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Scientific paper

Fresh Properties of Self-Compacting Concrete Containing Ground Waste Glass Microparticles as Cementing Material

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Abstract

In this study, the fresh properties of self-compacting concrete (SCC) incorporating ground waste glass (GWG) as cementing material were experimentally investigated. GWG was used as a partial replacement for cement at replacement levels of 0, 5, 10, 15, 20, 25 and 30% by weight. Reducing the consumption of cement in construction is a major issue in terms of economic performance. Such reduction would also contribute to the environment by lessening the harmful impact of the manufacturing process. Concrete mixtures containing different levels of GWG were prepared with the water to cementitious materials ratio of 0.51. The examined properties included workability, wet density, air content and setting time. Workability of the fresh concrete was determined by using the slump flow, visual stability index, V-funnel, J-ring, L-box and GTM screen stability tests. The results indicate that there is a slight decrease in the wet density of self-compacting ground waste glass concrete (SCGWGC) of nearly 1.37% with the increase of GWG content. The conclusion is that using GWG significantly increases the workability of SCC mixtures. As the GWG increases, the slump flow also increases at a constant amount of water and super-plasticizer, but the concrete flow time decreases. The results showed that it is possible to successfully produce SCC with GWG as cement replacement.

1. Introduction

Concrete is normally placed into formwork and then vibrated to fabricate building components. Two alternative construction strategies—self-compacting concrete (SCC) and sprayed concrete—have been developed to eliminate the compaction process (Le *et al.* 2012). In 1986, research studies on SCC and diffused concrete began at the University of Tokyo (Topcu and Bilir 2009). SCC offers various advantages in the construction process due to its improved quality, productivity and working conditions. Generally speaking, SCC has a higher powder content and a lower coarse aggregate volume ratio than normally vibrated concrete (NVC) in order to ensure SCC's filling ability, passing ability and segregation resistance (Liu 2011).

Some of the disadvantages of SCC are its high cement requirement and use of chemical admixtures, which lead to increased material cost. One alternative procedure to reduce the cost of SCC while producing SCC with better engineering properties is the addition of inert, pozzolanic/hydraulic material or waste and recycling materials (Ranjbar *et al.* 2013). Among solid waste materials, the most prominent are fly ash, blast furnace slag, rice husk (converted into ash), silica fume and ma-

terials from construction demolition (Ramasamy 2012).

Portland cement (PC) is one of the most widely used construction materials in the world, due to its great engineering properties and well-developed manufacture techniques. About 25 billion metric tonnes are produced globally each year. About 3.3 billion tonnes of PC were used in 2010, mainly for concrete construction projects (Celik *et al.* 2014). Production of Portland cement includes the grinding of raw materials, their calcination at 1500°C, and the grinding of cement clinker with gypsum. The average energy input required to produce one ton of cement is approximately 4.8 million Btu. This is an energy intensive process that releases a significant amount of pollution such as CO₂. As a matter of fact, the manufacturing process makes up about 7% of global CO₂ emissions (Geng and Li 2014). Consequently, the production of Portland cement poses various environmental issues, as well as economic ones (Shia *et al.* 2008). By reducing the use of Portland cement, CO₂ emission may be curbed. Due to growing environmental concerns and the need to conserve energy and resources, efforts have been made to utilize the waste material of industrial and agro products in the construction industry as a pozzolanic mineral admixture to replace ordinary Portland cement (Ramasamy 2012). Using these mineral admixtures to replace part of the PC will reduce the cost of SCC, especially if the mineral admixtures consist of waste or industrial by-product. Moreover, the use of mineral admixtures in the production of SCC not only provides economic benefits but also reduces heat of hydration (Uysal and Sumer 2011). Therefore, the attempt is to decrease the cost of SCC production by modifying the composition of the material mixtures through the use of cheaper materials, especially waste

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compositions (Sharifi 2012; Sharifi *et al.* 2013; Afshoon and Sharifi 2014).

Waste reduction and recycling are very important elements in a waste management framework because they help conserve natural resources and reduce demand for valuable landfill space (Ling *et al.* 2013). Glass is one of the oldest man-made materials. It is produced in many forms, including packaging or container glass, flat glass, bulb glass, and cathode ray tube glass, all of which have a limited life in the forms in which they are produced. Hence, glass needs to be reused/recycled in order to avoid environmental problems that may arise if used glass is stockpiled or sent to landfills. Theoretically, glass is a 100% recyclable material; it can be indefinitely recycled without any loss of quality (Emam Ali and Al-Tersawy 2012). Due to urbanization and industrialization, three million tonnes of waste glass is produced every year in the UK, of which 71% is from glass containers. Due to the high cost of cleaning and colour sorting, only a tiny proportion can be recycled by conventional markets such as container manufacture (Meyer 2001). For example, in Portugal in 2010, 425 thousand tonnes of glass were produced and only 192 thousand tonnes of waste glass were recycled (Serpa *et al.* 2013).

