



# Influence of recycled glass content and curing conditions on the properties of self-compacting concrete after exposure to elevated temperatures

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## ABSTRACT

The aim of this paper is to assess the performance of self-compacting glass concrete (SCGC) after exposure to four elevated temperatures of 300 °C, 500 °C, 600 °C and 800 °C. The influence of curing conditions on the high temperature performance of SCGC was also investigated. For each curing regime, five SCGC mixtures were prepared with recycled glass (RG) which was used to replace natural fine aggregate at the level of 0%, 25%, 50%, 75% and 100%. After exposure to the elevated temperatures, concrete mass loss, density, water porosity, ultrasonic pulse velocity (UPV) and water sorptivity were determined and then a compressive strength test was conducted. The test results indicate that regardless of the exposure temperature, all the water cured specimens had higher residual strengths and mass losses while the water porosity and water sorptivity values were lower as compared to the corresponding air cured specimens. The incorporation of RG in the concrete mixes helped to maintain the concrete properties after the high temperature exposure due to the melting and resolidification of the recycled glass in the concrete matrix.

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## 1. Introduction

Self-compacting concrete (SCC) was first developed in Japan in the late 1980s [1]. This type of concrete is known for its improved rheological properties and durability enhancement as compared to ordinary vibrated concrete (VC). With high fluidity, SCC can be placed under its own weight without vibration and is cohesive enough to be handled without segregation or bleeding during concreting [1]. For these reasons, SCC has become widely used in the production of tall walls, and it facilitates and ensures proper filling in complex shaped members and highly congested reinforcement structural members [1,2]. In the view of fire performance, SCC seems to maintain higher residual compressive strength than VC with a same strength grade and elevated temperature exposure [3]. However, the susceptibility of SCC to spalling due to high temperature is relatively higher than that of VC. This is thought to be related to the denser microstructure of SCC, which caused the build-up of higher internal pressure due to the water–vapour phase transition of the interlayer water [4].

Since the late 1990s, the use of recycled glass (RG) as a replacement for natural aggregates in mortar and normal concrete has been addressed in many research publications [5–11]. Consequently, more attention has turned to the use of recycled glass in self-compacting mortar and concrete within the last few years [12–16]. Previous research results indicated that the incorporation of RG increased the workability of fresh SCC, thus reducing the

amount of superplasticizer required to obtain the desired slump. Resistance to chloride ion penetrability and drying shrinkage of SCC were improved because the RG cullet has, basically, zero water absorption and porosity [12–14]. Nevertheless, the smooth surfaces of the glass cullet weakened the bonding between the glass and the cement paste, which resulted in strength loss. The use of 25% fly ash by cement weight in SCC was found to be effective to suppress alkali-silica reaction (ASR) expansion [6,14]. As the use of RG in SCC could become a potential new material in building construction and the risk of exposing it to fire could be increased. For this reason, it is important to understand the behaviour of SCC containing RG at elevated temperatures.

In this study, a series of self-compacting glass concrete (SCGC) specimens containing 0%, 25%, 50%, 75% and 100% RG as replacement of fine aggregate were prepared. At an age of 60 days, the SCGC specimens were exposed to elevated temperatures up to 300 °C, 500 °C, 600 °C and 800 °C. The effects of elevated temperatures on compressive strength, ultrasonic pulse viscosity, concrete mass loss, density, water porosity and water sorptivity of the prepared concrete were determined. Furthermore, the influences of water and air curing on the residual properties of SCGC specimens after exposure to elevated temperatures were compared.

## 2. Experimental details

### 2.1. Materials

The raw materials used to prepare the SCGC mixes in this study were coarse aggregate, fine aggregate, ordinary Portland cement

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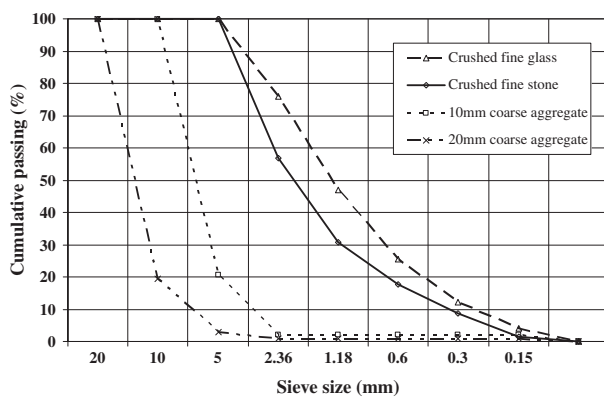
and fly ash. Two different sizes (20 mm and 10 mm) of crushed granite with a specific gravity of 2.62 were used as coarse aggregates. Crushed fine stone with a nominal maximum size of 5 mm and a specific gravity of 2.62 was used as the fine aggregate. Crushed recycled glass (with a gradation close to that of the crushed fine stone) obtained locally from a waste glass recycler was used as a fine aggregate replacement. Some physical properties and gradation curves of all the aggregates used are illustrated in Table 1 and Fig. 1, respectively. ASTM Type I ordinary Portland cement and fly ash complying with ASTM class F ash was used as binder material in the study. The physical properties and chemical analysis of the cement and fly ash are presented in Table 2. A superplasticizer of ADVA 109 with a specific gravity of 1.045, containing no added chloride, was used to achieve the desired workability in all the SCGC mixtures.

