



Properties of high volume glass powder concrete



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ABSTRACT

Mechanical and durability properties of concrete with cement replaced by finely grounded glass powder in high volume up to 60% were investigated. XRD and TGA analyses indicated that the fine glass powder reacted with calcium hydroxide to form calcium-silicate-hydrates. As such, the microstructures of concrete were more compact and homogeneous, especially at the interfacial transition zone. Concrete with cement replaced by 15% and 30% glass powder exhibited the highest strength increase and correspondingly the lowest porosity. Beyond a replacement of 30%, calcium hydroxide became insufficient for the pozzolanic reaction of glass powder. However, the high volume glass powder concrete retained distinct resistance against water and chloride ingress, due to the reduction in pore size and connectivity. Reductions of 77%, 83%, 96%, 91% and 92% were observed respectively for water penetration depth, sorptivity, conductivity, chloride diffusion and migration coefficients in concrete with cement replaced by glass powder by 60%.

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1. Introduction

Supplementary cementitious materials (SCMs) have been used widely to partially replace Portland cement in concrete. For instance, the cement manufacturers in Europe have substituted 25% of cement clinkers with other SCMs, in the past 20 years [1]. Utilization of SCMs such as fly ash from coal combustion, or silica fume from silicon and ferrosilicon alloy production, or blast furnace slag from pig iron production, as cement replacement represents a value-added approach to address the environmental concerns. As such, not only the energy consumption and carbon dioxide emission could be reduced during the cement manufacturing process, environmental advantages could also be obtained with respect to reduction in solid waste disposal and landfills.

Compared to those SCMs from industrial by-products, calcined clay is believed to have even greater potential to address the environmental impact of cement and concrete in the future, considering its availability on the earth [2,3]. On the other hand, another form of SCM, glass powder, should not be ignored due to its silica rich nature and huge amount of disposal globally. It was estimated that the global disposed solid waste was 200 million tons in 2004, 7% of which was glass products [4]. In 2013, 11.54 million tons of waste glass was generated in United States and only 27.3%

was reused [5]. Waste glasses were normally disposed into landfills if not recycled. Previous studies indicated the potential use of waste glass as constituent in concrete, such as in the form of aggregates [6–8], filler [9], alkali activated binder [10], and SCM [11–28]. The latter could bring about more economical and sustainable impact to the society.

Shao et al. [11] first reported that glass powder could exhibit pozzolanic activity if finely grounded to below 38 μm . Concrete with 30% glass powder as SCM showed lower compressive strength before 28 days but increased strength at 90 days, attributed to the pozzolanic reaction of glass powder. Similar to other SCM, pozzolanic activity of glass powder increases with decreasing particle size [11,12] and higher curing temperature [13,14]. Dyer and Dhir [15] found that the cement hydration was accelerated by the replacement of glass powder, due to the dissolution of alkalis from the glass particle. However, the amount of released alkalis is insufficient to compensate the hydration and early age strength reduction caused by the cement dilution. Similar findings were reported by Schwarz et al. [16], and Du and Tan [17].

Schwarz et al. [18] investigated the durability characteristics of concrete containing 10% glass powder as cement replacement and revealed that the chloride ingress and water intake were both reduced. However, its compressive strength was lower than plain cement concrete at each testing age up to 90 days. Matos and Sousa-Coutinho [19] examined the durability characteristics of mortar with cement substituted by glass powder by 10% and 20% and found that water sorptivity was not affected and carbonation

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resistance decreased with glass powder inclusion, while the chloride diffusion was lowered. At a high content of 30%, Carsana et al. [20] reported that the long term pozzolanic activity of glass powder, up to 7 years, was superior to natural pozzolans and similar to fly ash.

From the literature review, it is noted that the use of glass powder in mortar or concrete is still limited to 30% replacement of cement content. Recently, some previous studies have started to examine the use of glass powder as SCMs in high volume (up to 60% by weight of Portland cement) in concrete [17,21]. Both fresh and hardened properties were determined for such concretes. Although the early age strength (less than 7 days) was reduced continuously with glass powder content, the 28-day strength was found to increase, particularly for 30% replacement. Furthermore, the microstructure at the interfacial transition zone (ITZ) resulted in a denser and more compact concrete. Therefore, great improvement in the durability properties have been observed. However, with high cement substitution by silica-rich glass, the Ca/Si ratio in the formed calcium-silicate-hydrates (C–S–H) was lower and relatively more alkalis were bonded in the C–S–H phase [3]. As a result, the pH value in the pore solution would decrease while the porosity might increase with higher glass powder substitution because of the higher effective water-cement (w/c) ratio, as reported by Du and Tan [21]. However, it remains unclear as to the porosity and performance of high volume glass powder concrete after a longer curing age.

