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Use of waste glass in alkali activated cement mortar

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HIGHLIGHTS

- An alkali-activated cement (AAC) mortar containing waste glass is developed.
- The addition of glass cullet and powder in AAC mortar improves the workability.
- The glass-based AAC mortar has good strength and fire resistance performance.
- Combined use of glass powder and cullet in AAC mortar for non load bearing partitions is feasible.

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ABSTRACT

This paper presents a study on alkali activated cement (AAC) mortar produced with waste soda-lime-silica glass. The waste glass was used simultaneously as a precursor and fine aggregates in the alkali activated fly ash-slag mortar. The influences of waste glass in cullet and powder forms on workability, compressive and flexural strengths, fire resistance of the AAC mortar were investigated. The experimental results showed that the workability was gradually increased as the replacement level of natural sand by glass cullet was increased, and it was significantly improved with decreasing aggregates-to-binder ratios. The mechanical properties data indicated that the compressive strength was reduced as the glass cullet content increased. However, for the flexural strength, the optimum percentage of glass cullet replacement was 50%. Due to the low reactivity, a reduction in strength was observed when the glass powder was used to replace the fly ash and slag. Nevertheless, in terms of fire resistance, the incorporation of glass cullet could improve the resistance of the AAC to high temperature exposures (800 °C). In particular, the AAC mortar prepared with the glass powder as a precursor exhibited remarkable resistance to high temperature. The use of waste glass in AAC material was feasible from the mechanical properties and fire resistance points of view.

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1. Introduction

1.1. AAC material

It is generally known that the Portland cement industry produces 5–8% of the anthropogenic CO_2 [1] emission, which contributes significantly to the increase in greenhouse gas. Therefore, there is a need to develop alternate concrete binders other than Portland cement. According to previous studies [2,3], the properties of alkali activated cement (AAC) are comparable or even superior to Portland cement. A number of studies have demonstrated that the AAC exhibits high compressive strength [4,5], excellent sulphate and seawater resistance [6,7], good performance in the environment of acid corrosion [8,9], good resistance to chloride penetration [10] and freeze–thaw cycles [11,12]. These advantages are attributed to the special nature of the hydration products and the lower porosity and permeability of the AAC. Due to its high strength and excellent durability properties, the AAC mortar/concrete has potential applications in a range of applications. In Australia, pre-mixed alkali-activated concrete has been commercialized for the construction of a bridge upgrade project [13]. Also, AAC precast footpath panel segments produced from blends of fly ash, slag and alkaline activators has been successfully demonstrated in an industrial application [14]. In Ukraine, alkali activated blast furnace slag cement has been used in the construction of apartment buildings, road sections, pipes, drainage and irrigation channels, flooring for dairy farms, precast slabs and blocks [15]. Another known application for AAC was in the production of railway sleepers. Spain led the development of pre-stressed

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steam-cured sleepers based on alkali activated fly ash [16]. Basically, this AAC material can be produced through the alkaline activation of aluminosilicate materials such as coal fly ash (FA) and ground granulated blast furnace slag (GGBS). But in Hong Kong, there is no any steel plants for producing GGBS and almost all FA has already been used up by the construction industry.

1.2. Waste glass

Waste glass bottle (soda-lime silicate glass) is a significant solid waste type in the municipal solid waste (MSW) stream in Hong Kong. Due to the lack of a glass manufacturing industry, the current recycling rate of waste glass bottles is low (less than 10%) [17]. By contrast, based on the European Container Glass Federation [18], 11.6 million tons of waste glass bottles were collected in 2014 and the glass recycling rate has reached 74% in Europe.

The Hong Kong SAR government plans to promote the recycling of waste glass beverage bottles in Hong Kong by introducing a producers' responsibility legislation to be implemented in late 2017. It has been estimated that about 50 kt/annum of waste glass beverage bottles will be collected after the scheme is implemented. There is an urgent need to find practical outlets for the collected waste glass.

Previously, Poon and co-workers in the Hong Kong Polytechnic University have spent much effort on developing practical methods for recycling waste glass cullet as fine aggregates in concrete blocks or mortar production [19–29]. The results indicated that the incorporation of glass cullet as natural fine aggregates could reduce the drying shrinkage [19,20] and water absorption due to the non-absorbent nature of glass [20]. The replacement of river sand by glass cullet enhanced the fresh properties of concrete since the glass particles had smooth surfaces and low water absorption [21]. Also, the addition of glass cullet could improve the resistance to acid attack [22] and high temperature exposures [23]. Furthermore, the use of glass cullet as aggregates could reinforce photocatalytic activities because of its light transmittance property [24]. Based on our past research, it was demonstrated that it was feasible to use the glass cullet as partial substitution of fine aggregates in producing cement based building materials. And several practical and potential applications have been developed such as eco-glass concrete paving blocks [25], glass-based self-compacting concrete [26] and architectural mortars [27,28]. In particular, the eco-glass concrete paving block technology developed has been commercially transferred to the local block manufactures and the blocks have already been put into successful uses at various different sites in Hong Kong [29].

Additionally, after the further grinding to the glass cullet, the produced waste glass powder (WGP) with proper particle size can be used as a Portland cement replacement since it has been proven in many studies [30–34] that the WGP has pozzolanic activities. Therefore, efforts have been made in the concrete industry to use WGP as a supplementary cementitious material [33–35] due to there are large quantities of amorphous silica and calcium in the glass. Also, attempts have been made to use WGP as an alkali-silica-reaction suppressor although it has a high alkali content [36–38]. Recently, more studies have also pointed out that the finer glass powder showed significantly improved ability to enhance durability characteristics of concrete products [39,40].

