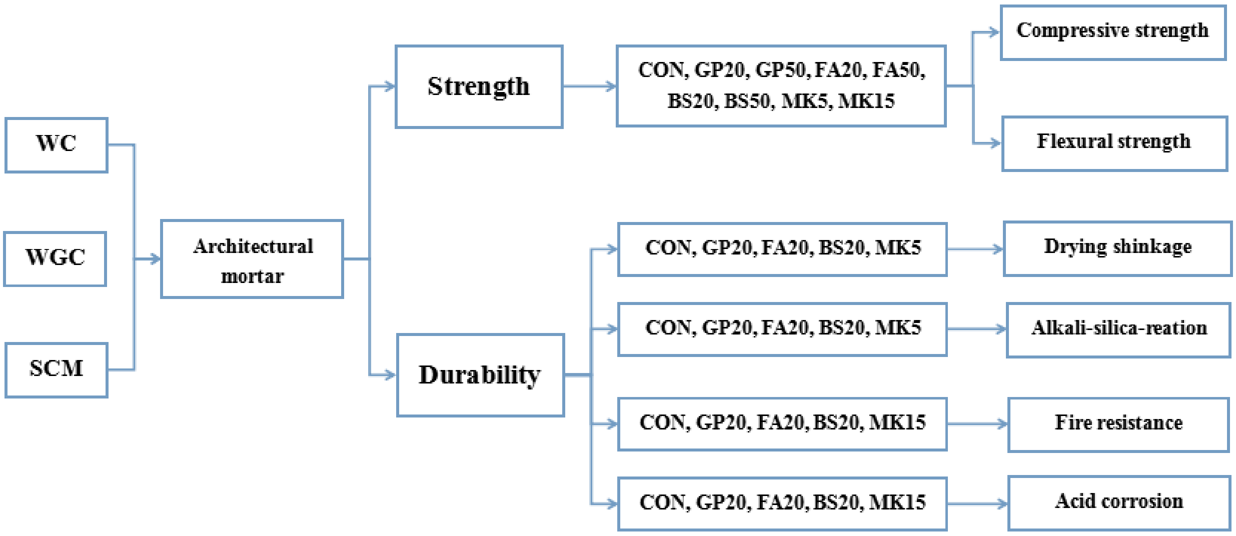


Fig. 5 Research framework

Table 2

Mix proportions of different mixtures.

Mix	WC (kg/m^3)	GP (kg/m^3)	FA (kg/m^3)	BS (kg/m^3)	MK (kg/m^3)	WGC (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)
CON	706							4.24
GP20	565	141						4.24
GP50	353	353						4.24
FA20	565		141					4.24
FA50	353		353			1412	283	4.24
BS20	565			141				4.24
BS50	353			353				4.24
MK5	671				35			5.65
MK15	600				106			8.47

Note: The numbers in the mix designation correspond to the percentage of SCMs present in the binder. For example, FA20 means that the cement mortar was prepared with FA (20%) and the rest was cement. CON stands for the control mix with 100% WC.

2.3 Test methods

2.3.1 Heat of hydration

The heat of hydration test was used to investigate the effect of different SCMs incorporation on the hydration of the cement. During the test, up to 20% by weight of cement was replaced by SCMs. The cement and SCMs were firstly mixed in an insulated container thoroughly, then water was added at a 0.4 water to binder ratio to the paste for 2 minutes. Shortly afterward, the containers were sealed and put into the isothermal calorimeter. After 7 days, the measurement was stopped and the data were analyzed.

2.3.2 Mechanical properties

A three-point flexural strength test in conformity with ASTM C348 [31] was performed at 7 and 90 days of water curing. The specimens with the size of 40 mm × 40 mm × 160 mm were tested. The equivalent compressive strength test was carried out according to ASTM C349 [32], which was determined using a compaction machine with a maximum capacity of 3000 kN. The load was increased at a rate of 0.6 MPa/s until failure.

2.3.3 Durability

2.3.3.1 Drying shrinkage

The drying shrinkage test was carried out in accordance with a modified British Standard (BS ISO, Part 8: 1920) method [33]. The initial lengths of three prisms with dimension of 25 × 25 × 285 mm were measured after demolding at 24 hours casting. Then the specimens were immediately transferred to a drying chamber at 25 ^{o}C and 50% relative humidity. Further measurements were carried out at the age of 1, 3, 7, 14, 28, 60, 90 days.

2.3.3.2 ASR

Expansion caused by ASR was measured on mortar prisms (25 × 25 × 285 mm) according to ASTM C1260 [34]. A zero reading was taken after storing the prisms in distilled water at 80 ^{o}C for 24 hours. The bars were then transferred and immersed in 1 N NaOH solution at 80 ^{o}C until the testing time. The expansion of the mortar bars was measured within 15 ± 5 s after they were removed from the 80 ^{o}C water or alkali storage conditions by using a length comparator. The measurements were conducted at the storage duration of 1, 4, 7, 14, 21 and 28 days.

