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Mechanical and Durability Properties of Sustainable Self-compacting Concrete with Waste Glass Powder and Silica Fume

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Abstract

Environmental protection approach has caused to ignore the conditions and the possibility of using solid waste as a substitute for concrete. In this research, the effect of glass powder in percentages of 0-30 (in steps of 7.5%) and micro-silica (10% as a constant) as a substitute for cement is investigated on efficiency, compressive strength, tensile strength, and bending strength. surface water absorption, capillary water absorption, and freeze/thaw cycle are paid. The results showed that the use of glass powder leads to increases the fluidity and properties of fresh concrete. The mechanical parameters decrease slightly when 30% of cement is replaced with glass powder.

Keywords

cementitious material, glass powder waste, self-compacting concrete, mechanical properties, freeze-thaw damage

1 Introduction

As glass wastes are non-biodegradable and incompatible with the environment, transferring them to waste disposal sites is not desirable [1]. Compared to other wastes such as paper or organic constitutes, a large amount of the glass waste remains in the disposal site as residue even after incinerating for purification purposes [2]. Ordinary glasses include amorphous silicon and magnesium oxides, potassium and sodium carbonates and calcium lime, and their difference is usually in the type and amount of the used raw materials [3]. The glass CaO reacts with water and amorphous SiO2 and produces low-basicity calcium-silicate-hydrate (C-S-H) crystals, and its Na2O is always challenging because it increases the probability of alkali-silica reactions; it is worth noting that such reactions require a sufficient amount of water, alkali and reactive grains, and other factors - aggregate type/size, water to cement ratio (W/C), concrete type and alkali permeability/solubility - highly affect how they begin and how fast they proceed [4]. Replacing cement with glass and creating pozzolanic properties is quite logical and the resulting material is available as a shapeless X-ray amorphous. Substituting glass for part of the cement is both nature-friendly and economical [5]. Using an ideal particle size distribution will not only reduce the binder quantity, but will also lessen the packing density without evident negative effects on the rheological properties [6]. Lee et al. [7] believes that in producing cementitious composites, the mean particle size and surface area of pozzolanic materials should be equal to or less than those of the Portland cement to create desirable pozzolanic properties. Positive effects of the glass powder on the concrete strength and durability, and its pozzolanic behavior become evident when its particles are smaller than 38 μm [8]. Substituting glass powder for part of the cement will reduce the negative effects of alkaline-silica reactions in concrete [9]. Silica fume (SF) is generated as fine particles during the production of silicon and Ferro-silicon alloys and is removed from the furnace by exhaust gases [10]. Using it in concrete/cement composites: 1) is expensive, 2) reduces the reactivity due to the particles' high fineness and agglomeration and 3) can be considered as an inert micro-filler instead of pozzolanic material or hydration accelerator [11]. When part of the cement is replaced with the SF, a large amount of portlandite is consumed and, hence, a large amount of C-S-H gel, which is the main agent in creating resistance in cement-based materials, is produced. The so-called seeding effect

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phenomenon is defined as selecting the silica surface and introducing it as a nucleation center for the formation of the C-S-H structure produced by the alite and belite hydration [12]. While SCC creates good quality, productivity and working conditions in the construction process, superplasticizer help it achieve such desirable properties and features as permeability, flowability, fillability and so on without increasing the W/C ratio [13].

Previous research have evaluated the use of glass waste as alternative supplementary cementitious materials (ASCMs) considering its chemical composition and particle-size distribution [13]. Sharifi et al. [14] observed that using 0-30% glass powder in SCC would specifically increase its workability and reduce its density by about 1.37%. After a quantitative and qualitative examination of the X-ray diffraction (XRD) of ultra-high-performance concretes (UHPC). Ling et al. [15] and Ling and Poon [16] have claimed that the presence of the recycled glass in SCC and applying high temperatures (up to 600 °C) will reduce the concrete residual strength, but increasing the temperature up to 800 °C will noticeably improve the water absorption and elasticity modulus [17]. Merits enumerated by Ling et al. [2] regarding the use of waste glass in the production of concrete products include positive effects on durability due to its high resistance against abrasion and acids. Increasing the optimum SF up to 25% will create more dense concrete mixtures and increasing it to 30% will yield the highest compressive strength [18]. Matte and Moranville [19] believe that the SF required theoretically for reaction with hydration products is about 18%. Ali et al. [20] have stated that the SF can reduce the negative effects of plastic aggregates on the concrete strength and decrease the compressive and tensile strengths by 4.7 and 1.1%, respectively. Sadrmomtazi et al. [21] have reported that using 5-15% silica fume in fiber-reinforced concrete will improve the bond behavior to strength due to reduced crystallization and appearance of amorphous structures and will positively affect the fiber-matrix transition zone. Producing better-quality hydration products and improving the ITZ structure around the fibers will result in greater micro-hardness and better fiber-cement paste bond. Copetti et al. [22] believe that using silica fume in tire-rubber concretes will increase the compressive strength by about 80% and attribute the improved concrete mechanical properties to reduced volume of the pores (about 13%) and the increased ITZ strength. Strength and water absorption of the modified reactive powder concrete containing powder glass and ceramic were evaluated by Radhi et al. [23]. A significant enhancement was observed in mechanical behavior of modified reactive powder concrete containing 15 % waste pozzolanic material [23]. Cao et al. [24] showed that the workability, compressive strength and durability indicators improved with the increased of glass powder content in concrete. Moreover, the results revealed that the presence of waste glass powder has a great effect on the flowability and flowability retention time when were used with especial superplasticizer [25].