During the past few years, there has also been increasing research efforts [41–50] directed to recycle WGP into AAC taking advantage of its chemical instability in alkaline environments and high content of silica-rich glassy phase. These WGPs include waste cathode ray tubes glass [41], post-consumer window glass [42,43], waste solar panel glass [44], spent linear fluorescent lamps [45] and waste LCD glass [46]. However, there is a lack of information on the alkali activation of soda-lime silicate glass [47–50]. It is expected that the high alkali and silicon contents of soda-lime silicate glass would facilitate the alkali-activation reaction [48,51] making it an attractive material for partial replacement of FA or GGBS in the production of AAC. Furthermore, it is also believed that using waste soda-lime silicate glass cullet to partially replace natural aggregates in the AAC is feasible.

1.3. Research significance

This research will contribute to the environmental improvement and conservation of Hong Kong by recycling waste glass and develop new technologies on waste glass recycling. Waste glass was reused in two forms: (1) using waste glass powder to replace FA and GGBS in AAC mortar, (2) using the waste glass cullet to replace natural aggregates for producing AAC mortar. Therefore, this study focused on developing a novel way to maximize the re-utilization of waste soda-lime silicate glass both as a precursor and aggregates for producing AAC materials. It is anticipated that recycled glass would constitute about 60% by mass of the novel construction product developed. One intended use of the products can be precast partition wall blocks with enhanced fire rating performance.

2. Experimental work

2.1. Materials

The materials used to fabricate the AAC mortar were natural fine aggregates (river sand), recycled soda-lime silicate glass, FA, GGBS and an alkaline activator. Natural fine aggregates (NFA) and recycled waste glass were sourced from aggregate suppliers and waste recycling facilities in Hong Kong, respectively. The soda-lime silicate glass was crushed by the glass bottle recycler in Hong Kong to obtain suitable particle sizes for use as fine aggregates. The collected waste glass cullet (WGC) was washed to remove most of the contaminants in the waste glass. The gradation and appearance of the NFA and WGC are presented in Fig. 1a. From the gradation curves of NFA and WGC, it can be found that the WGC has a lower fineness than the NFA. The alkaline activator used in this study was a commercially available sodium hydroxide (NaOH).

For the glass powder, the WGC was furthered ground with a specified milling time (2 h) by a laboratory ball mill. Two types of commonly used mineral admixtures, i.e. FA and GGBS, were used in this study. FA was produced as a by-product during the generation of electricity from coal fired power plants. GGBS (supplied from China, a byproduct of steel production) was sourced from a commercial source. The particle size distributions of the FA, GGBS and WGP were determined by a laser scattering technique (see Fig. 2d). In addition, the surface areas (Blaine method) of FA, GGBS and WGP were determined and they were 3252 cm^2/g, 3163 cm^2/g and 1899 cm^2/g, respectively. The chemical compositions of the FA, GGBS and WGP are shown in Table 1. Scanning electron microscopy (SEM) was employed to observe the morphologies of FA, GGBS and WGP (Fig. 2). The micrographs show that the FA was consisted of many spherical particles in micrometer range, and GGBS and WGP were made up of vitreous structure with a smooth surface texture, irregular shape with sharp edges.

2.2. Mixture proportions

As a benchmark, 30% FA and 70% GGBS by mass were used as precursors in the control alkali-activated binder due to their high calcium and aluminum contents. The NFA (river sand) in the AAC mortar was replaced by the WGC at 0, 25%, 50%, 75%, 100% to

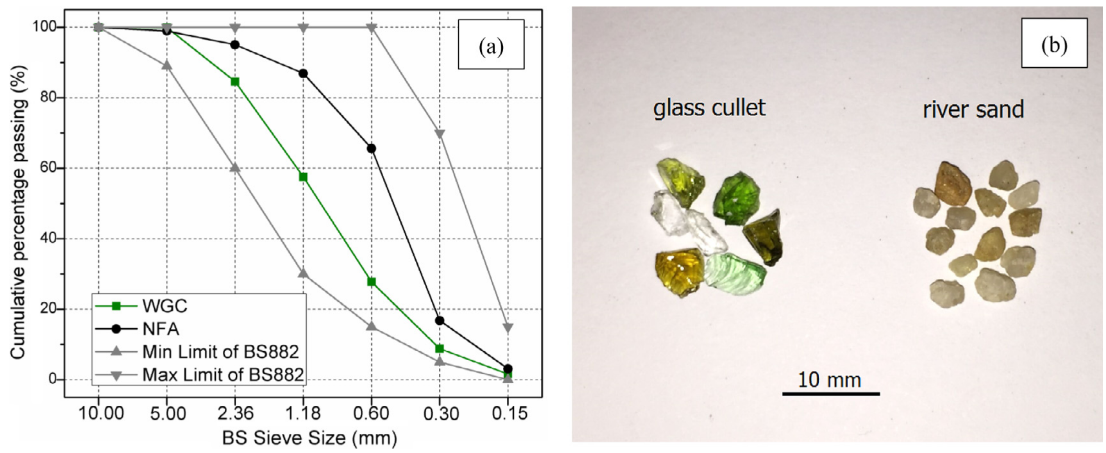

Fig. 1. Gradation curve (a) and appearance (b) of NFA and WGC.