2.3.3.3 Resistance to high temperature

The mixes of CON, GP20, FA20, BS20 and MK15 were selected to evaluate the high temperature exposure resistance of cement mortar containing the SCMs. For each mix, twelve cubes (50× 50× 50 mm) were cast and then cured under standard conditions. After 90 days of curing, three cubes were tested for initial compressive strength. The other nine cubes were transferred to the oven at 105 ^{o}C for 24 hours to remove moisture before the mortars were subjected to heating at high temperatures. Then, the samples were heated at a rate of 5 ^{o}C/min to reach the specific temperature (300 ^{o}C, 600 ^{o}C, and 800 ^{o}C, respectively) in an electric high temperature furnace. After a 2-hour holding period, the furnace was switched off and the door was open, the samples was left in the furnace until then the residual compressive strength of samples were tested. Based on the results of initial and residual compressive strength of mortar samples, the residual strength index (RSI) was calculated by the following equation:

$$RSI = S_r / S_i \times 100\% \quad (1)$$

Where S_r is the residual compressive strength of mortar after heating at 300 ^oC, 600 ^oC, and 800 ^oC; S_i is the initial compressive strength of mortar after 90 days of curing.

2.3.3.4 Acid resistance

The acid resistance was studied by immersing the specimens in a sulphuric acid solution in accordance with ASTM C 267 [35]. After 90 days of curing, three prisms (40 × 40 × 160 mm) were removed from the water tank and the initial weight was recorded under saturated surface dried (SSD) condition, then all samples were immersed in a 3% H_2SO_4 solution. The measurements of mass changes of the samples at the SSD condition were taken weekly until 8 weeks. The acid solution was renewed every two weeks to maintain a stable acid concentration. The cumulative percentage mass change of each specimen was determined by the following formula:

$$\text{Cumulative mass change} = (M_t - M_i)/M_i \times 100\% \quad (2)$$

Where M_t is the mass at time t; M_i is the initial mass before immersion in sulphuric acid.

2.3.4 Microstructure test

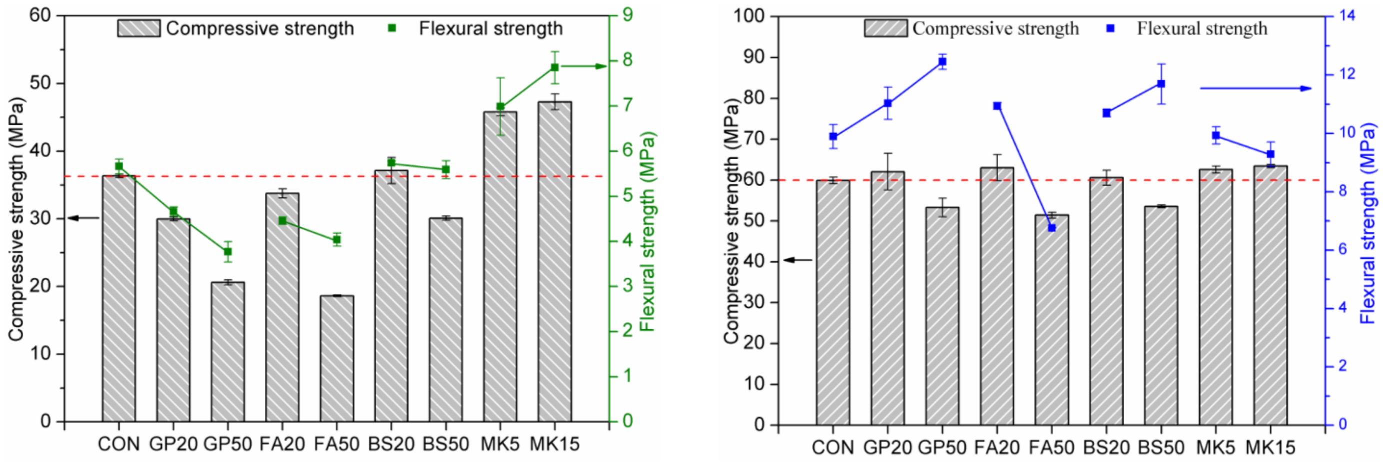
The samples for the morphology observation were collected after the ASR expansion test. The mortar specimens were broken up into fragments and stored in sealed bottles which were filled with anhydrous ethanol. After at least of a week of immersion, the small pieces of mortar were transferred to an oven at a constant temperature of 105 ^oC to remove the residual ethanol. Morphological characterization plus composition analysis were carried out on the fractured surfaces by using scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX).

3 Results and discussion

3.1 Mechanical properties

Fig. 6 presents the influence of SCMs on the compressive and flexural strength of the cement mortars. At the early age (see Fig. 6a), the development of compressive strength for all the mortars are consistent with that of flexural strength. 20% replacements of cement by GP or FA resulted in a reduction in strength, while the inclusion of 5% or 15% MK into the mortar brought about a distinct improvement in strength. For the case of mortar containing 20% BS, a comparable strength is shown in comparison with the control mortar.