Among the diverse types of glasses, soda-lime glass is the most commonly used, such as in bottles, windows and bakeware. This is the reason why most previous literature focused on the reuse of soda-lime glass as SCM in concrete despite some parallel research on other glass types [27–29]. This study aims to investigate the pozzolanic reaction of soda lime glass powder and its influence on the microstructure of cement composites, particularly at high cement substitution levels of up to 60%. Mechanical and durability properties were assessed at the age of one year to examine the long-term performance. Alkali-silica reaction (ASR) is not considered in this study since previous works have consistently reported that no deleterious ASR would occur once the glass particle is sufficiently fine, for instance below $75\ \mu\text{m}$ [29–31]. This initiative study could help address the question as to whether glass powder could be used in concrete as SCM in high volume and shed light on the long term performances of concrete with such high volume of glass powder.

2. Experimental program

2.1. Materials

Granite stones with a maximum particle size of 10 mm and a unit weight of $1650\ \text{kg/m}^3$ were used as coarse aggregates. Natural sand used had a specific gravity of 2.65 and fineness modulus of

2.80. Portland cement CEM I 52.5N with chemical composition tabulated in Table 1, was used in this study. Glass powder was obtained by finely grinding recycled soda-lime glasses in a ball miller until the desired fineness was achieved. Detailed description of recycling and crushing glass bottles can be found in Refs. [6,7]. The specific gravity of cement and glass powder was 3.25 and 2.53, respectively. The surface texture of glass powder observed under scanning electron microscope (SEM) is shown in Fig. 1.

Also from Table 1, the sum of $(\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3)$ of glass powder is higher than the minimum requirement of 70% for pozzolans, according to ASTM C 618 [32]. Fig. 2 schematically shows the chemical composition for different SCMs including the cement and glass powder used in this study, in the $\text{CaO}_{\text{eq}}\text{-Al}_2\text{O}_3\text{-SiO}_2$ ternary diagram. X-ray diffraction (XRD) patterns for cement and glass powder are compared in Fig. 3. It is clear that the glass powder is amorphous since no clear crystalline peaks could be found. Fig. 4 displays the particle size distribution for the coarse and fine aggregates, as well as cement and glass powder. A naphthalene-based high range water reducing admixture was added as superplasticizer (SP) to adjust the workability for each mix to a slump of $75 \pm 20\ \text{mm}$.

2.2. Mix proportion

In this study, a normal strength concrete was selected as the reference mix. Glass powder was used as cement substitution at 15%, 30%, 45% and 60% respectively by weight. All the mixes are summarized in Table 2. To characterize the pozzolanic reaction of glass powder, paste samples (that is, without aggregates) were also prepared with the same water-cementitious materials (w/cm) ratio.

2.3. Specimens and test methods

For paste characteristics, 50 mm cubes were prepared and stored in saturated lime water for one year. Samples about 10 mm in size were collected from the center of each cube specimen for mercury intrusion porosimetry (MIP), thermo-gravimetric (TG) and XRD analyses. Paste samples were grounded to be less than $150\ \mu\text{m}$ and oven dried at $105\ ^\circ\text{C}$ for 18 h for the purpose of XRD and TG analyses. XRD analysis was carried out using Shimadzu XRD-6000 diffractometer with $\text{Cu K}\alpha$ ($\lambda = 1.54056\ \text{\AA}$) radiation at 40 kV and 30 mA. XRD scan was between 5° and 70° (2θ), at a speed of $0.5^\circ/\text{min}$. TG analyses were carried out in a dry nitrogen atmosphere with LINSEIS L81-II. Powder sample was heated from 30 to $950\ ^\circ\text{C}$ at a constant rate of $10\ ^\circ\text{C}/\text{min}$, under a nitrogen flow rate of 30 ml/min while the weight was continuously recorded. Before MIP test, samples were conditioned in a desiccator at $40\ ^\circ\text{C}$ until a constant weight was achieved. A maximum mercury pressure of 412.5 MPa was applied in the micromeritics AutoPore III machine.

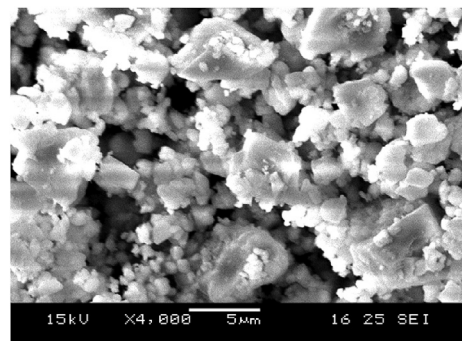


Fig. 1. SEM image of finely grounded glass powder.

Table 1
Chemical composition of cement and glass powder.

Composition, %	Cement	Glass powder
SiO_2	20.8	72.08
Al_2O_3	4.6	2.19
Fe_2O_3	2.8	0.22
CaO	65.4	10.45
MgO	1.3	0.72
SO_3	2.2	–
Na_2O	0.31	13.71
K_2O	0.44	0.16
TiO_2	–	0.1
Cr_2O_3	–	0.01

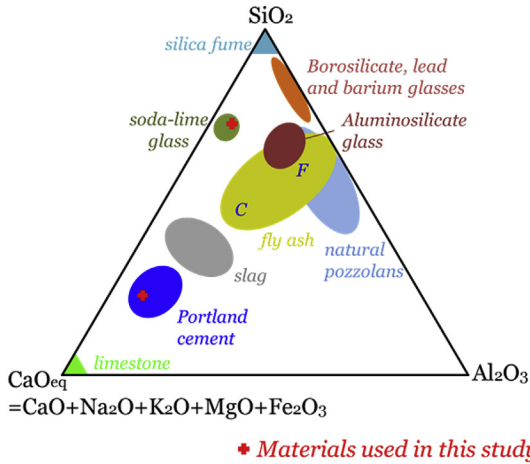


Fig. 2. Ternary diagram of mainly used supplementary cementitious materials and glasses.