## 2.2. Mix proportions

The weight of raw materials to prepare 1 cubic metre of SCGC mix is given in Table 3. As seen in the table, all the SCGC mixtures were designed to have a constant binder content of 623.3 kg/m<sup>3</sup>,

**Table 1**  
Some physical properties of coarse and fine aggregates.

Physical properties	Crushed granite	Crushed fine stone	Recycled glass
Fineness modulus	N/A	3.85	3.33
Relative density (g/cm <sup>3</sup> )	2.62	2.62	2.49
Water absorption (%)	0.89	0.89	~0



**Fig. 1.** Sieve analysis of coarse and fine aggregates.

**Table 2**  
Chemical compositions and physical properties of cement and fly ash.

Chemical analyses (%)	Cement	Fly ash
Calcium oxide (CaO)	63.15	<3
Silicon dioxide (SiO <sub>2</sub> )	19.61	56.79
Aluminium oxide (Al <sub>2</sub> O <sub>3</sub> )	7.33	28.21
Ferric oxide (Fe <sub>2</sub> O <sub>3</sub> )	3.32	5.31
Magnesium oxide (MgO)	2.54	5.21
Sodium oxide (Na <sub>2</sub> O)	0.13	0.45
Potassium (K <sub>2</sub> O)	0.39	1.34
Sulphur trioxide (SO <sub>3</sub> )	2.13	0.68
Loss on ignition	2.97	3.90
<i>Physical properties</i>		
Specific gravity	3.16	2.31
Blaine fineness (cm <sup>2</sup> /g)	3519	3960

water–cement ratio of 0.35 and total aggregates–cement ratio of 2.5. To prepare the SCGC, crushed fine stone (CFS) was replaced with the crushed recycled glass (RG) at five designed contents of 0%, 25% 50%, 75% and 100% by weight. In order to achieve a 750 ± 50 mm targeted slump flow diameter of SCGC, the dosage of superplasticizer was varied from 4.2 to 6.6 kg/m<sup>3</sup>.

## 2.3. Samples preparation, curing conditions and heating regimes

All the SCGC mixes were mixed for approximately 5 min using a laboratory pan mixer. Besides to ensure that the slump flow diameter of the all fresh SCGC mixtures met the desired value, the slump loss, blocking ratio and resistance to segregation of the SCGC were also determined. Following the fresh properties tests, the prepared concrete mixture was used to cast 30 cubic samples with dimensions of 100 × 100 × 100 mm. All the cubic samples were then covered with a thin plastic sheet in the laboratory at room temperature. After 1 day, all the samples were demoulded, 15 concrete cubes were stored in a water tank at an average temperature of 25 ± 3 °C, and the remaining 15 concrete cubes were kept in air at room temperature of 23 ± 3 °C and 75 relative humidity. At the age of 60 days, both water and air cured samples were conveyed to an electrical furnace and heated at a constant rate of 5 °C/min from room temperature (20 °C) up to 300 °C, 500 °C, 600 °C and 800 °C. Once the electrical furnace reached the target temperature, the temperature was maintained for 4 h in order to ensure uniform heating throughout the concrete samples. After such heating treatment, the samples were allowed to cool naturally to room temperature. Physical and mechanical tests were performed on unheated (20 °C) and heated samples in order to compare the initial and residual properties.

## 2.4. Test methods

### 2.4.1. Fresh properties

Tests in the fresh state were performed according to the EFN-ARC standard [17]. Slump flow was conducted to assess the flowability and the flow rate of fresh SCGC mixture in the absence of obstructions. The measurement was repeated at 30 min after mixing to evaluate the slump loss properties. A blocking ratio (L-box) test was also adopted to assess the passing ability of fresh mixtures to flow through tight openings and other obstructions including spaces between reinforcing bars. A GTM screen stability test [17] developed by the French contractor GTM was carried out to assess the segregation resistance and stability of the fresh mixtures.

### 2.4.2. Compressive strength

A compressive strength test was performed on 100 mm cubic specimens according to BS 1881: Part 116 [18]. Three specimens were tested for each temperature and the average values are reported.

### 2.4.3. Ultrasonic pulse viscosity

The ultrasonic pulse velocity (UPV) value was determined according to ASTM C597 [19] for quick checking of the uniformity of SCGC specimens after each heating. The mean values of three specimens were recorded.

### 2.4.4. Concrete mass loss, apparent density and water porosity

Concrete mass before and after each heating temperature was determined using an electronic digital balance with an accuracy of ±0.1 g. Concrete mass loss of SCGC specimens was calculated according to Eq. (1), where  $M_{initial}$  and  $M_{heated}$  are the initial mass (before heating) and heated mass (after heating) weighed in the air, respectively.

**Table 3**Mix proportions (kg/m<sup>3</sup>).

Notation	Cement	Fly ash	Coarse aggregate		Fine aggregate		Water		SP	
			20 mm	10 mm	CFS	RG	Amount	w/c	amount	% <sup>a</sup>
SCGC-0	467.5	155.8	249.4	498.7	810.4	0	218.2	0.35	6.6	1.06
SCGC-25	467.5	155.8	249.4	498.7	709.1	101.3	218.2	0.35	6.4	1.02
SCGC-50	467.5	155.8	249.4	498.7	405.2	405.2	218.2	0.35	6.1	0.98
SCGC-75	467.5	155.8	249.4	498.7	101.3	709.1	218.2	0.35	5.9	0.94
SCGC-100	467.5	155.8	249.4	498.7	0	810.4	218.2	0.35	4.2	0.64

<sup>a</sup> Note: Superplasticizer dosage as a percentage of cementitious materials (cement + fly ash) weight.

$$M_{\text{Loss}} = \left( \frac{M_{\text{initial}} - M_{\text{heated}}}{M_{\text{initial}}} \right) \quad (1)$$