This reveals that the reactivity of these SCMs at the early age follow such a sequence: MK>BS>FA>GP. This may be partly due to the fact that the MK and BS had smaller particle sizes than the cement (as shown in Fig. 1), thus the filling effect could play an important role in enhancing the early strength [36,37]. On the other hand, the smaller particles also facilitated the pozzolanic reaction to densify the microstructure [36,37]. However, the experimental results also show dramatic drops in strength when 50% GP, FA or BS was incorporated into the mortar, this was probably attributed to the dilution effect.



(a) 7 days of curing (b) 90 days of curing

Fig. 6 Mechanical properties of mortars with different SCMs

After 90 days of curing, it can be observed that when cement was replaced with SCMs at up to 20% level, the blended cement mortars showed a comparable or even higher compressive strength than that of the control mortar (as shown in Fig. 6b). In particular, although the particle size of GP was larger than FA and BS, the substitution of cement with 50% of GP led to a satisfactory compressive strength compared to FA and BS blended mortars, which reached to about 90% of the strength value of the control mortar. Therefore, the results suggest that the reactivity of GP can compete with the traditional pozzolana after prolonged curing. Based on the composition of GP (Table 1), it is believed that high content of amorphous SiO_2 in GP may be responsible for its high reactivity.

For the 90 days flexural strength, it can be noticed that there is an increase in flexural strength with the increasing GP content while an opposite trend was observed for the mortars prepared with FA. This may be due to the difference in morphology between the GP and the FA. As shown in Fig. 3, the FA has small spherical particles, while the GP is angular in shape with high aspect ratios. According to the study of Dey and co-workers [38], the addition of 15% micro-fibers with an average particle size of 55 µm into cement mortar was far more effective for flexural strength enhancement. It is expected therefore that the GP with high aspect ratios could play the same role as micro-fibers in increasing the flexural strength. Confirming result was obtained in the case of BS blended mortar, the flexural strength of the cement mortar incorporating 50% BS surpassed that of the control mortar, revealing that the inclusion of BS with irregular shape and sharp edges could benefited the flexural strength. For the mortars prepared with MK, similar values of flexural strength were obtained compared with the control group. And, with the increase of the MK content from 5% to 15%, a slight decrease in the flexural strength was noticed. This indicates that addition of MK as a cement replacement in cement mortar has a positive effect on the early strength, whereas the inclusion of up to 15% MK has little effect on the strength enhancement of the cement mortar. Similar finding was observed by Poon et al. [11], who showed little strength gain in cement paste for MK replacement level in excess of 10%.

3.2 Drying shrinkage

Fig. 7 shows the drying shrinkage values of the mortars containing various SCMs up to 90 days. Regardless of the types of SCMs, the drying shrinkages of mortar increased with the age of drying and most of the shrinkage took place during the early ages. This is directly related with the reduction in volume resulting from the intense chemical reaction between the reagent and water. The degree of hydration results in Fig. 8 supports this explanation, showing that the cumulative heat of hydration increased sharply at the beginning and then tend to slow down. In addition, the removal of the physically adsorbed water to the environment caused further shrinkage.

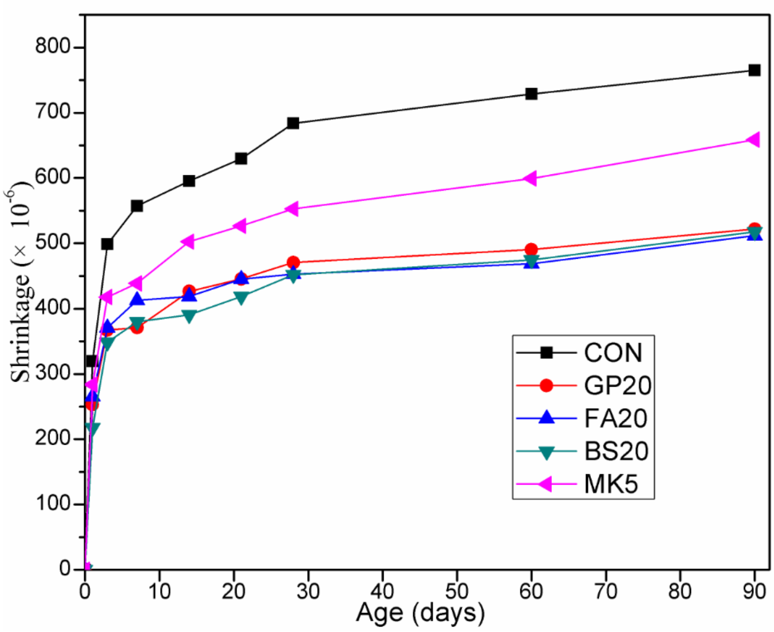


Fig. 7 Effect of different SCMs on shrinkage of glass-based mortars

However, it can be clearly observed that the cumulative drying shrinkage for the control mortar is much higher than those mortars prepared with SCMs. For the mortars containing 20% GP, FA, BS, the dilution effect played an important role in mitigating the drying shrinkage. This is verified by the results of the heat of hydration test (Fig. 8). The inclusion of GP, FA, BS not only led to retarded hydration process, but also resulted in higher effective water-to-cement ratios due to their vitreous characteristics. It is of general acceptance that the autogenous shrinkage decreased with increasing water-to-cement ratio [39,40]. Therefore, the reduction of total shrinkage in the mortars incorporating GP, FA, BS can be attributed partly to the reduced autogenous shrinkage.