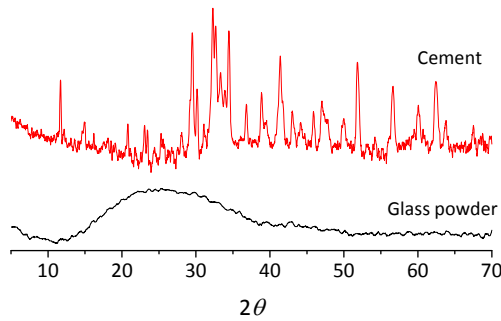


Fig. 3. XRD patterns for cement and glass powder.

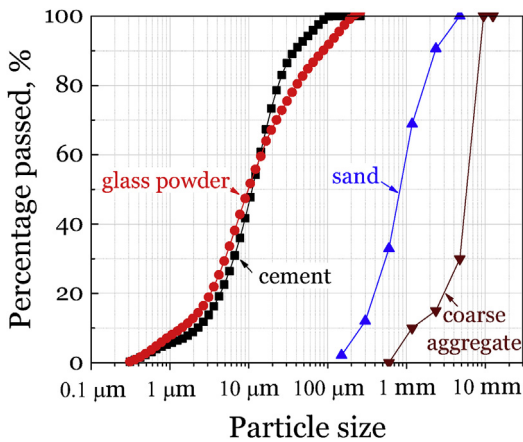


Fig. 4. Particle size distribution of raw materials.

Table 2
Mix proportions of concrete with glass powder.

Mix no.	Content, kg/m ³					SP
	Water	Cement	Glass powder	Coarse aggregate	Sand	
REF	185	380	0	825	960	3.8
15GP	185	323	57	825	948	3.2
30GP	185	266	114	825	936	3.0
45GP	185	209	171	825	925	3.9
60GP	185	152	228	825	913	4.5

For concrete performance investigation, all the specimens were stored in water until the testing age. Three $\text{Ø}100 \times 200$ mm concrete cylinders were made to determine compressive strength at each testing age of 7, 28 and 365 days, as per ASTM C 39 [33]. Samples void of large aggregates were collected from the fractured surface for MIP test. Conditioning was kept the same as described for paste samples. All the transport properties were obtained for concrete specimens after curing for one year. Three $\text{Ø}100 \times 50$ mm cylindrical slides were cut from one cylinder to determine the water accessible porosity, as per ASTM C 642 [34].

Water penetration depth was recorded for two $\text{Ø}100 \times 200$ mm cylinders under a water pressure of about 7.5 bars for 7 days, following BS EN 12390-8 [35]. Water absorption was also determined in accordance with ASTM C 1585 [36], for three $\text{Ø}100 \times 50$ mm cylindrical slices during initial absorption (between 1 min and 6 h). The water sorptivity (s) was determined from:

$$\frac{W}{\rho A} = s\sqrt{t} + s_0 \quad (1)$$

where W is the weight gain, ρ is density of water, A is the exposed area, t is the time, s_0 is the initial disturbance, a constant.

To evaluate the resistance against chloride penetration, both accelerated and non-accelerated tests were carried out. Rapid chloride penetration test (RCPT) and rapid chloride migration (RCM) test were performed according to ASTM C 1202 [37] and NT Build 492 [38], respectively. Three $\text{Ø}100 \times 50$ mm cylindrical slices were prepared for each test. For RCPT, the specimens were applied a constant electric potential of 60 V for 6 h. The amplitude of the current (I) was recorded every 10 min and the result was expressed as the amount of total charge (Q) passing the specimen, given by:

$$Q = \sum_0^{6h} I_i \cdot \Delta t \quad (2)$$

Compared to RCPT, RCM result reflects the ability of concrete to resist chloride ions under migration. For RCM, a 30 V electric field (U) was applied for 24 h (t) to the specimen. After that, the specimen was axially split and the chloride penetration depth (d) was determined. Non-steady state migration coefficient (D_{nssm}) was obtained from the following formula [38] considering the average temperature (T) before and after the testing.

$$D_{nssm} = \frac{0.0239(273 + T)}{(U - 2)t} \left(d - 0.0238 \sqrt{\frac{(273 + T)Ld}{(U - 2)t}} \right) \quad (3)$$

Apparent chloride diffusion coefficient (D_{app}) was calculated by analyzing the chloride content at different concrete depths at a specific period, that is $C(x, t)$ as described by NT Build 443 [39]. In this study, one $\text{Ø}100 \times 100$ mm cylindrical slice was immersed in 185 g/L NaCl solution for 56 days (t) and the chloride was determined at every 10 mm depth. Thus, D_{app} could be obtained from Eq. (4):

$$C(x, t) = C_0 \left[1 - \operatorname{erf} \left(\frac{x}{2\sqrt{D_{app}t}} \right) \right] \quad (4)$$