The apparent density of each SCGC specimen after heating was determined according to Eq. (2), where  $M_{\text{initial}}^{\text{imm}}$  is the initial mass (before heating) weighed in the water.

$$D = \left( \frac{M_{\text{heated}}}{M_{\text{initial}} - M_{\text{initial}}^{\text{imm}}} \right) \quad (2)$$

Finally, the water porosity of the specimens was calculated using Eq. (3)

$$P = \left( \frac{M_{\text{initial}} - M_{\text{heated}}}{M_{\text{initial}} - M_{\text{initial}}^{\text{imm}}} \right) \quad (3)$$

#### 2.4.5. Water sorptivity

Prior to the water sorptivity test, the four side surfaces of the cubic specimens were sealed with water-impermeable tape to ensure free water movement only through the bottom surface. The specimens were then placed on aluminium rods in a tray such that the free water level was about 5 mm above the bottom surface of the specimens in contact with water. The mass of water absorbed per unit area before immersion and subsequently after intervals of 10 min, 20 min, 30 min, 60 min, 2 h, 4 h and 24 h was determined. Three specimens were used for each test.

### 3. Results and discussion

#### 3.1. Fresh properties

According to EFNARC [17], there are some typical acceptance criteria ranges for SCC. Therefore, it was essential to check and ensure that all the fresh SCGC mixtures produced met the requirements specified for SCC. The results of the fresh properties test for all the SCGC mixes are summarised in Table 4.

As can be seen in the table, the flow diameter of all the SCGC mixtures prepared with 0% to 100% RG were maintained within the specific limit of  $750 \pm 50$  mm by adjusting the dosage of superplasticizer. Comparatively, the inclusion of RG in the SCGC mixtures improved the fluidity of the mix, as indicated by the reduced superplasticizer dosage to achieve a similar slump flow diameter (see Table 3). This result is in agreement with those of previous

studies [14,15]. Furthermore, the increase in RG content tended to decrease the slump loss rate. This implies that the RG would be able to maintain the consistency of the fresh SCGC mixtures.

As regards the blocking ratio, it was observed that without any difficulties, all the fresh SCGC mixtures were able to flow through the confined gaps and narrow opening areas of the L-box, and all the height ratios measured satisfied the minimum acceptance value of 0.80.

For the GTM screen stability test, it was observed that the control SCC mixture without using RG tended to have higher resistance to segregation. As the RG content increased, the resistance to segregation reduced. This might be related to the impermeable property and smooth surface of RG which was prone to segregation [12]. When the replacement of RG content reached 100%, a segregation ratio of 16.08% was obtained which was slightly higher than the maximum limit of 15% suggested by EFNARC [17].

#### 3.2. Compressive strength

##### 3.2.1. Initial compressive strength

Fig. 2 shows the effect of curing regime and RG content on the initial compressive strength of unheated SCGC samples. It can be clearly observed that, as expected, the compressive strengths of water cured samples were higher than those of the corresponding air cured samples. The availability of moisture for strength development is particularly important for concrete containing fly ash. When the strengths are compared within each respective curing regime, the strength decreased with increasing RG content. This result is consistent with previous results [14,16]. The loss of strength could be attributed to the weak adhesion between the interface between the RG aggregates and the cement pastes.

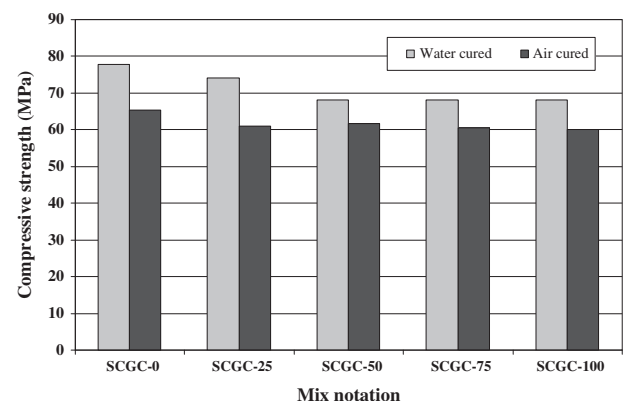
##### 3.2.2. Residual compressive strength

Fig. 3 shows the results of residual compressive strength of the water and air cured SCGC specimens after being subjected to the elevated temperatures. The dotted and solid lines represent the

**Table 4**

Results on fresh SCGC properties.

Notation	Slump flow diameter (mm)		Blocking ratio	Segregation ratio (%)
	$D_{\text{Initial}}$	$D_{30\text{min}}$		
SCGC-0	740	595	0.81	5.03
SCGC-25	750	650	0.80	11.32
SCGC-50	775	740	0.94	13.38
SCGC-75	740	715	0.86	11.38
SCGC-100	770	715	0.89	16.08



**Fig. 2.** Effect of curing regime and RG content on the initial compressive strength of water and air cured SCGC samples.

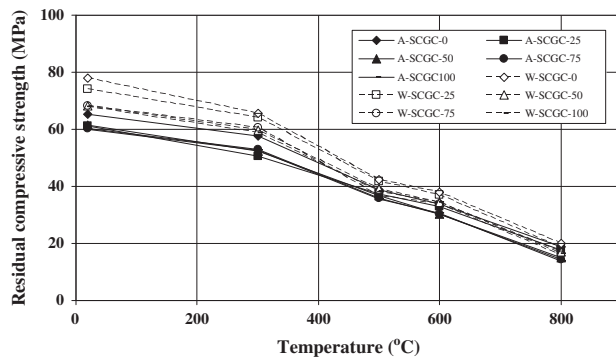


Fig. 3. Residual compressive strength of water and air cured SCGC after exposure to elevated temperatures.

residual strength of water and air cured specimens, respectively. The relative residual strength (ratio of residual compressive strength at elevated temperature to initial compressive strength at ambient temperature) of the SCGC specimens is shown in Fig. 4. The strength of SCGC specimens decreased as the temperature increased. At 300 °C, the residual strength ranged from 84% to 89% and 82% to 88% of the initial values (unheated specimens) for water and air cured specimens, respectively. The strength reduction observed at 300 °C was mainly attributed to the evaporation of capillary pore water (25–105 °C), and dehydration of ettringite, C–S–H and calcium carboaluminate hydrates (105–300 °C) [20,21].