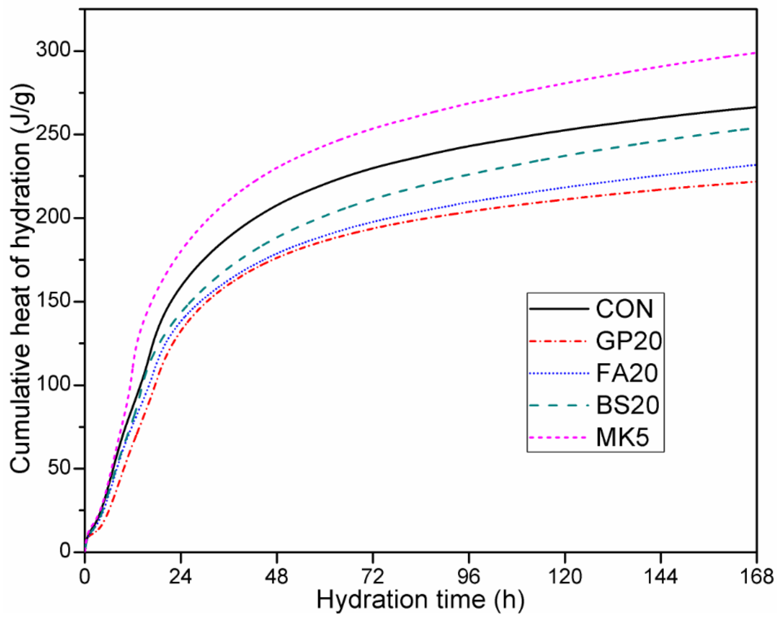


Fig. 8 Cumulative heat of hydration of cement pastes with different SCMs

When MK was used to replace cement at the level of 5%, it can be seen that the hydration process is accelerated (Fig. 8) because of its high pozzolanic reactivity. An increase in hydration heat is expected to produce a larger amount of C-S-H, which is commensurate with the strength development of MK blended mortar at 7 days of curing (as shown in Fig. 6a). The higher degree of hydration and pozzolanic reaction consumed a significant amount of free water leading to a lower amount of evaporation water. Therefore, the decreasing of water loss in small capillary pore and adsorbed water from calcium silicate hydrate (C–S–H) would contribute to mitigating the drying shrinkage due to the reduction of capillary tension. Furthermore, the incorporating of MK can also strengthen the mortar, which could reduce its deformability. For these reasons, it is noticed that the effect of replacing cement by MK led to a reduction in total shrinkage of the mortar remarkably. The results obtained are also in agreement with the test results of Brooks and Johari [41].

3.3 ASR

Fig. 9 shows the effect of different SCMs on the ASR expansion of glass-based mortars. It is intuitive to find that the control mortar containing 100% of glass aggregates experienced severe expansion and the expansion at 14 days was much higher than the deleterious expansion limit (0.1%). However, the inclusion of SCMs can successfully suppress the expansion due to ASR. It is widely accepted that FA, BS and MK have positive effects on mitigating ASR [42-44]. Several reasons are mainly responsible for the reduced ASR expansion:

1. Reduction of pore solution alkalinity due to the dilution effect [45] and reduced ion diffusion coefficient [46].
2. Production of C-S-H with low Ca/Si ratios which has capacity to absorb a significantly higher quantity of alkalis than normal C-S-H [43].

3. Reduced permeability of the cement paste reduces the migration of alkalis towards the reactive aggregates [42].
4. Improved strength developed by the addition of SCMs provides higher resistance to the expansive stress produced by ASR [46].

In this study, it is interesting to note that the substitution of GP for cement can effectively suppress the detrimental expansion when aggregates were fully replaced by WGC. This means there may be two antagonistic effects occurring in the mortar containing different particle sizes of glass. The coarser WGC resulted in degradation due to excessive expansion and the finer GP led to improvement of mechanical property. This observation is supported by the conclusion of Idir et al. [47], who showed that the glass particle with size below a critical diameter (1 mm) was not deleterious in terms of ASR, but those above 1 mm would cause significant expansion. Meanwhile, it is worth to note that the GP has a comparable ability to suppress ASR to traditional SCMs (FA, BS and MK) although the GP contains a large amount of alkalis (see Table 1). Therefore, the satisfactory inhibition effect of GP on ASR encourages its promising application in the production of architectural mortars by combining the use of WGC and GP.