This research is aimed to provide a suitable, scientific solution to remove or reduce glass-waste-related environmental problems, reduce the concrete production costs, reduce the cement production-related pollutants and improve the SCC characteristics. To this end, the cement was replaced with 0, 7.5, 15, 22.5 and 30% glass powder and 10% (fixed) Silica fume (SF), and parameters of fresh concrete, properties of hardened concrete as well as their durability were evaluated. Results of this research, confirmed by scanning electron microscope (SEM) images, show that producing desirable-technical-performance, nature-friendly SCC is possible through the use of the glass powder and SF. The environmental problems of cement production and using of larger volumes of cement in the production of self-compacting concrete require investigating the performance of concretes containing cement additives. Examining the performance of these types of concrete in the field of fresh concrete, hardened concrete, as well as different durable environments requires scientific evaluation. Meanwhile the use of glass powder as a substitute for part of cement (in combination with micro-silica), in addition to environmental benefits, improves the properties of fresh concrete and the mechanical characteristics and durability of concrete too. In this research, it has been tried to implement two complementary materials which have a very high power in increasing hydration products and strengthen the resistance and durability of concrete. In the former research, the effects of these two materials (micro-silica and waste glass powder) have been studied separately on mechanical properties of concrete. While the freezing and thawing cycle has been surveyed rarely.

2 Experimental plan

2.1 Materials

Scrap glass pieces, brought from glass factories, were crushed and powdered in an electric mill with a maximum size of 100 μm and concrete specimens were prepared using natural broken fine and coarse aggregates with maximum sizes of 4.75 and 19.5 mm, respectively. Both aggregate types were saturated surface dry (SSD) and were prepared and used based on the ASTM C33-08 [26] requirements. The water used to produce and cure concrete specimens was of the drinking type (ASTM C94) [27].

2.2 Mixture proportions

In the five mixes designed in this study, the first one (GPSF0) is a control design and the other four (GPSF1, GPSF2, GPSF3 and GPSF4) have been prepared by replacing cement with 7.5, 15, 22.5 and 30% glass powder and 10% (fixed) silica fume; W/C, superplasticizer and fine and coarse aggregates are fixed and equal to 0.47, 0.65%, 680 kg/m^3 and 1050 kg/m^3, respectively, in all designs. Details of all mix designs (containing glass powder and silica fume) are shown in Table 1. In Order to maintain the stability and consistency of the self-compacting concrete produced, limestone powder has been used at a constant rate of 120 kg/m^3.

2.3 Testing of specimens

2.3.1 Fresh SCC properties

SCC is known for its high flowability, non-separability, high fillability, good passability and distributability without mechanical compaction. Its efficiency describes the conditions of mixing, spreading, placement, stability and flowability and is evaluated for flowability and performance by various tests [28] including slump, J-ring, V-funnel and L-box [29]. The movability and deformation of concrete under its own weight is tested by its slump [30], which usually varies in the range of 550–850 mm for the SCC. Siddique et al. [31] believe that slumps less than 500 mm prevent proper passage of concrete through the rebar density and more than 700 mm increase its separability. The L-box test models the SCC passability through the density of rebars and describes its blocking behavior when meeting them [29]; here, the SCC passability evaluation criterion is the ratio of the concrete height in the horizontal part of the machine to that in its vertical part.