3. Test results and discussion

3.1. XRD and TG analyses

The XRD patterns for paste containing varying glass powder contents after one year of curing are shown in Fig. 5. It is noted that

the intensity of peaks corresponding to calcium hydroxide gradually decreased with higher glass powder replacement, qualitatively indicating that the cement hydration products reacted with glass powder in the pozzolanic reaction. When cement grains start to hydrate, the pore solution becomes rich in Ca^{2+} , SiO_4^{2-} and OH^- . Amorphous silica in glass powder (Si–O–Si bond) could be dissolved under this high pH solution, producing a layer rich in Si on the surface of glass powder. This layer reacts with Ca^{2+} ions in the solution and transforms to calcium silicate hydrates (C–S–H). This formed C–S–H has lower Ca/Si ratio and thus uptake more Na^+ released from the glass powder. The degree of glass powder hydration depends on the cement substitution level. With increasing glass powder content, less available Ca^{2+} and lower pH in the pore solution would weaken the hydration degree of glass powder. Similar findings were reported for fly ash at high replacement levels [40]. To accurately examine the calcium hydroxide content, TG analysis was carried out as follows.

Original TG curves are plotted in Fig. 6a, which shows a continuous reduction in weight of sample with increasing temperature. Calcium hydroxide decomposes to calcium oxide and water in the temperature range of 410–550 °C [17]. The calcium hydroxide content was calculated taking into account the molecular weight of each component and expressed as the percentage of sample dry weight at 105 °C in Fig. 6b. After one year of curing, the OPC paste had a calcium hydroxide content of 21.5%. Calcium hydroxide from cement hydration slowly reacted with glass powder to form C–S–H. With higher glass powder replacement, calcium hydroxide consistently decreases in the hydrated paste, particularly when more than 30% cement was substituted by glass powder. At 15% and 30% glass powder replacement rates, there still remained calcium hydroxide from the pozzolanic reaction with glass powder. At 45% and 60% glass powder replacement rates, the calcium hydroxide was reduced significantly, indicating that all the formed calcium hydroxide participated in the pozzolanic reaction. The average molar ratio of Ca/Si was about 1 for 45% glass powder replacement rate. Meanwhile, the Ca/Si molar ratio was as low as 0.67 for 60% glass powder concrete. From the content of calcium hydroxide in the glass powder-cement system, the complete pozzolanic reaction of glass powder laid in between the replacement rate of 30% and 45%.

3.2. Porosity and microstructure

Water accessible porosity was determined and displayed in Fig. 7 for concrete with different OPC replacement level. According to Meyer et al. [41], this water accessible porosity is a reflection of the total volume of open pores larger than 100 nm. Open pores are the pathways for water as well as ions to permeate the concrete system. It is clear that the water accessible porosity were

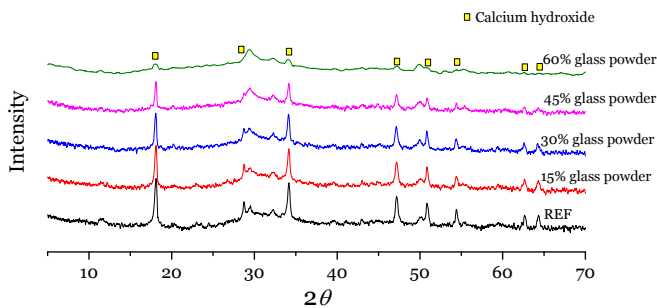


Fig. 5. XRD patterns for pastes containing different contents of glass powder after one year of curing.

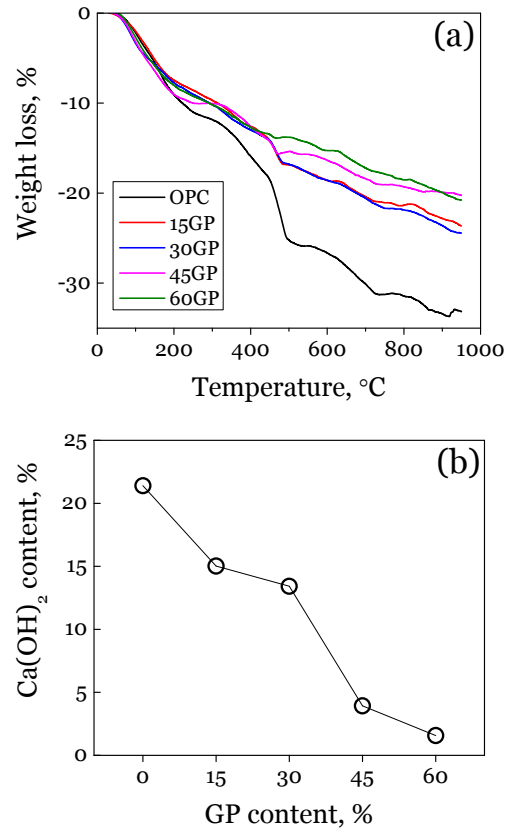


Fig. 6. (a) TGA curves and (b) $\text{Ca}(\text{OH})_2$ content for paste containing varying amounts of glass powder.

continuously increased for higher glass powder substitution, from 14.3% for plain concrete to 16.6% for 60% GP concrete. In this study, OPC was replaced by glass powder by mass with the latter having a smaller specific gravity. It means that the volume fraction of paste (including water, cement and glass powder) increases from 30.2% for the reference mix to 32.2% for 60GP mix, which might contribute to the slight increase in the porosity.