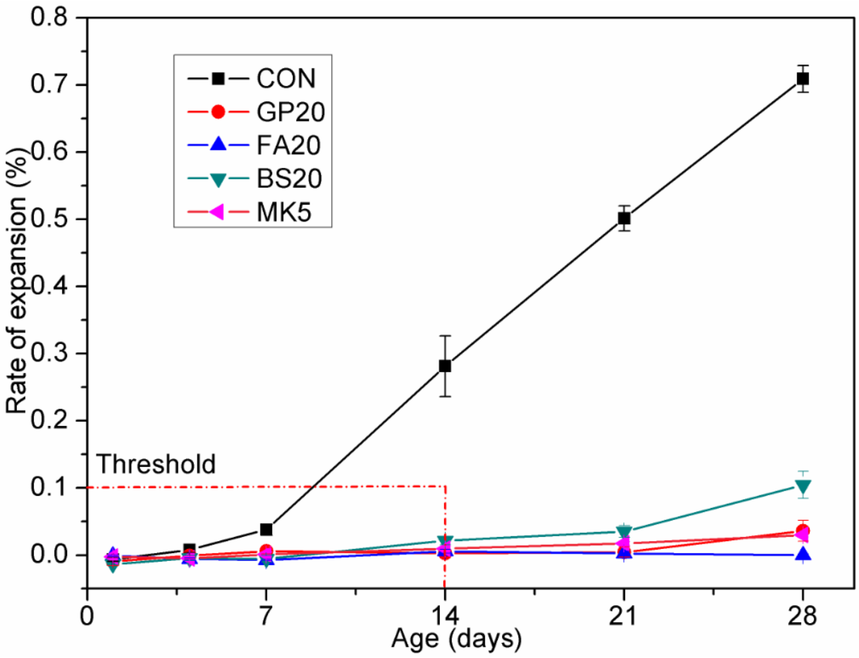


Fig. 9 ASR expansion of mortars with different SCMs

In order to explain the effectiveness of GP against ASR, the microstructure of the GP blended mortar was further investigated by the mean of SEM-EDX. Fig. 10 shows the morphological and compositional characteristics of the control mortar and the GP blended mortar after ASR expansion measurements. It is clearly seen that visible cracks are present in the vicinity of the glass surface (Fig. 10a). Apparently, the expansion caused by ASR was responsible for the cracking damages of the control mortar. Based on the EDX results of zones 1 and 2 (Fig. 10c), it can be noticed that the glass aggregate (zone 1) has low Na/Si and Ca/Si ratios due to the high content of silica in glass. While the surrounding matrix (zone 2) exhibits by far much higher Na/Si and Ca/Si ratios than the glass aggregate. Compared to the typical C-S-H [48], the paste layer formed adjacent to the glass aggregate is low in calcium and high in alkali. Therefore, it can be inferred that these alkali-calcium-silicate products are the expansive ASR gel causing microcracking of the surrounding cement paste by imbibing water. With respect to the low Ca/Si (0.634) reaction rims, the combination of high concentration of silicate released by glass aggregates dissolution and locally low availability of Ca ions or Ca-rich C-S-H at the glass surface probably formed the deleterious ASR gels. This explanation is supported by the work of Maraghechi et al. [49], which reported that a dense and protective layer with high Ca/Si (1.84) formed on the surface of glass provided a diffusion barrier against the aggressive ions (such as OH^-, Na^+ ions), while the low Ca/Si (0.54 to 0.78) layer with a high porosity and weak bond to the glass substrate could not protect the glass from further dissolution.