Table 1 Mix design of SCC studied

Mix	W/C (%)	Cement (kg/m^3)	Limestone powder (kg/m^3)	Glass powder (%)	Glass powder (Kg/m^3)	Silica fume (%)
GPSF0	0.47	400	120	0	0	0
GPSF1	0.47	330	120	7.5	30	10
GPSF2	0.47	300	120	15	60	10
GPSF3	0.47	270	120	22.5	90	10
GPSF4	0.47	240	120	30	120	10

It hould vary in a 0.8-1 range; less than 0.8 means very high viscosity and increased possibility of concrete blockage. Slump flow test is shown in Fig. 1.

2.3.2 Hardened SCC properties

To evaluate the compressive strength of concretes with/without glass powder/silica fume, 150 × 150 × 150 mm cubic specimens were used and the average of three cubes was reported as the final compressive strength. Tensile strength test for all mix designs was performed on three 150 × 300 mm cylindrical specimens and flexural strength was calculated using three 150 × 150 × 450 mm beams. In the hardened part and for mechanical tests, all the specimens were evaluated at 28 days of age.

2.3.3 SCC durability

Three 100 × 100 × 100 mm cubic specimens were tested for surface water absorption and the average was determined. The specimens were put in the oven after 28 days of curing to reach a fixed weight and their dry weight was recorded. Next, after immersion in water for 1 h, 1 day, 7 days and 28 days, they were taken out of the tank, dried with a piece of linen cloth and their saturated weight was recorded.

The capillary water absorption of concretes containing glass powder and silica fume was evaluated using three 100 × 100 × 100 mm cubic specimens. After curing for 28 days, the specimens reached a constant weight and their four sides were isolated with paraffin wax and the dry weight was recorded as the initial weight. With water moving from the lower to the upper side, the sorptivity coefficient (K) was found at 0.5 h, 1 h, 5 h and 24 h [32]:

$$K = \frac{Q^2}{A^2 T}, \quad (1)$$

where K, Q, A and T are the sorptivity coefficient, adsorbed water, section area and time, respectively.

Fig. 1 slump flow test

Three 150 × 150 × 150 mm 28d-age specimens were used to examine the effects of the glass powder/silica fume on the SCC compressive strength/weight loss under freeze-thaw cycles. The average flexural strength of three 150 × 150 × 450 mm beams was calculated after being placed under freeze-thaw cycles and the strength loss was evaluated. Numbers of test cycles were 25 and 50, thaw temperature was 18–20 °C, freeze temperature was -18 to -20 °C and the freeze-thaw process time was 4 h to find the weight and compressive strength variations [33]. After the completion of the freeze-thaw cycles, the specimens were removed from the device, their sides were dried with a piece of linen cloth and their losses of weight, compressive strength and flexural strength were found after 25 and 50 freeze-thaw cycles.

2.3.4 Microstructural properties of SCC

To scientifically confirm the test results of the hardened concrete, pieces were cut from the middle of the compressive strength test specimens and analyzed with SEM (scanning electron microscope) images for microstructural and surface morphology variations. Results showed the effects of microcracks, pores, and ettringite and hydration products on the hardened concrete behavior.

3 Results and discussion

In Fig. 2 that shows the fresh concrete test results, the slump diameter of all mix designs lies in the 66.3–71.1 cm range. Fig. 2(a) shows that increasing the glass powder from 0 to 30% increases the slump diameter by about 7.24%. The J-ring test results show that GPSF2 has less passability than other mix designs (Fig. 2(b)). All mix designs have inner-outer ring height-difference in the 12–20 mm range. The J-ring test T500 variations are similar to those of the concrete passability through the ring rebars. When glass powder is in the 0–15% range, concrete accumulates inside the ring causing passability to reduce, but increasing it up to 30% improves the passability due to less water absorption and increased W/C. V-funnel test results show that increasing the SCC glass powder reduces the T500; however, GPSF1 has a longer T500 than the control design (Fig. 2(c)). Based on Table 1, GPSF0, GPSF1, GPSF2, GPSF3 and GPSF4 meet the EFNARC requirements. Only GPSF3 and GPSF4 lie in VF1; other mix designs show the VF2 classification requirements. Studies show that proper viscosities maintain good suspension of coarse aggregate and prevent separation in the concrete deformation process. This feature reduces the inter-particle contact and concentration of coarse aggregates and increases the grout