Besides total porosity, pore size distribution (PSD) is of great significance to govern the transport of water and species in concrete. PSD curves were determined by MIP for both paste and concrete samples and shown in Fig. 8. Pastes containing different glass powder contents showed similar PSD curves (Fig. 8a).

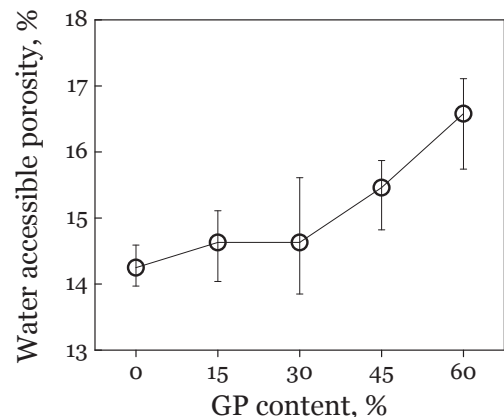


Fig. 7. Water accessible porosity of concrete with different contents of glass powder.

Compared to the reference paste, glass powder pastes had more refined pores, as indicated by the shifted curves. This could be due to the pozzolanic reaction of glass powder which densified the microstructures of paste. Some previous research works on SCM reveal that the total porosity of SCM-cement paste would only slightly change [42] or increase due to the increased effective w/cm ratio while the capillary pores would be refined [43,44]. This is consistent with the current study in which the PSD curve moves towards a finer pore size while the total porosity remains similar.

Concrete consists of paste and aggregates, as well as interfacial transition zone (ITZ) which is more porous compared to the bulk paste. As reflected by the PSD curve (Fig. 8b), concrete has a lower total porosity than paste due to the inclusion of impermeable aggregate particles but a much higher threshold pore diameter because of the porous ITZ. In contrast to the slight influence of glass powder on paste microstructure, PSD of concrete was refined with the replacement of cement by glass powder. Threshold and critical pore diameter were determined from PSD curves for each paste and concrete mix, as listed in Table 3. This should be attributed to the modification of ITZ in concrete by the pozzolanic reaction of glass powder. The formed secondary C–S–H gels filled the pore structure at the ITZ and reduced the critical pore size, as revealed by the PSD curves of concrete with 15%, 30% and 45% glass powder substitution rates. At 60% replacement level, there was insufficient calcium hydroxide to react with glass powder to further fill the pores. Thus, the PSD of concrete has a higher volume fraction of pores in the range of 0.1–10 μm , at this high replacement rate.

Microstructures of plain and 30% glass powder concrete were also visually observed by using SEM, as shown in Fig. 9. For the plain concrete, ITZ could be easily identified from its relatively more porous microstructure caused by the high w/c ratio. This zone is considered as the weakest link under mechanical loadings and also the most readily pathway for water and aggressive ions. In contrast, the interfacial microstructures were clearly more compacted in 30% glass powder concrete, as displayed in Fig. 9b. Consistent with the MIP results, the pozzolanic reaction of glass powders could densify the bulk and ITZ paste due to the formed C–S–H gels. Hence, it is deduced that the mechanical and durability performances should be improved for the glass powder concrete which has better ITZ.

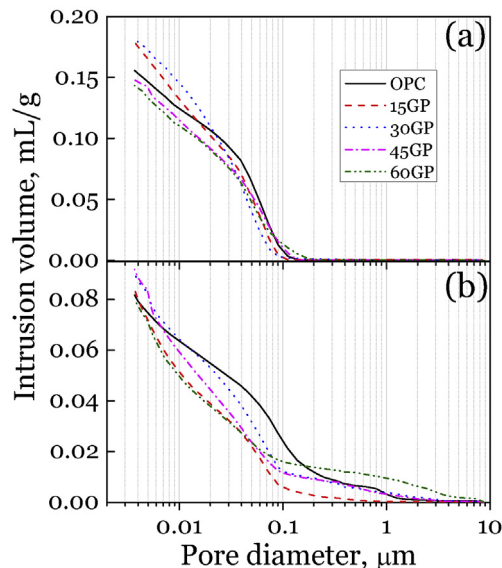


Fig. 8. Pore size distribution of (a) paste and (b) concrete with different contents of glass powder.

Table 3
Threshold and critical pore diameter determined by MIP for paste and concrete.