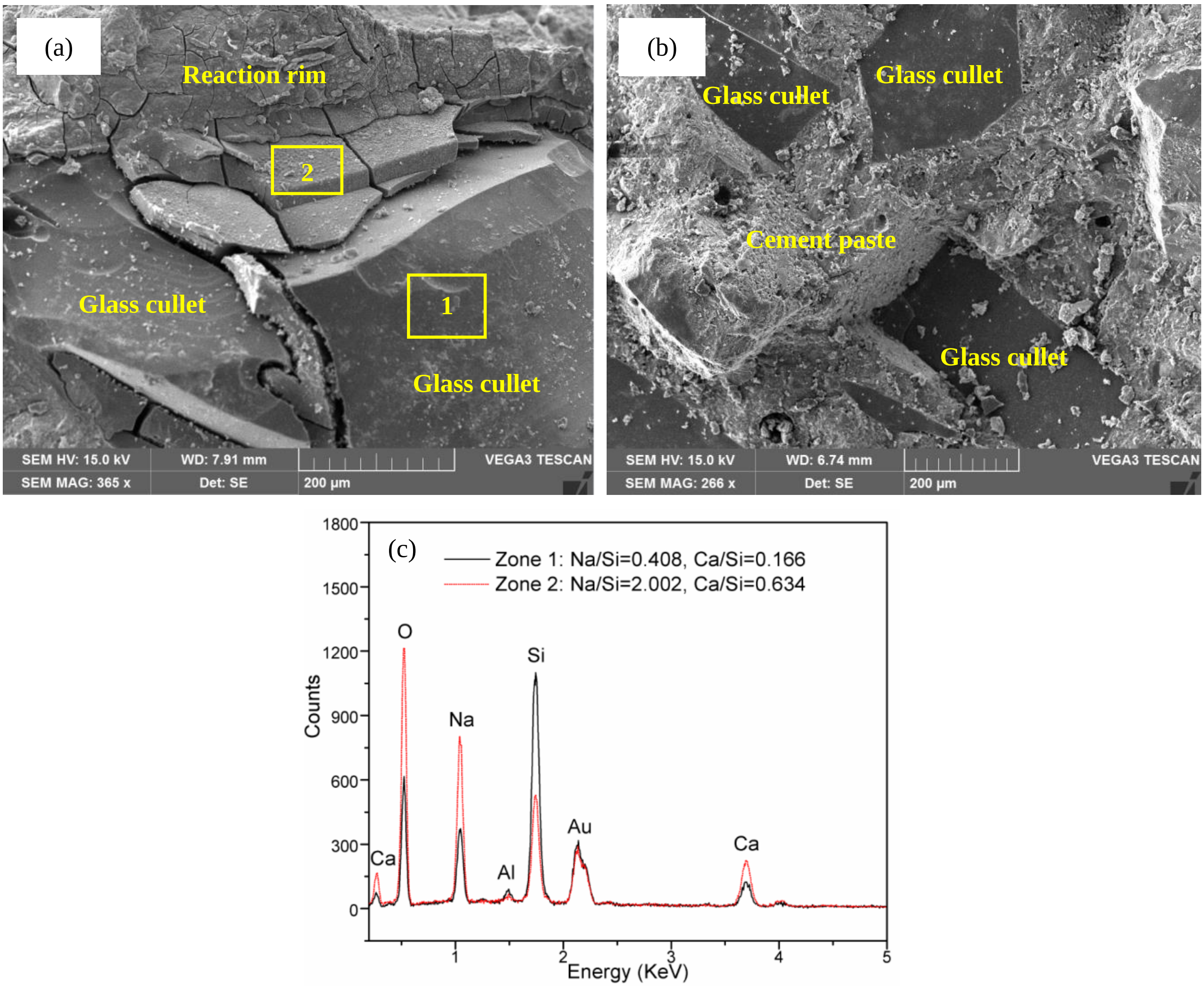
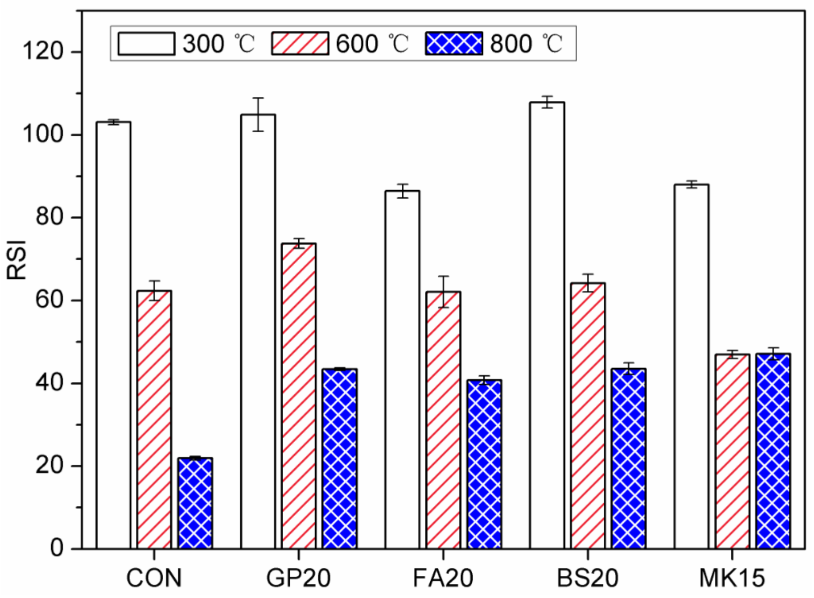


Fig. 10 SEM images and EDS spectrums of mortars with and without GP (a) ASR damage in control mortar (b) absence of ASR cracks in GP blended mortar (c) compositions of zones 1 and 2.

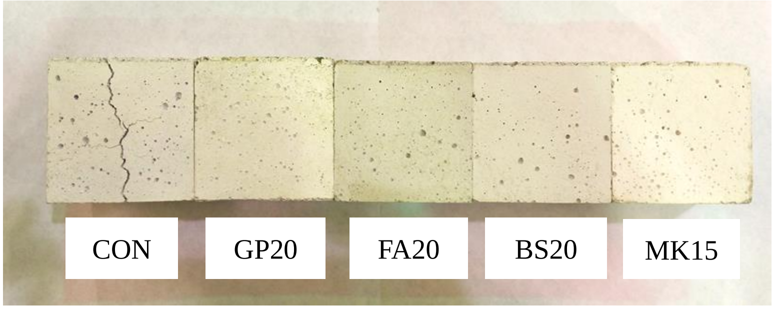
On the contrary, no obvious ASR gel could be identified in the case of GP blended mortar (see Fig. 10b), which is a strong evident that the addition of GP could suppress the ASR expansion. According to the findings of Shi et al. [50], GP consumed more alkalis and free CH in solution to form a sodium-calcium-silicate hydrate gel, leading to lower expansion around the reactive aggregates. Another possible reason for GP inhibiting the ASR is the refinement of pore structures due to the pozzolanic reaction of GP [51] which reduced the mobility of alkalis. In addition, our previous study [52] revealed that the inclusion of fine GP in the glass-based mortar improved the interfacial transition zone (ITZ) between the glass aggregates and the cement paste. As known, the ASR deleterious gels are predominantly localized on the periphery of the reactive aggregates. Therefore, it is envisioned that the densified ITZ would reduce the penetration of aggressive alkalis and dissolved silicate ions, and hence restrained the development of the swelling gel.