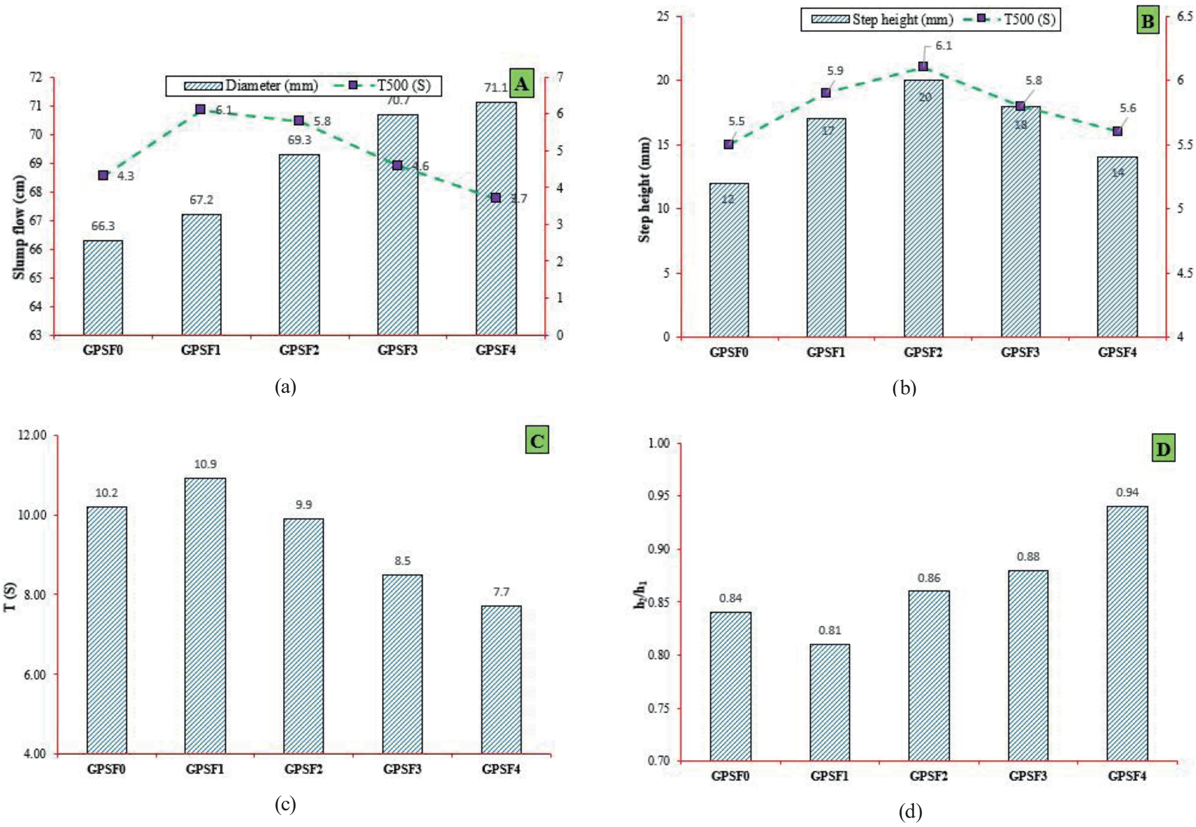

Fig. 2 Fresh specimens' tests: a) slump flow test, b) J-ring test, c) V-funnel test, d) L-box test

mixture's ability to fill the mold. In Fig. 1(d), all concrete specimens with/without glass powder have h2/h1 parameters in the 0.81–0.94. Among all the mix designs, only GPSF1 has less passability than GPSF0. As the cement-glass powder replacement is by weight and glass weighs less than cement, the solid particles-to-water ratio increases causing the cement-glass paste inter-particle friction to increase and the performance to improve slightly [7].

In Fig. 3, the compressive strengths of 28d SCC specimens with glass powder and SF are, respectively, 31.2, 32.8, 34.7, 36.5 and 34.5 MPa for GPSF0, GPSF1, GPSF2, GPSF3 and GPSF4 with the best performance relating to the design with 22.5% glass powder and 10% SF. The strength increase of all mixtures compared to the control design lies in the 5.13–16.99% range, but when the glass powder increases to its maximum value (glass powder = 30%), there is a strength loss of about 6.41% compared to GPSF3. Federico and Chidiac [34] have shown that conventional concretes with 20% cement-glass powder replacement have compressive strengths similar to the control design, but the best performance belongs to the 5% glass-powder design. Shao et al. [35] have stated that the particle size of glass, as a substitute for cement, affects the performance of the produced mortar and have claimed that the compressive strength increases and shrinkage decreases because smaller glass particles are more probable to react with lime. Oliveira et al. [36] have observed that replacing cement with 45–75 µm particle-size glass powder will increase the compressive strength, reduce the ASR effects and create a denser cement-paste matrix structure. This increasing effect is due to pozzolanic activity of glass powder in this type of concrete. There is a strong ascending linear correlation between tensile and compressive strengths with a desirable regression coefficient (Fig. 4).