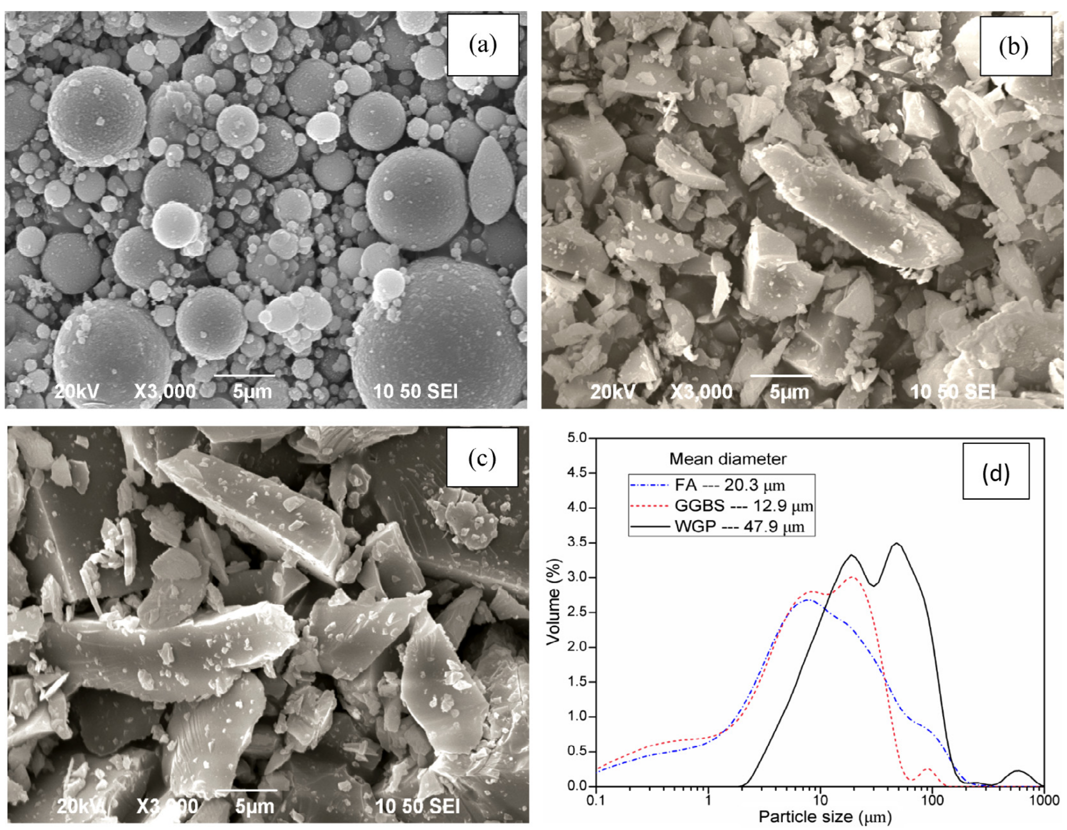

Fig. 2. Morphologies of FA (a), GGBS (b), WGP (c) and their particle size distributions (d).

Table 1
Chemical compositions of FA, GGBS and WGP (ms%).

	FA	GGBS	WGP
SiO_2	45.70	34.78	73.5
Al_2O_3	19.55	14.22	0.73
Fe_2O_3	11.72	0.27	0.38
CaO	12.27	38.38	10.48
MgO	4.10	7.32	1.25
K_2O	1.71	0.77	0.69
Na_2O	1.36	–	12.74
TiO_2	1.09	0.71	0.087
SO_3	1.82	3.12	–
$SiO_2 + Al_2O_3 + Fe_2O_3$	76.97	49.36	74.61

investigate the effects of various levels of WGC replacements on the properties of AAC mortar. In the case of AAC mortar containing 100% WGC as aggregates, 30% of WGP was further used as a replacement for FA or GGBS in the production of AAC mortar to maximize the use of waste glass.

It took two steps to prepare the AAC mortar. First, the pure sodium hydroxide was mixed with water to prepare a NaOH solution (10 M). Then, the cooled NaOH solution was introduced to the dry mixture of the precursors-aggregates until a homogeneous mixture was formed. The water-to-binder (w/b) ratio was set to 0.4. Three aggregate-to-binder (a/b) ratios (2.0, 2.5, 3.0) were taken to assess the effect of a/b on the workability, strength and fire resistance properties of AAC mortar. The procedure of fabricating the AAC mortar is shown in Fig. 3. The mix proportions of AAC mortar are listed in Table 2. A range of mixes were prepared and named based on the variations of the compositions as follows:

- M0G: NFA only used as the fine aggregates.
- M25G: 25% of NFA was replaced by the WGC.
- M50G: 50% of NFA was replaced by the WGC.
- M75G: 75% of NFA was replaced by the WGC.
- M100G: 100% of NFA was replaced by the WGC (total fine aggregates are WGC).
- M2.5: The *a/b* in the mix was set to 2.5 (total fine aggregates are WGC).
- M2.0: The *a/b* in the mix was set to 2.0 (total fine aggregates are WGC).
- MGF: The WGP was used to fully replace the FA by mass (total fine aggregates are WGC).
- MGG: The WGP was used to partially replace the 30% GGBS by mass (total fine aggregates are WGC).

2.3. Test methods

2.3.1. Workability

The workability of the AAC mortar was determined according to BS EN1015 [52]. The workability value was measured by using a mini-slump flow cone with a 100 mm internal diameter on a 250 mm flow table disc. Firstly, the mold was filled with the fresh mortar, then raised vertically to spread out the mortar on the table by vibrating the disc 15 times at a constant frequency. The spread diameters of the mortar after vibration were recorded.