As the heating temperature was increased to 500 °C, the strength dropped significantly. For instance, the strength values were in the range of 36.7–42.5 MPa and 35.5–38.8 MPa for the water and air cured specimens, respectively. The reduction in strength of the water and air cured specimens was approximately 42–46% and 39–42% in comparison with the initial values, respectively. The reason for the strength reduction at 500 °C was probably due to the dehydroxylation of calcium hydroxide or the portlandite [22].

A small reduction in strength is observed for both the water and air cured SCGC specimens after the heating temperature was increased from 500 °C to 600 °C. At 600 °C, the strength of water and air cured SCGC specimens were reduced to 33.8–38.1 MPa and 30.2–33.9 MPa, which indicated an average of 10.5% and 14.1% reduction in strength as compared to the 500 °C heated specimens, respectively. The further reduction in strength might be due to the formation of micro-cracks in the specimen, thus weakening the interfacial transition zone and bonding between the aggregate and the cement paste [23].

It is known that the rate of C–S–H decomposition is low when the temperature is <600 °C, but significantly increases when the

temperature is further increased to 800 °C [22]. Therefore, as the heating temperature reached 800 °C, the main hydration products of hydrated cement paste and C–S–H decomposed considerably and resulted in a significant drop in strength. This revealed that the decomposition of C–S–H greatly affected the strength loss of concrete, which, in turn, resulted in a 75% loss of strength as compared to the initial strength values (unheated specimens).

For 800 °C, the relative residual strength of both the water and air cured specimens are given in Fig. 4. The residual strength of all the SCGC specimens was approximately the same within the respective curing regime. This indicates that the change of physical and mechanical properties of recycled glass during its melting threshold at about 700 °C did not have significant impact on concrete strength degradation. Also, at this temperature, the differences between the strength of SCGC specimens made with crushed RG and crushed fine stone was almost negligible.

Comparing the water and air cured specimens, in general, the residual strength of the water cured specimens remained higher than that of the air cured specimens for all the tested temperatures. Nevertheless, the effect of curing regimes became less important with increasing temperature.

### 3.3. Residual ultrasonic pulse velocity

The residual and relative residual ultrasonic pulse velocities (UPV) of the water and air cured SCGC specimens are shown in Figs. 5 and 6, respectively. For unheated SCGC specimens, it was observed that the UPV values of the water cured samples were higher than those of the corresponding air cured samples. This is consistent with the compressive strength results. Indeed, the transmission of ultrasonic waves through a water cured specimen (sufficient moisture in concrete) was faster than that through an air cured (drier) specimen [24].

With regard to strength, the UPV values of both the water and air cured concrete specimens decreased with increasing temperature. However, the rate of reduction in UPV was slightly different from that for strength. For residual UPV, the heating regimes could be divided into four stages, ranging from 20 to 300 °C, 300 to 500 °C, 500 to 600 °C and 600 to 800 °C. It is known that concrete quality can be classified by UPV value: if the value is >4500 m/s, 3500–4500 m/s, 3000–3500 m/s, 2000–3000 m/s and <2000 m/s, the concrete is classified as “excellent”, “good”, “doubtful”, “poor” and “very poor”, respectively [25]. Therefore, as the SCGC specimens were exposed to the heating regimes of 20–300 °C, 300–500 °C, 500–600 °C and 600–800 °C, the SCGC specimens degraded from “excellent” to “good”, “good” to “doubtful”, “doubtful” to “poor” and “poor” to nearly “very poor”, respectively.

By comparing the effect of curing regime on the residual UPV at different heating temperatures, it can be seen that the influence of

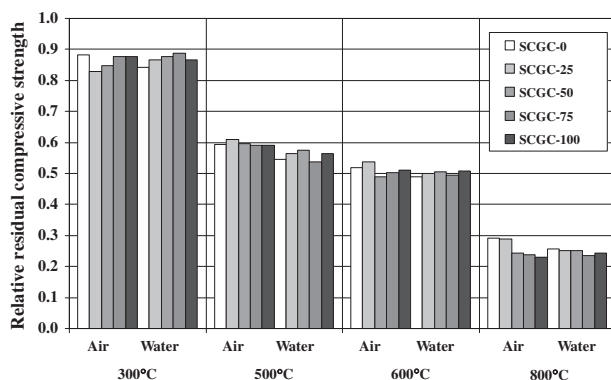


Fig. 4. Relative residual compressive strength of water and air cured SCGC after exposure to elevated temperatures.

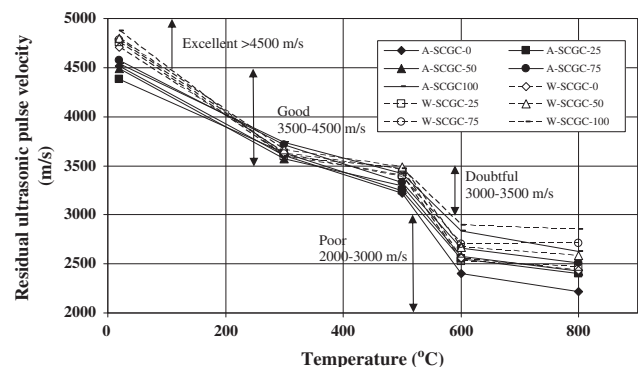


Fig. 5. Residual UPV of water and air cured SCGC specimens after exposure to elevated temperatures.