In Fig. 5, the tensile strength of all the 28d SCC specimens containing 0-30% glass powder and 10% SF is in the 3.4–4.2 MPa range; compared to other designs, GPSF3 has the most tensile strength improvement (23.53%) and GPSF4 shows a 20.59% increase in tensile strength compared to the control design although it has suffered a slight decrease in this strength. The increased tensile strength of SCCs with up to 15% cement-glass powder replacement is attributed to the increased quantity and quality of such hydration products as C-S-H due to the glass-calcium hydroxide interaction [3].

In Fig. 6 that shows the flexural strength variations for the 28d GPSF0, GPSF1, GPSF2, GPSF3 and GPSF4 designs, the trend is similar to that of the tensile strength

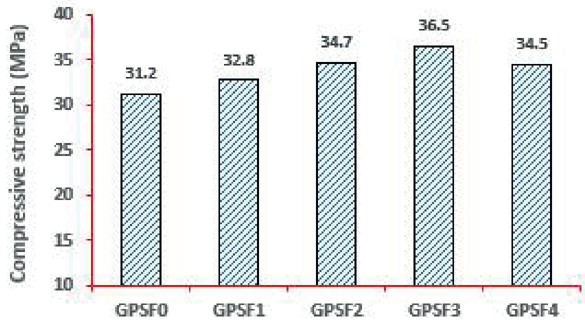

Fig. 3 Compressive strength of SCCs

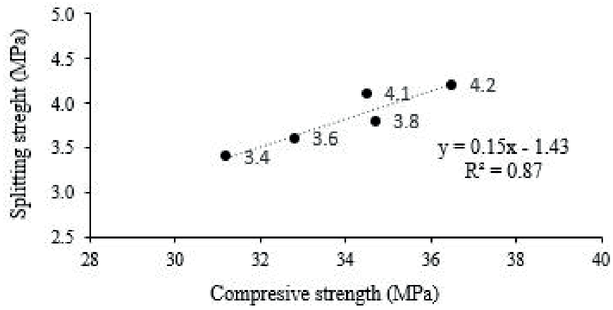

Fig. 4 Splitting tensile strength versus compressive strength

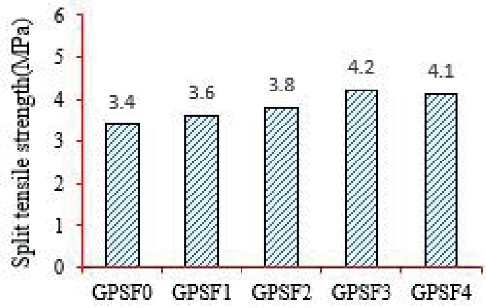

Fig. 5 Split tensile strength of SCCs

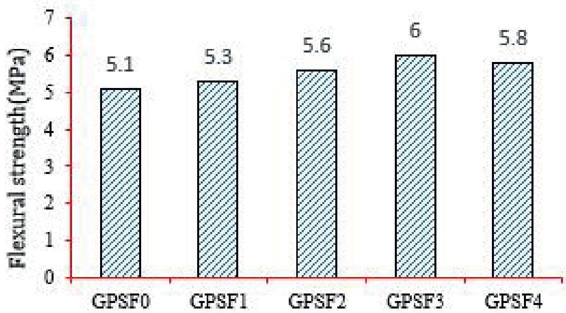

Fig. 6 Flexural strength of SCCs

of concretes produced with glass powder and SF. Keeping the SF constant and using 7.5, 15, 22.5 and 30% glass powder to produce SCC, the flexural strength will increase by 3.92, 9.8, 17.65 and 13.73%, respectively, compared to the control design. When the glass powder exceeds 22.5%, the flexural strength will have a descending trend and face a decrease of about 3.92% compared to GPSF3.

Wang [37] observed that increasing the LCD glass powder in concrete reduced the compressive, tensile and flexural strengths.

Water absorption is an important concrete-durability parameter the reduction of which highly improves the long-term concrete performance under aggressive service conditions. Surface water absorption helps recognize and model the concrete behavior under freeze-thaw cycles. In Fig. 7 that shows this parameter for all 1h, 1d, 7d and 28d mix designs, effects of glass powder and SF on reducing the surface water absorption is positive (for all specimens it is < 6.5%). The design with the highest glass powder (30%) shows 29.27, 32.69, 28.81 and 26.56% decrease in surface water absorption compared, respectively, to 1h, 1d, 7d and 28d GPSF0; the difference is more evident for the 28d specimen. Liaqat et al. [38], too, have reported that increasing the glass powder will decrease the concrete water absorption.