Mix	Paste		Concrete	
	d_c , nm	d_t , nm	d_c , nm	d_t , nm
OPC	47.9	170.6	90.3	1256.4
15GP	47.9	111.7	59.6	214.5
30GP	47.9	111.7	73.8	1256.4
45GP	47.9	139.4	39.2	1256.4
60GP	47.9	170.6	47.7	3502.3

d_c : critical pore diameter.

d_t : threshold pore diameter.

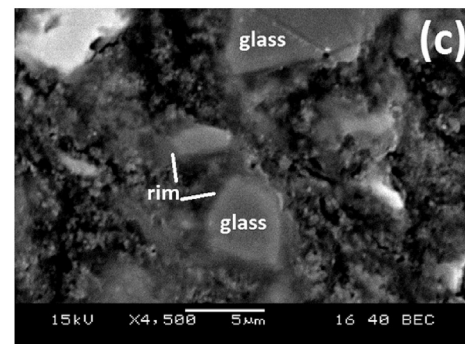
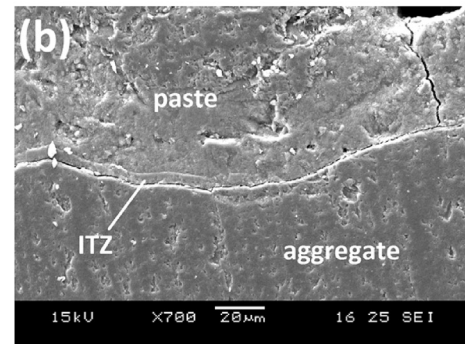
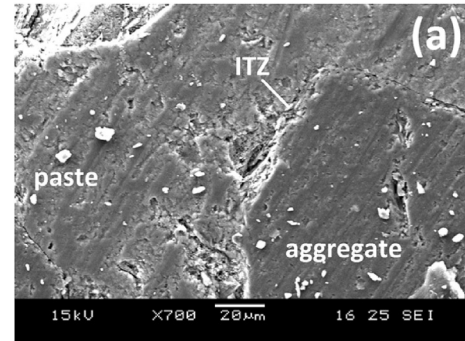


Fig. 9. SEM images of (a) plain concrete and (b) 30% GP concrete, and (c) 60% GP paste.

Though no previous literature has reported the ASR of concrete system containing high volume glass powder (above 30%), it is assumed that ASR would not be deleterious. Glass powder do not only reduces the pH level but also increases aluminum concentration in the pore solution which can depress the dissolution rate of silica [45] as well as decrease the pre-existing micro-cracks that favor the formation of ASR gel [46]. In this study, obvious pozzolanic reaction of glass powder has been observed from TG analysis.

Fig. 9c shows the microstructure of paste containing 60% glass powder at the age of one year. No clear sign of ASR gel could be noticed while a pozzolanic reaction rim was seen around the glass grains. This is consistent with previous works that found pozzolanic reaction to more readily occur at the interface of glass grain, rather than ASR [45,46].

3.3. Compressive strength

The advantages of high volume glass powder concrete can be seen by the compressive strength development history, up to one year in Fig. 10, whereas plain cement concrete exhibited high strength at 7 days, it had the lowest strength at 365 days. Due to the slow rate of glass powder pozzolanic reaction, the replacement of cement would reduce the early age strength. With longer curing age, the amorphous silica in glass powder slowly dissolved under the alkaline environment and reacted with Ca^{2+} to form C–S–H gels.

With this process, concrete porosity would decrease and strength could increase. At the age of one year, mixes with 15% and 30% glass powder exhibited the highest compressive strength, about 27% higher than the reference plain concrete mix. Concrete with 60% glass powder, which gained only 65% of that of the plain concrete mix at 7 days, exceeded the reference mix by 12% at 365 days. A more compact microstructure of the paste matrix, especially at the ITZ, contributed to the enhanced mechanical strength. It should be noted that the pozzolanic reactivity of glass powder is directly related to its particle size [24]. Smaller particle size would yield higher pozzolanic reactivity. Hence, the strength development rate would also be influenced by the particle size distribution of glass powder, which is worthy of further investigation, especially when early age strength is critical.

The observations on compressive strength correlate well with the reduced porosity of concrete, determined by MIP. Mixes with 15% and 45% glass powder showed the highest strength and at the same time exhibited the lowest porosity. With respect to 28-day or later strengths, the optimum glass powder replacement rate seems to be in the range of 15% and 45%.

3.4. Transport of water in glass powder concrete

The penetration depth of water into concrete under a constant pressure is displayed in Fig. 11. An average water penetration depth of 31.8 mm was observed for the reference concrete mix. Comparatively, all mixes with various glass powder replacements showed greatly reduced penetration depths, about 75% lesser. At the same time, it is interesting to note that there was no further

improvement when glass powder exceeded 15%. This is different from the influence on the compressive strength, as discussed above. Water permeability of concrete depends on porosity, pore size distribution and pore connectivity. The refined pore sizes and porosity of paste at ITZ, due to pozzolanic reaction of glass powder, could partially block the pathways for water ingress.