2.3.2. Mechanical properties

The mix proportions of the AAC mortar for the compressive strength tests are given in Table 2. All the well mixed composites were poured into cubic molds with the sizes of 50 × 50 × 50 mm. Each mold was put on a vibrating table for 15 s for compaction. After 24 h, the specimens were demolded and kept in laboratory conditions of 25 ± 2 °C and 50 ± 5% relative humidity. After 1, 4, 7, 14, 28 and 60 days of air curing, three cubes were tested for the compressive strength by a hydraulic compression machine with a loading rate of 0.3 MPa/s. For the three-point flexural test, specimens of 40 mm × 40 mm × 160 mm size were prepared. The mixtures (M0G, M25G, M50G, M75G and M100G) were mixed thoroughly before the fresh mortars were cast into the steel molds. After 60 days of air curing, three specimens were tested for flexural strength in conformity with ASTM C348 [53].

2.3.3. Fire resistance

For the high temperature exposure test, after 60 days of curing for each mix (Table 2), three cube specimens were transferred to the oven at 105 °C for 24 h to remove moisture. Then, the specimens were heated in an electric high temperature furnace at a rate of 5 °C/min from room temperature to 800 °C. After a 2 h holding period, the furnace was switched off and the specimens were allowed to be cooled down in the furnace before the residual compressive strength were tested. Based on the compressive strength values of AAC mortar with and without exposure to 800 °C, 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 AAC mortar after heating at 800 °C; S_i is the initial compressive strength of AAC mortar after 60 days of curing (without exposure to 800 °C).

The RSI was employed in this study in order to evaluate the fire resistance of AAC mortar. A higher RSI value means a higher resistance to high temperature exposure, and vice versa.

2.3.4. Pore structures

The pore structures of AAC mortars (after 60 days of curing) before and after subjecting to 800 °C were evaluated by a mercury intrusion porosimeter (MIP, Micromeritics AutoPore IV 9500 Series). For the mortars without exposure to 800 °C, fractured samples were collected after testing the compressive strength (Section 2.3.2), and then the samples were soaked in the anhydrous ethanol for one week to exchange the water inside. Afterwards, the debris samples were dried in an oven at 60 °C for 3 days to remove the residual ethanol. For the mortar samples after exposing to 800 °C, the fractured samples were immediately kept in sealed bottles after testing the residual strength (section 2.3.3) until the MIP measurement. The MIP equipment had a maximum intrusion pressure of 207 MPa. The measured pore size was in the range from 7 nm to 150 μm. The test used the usual assumption that the pores were cylindrical and the contact angle was 140°.

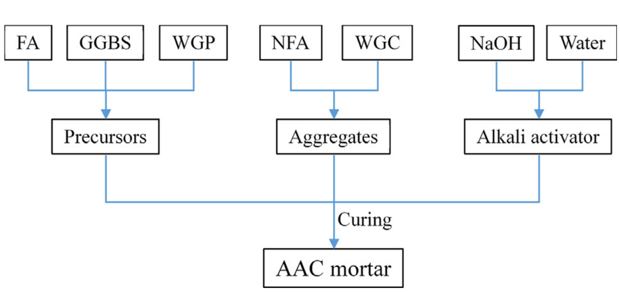

Fig. 3. Procedure of producing AAC mortar.

3. Results and discussion

3.1. Workability

Fig. 4 shows the effect of waste glass including WGC and WGP on the workability of AAC mortar. Obviously, it was found that the increasing the replacement level of NFA by WGC improved the workability of the AAC mortar (blue arrow). This behavior was also observed by Wang et al. [54] and Terro [55] in the case of ordinary Portland cement (OPC) concrete. They attributed the enhancement of workability to the inherent smooth surface and negligible water absorption of glass. Another reason may be due to the larger particle size of WGC compared to the NFA (see Fig. 1a), as a lesser amount of cement paste was needed to coat the WGC which resulted in more available cement paste to ensure higher fluidity. However, the increase magnitude in the flow value due to the replacement of NFA by WGC was not significant. In addition, no bleeding nor segregation occurred when 100% NFA were replaced by WGC. Conversely, a previous study found that there were severe bleeding and segregation in OPC concrete when 100% of the fine aggregates was replaced by the recycled glass aggregates [56]. This difference is because the alkali activated cement is fast-setting whereas OPC has slow-setting characteristics [57]. Therefore, in terms of workability, the use of waste glass in AAC materials is feasible without the concern of worsening the consistency and homogeneity.

In order to enhance the workability of AAC mortar containing 100% WGC, different *a/b* ratios were adopted to produce the desirable flow. As indicated in Fig. 4, the flow values were effectively increased as the *a/b* ratio decreased (red arrow). The improvement in workability was caused by additional cement paste was available in the AAC mortar. Furthermore, a lesser amount of WGC could reduce the impediment effect due to the edged and angular grain shapes of WGC.

Table 2
Mix proportions of AAC mortar.