In Fig. 8 that shows the capillary water absorption variations for all 0.5h, 1h, 5h and 24h SCCs containing glass powder and SF, increasing the glass powder with no changes in the SF highly reduces the capillary water absorption at all ages. The 24h design with 30% glass powder has about 46.77% reduction in capillary water absorption compared to the control design. As pozzolanic

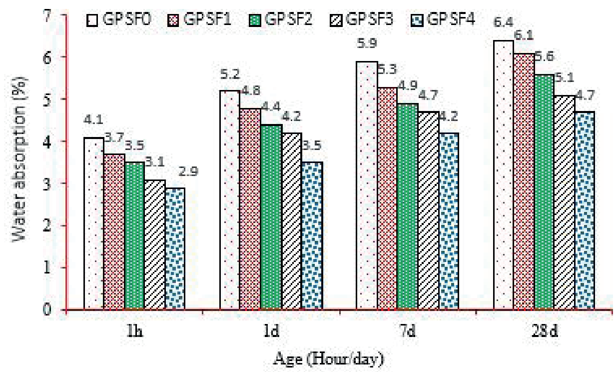

Fig. 7 Surface water absorption of SCCs

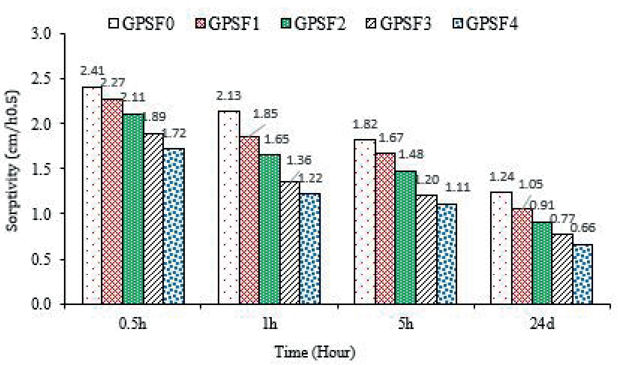

Fig. 8 Capillary water absorption of SCCs

materials (silica fume, fly ash, etc.) increase the C-S-H production and decrease the CH, porosity and capillary holes are reduced in the concrete microstructure [39].

In Fig. 9 that shows percent variations of the total weight of the specimens after 25 and 50 freeze-thaw cycles, only the control design (GPSF0) has a weight loss (about 0.23%) at 25 cycles; other designs show a weight increase. GPSF1, GPSF2, GPSF3 and GPSF4 gain weight due to high water absorption because when the weight of the absorbed water is more than that of the spalled concrete, the weight of concrete specimen increases. After 50 freeze-thaw cycles, GPSF3 still shows a slight weight increase because: 1) it can no longer absorb water after saturation and 2) the concrete surface is slightly spalled; in this process, the absorbed water weight is greater than that of the spalled concrete. Under 50 freeze-thaw cycles, not only the control design, but also GPSF2, GPSF3 and GPSF4 show a weight loss. According to Fig. 9, the weight loss of all mix design is less than 0.7%. Theoretically, the weight loss in concrete specimens subjected to freeze-thaw cycles is usually due to surface pop-outs because of the expansion of saturated aggregates in areas close to the surface and destruction of the surrounding cement paste [40]. Hang et al. [41] believed that increasing the freeze-thaw cycles would generally increase the weight loss and reported that the weight loss rate would be small below 75 freeze-thaw cycles and high above 225 cycles. Examining specimens after 25, 50 and 75 freeze-thaw cycles, Feo et al. [42] reported that difference in their dimensions and weights was negligible. Lee et al. [7] stated that the weight loss of specimens with 20% glass powder would be 24% after 50 freeze-thaw cycles and the scaling resistance would improve due to increased pozzolanic reactions and fine particle filling effect.