The influence of glass powder on the initial water sorptivity of concrete is shown in Fig. 12. The reference plain concrete exhibited the highest sorption rate of $4.27 \times 10^{-4} \text{ mm/s}^{0.5}$. The glass powder substitution significantly decreased this sorptivity, similar to the water penetration depth. At 15% replacement rate, glass powder concrete exhibited the highest resistance against water sorption, that is, only 9% of that for the reference concrete. Water sorptivity reflects the ability of water uptake rate into unsaturated concrete. The measured improvement in sorptivity is attributed to the reduced size and connectivity of pores in paste matrix and ITZ. With increasing glass powder volume, sorptivity appears to increase slightly until a 60% replacement rate, due to the lower effective w/cm ratio at higher cement replacement rates. Schwarz et al. [18] reported that concrete with 10% glass powder exhibited reduced sorptivity at the age of 14 days. However, that concrete showed higher sorptivity than the reference mix at the age of 90 days. Matos and Sousa-Coutinho [19] reported no influence for the sorptivity of concrete with 10% and 20% glass powder as SCM, because of the similar fineness of cement clinker and glass powder.

From the water transport measurements in this study, regardless of driving mechanism of permeability or absorption, the use of glass powder as SCM in concrete effectively hindered the movement of water (and potentially the harmful agents in water such as chloride and sulfate). At the same time, the glass powder replacement level seems to have minor influence on the transport of water. Hence, high volume glass powder concrete could provide excellent resistance to water penetration in the long term.

3.5. Electrical conductivity

In this study, RCPT result is interpreted as an indicator for electrical conductivity since it is a technique measuring the accumulated charges (not only chloride) passing through the specimen under a constant voltage [47]. The results are shown in Fig. 13. The average amount of charges passing the reference concrete is 3587 Coulombs. This value continuously decreases with higher glass powder content up to 60%. Electrical conductivity of concrete is governed not only by the porosity and pore structures but also by the pore solutions. For plain cement paste, the pore solution is filled

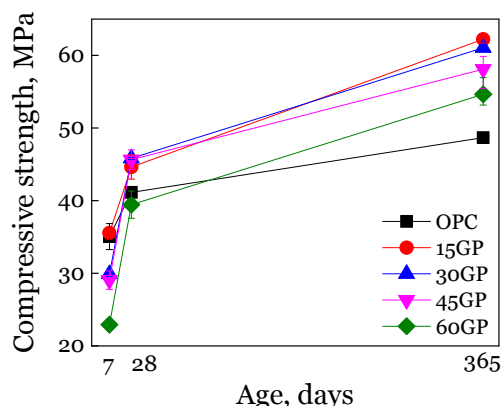


Fig. 10. Compressive strength of concrete with different contents of glass powder.

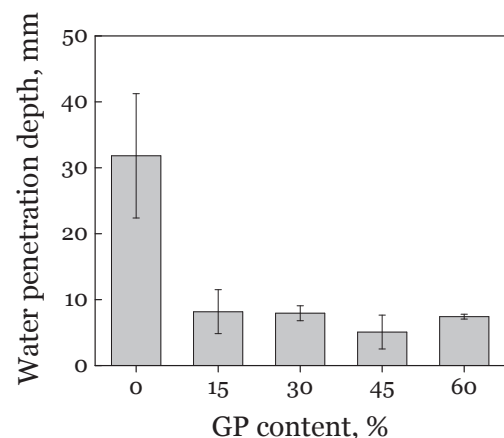


Fig. 11. Water penetration depth of concrete with varying amounts of glass powder.

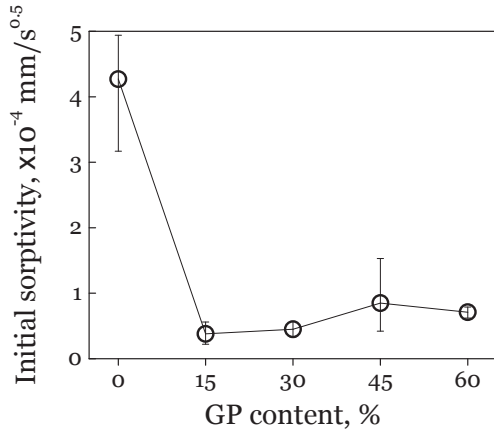


Fig. 12. Initial water sorptivity of concrete with varying amounts of glass powder.

with hydration products, including Na^+ , K^+ , Ca^{2+} , and OH^- . With more cement replaced by glass powder, the amount of OH^- and Ca^{2+} would be reduced, and at the same time alkalis might also be uptaken into the formed C–S–H gels with low Ca/Si ratio. Therefore, both the enhanced microstructure and reduced ions concentration in the pore solution result in the reduction of electrical conductivity. Similar finding on the reduced conductivity was also reported for mortars or concretes containing glass powder as partial cement replacement. Schwarz et al. [18] reported a slight decrease in the total RCPT result by replacing 10% of cement by glass powder in concrete. An increase in electrical resistance (inverse of conductivity) about 7–8 times was observed by Carsana et al. [20], which is comparable to the observations as obtained in this study. Furthermore, the substantial reduction in the electrical conductivity was similar to the high volume fly ash concrete which is commonly known for its excellent durability [48].