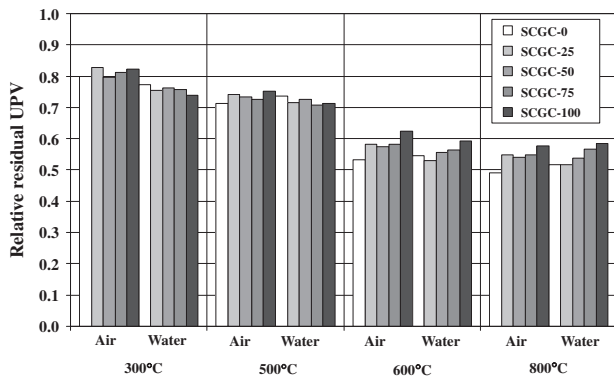


Fig. 6. Relative residual UPV of water and air cured SCGC specimens after exposure to elevated temperatures.

water curing was more dominant at 20 °C since the UPV values of all the water cured specimens were higher than the corresponding air cured specimens. On the contrary, the effect of RG was more dominant for the heated SCGC specimens, particularly at higher temperatures. This is probably because as the heating temperature approached to glass transition temperature (at 560 °C) of soda lime glass [26], a transformation behaviour of RG from “glassy” to “rubbery” occurred in the concrete matrix, which could enhance the pore structures and micro-cracks within the concrete, thus giving a higher residual UPV. The same phenomenon was also observed at the heating temperature of 800 °C. For instance, the UPV values were increased by 1.3%, 6.2%, 9.5% and 17.3% for the water cured specimens, and by 8.2%, 11.3%, 13.0% and 18.5% for the air cured specimens as the RG content was increased from 0% to 25%, 50%, 75% and 100%, respectively.

### 3.4. Concrete mass loss

Fig. 7 shows the concrete mass loss of the water and air cured SCGC specimens as a function of the elevated temperatures. When the temperature was increased from 20 °C to 300 °C, the average mass losses of 5.5% and 6.6% for the water and air cured specimens were observed, respectively. In other words, after the specimens were exposed to 300 °C, approximately 69% and 67% of free water contained in the water and air cured specimens evaporated, respectively. As discussed earlier, the loss of weight between 20 °C and 300 °C was mainly attributed to the loss of free water contained in the capillary pores and loss of water from the dehydration of the C–S–H. Consequently, the rate of concrete mass loss was lowered when the heating temperature was increased from 300 °C to 800 °C.

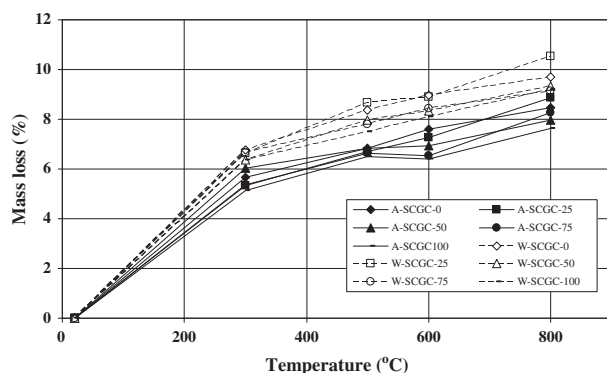


Fig. 7. Mass loss of water and air cured SCGC specimens after exposure to elevated temperatures.

### 3.5. Residual density

The effect of elevated temperatures on the apparent density of the water and air cured SCGC specimens are plotted in Fig. 8. The results indicate that the RG content and curing regime affected the loss of density. At 20 °C, the unheated SCGC specimens cured under water showed higher density because these specimens were exposed to sufficient moisture to sustain the hydration of the cement. A decrease in density with increasing RG content was also noted in the SCGC specimens, irrespective of curing regimes. This corresponded to the lower specific gravity of RG than the crushed fine stone. It is important to note that the influence of both the RG content and curing regime on density reduced as the exposure temperature rose above 500 °C.

### 3.6. Water porosity

Fig. 9 shows the water porosity of the water and air cured SCGC specimens as a function of elevated temperatures. It shows that after exposure to 300 °C, there was a great increase in water porosity for both the water and air cured specimens, in which water cured SCGC-0 specimen showed the largest increase by 397%. On the contrary, the air cured SCGC-100 specimen had much lower porosity as compared to other SCGC specimens within the respective curing regime. As expected, the influence of RG content on the water porosity was more pronounced after the SCGC specimens were exposed to the high temperatures. This is consistent with the results observed in residual UPV. At 800 °C, the total replacement of crushed fine stone by RG reduced the porosity by approximately 18.2% and 19.3% for the water and air cured specimens,

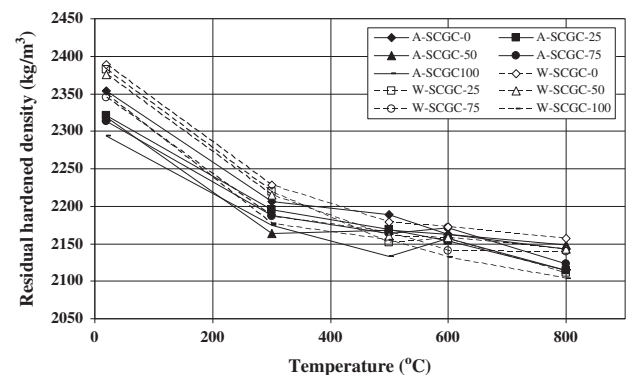


Fig. 8. Residual density of water and air cured SCGC specimens after exposure to elevated temperatures.