In Fig. 10, compressive strength of all mix designs increases with an increase in the number of freeze-thaw cycles; the strength loss is less than 8% after 25 cycles with the lowest loss relating to GPSF3. Although the loss

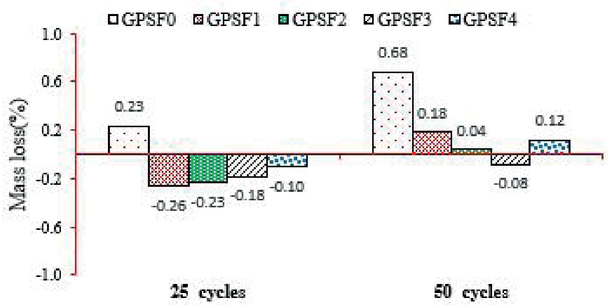

Fig. 9 Weight changes of SCCs after freezing and thawing cycles

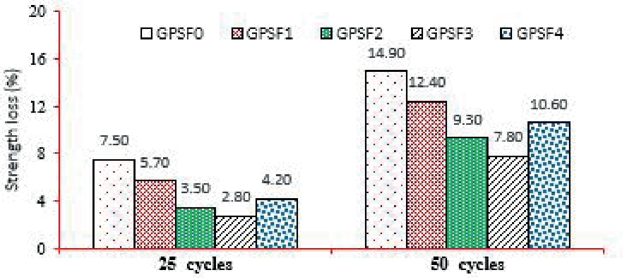

Fig. 10 Compressive strength changes after freezing and thawing cycles

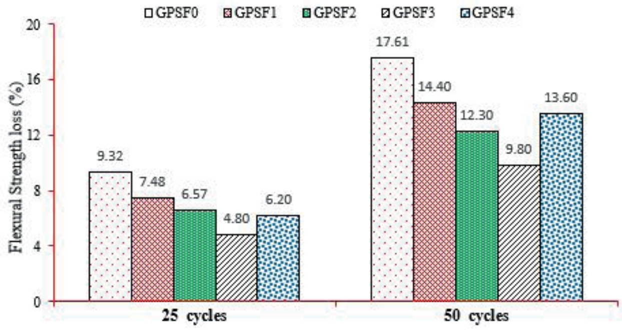

Fig. 11 Flexural strength changes after freezing and thawing cycles

trend is descending up to 22.5% glass powder replacement, it increases at the highest glass powder volume. After 50 freeze-thaw cycles, the resistance drop lies in the 7.8–14.9% range having a variations trend similar to that of 25 cycles (for all mix designs). With an increase in the number of cycles from 25 to 50, the resistance drop difference is more obvious among the mix designs. GPSF3's desirable performance in freeze-thaw environments can be attributed to the improved microstructure and filling of surface cavities and inter-aggregate spaces due to the formation of hydration compounds of the SF-glass powder-cement-water interaction. Feo et al. [42] have attributed the reduced equivalent post-cracking strength of high-performance fiber-reinforced concrete (HPFRC) to degradation due to freeze-thaw cycles of the concrete/fiber interface.

In Fig. 11, flexural strength losses of GPSF0, GPSF1, GPSF2, GPSF3 and GPSF4 lie, respectively, in the 4.80-9.32 and 9.81-17.61 percent ranges under 25 and 50 freeze-thaw cycles. As shown, increasing the number of cycles highly reduces the flexural strength in the control design. The lowest flexural strength loss in both freeze-thaw cycles relates to the mix design with 22.5% glass powder and 10% SF. The flexural strength loss of GPSF4 is slightly higher than that of GPSF3 after 25 cycles, but it is still less than those of other mix designs; increasing the cycles from 25 to 50 increases the flexural strength loss of the design containing the highest glass powder compared to GPSF2 and GPSF3. Feo et al. [42] have claimed that freeze-thaw cycles have obvious effects on the flexural behavior and the average first crack strengths of high-performance fiber-reinforced concretes (HPFRCs) containing 0, 1.5 and 2.5% steel fiber are reduced by 23.1, 15.5 and 16.9%, respectively, after 75 cycles.

In Fig. 12 that shows the SEM images of all mix designs, the loss of strength in GPSF0 is due to large unhydrated particles, cracks, large number of cavities and formation of needle-shaped ettringite structure; formation of hydration products and C-S-H structure are negligible in this mix design. Although ettringite pieces are removed from the GPSF1 microstructure and the size of unhydrated particles is reduced, continuous cracks prevent the resistance to highly grow. A similar trend is also observed in GPSF2, but the increased C-S-H structure in its microstructure is quite visible and has positive effects on the resistance increasing trend. Increasing the glass powder up to 22.5% creates a large volume of dense and uniform C-S-H structure in the produced concretes that fill the cavities and reduce the continuity of the cracks. This consistent structure of the hydration products is the reason for the increased resistance in GPSF3; however, small unhydrated particles are still observed in some parts. At this replacement percentage, such resistance-drop factors as cracks, cavities and needle-shaped ettringite particles are either totally eliminated or exist to a small extent. Despite the presence of C-S-H structure in concretes containing the largest volume of glass powder (GPSF4), there is a slight decrease in strength due to the formation of unhydrated particles and cavities.