Mix	Precursors (g)			Aggregates (g)		Alkaline activator (g)	a/b	w/b
	FA	GGBS	WGP	NFA	WGC	NaOH solution		
M0G	480	1120	0	4800	0	896	3.0	0.4
M25G	480	1120	0	3600	1200	896	3.0	0.4
M50G	480	1120	0	2400	2400	896	3.0	0.4
M75G	480	1120	0	1200	3600	896	3.0	0.4
M100G	480	1120	0	0	4800	896	3.0	0.4
M2.5	480	1120	0	0	4000	896	2.5	0.4
M2.0	480	1120	0	0	3200	896	2.0	0.4
MGF	0	1120	480	0	3200	896	2.0	0.4
MGG	480	640	480	0	3200	896	2.0	0.4

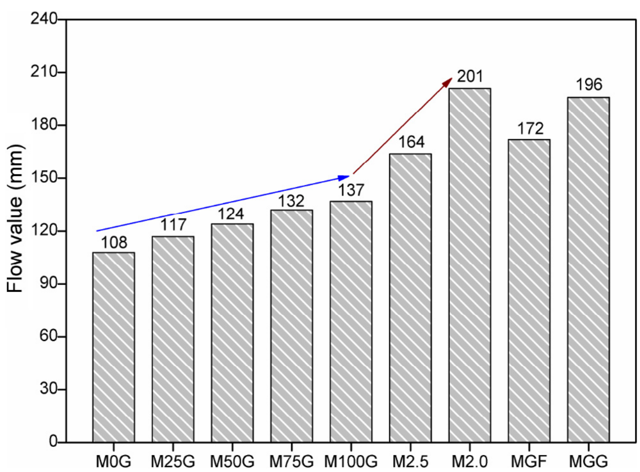

Fig. 4. Flow values of AAC mortar. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In addition, when the FA was fully replaced by the WGP in AAC mortar, a reduction of flow value was observed. This was related to the coarser particle size and irregular shape of WGP, which would reduce the mobility of the mortar. Similar results were obtained in our previous study [58]. On the other hand, it is well known that the addition of FA in OPC-based mortar or concrete would improve the workability because of the ball-bearing effect and the effect of electrical surface charges [59]. Hence, the replacement of FA by WGP resulted in a reduction in the workability. However, it can be noticed that the replacement of GGBS by 30% of WGP had only little effect on the flow value. The reason may be due to the similar morphology and structure of the WGP and the GGBS (as seen in Fig. 2). Therefore, the combined use of WGC as aggregates and WGP as a precursor in AAC mortar seems to be attractive with respect to the workability property.

3.2. Mechanical properties

3.2.1. Effect of WGC content on the strength of AAC mortar

Fig. 5 shows the development of strength for the AAC mortar with the curing age up to 60 days. From Fig. 5a, the compressive strength increased with curing age regardless of the replacement level of WGC. Not only did the strength increase at the early age, but it also increased at the late age. It is expected that the compressive strength would be further enhanced after 60 days of curing. However, the compressive strength was slowly reduced as the WGC content was increased. This is related to the smooth surface of WGC, which resulted in weaker bond strength between the glass and the matrix [27]. In addition, the micro-cracks in WGC induced during the glass crushing process might also lead to a reduction in the compressive strength [60].

In terms of flexural strength, the development trend is different from that of the compressive strength. The flexural strength was increased with an increase of WGC content of up to 50%, and then decreased as the WGC content was further increased. This means that, for the flexural strength, the optimal percentage of WGC replacement was 50%. As indicated in Fig. 1b, the NFA was made up of relatively round shape particles, while the WGC exhibited angular shape and a higher aspect ratio than NFA. Such a difference would result in the enhancement of flexural strength for the mix prepared with WGC. This speculation was consistent with the positive effect of incorporating glass fibers (with a high aspect ratio) in improving the flexural or bending strength of cement mixtures [61,62]. However, when most of the NFA was replaced by the WGC, the weakening effect of WGC due to the smooth surface and micro-cracks present would play an important role in controlling the flexural strength. Thereby a reduction in the flexural strength was observed.

3.2.2. Effect of a/b ratio on the compressive strength of AAC mortar

The development of compressive strength of the AAC mortars produced with different *a*/*b* ratios is given in Fig. 6. It is obvious that the *a*/*b* ratio had only a slight influence on the compressive strength regardless of the curing ages. This phenomenon was not consistent with the case of the OPC-based system. Generally, the reduced *a*/*b* ratio should lead to an enhancement of strength induced by the increased OPC content. However, in AAC mortar, the increased binder content did not contribute to the strength development. The explanation lied probably in the higher shrinkage due to the higher binder content [63,64]. As pointed out by many researchers [65–67], AAC mortar/concrete experiences considerably higher drying shrinkage than OPC mortar/concrete. When the AAC materials were cured under dry conditions, the formation of microcracks due to the high shrinkage would lead to a lower compressive strength [68]. Hence the reduced *a*/*b* ratio (higher binder content) was not helpful to the development of compressive strength. In addition, the effective *w*/*b* ratio was increased for the AAC mortar with lower *a*/*b* ratios since a lesser amount of water was required to coat the aggregates. Therefore, the effect of *a*/*b* ratio on the compressive strength was insignificant. Regardless of the *a*/*b* ratio, the compressive strength of the mortar prepared with 100% WGC obtained at 60 days was about 30 MPa. Such a high strength was encouraging for further use of WGP in this type of AAC mortar.