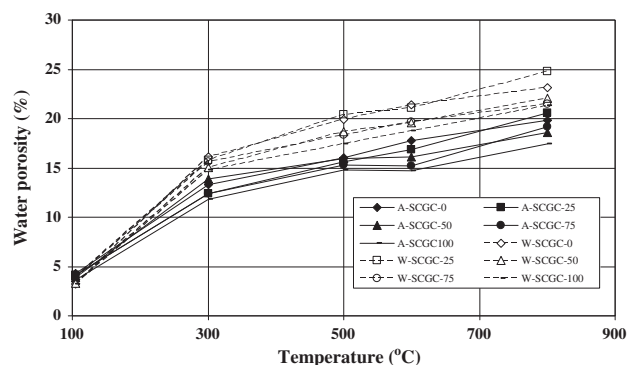
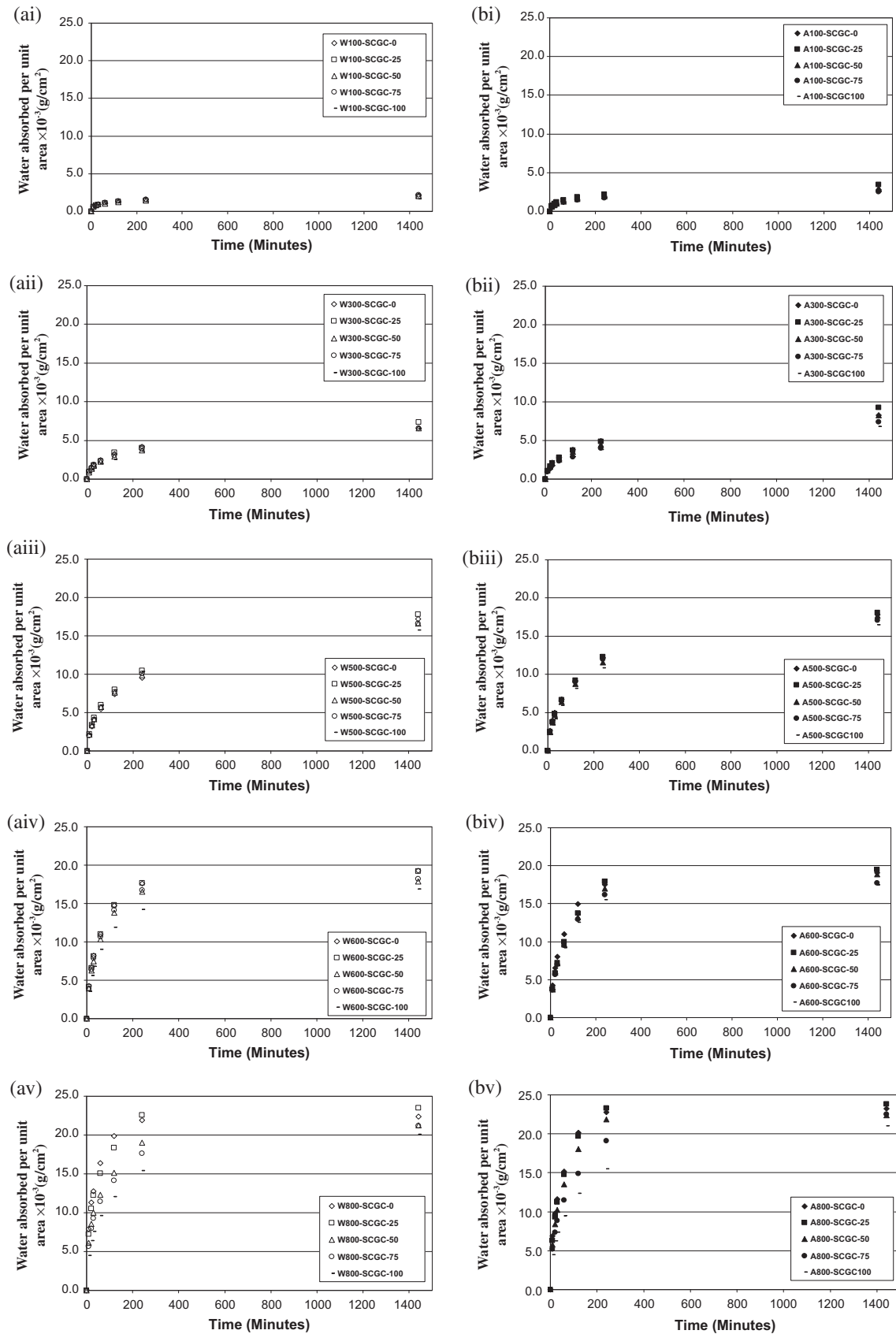


Fig. 9. Water porosity of water and air cured SCGC specimens after exposure to elevated temperatures.



**Fig. 10.** Water absorbed per unit area for (a) water and (b) air cured SCGC specimens after exposure to temperature of (i) 100 °C, (ii) 300 °C, (iii) 500 °C, (iv) 600 °C and (v) 800 °C.

respectively. As previously discussed, this result may be attributed to the pore-filling effect of the molten RG, which reduced the pore voids and consequently reduced the total water porosity in the concrete upon resolidification.