3.6. Transport of chloride ions in glass powder concrete

Both chloride diffusion and migration tests were carried out in this study to investigate the resistance against chloride penetration. Fig. 14a shows the chloride content profiles along the diffusion distance, after 56 days of immersion. The reference concrete had the highest chloride content at each depth, indicating that it has the lowest resistance. Also, the value of apparent diffusion coefficient was obtained by regression analysis and shown in Fig. 14b, and the resultant best fitted curves are also plotted in Fig. 14a. The obtained apparent diffusion coefficient is 36.92×10^{-12} m²/s for the

reference concrete. It decreases significantly with the incorporation of glass powder in the binder, regardless of replacement level. A reduction of 90% in the diffusion coefficient was recorded for 30% glass powder concrete, which is higher than a previously reported reduction of between 50% and 60% [20]. The reduced diffusivity of chloride into concrete with glass powder is due to the more compact microstructures of paste at ITZ and the reduced pore size and connectivity.

Non-steady state migration coefficient D_{nssm} is displayed in Fig. 14b for concrete with different glass powder contents. Consistent with the electrical conductivity, the value of D_{nssm} decreased with increasing glass powder ratio in the binder, particularly beyond 15%. At 15% and 30% glass powder, D_{nssm} was lowered to 17% and 10% of plain concrete, respectively. This reduction is more significant than the results obtained by Matos and Sousa-Coutinho [19]. At 60% glass powder rate, D_{nssm} was reduced by 92% from the reference concrete.

From both accelerated and non-accelerated test results, chloride ions were found to be less readily to diffuse/migrate into concrete with glass powder as SCM up to 60%. Main reasons include the denser microstructure and more tortuous pathways for chloride ions, as a result of the pozzolanic reaction of glass powder. This could help prolong the lifetime of reinforced concrete structures under the attack of chloride.

4. Conclusions

The use of high volume glass powder as cement replacement in concrete was proposed in this study. A comprehensive experimental program was conducted to investigate the microstructures, mechanical and durability properties of such concretes, focusing on the performances in the long term. After one year of curing, XRD

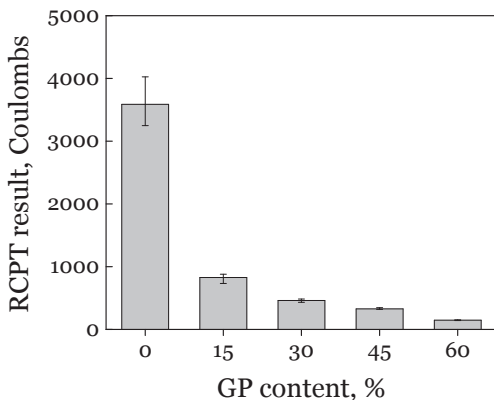


Fig. 13. Influence of glass powder on RCPT results of concrete.

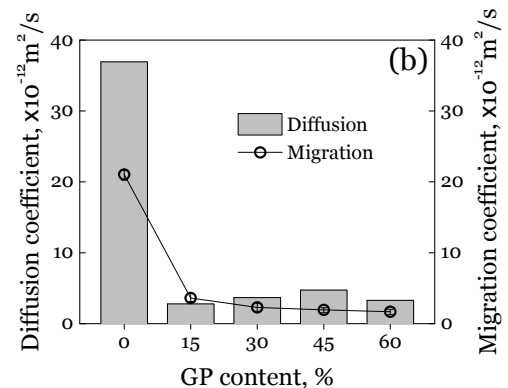
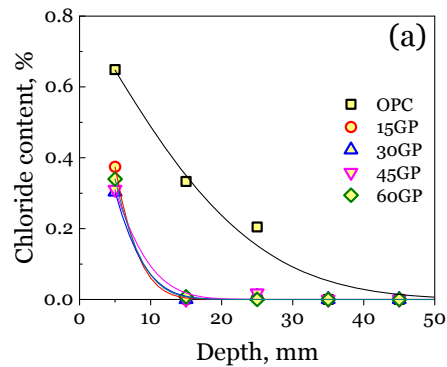


Fig. 14. (a) Chloride content profiles and (b) chloride diffusion coefficient and migration coefficient for concrete containing glass powder.

and TG results indicated that calcium hydroxide had become significantly consumed by the pozzolanic reaction of glass powder where more than 30% cement was replaced by glass powder. As a result of this pozzolanic reaction, all mixes containing glass powder exhibited superior performances compared to the reference concrete. Despite a higher porosity in the mixes with high volume glass powder (45% and 60%), they still exhibit much better resistance to the transport of water and chloride ions, attributed to the refined pore system and densified transition zone.

Compared with previous works, this study extended the application of recycled glass as supplementary cementitious material to a much larger amount, up to 60%. Besides the lower amount of raw materials, waste disposal, energy consumptions and carbon footprint, the advantages of high volume glass powder concrete have been demonstrated in this study by the better mechanical behaviors, and more distinctly by the higher durability performance. Also, in this study, a laboratory scale ball mill was used to reduce the glass particle size to the desired fineness. In practice, more efficient equipment such as industrial scale mill can be used for this purpose which could further reduce the energy consumption in the grinding.

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