3.4 Resistance to high temperature

The residual strength index (RSI) of the mortar specimens are shown in Fig. 11(a). Irrespective of SCMs species used, severe reductions in strength are observed as the temperature was raised from 300 ^{o}C to 800 ^{o}C. The decomposition of the main hydration products (calcium hydroxide and C-S-H) in the hydrated cement paste is mainly responsible for the decrease in strength [53]. A close examination of strength values at 300 ^{o}C indicates that the RSI of CON, GP, BS blended mortars exceed 100% and are higher than that of FA and MK blended mortars. This reveals that the strengths of the CON, GP, BS blended mortars were enhanced after exposure to 300 ^{o}C, while the strengths of the mortars prepared with FA and MK were reduced. For heating up to 300 ^{o}C, two opposite effects need to be taken into consideration. One is the strengthening effect caused by the evaporation of interlayer water, thus making the mortar mixes more compact as a result of greater Van der Waal’s forces between the C-S-H layers [54]. The other is the detrimental effect due to the dehydration of ettringite, calcium carboaluminate hydrates and part of C-S-H [55], which leads to increase in porosity in the hardened cement paste. For CON, GP, BS blended mortars, the hardening effect played a more important role and compensated for the loss of strength. Dehydration of the aluminate hydrates (rich aluminate phases in FA and MK, see Table 1) and C-S-H became the predominant influence on the strength reduction for the mortar containing FA or MK.



(a) Residual strength index



(b) Appearance of mortars subjected to 800 ^{o}C

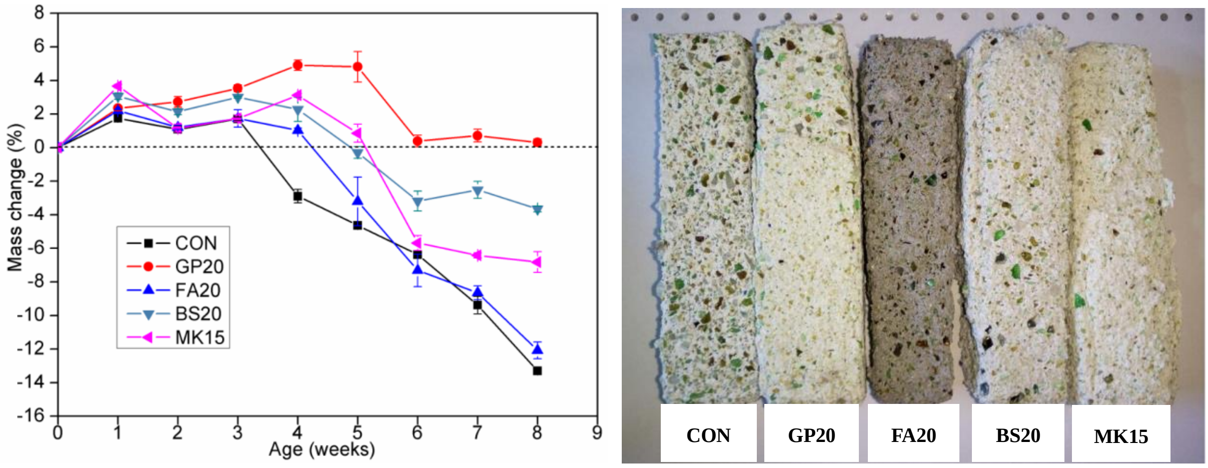
Fig. 8 Fire resistance of mortars with different SCMs

As the specimens were exposed to 600 ^{o}C, the strengths dropped significantly. However, the GP blended mortar performed the best amongst all the mixes. According to the work of Ling et al. [56], as the temperature approached the glass transition temperature (at 560 ^{o}C) of soda lime glass, a transformation behavior of glass in the matrix was helpful to fill up some pores and micro-cracks induced by the high temperature. Therefore, it is believed that the beneficial effect of fine glass particles was more pronounced in enhancing the RSI. On the contrary, the RSI of the MK blended mortar is lower than the other mortars with and without SCMs. This is because the addition of MK significantly densified the pore structure of the mortar, which resulted in thermal cracks due to the buildup of vapor pressure [57].

At 800 ^{o}C, all the mortars showed severe deterioration in strength because of the breakdown of C-S-H gel and difference in thermal expansion coefficients between the cement paste (typical value of 15-20×10^{-6}/ ^{o}C [58]) and the soda-lime glass cullet (7-9×10^{-6}/ ^{o}C [59]). The average RSI is 21.9% for the control mortar, but in the cases of the mortars prepared with GP, FA, BS, MK, the respective RSIs are 43.4%, 40.8%, 43.5% and 47.1%, which are approximately two times higher. This indicates that the inclusion of SCMs improved the high temperature exposure resistance of the glass-mortar at 800 ^{o}C. The phenomenon might be partially replacing cement with SCMs reduced the thermal expansion coefficient of the cement paste matrix [58], which was beneficial for mitigating the thermal mismatch between the cement paste and the glass cullet. As shown in Fig. 11(b), the control mortar experienced extensive cracking and spalling after exposure to 800 ^{o}C, while no visible cracking and spalling were present in all the SCM specimens.