3.2.3. Effect of WGP on the compressive strength of AAC mortar

Fig. 7 presents the effect of using WGP as a precursor on the compressive strength for AAC mortar with *a*/*b* ratio of 2.0 (M2.0). In this study, 30% WGP was used to replace FA and GGBS, respectively. However, with increase in time, M2.0 which was prepared without any WGP performed better than the composites prepared with WGP. This is a clear indication that the use of WGP as a partial

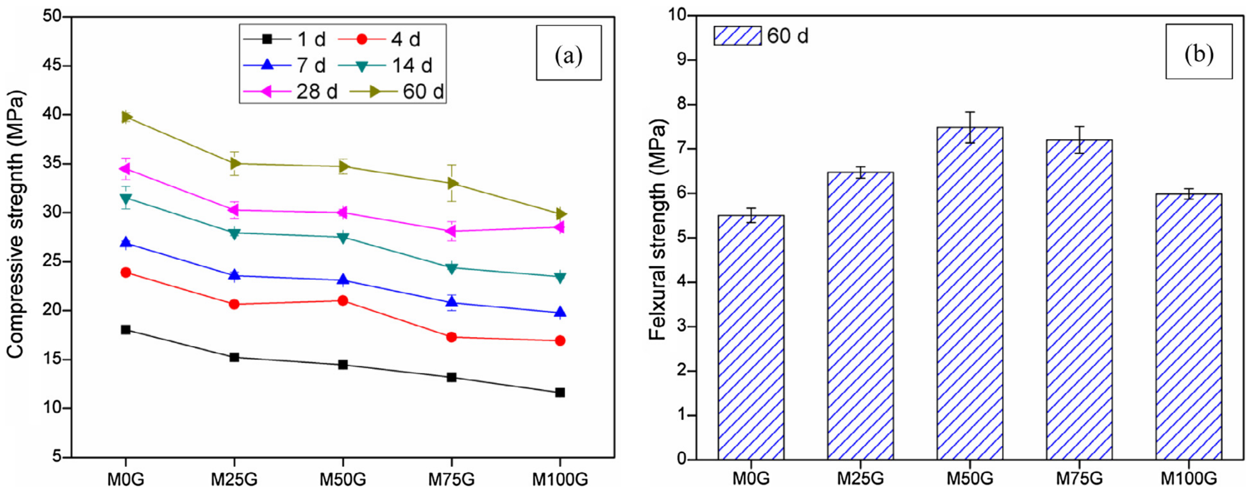

Fig. 5. Effect of WGC content on the strength of AAC mortar.

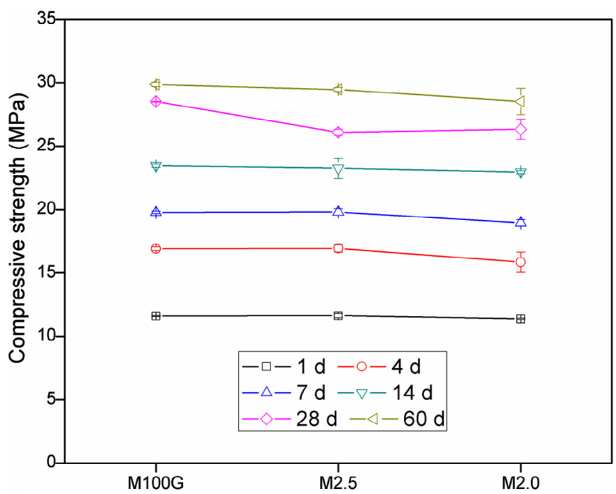

Fig. 6. Effect of *a*/*b* ratio on the compressive strength of AAC mortar.

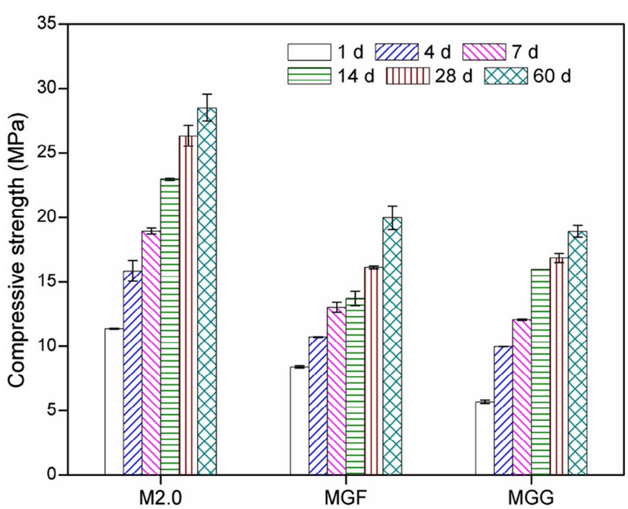

Fig. 7. Effect of WGP on the compressive strength of AAC mortar.

precursor replacement significantly reduced the strength of AAC mortar. The explanation was directly related to the lower reactivity of WGP due to the coarse particle size of WGP (Fig. 2) when compared with FA and GGBS. The reduction in strength was also found by Torres et al. [69], who mentioned that the glass had a lower activation potential by the alkaline solution compared to GGBS. Nonetheless, the compressive strength values of AAC mortar prepared with WGP still exceeded 15 MPa, which can meet the strength requirement for the non load bearing partition wall blocks [70].