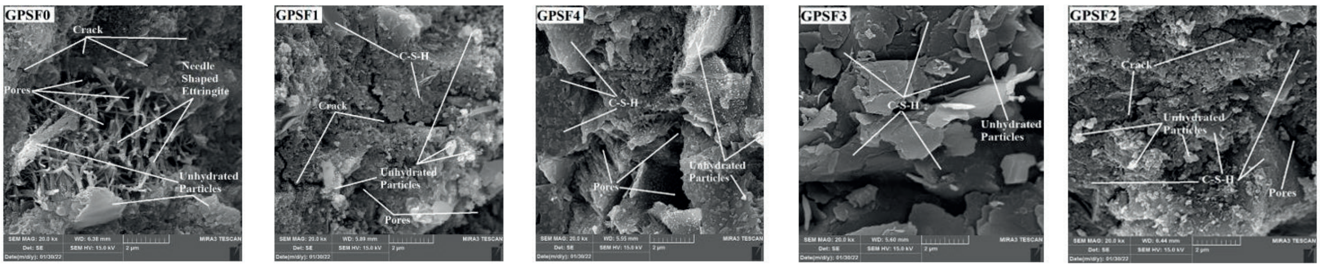

Fig. 12 SEM images of GPSF0, GPSF1, GPSF2, GPSF3 and GPSF4

Table 2 Cost of SCC studied

Material (kg)	Cost ($/Kg)	Mix Description				
		GPSF0	GPSF1	GPSF2	GPSF3	GPSF4
Cement	0.021	400	330	300	270	240
Limestone powder	0.042	400	330	300	270	240
Glass powder	0.007	0	30	60	90	120
Silica fume	0.0076	40	40	40	40	40
Fine aggregate	0.00241	1050	1050	1050	1050	1050
Coarse aggregate	0.0017	680	680	680	680	680
Water	0.00056	188	188	188	188	188
HRWR	1.39	2.6	2.6	2.6	2.6	2.6
Total ($/m3)	-	32.76	28.52	26.81	25.11	23.41

Table 2 shows the production cost/cm3 of concrete with and without 7 glass powder/silica fume; costs of material purchasing, transporting and quality control for producing GPSF0, GPSF1, GPSF2, GPSF3 and GPSF4 are based on March 2022 prices. As shown, costs of concretes containing 7.5, 15, 22.5 and 30% glass powder and 10% silica fume are 12.94, 18.16, 23.35 and 28.54% lower than GPSF0, respectively. Sharifi et al. [14] have claimed that using 30% glass powder to replace cement in the production of SCC would reduce the costs by 23.67%.

4 Conclusions

The present study was aimed to solve the environmental problems of the cement production and waste-glass depots, reduce CO2 and energy consumption and improve the properties of concrete. To this end, cement was replaced with 0, 7.5, 15, 22.5 and 30% glass powder and 10% silica fume in the production of the self-compacting concrete (SCC). Various tests - fresh concrete, compressive/tensile/flexural strength and surface/capillary water absorption – were performed and effects of freeze-thaw cycles were evaluated. Results, approved by SEM images, are as follows:

1. Replacing cement with glass powder will improve the fresh concrete properties and performance due to the glass particles' smooth surfaces and almost zero water-absorption; the EFNARC requirements for the production of SCC are also met.
2. Concretes containing 22.5% glass powder have the highest increase in the compressive, tensile and flexural strengths (16.99, 23.53 and 17.65%, respectively) compared to other mix designs. Despite a slight reduction in the strength parameters, concretes containing 30% glass powder still perform better than the control design.
3. Increasing the glass powder reduces the surface and capillary water absorption due to the particles' reactivity, proper filling and less water absorption, increased C-S-H in the concrete microstructure, improved particle packing and reduced internal cavities.
4. Glass-powder concretes exposed to 25 and 50 freeze-thaw cycles show very good compressive and tensile strengths and have less weight loss than the control design due to the formation of a dense and homogeneous microstructure, proper pore filling and desirable glass particles reactivity as a result of the increased C-S-H gel production.
5. SEM images attribute: 1) the resistance drop to the presence of unhydrated particles, cracks, porosity and needle-shaped ettringite particles, and 2) the strength increase, especially in concretes containing 22.5% glass powder, to the formation of the dense C-S-H structure.
6. Replacing part of the cement with glass powder not only solves part of the environmental problems caused by the cement production and glass-waste disposal, but also improves the concrete properties and reduces its production costs by about 23.67%.

The future research plan will be concentrated on alkali-aggregate reaction of this concrete.

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