### 3.7. Water sorptivity

After the SCGC specimens were exposed to the elevated temperatures, the water sorptivity of the specimens was assessed to determine the inner concrete properties since the test is directly related to the presence of voids and cracks in the heated concrete specimens. Fig. 10 shows the results of the water absorbed per unit area for (a) water and (b) air cured SCGC specimens after exposure to (i) 100 °C, (ii) 300 °C, (iii) 500 °C, (iv) 600 °C and (v) 800 °C. The rate of water sorptivity increased sharply with increasing temperature. Two probable explanations are: firstly, the rate and total water sorptivity were affected greatly by the loss of moisture in the concrete after exposure to the elevated temperatures [27]. Secondly, it might be due to the formation of micro-cracks or shrinkage cracks when the exposure temperature was above 300 °C [28]. Moreover, internal cracking might be caused by the continuous increase in temperature.

A comparison of measured values between the water and air cured control specimen (SCGC-0) after being subjected to elevated temperatures is presented in Fig. 11. As expected, the water sorptivity values of the specimens cured in air were found to be somewhat higher than those corresponding specimens cured in water.

When the influence of RG content on the water sorptivity of the water and air cured specimens at 800 °C is examined, as shown in Fig. 12, the sorptivity values of both the water and air cured specimens decreased as the RG content increased. This shows SCGC specimens incorporating RG were able to provide better resistance to water penetration.

The beneficial effect of RG on reducing the capillary porosity of the heated SCGC specimens was also apparent when the tested specimens were visually examined after the water sorptivity test. Fig. 13 shows that damp patches could be seen on the top surface of both the water and air cured 800 °C heated specimens incorporating low content of RG (0%, 25% and 50%). This indicates that water had travelled all the way from the bottom surface of the specimens to the top surface. When the RG content was increased to 75% and 100% in the SCGC specimens, the appearance of water patches on the top surface was less obvious. For SCGC containing 100% RG, no water patch was noticeable on the top surface for both the water and air cured specimens after 4 h of the water sorptivity test. This is consistent with the results discussed previously. As RG reached its melting threshold at 700 °C [29], the molten glass could

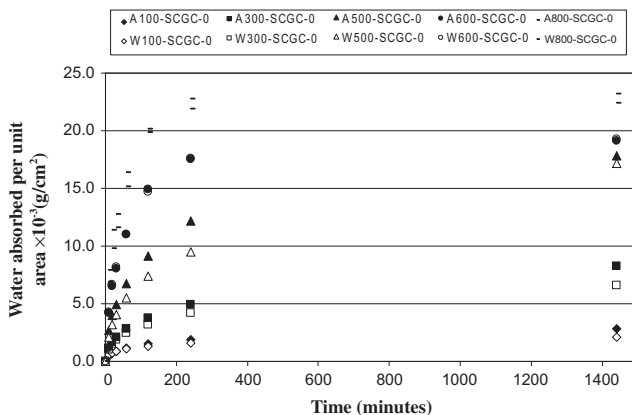


Fig. 11. Effect of water and air cured on water absorbed per unit area for control specimens after exposure to elevated temperatures.

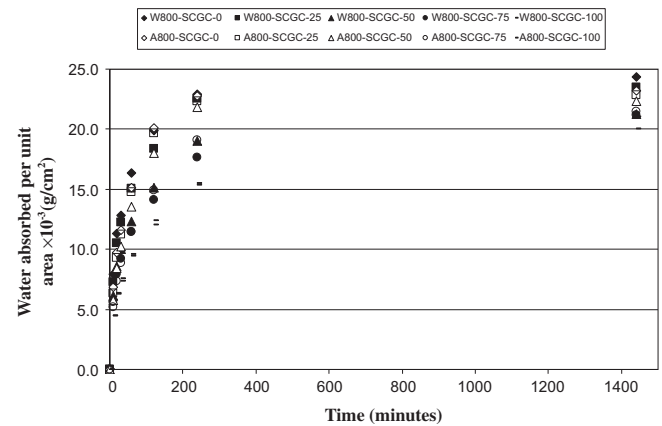


Fig. 12. Effect of RG content on water absorbed per unit area for water and air cured SCGC specimens after exposure to temperature of 800 °C.



Fig. 13. Appearance of water on the top surface of water and air cured SCGC specimens after exposure to 800 °C and 4 h of water sorptivity test. Note: The labels on each sample represent: Gxx (glass content), A or W (air or water cured), D (800 °C) and Sx (sample number).

have a pore-filling effect to fill up some pores and thus increase the resistance to water penetration.

### 4. Conclusions

In this study, the influences of curing condition and recycled glass (RG) content on the residual properties of self-compacting glass concrete (SCGC) after exposure to elevated temperatures have been investigated. Based on the experimental results, we conclude that:

- At room temperature, the initial compressive strength of the water cured specimens was relatively higher than the corresponding air cured specimens. This is attributed to the improved pore structure and lower porosity resulting from a greater degree of cement hydration and pozzolanic reaction. Upon exposure to elevated temperatures, although the strength of the water cured SCGC specimens reduced more significantly than the air cured SCGC specimens, the water cured samples had higher residual strength. This indicated that the positive effect of water curing conditions reduced as the heating temperature increased.
- It was found that the curing condition has more influence on UPV of the unheated SCGC specimens than changes of RG content. However, an opposite trend was observed after the concrete was exposed to high temperatures. This is because as

the heating temperature approached to glass transition temperature (at 560 °C), a transformation behaviour of RG from “glassy” to “rubbery” occurred in concrete matrix, which could help to fill up some pores and micro-cracks and thus giving a higher residual UPV.