3.3. Fire resistance

The residual compressive strength and the residual strength index (RSI) of the AAC mortar after exposure to 800 °C are shown in Fig. 8. It can be found that the residual compressive strengths of the mortars prepared with WGC were slightly lower than that of the mortar prepared without WGC. And, the residual strength tended to be stable with the increase of WGC replacement level. These behaviors indicate that the potential melting of WGC at the high temperature did not cause severe deterioration in strength for the AAC mortar. This result is in agreement with the findings of Ling et al. [71], who concluded that the properties change of recycled glass at 800 °C did not have significant effect on the strength degradation of the concrete prepared with glass cullet incorporation. On the contrary, the RSI values tended to increase as the WGC content was increased in the mortars, which suggests that the introduction of WGC could mitigate the strength loss due to the exposure to the high temperature. The beneficial effect was probably attributed to the lower thermal incompatibility between the AAC paste matrix and the WGC. According to the

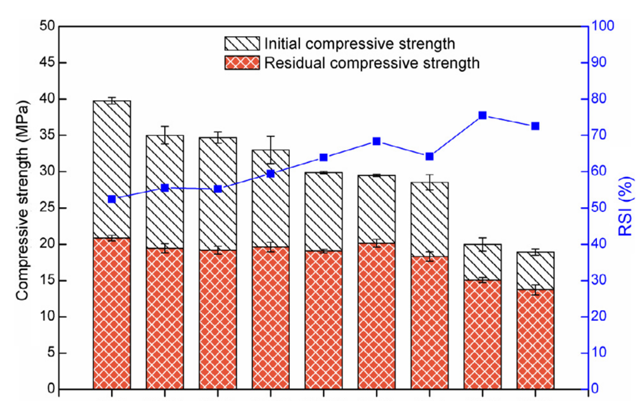

Fig. 8. Residual compressive strength and RSI of AAC mortar subjected to 800 °C.

previous investigations [72,73], the alkali-activated aluminosilicate composites exhibited thermal shrinkages after elevated temperature exposures. While both the soda-lime glass and quartz sand used in this study expanded under high temperature, and the thermal expansion coefficients of quartz (18×10^{-6}/°C [74]) was much higher than that of glass ($7–9 \times 10^{-6}$/°C [75]), thus the replacement of NFA by WGC alleviated the thermal expansion mismatch between the AAC paste and the glass aggregates. In addition, the transition of quartz in the NFA from the β-form to the α-form at 573 °C was known to be accompanied by volume changes and resulted in damages of the aggregate-binder interface zone, thus promoted the strength loss [76]. Obviously, the different thermal expansion between the gel matrix and aggregates was also partly responsible for the strength deterioration after exposure to the elevated temperature [73].

In order to verify this explanation, the characteristics of the pore structure were evaluated by using MIP (see Fig. 9) before and after high temperature exposure. From Fig. 9a, it is clear seen that the pore volumes of the mortars after exposure to the high temperature were much higher than those of the mortars without subjecting to the high temperature, which indicates that the porosity was largely increased after elevated temperature exposure. This result is also consistent with the severe strength losses of AAC mortars after subjecting to 800 °C. However, the presence of WGC in the AAC mortar could effectively mitigate the porosity increase, i.e. the mortars prepared with WGC had a lower pore volume compared to the NFA mortar after exposure to 800 °C. The porosity value in Fig. 9a also show the same trend intuitively. Fig. 9b describes the pore size distributions of AAC mortars with and without exposure to 800 °C. Apparently, the pore sizes of AAC mortar were significantly coarsened after the exposure to the high temperature. However, the coarsening effect was abated when the NFA was replaced by WGC, especially for the large pore sizes, which means that the addition of WGC could reduce the number of coarsened large pore after the high temperature exposure. It is believed that the mitigation of the coarsening pore was attributed to the lesser thermal incompatibility between the AAC paste matrix and the WGC.

In Fig. 8, another interesting phenomenon is that the RSIs of the AAC mortar prepared with and without WGC were higher than 50%. Furthermore, visual examination showed that there were no visible cracking and spalling in any AAC specimens. By contrast, previous research [71,77] revealed that the RSIs of OPC-based composites were approximately 20%. This difference demonstrates that the high temperature resistance of AAC glass mortar was superior to OPC mortars or concrete. Similar results were obtained by Zuda and Černý [74], who found that the thermomechanical behavior of the alkali-activated aluminosilicate composite was mostly better than of the OPC-based composites. The improvement in the mechanical property of the AAC mortar after elevated temperature exposure may be due to the fact that the crystallization of akermanite produced in the aluminosilicate material at 800 °C led to a formation of ceramic bond with very high thermal stability [78]. Furthermore, no calcium hydroxide was present in AAC mortar which also contributed to the better high temperature performance [72].

From Fig. 8, the residual compressive strength and RSI values of AAC mortars prepared with different *a*/*b* ratios were similar, which shows that the *a*/*b* ratio has only a slight impact on the fire resistance of AAC mortar. The reasons may be considered from two negative effects caused by the high temperature, one is the decomposition of reaction products [79], and the other is the thermal incompatibility between the matrix and the WGC as discussed before. Therefore, for the composites prepared with higher *a*/*b* ratios, the latter effect may be dominant due to the higher aggregates content; while for the lower *a*/*b* ratio composites, the resistance to elevated temperature exposure was probably controlled by the former effect because of the higher binder content. An interesting observation is that the replacement of FA and GGBS by WGP could develop higher RSI values compared with the AAC mortar without the WGP. And, the RSI values of MGF and MGG were able to reach 75.5% and 72.5%, respectively. The results indicate that the introduction of WGP into the AAC mortar effectively improved the resistance to elevated temperature exposure. The higher RSI values in WGP blended AAC mortar may be explained by phenomena similar to those observed in WGP blended OPC mortar [80], i.e. the transformation behavior of unreacted WGP from solid to liquid above the melting point (below 700 °C [81]) was helpful to fill up open pores and microcracks induced by the high temperature. On the other hand, based on the fusion characteristic, fine glass powder has been commonly used as a fluxing agent to accelerate the sintering progress in the fabrication of ceramic products [82,83]. As mentioned, when the AAC mortar was subjected to high temperature, a much stronger ceramic bond would form due to the crystallization of akermanite [78,79]. Therefore, it is believed that the vitreous phase originated from the melted WGP would