3.5 Resistance to acid attack

Fig. 12 shows that the effect of various SCMs on the chemical resistance of the mortar specimens after immersion in sulphuric acid solutions for eight weeks. As seen in Fig. 12a, all the mortars exhibited initial gains in mass in the early weeks, which is consistent with the results observed by O'Connell et al. [60]. This can be probably attributed to the formation of additional ettringite and gypsum on the surface of the mortars [61]. However, after one month of immersion, the control mortar suffered dramatic rapid mass losses until the end of the testing period. Due to the general etching and dissolution of the hydration products in the acid solutions, sulphuric acid could be neutralised by reacting with the alkali hydration products (e.g. calcium hydroxide, C-S-H gel) in the matrix to form gypsum and ettringite. These nearly insoluble compounds with low strength and larger volume resulted in internal stresses and the formation of cracks due to expansion. Thus, the mortar may ultimately disintegrate [13, 62].



(a) Mass change (b) Appearance of mortars after acid attack

Fig. 12 Acid corrosion of mortars with different SCMs

For the FA blended mortar, the sulfuric acid exposure results in severe degradation of the mortar. And the value of cumulative mass loss was quite close to that of the control mortar. This result is in agreement with those reported by others [63,64], who mentioned that a partial replacement of cement by FA could not effectively prevent the acid-type deterioration. In the case of mortar containing MK, a much lower mass loss was of 6.8% was experienced (mass loss of the control specimen was 13.3%), indicating the enhancement in acid resistance of mortar by incorporating MK. Hewayde et al. [65] attributed this behavior to the formation of calcium aluminate hydrates (C_2ASH_8, C_4AH_{13}, C_3AH_6) in the MK modified specimens, which were believed to be more chemically stable in highly acidic environment than calcium silicate hydrates. Fig. 12a also shows that the use of BS and GP as partial replacement of cement significantly reduce both the rate and amount of mass loss of the mortars in comparison with that of the control mortar. In particular, the least mass loss was achieved by the GP blended mortar. This is mainly because the glass with a vitreous structure (as seen in Fig. 3) was good in acid resistance [66]. Furthermore, GP particles with high aspect ratios could also act as crack-arresters in the mortar, inhibiting internal crack propagation. This is indirectly supported by past study results on using micro glass fibers in concrete to improve sulfate resistance [67].

The appearance of the mortars after 8 weeks of exposure to the acidic environment are presented in Fig. 12b. The appearances of the samples surface are consistent with the mass loss results. The positive influences of MK, BS and GP on sulphuric acid attack are very prominent although a lack of cohesion and spalling occurred at the edges and corners of the mortars. The decalcification of C–S–H gel was responsible for the decomposition due to the absence of free calcium hydroxide when the pozzolanic mortars were exposed to the sulfuric acid environment [68].

4 Conclusions

This work investigated the effects of partially replacing cement with SCMs on the mechanical and durability properties of recycled glass architectural mortars. In reviewing and analyzing the experimental results presented above, the following conclusions can be drawn:

1. At a curing age of 7 days, the glass-based mortars prepared with FA or GP had lower strengths than the control mortar. However, the addition of 5% or 15% MK significantly improved the early compressive and flexural strength of the glass mortars. After 90 days of curing, the replacement of 20% of cement by the SCMs resulted in a comparable or even higher compressive strength than the control mortar.
2. For the case of the GP blended mortar, the inclusion of GP brought a distinct improvement in the flexural strength, which was contrary to the development trend for compressive strength.
3. The drying shrinkages of the mortars containing GP, FA, BS were much lower than that of the control mortar. The reduction of evaporation water and improvement of strength might decrease the drying shrinkage as 5% of MK was used to replace cement.
4. The deleterious ASR gels with high Na/Si and low Ca/Si ratios were observed on the surface of glass cullet, which resulted in severe expansion for the glass-based mortar. The introduction of SCMs could inhibit the ASR expansion for the mortar prepared with 100% glass aggregates.
5. The use of SCMs as cement replacements improved the resistance of the glass-based mortar to elevated temperature exposure. This beneficial effect was related to the fact that partially replacing cement with SCMs mitigated the thermal mismatches between the cement paste and the glass cullet.
6. Compared to the control mortar, the sulfuric acid resistance of the glass mortar could be improved significantly by the incorporation of GP, BS and MK. The FA glass-based mortar still had poor resistant to H_2SO_4 attack, while the mortar containing 20% GP had the best resistance against the sulphuric acid attack.
7. The good technical results achieved shows that the inclusion of GP could effectively improve the strength

and durability performance of glass-based architectural mortar. Industrial production of architectural glass mortars by the combined use of waste glass cullet and GP can be developed to maximize the recycling of waste glass in cement based materials.

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