- The rates of concrete mass loss were significantly higher at 300 °C, approximately 69% and 67% of the free water contained in the initial water and air cured specimens evaporated, respectively. This is due to the loss of free water in the capillary pores and loss of water from the dehydration of the C–S–H. This substantial loss of free water directly affected the residual density of concrete specimens. But, the influence of RG contents and curing regimes on density reduced as the exposure temperature exceeded 500 °C.
- The use of RG has significant effect on the water porosity and water sorptivity of the heated concrete, particularly at temperatures above 600 °C. This is because when the RG reached its melting threshold at 700 °C, the molten glass could fill the internal cracks, leading to an enhanced pore structure and better resistance to water penetration in the concrete matrix after resolidification. This demonstrates the benefit of incorporating RG in concrete especially when exposure to high temperature is anticipated.

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## References

- [1] Okamura H, Ouchi M. Self-compacting concrete. *J Adv Concr Technol* 2003;1(1):5–15.
- [2] Domone PL. A review of the hardened mechanical properties of self-compacting concrete. *Cem Concr Compos* 2007;29(1):1–12.
- [3] Sideris KK. Mechanical characteristics of self-consolidating concretes exposed to elevated temperatures. *J Mater Civ Eng* 2007;19(8):648–54.
- [4] Noumowe A, Carre H, Daoud A, Toutanji H. High-strength self-compacting concrete exposed to fire test. *J Mater Civ Eng* 2006;18(6):754–8.
- [5] Shao Y, Lefort T, Moras S, Damian R. Studies on concrete containing ground waste glass. *Cem Concr Res* 2000;30(1):91–100.
- [6] Gerry L, Ling T-C, Wong Y-L, Poon C-S. Effects of crushed glass cullet sizes, casting methods and pozzolanic materials on ASR of concrete blocks. *Constr Build Mater* 2011;25(5):2611–8.
- [7] Shayan A, Xu A. Value-added utilisation of waste glass in concrete. *Cem Concr Res* 2004;34(1):81–9.
- [8] Park SB, Lee BC. Studies on expansion properties in mortar containing waste glass and fibers. *Cem Concr Res* 2004;34(7):1145–52.
- [9] Özkan O, Yüksel I. Studies on mortars containing waste bottle glass and industrial by-products. *Constr Build Mater* 2008;22(6):1288–98.
- [10] Schwarz N, Cam H, Neithalath N. Influence of a fine glass powder on the durability characteristics of concrete and its comparison to fly ash. *Cem Concr Compos* 2008;30(6):486–96.
- [11] Shayan A, Xu A. Performance of glass powder as a pozzolanic material in concrete: a field trial on concrete slabs. *Cem Concr Res* 2006;36(3):457–68.
- [12] Ling T-C, Poon C-S. Properties of architectural mortar prepared with recycled glass with different particle sizes. *Mater Des* 2011;32(5):2675–84.
- [13] Ling T-C, Poon C-S, Kou S-C. Feasibility of using recycled glass in architectural cement mortar. *Cem Concr Compos* 2011;33(8):848–54.
- [14] Kou S-C, Poon C-S. Properties of self-compacting concrete prepared with recycled glass aggregate. *Cem Concr Compos* 2009;31(2):107–13.
- [15] Wang HY, Huang WL. A study on the properties of fresh self-consolidating glass concrete (SCGC). *Constr Build Mater* 2010;24(4):619–24.
- [16] Wang HY, Huang WL. Durability of self-consolidating concrete using waste LCD glass. *Constr Build Mater* 2010;24(6):1008–13.
- [17] EFNARC. Specification and guidelines for self-compacting concrete. European Federation for Specialist Construction Chemicals and Concrete System, Norfolk, UK, English ed.; February 2002.
- [18] BS 1881-116. Testing concrete. Method for determination of compressive strength of concrete cubes. British Standards Institution; 1983.
- [19] ASTM C597. Standard test method for pulse velocity through concrete. American Society of Testing Materials; 2002.
- [20] Zhou Q, Glasser FB. Thermal stability and decomposition mechanisms of ettringite <120°. *Cem Concr Res* 2001;31(9):1333–9.
- [21] Khoury GA. Compressive strength of concrete at high temperatures: a reassessment. *Mag Concr Res* 1992;44(161):291–309.
- [22] El-Jazairi B, Illston JM. The hydration of cement paste using the semi-isothermal method of derivative thermogravimetry. *Cem Concr Res* 1980;10(3):361–6.
- [23] Alarcon-Ruiz L, Platret G, Massieu E, Ehrlicher A. The use of thermal analysis in assessing the effect of temperature on a cement paste. *Cem Concr Res* 2005;35(3):609–13.
- [24] Ohdaira E, Masuzawa N. Water content and its effect on ultrasound propagation in concrete – the possibility of NDE. *Ultrasonics* 2000;38(1–8):546–52.
- [25] Whitehurst EA. Soniscope tests concrete structures. *J Am Concr Inst* 1951;47:443–4.
- [26] Dériano S, Rouxel T, Malherbe S, Rocherullé J, Duisit G, Jézéquel G. Mechanical strength improvement of a soda-lime-silica glass by thermal treatment under flowing gas. *J Eur Ceram Soc* 2004;24(9):2803–12.
- [27] Demirel B, Keleştemur O. Effect of elevated temperature on the mechanical properties of concrete produced with finely ground pumice and silica fume. *Fire Safety J* 2010;45(6–8):385–91.
- [28] Wang X-S, Wu B-S, Wang Q-Y. Online SEM investigation of microcrack characteristics of concretes at various temperatures. *Cem Concr Res* 2005;35(7):1385–90.
- [29] Terro MJ. Properties of concrete made with recycled crushed glass at elevated temperatures. *Build Environ* 2006;41(5):633–9.