The components in glass are sodium carbonate, potassium carbonate, calcium lime, magnesium oxide, aluminum oxide, and silicon oxide. Waste glass containers can be re-used as concrete aggregate, glass ceramics, pozzolanic material, artificial stone, and colored glass (Chiou and Chen 2013). The use of recycled waste glass in Portland cement and concrete has attracted much interest worldwide due to increased disposal costs and environmental concerns (Wang and Huang 2010).

Although work on the use of finely ground glass as a pozzolanic material also started as early as 1970s, most of the work in this area is relatively recent and has been encouraged as the continuous accumulation of waste glass has given rise to environmental issues. Moreover, waste glass is potentially a very useful material and appropriate economical applications need to be found for it (Shayan and Xu 2006).

There are a number of new applications of recycled waste glass, including the use of glass cullet in granular base/fill and asphalt pavement. Recycled waste glass has also been widely used as aggregate in cement mortar and concrete mixtures (Ling and Poon 2011). Zhao *et al.* (2013) conducted a study on the utilization of recycled cathode ray tube funnel glass sand as river sand replacement in high-density concrete.

Recycled glass as a partial replacement for fine aggregate in SCC was also investigated by (Afshoon and Sharifi 2014). They reported that the slump flow increased with the increase of recycled glass content. On the other hand, the compressive strength, splitting tensile strength, flexural strength and static modulus of elasticity of recycled glass (SCC) mixtures decreased with the increase of the recycled glass content. These

results indicate that recycled glass aggregate can successfully be used for producing SCC.

Asokan *et al.* (2009) assessed the recycling potential of glass fiber reinforced plastic waste in concrete and cement composites. The results revealed that the mean compressive strength of concrete composites using 5%–50% GRP waste powder under water curing varied from 37 N/mm² to 19 N/mm². Increase in the concentration of GRP waste decreased the compressive strength. However, increase in curing duration (14–180 days) resulted in improving the compressive strength of concrete with 5% GRP to 45.75 N/mm². Moreover, the density of concrete with 50% GRP waste was reduced by about 12% as compared with the control sample.

Park *et al.* (2004) studied the mechanical properties of concrete containing waste glass aggregate. The test results for fresh concrete show that both slump and compacting factors are decreased due to the angular grain shape and that air content is increased due to the involvement of the numerous small-sized particles that are found in waste glass. In addition, the compressive, tensile and flexural strengths of concrete have been shown to decrease when the waste glass content is increased.

Shayan and Xu (2006) investigated the performance of glass powder (GLP) as a pozzolanic material in concrete. They reported that mixtures containing GLP also performed satisfactorily with respect to drying shrinkage and alkali reactivity, and there were indications that GLP reduces the chloride ion penetrability of the concrete, thereby reducing the risk of chloride induced corrosion of the steel reinforcement in concrete. The results demonstrated that GLP can be incorporated into 40 MPa concrete at dosage rates of 20–30% to replace cement without harmful effects. The use of GLP provides for considerable value-added utilisation of waste glass in concrete and significant reductions in the production of greenhouse gases by the cement industry. As presented in the foregoing, data on the behavior of SCC containing GWG is quite limited. The present paper is an attempt to investigate the fresh properties of SCC incorporating partial replacement of cement with GWG. Up to 30% of the cement was replaced with waste glass microparticles. The superplasticizer dosage was adjusted so that the concrete fell within the SCC requirement code provisions. Then, the fresh characteristics of the resulting mixes were investigated in depth.

2. Materials

2.1 Cement

Ordinary Portland Cement Type (II) (OPC) meeting the requirements of ASTM C150 (2009) was used in the preparation of the concrete mixes. The chemical and physical properties of this cement are given in **Table 1**. The nanoparticle size distribution pattern of the used OPC is illustrated in **Fig. 1**. **Figure 2** shows the cement used in the SCC mixtures.

Table 1 Chemical and physical properties of cement and GWG.