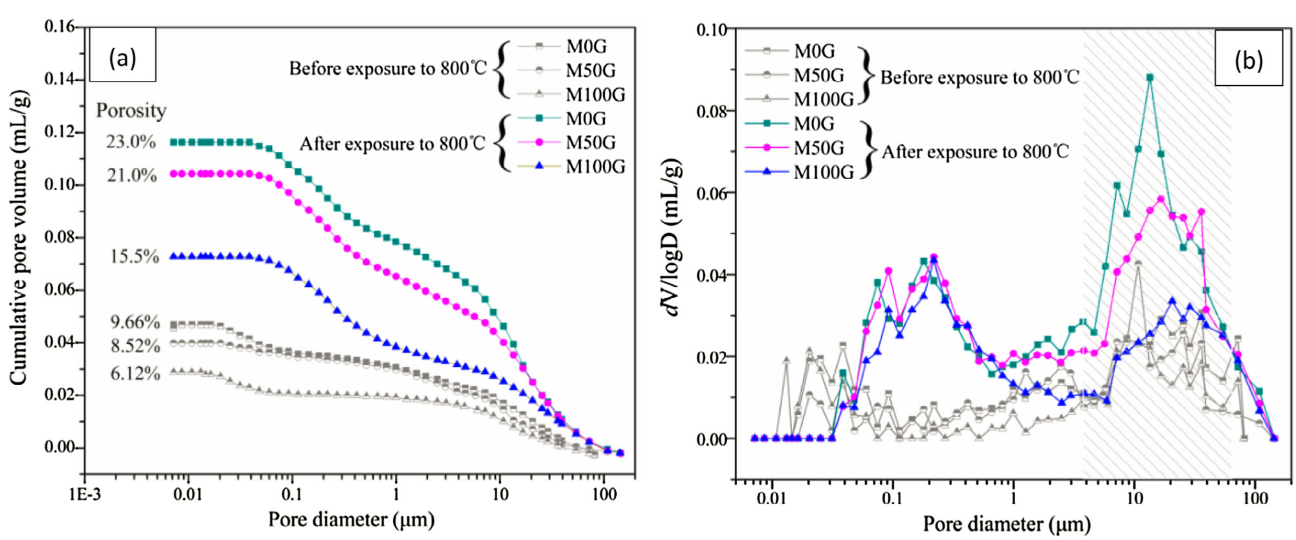

Fig. 9. Pore structure of AAC mortar before and after exposure to 800 °C: cumulative pore volume (a) and differential pore size distributions (b).

promote the crystallization process, which contributed to the high temperature resistance. However, this speculation still need to be investigated in details.

The glass-based AAC material has potential to be used as partition wall blocks since it not only offers the feasibility to massive use of waste glass in non-OPC material, but also develops good mechanical properties and fire resistance. Nonetheless, more studies are required to shed more light on the effect of incorporation of waste glass in the AAC material, for example, the ASR risk of glass aggregates in AAC material with high alkali concentrations; the effect of waste glass on the drying shrinkage, efflorescence and carbonation of AAC material.

4. Conclusions

This study developed a good mechanical strength and fire resistance non-OPC cement mortar, which can be used for the fabrication of new precast construction products. The following conclusions can be drawn from this study:

- The increasing replacement of NFA by WGC gradually improved the workability of AAC mortar. The reason mainly due to the smooth surface, non-absorption and larger particle sizes of glass. The reduction in *a*/*b* ratio led to a large enhancement in flow values. However, the replacement of FA by WGP caused a decrease in the workability related to the coarser particle size and irregular shape of WGP. But, there was only a slight effect on the flow value with the replacement of GGBS by WGP due to their similar shapes.
- The compressive strength of AAC mortar slowly decreased as the WGC content increased. Nevertheless, the flexural strength was increased with an increase of WGC content up to 50%, and then decreased as the WGC content was further increased.
- The *a*/*b* ratio had little influence on the compressive strength of AAC mortar. The explanation lied probably in the higher shrinkage due to the higher binder content (i.e. lower *a*/*b* ratio).
- The use of WGP as a partial precursor replacement significantly reduced the strength of AAC mortar. This phenomenon was attributed to the low reactivity of WGP compared to the FA and GGBS. Nonetheless, the compressive strength values of WGP blended AAC mortar could still meet the strength requirement for non load bearing partition wall blocks.
- The use of waste glass in AAC mortar did not cause severe deterioration in strength after subjecting to high temperature (800 °C). On the contrary, the introduction of WGC could mitigate the strength loss after exposure to the high temperature. The reason may be due to the replacement of NFA by WGC alleviated the thermal expansion mismatch between the AAC paste and the expanding aggregates.
- The high temperature resistance of AAC mortar is normally considered as a superior quality to OPC mortars or concrete. The study found that the inclusion of WGP in the AAC mortar could further improve the resistance of the AAC to elevated temperature exposures.

The findings of the present investigation have shown encouraging results and opened up an outlet for the recycling of WGC and WGP in AAC composites. But more studies on the durability aspects are needed before such application can be realized.

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