Compound (%)	Cement	GWG	Physical Properties	Cement	GWG
SiO ₂	21.74	70.5	Water absorption (%)	—	—
Al ₂ O ₃	5	2.6	Specific density	3.15	2.50
Fe ₂ O ₃	4	—	Specific surface area (cm ² /g)	2900	2480
CaO	63.04	5.7	Setting time (final) (min)	170	—
MgO	2	2.9	Setting time (initial) (min)	120	—
Na ₂ O	2.3	16.3	Autoclave expansion (%)	0.1	—
K ₂ O	1	1.2	Compressive strength (kg/cm ²)	220	3 days
SO ₃	2.9	0.2		275	7 days
LOI	1.3	—		380	28 days

2.2 Waste glass

Waste glass (**Fig. 2**) procured from Rafsanjan-Iran was then ground in the laboratory using an electric mill (**Fig. 3**) for several durations to determine the best duration to obtain a particle size distribution equivalent to that of cement powder. After some trials, 10 min of electronic milling was determined to give a suitable particle size distribution similar to that of cement, as shown in **Fig. 1**. The ground waste glass was then added to the concrete mixtures as a secondary binder replacing cement by up to 30% by weight and was also utilized for producing SCCGWG. Incorporation of a large amount of mineral admixtures reduces the heat of hydration as the cement content in concrete is reduced and thus the rate of hydration is reduced. The total heat of hydration produced by the pozzolanic reactions with mineral admixtures is considered as half of the average heat of hydration produced by PC. The reduced heat of hydration improves the rheology properties and reduces thermally-induced cracking of concrete as well as the long-term properties of concrete (Nuruddin *et al.* 2014). The chemical and physical properties of waste glass are given in **Table 1**.

2.3 Aggregates

Locally available sand from natural sources was used in the present experimental investigation. The aggregates used in this experiment were both angular-shaped sand and circular-shaped sand procured from river materials. The fine aggregate was natural sand free of impurities with minimum and maximum grain sizes of 0.3 and 4.75 mm, respectively. Dolomite with a maximum nominal size of 19.5 mm and minimum nominal size of 4.75 mm was used as coarse aggregate. Dolomite powder was used to replace sand of particle size smaller than 300 microns. **Table 2** lists the physical properties of coarse and fine aggregates. The aggregate was kept in a condition drier than saturated surface dry (SSD) level. Aggregate particle-size distribution was determined in accordance with ASTM C33 (2008). The gradations of coarse and fine aggregates are shown in **Table 3**. The particle size distribution indicates that the particle sizes are continuously distributed with 35% over the size range of 9.5–19.5 mm. The particle size distribution was well-graded with over 47% of the sand over the size range of 0.3–1.18 mm.

Fig. 1 Particle size distribution for binders.

Fig. 2 Binders (cement and GWG) used in this study.

Fig. 3 Electric mill used in this study.

Table 2 Physical properties of aggregates.

Properties	Fine aggregate	Coarse aggregate
Specific density	2.73	2.81
Bulk density (kg/m^3)	1590	1565
Void content (%)	36.71	47.58
Water absorption (%)	1.09	0.32
Finesse modulus (F.M.)	3.4	-

Table 3 Gradations of coarse and fine aggregates.

Mesh (mm)	9.5	4.75	2.36	1.18	0.6	0.3	plate
Fine aggregates (% passing)	100	97	91	65	45	18	0
Mesh (mm)	37.5	25	19	12.5	9.5	4.75	plate
Coarse aggregates (% passing)	100	100	100	92	65	2	0

2.4 Water

Potable water as defined by ASTM C94 (2009), at a temperature of $20 \pm 1^\circ\text{C}$, was used in order to prepare the SCC.

2.5 Superplasticizer

The essential component of SCC is a high-range water reducer admixture (HRWRA), which is also known as superplasticizer (SP). Polycarboxylate ether (PCE) was used as the SP in SCCGWG. This product, P10-3R, with density between 1.08 and 1.12 g/cm^3 (at 20°C), was used to enhance the flowability of the mixtures. It is a third-generation SP for concrete and mortar that gives self-compacting abilities. The properties of the superplasticizer are presented in **Table 4** according to ASTM C494 (2010).

3. Experimental program

Seven SCC mixtures were designed in order to obtain different fresh-state properties. The details of the mixes for the study are presented in **Table 5**. Seven different mixes (SCCG-0, SCCG-5, SCCG-10, SCCG-15, SCCG-20,

SCCG-25 and SCCG-30) were employed to examine the influence of GWG on SCCs fresh properties when Portland cement was replaced with GWG. These included one control mix (SCCG-0) and six mixes (SCCG-5 to SCCG-30) made by replacing 5%, 10%, 15%, 20%, 25% and 30% of cement with GWG. The amount of cementitious materials was kept constant at 400 kg/m^3 . All the mixtures were proportioned with a fixed water/cementitious materials (W/CM) ratio of 0.51. As stated previously, the essential component of SCC is a HRWRA, which is also known as SP. SCC mixtures always include a SP to ensure that the concrete is able to flow under its own mass. Several trial mixes were conducted to determine the optimum dosage of SP for each of the mixtures in order to achieve the required self-compacting properties as per the EFNARC Committee (European Federation for Specialist Construction Chemicals and Concrete Systems) (2002; 2005). Liu (2011) found out that the use of ground glass in SCC decreases the SP dosage slightly. Therefore, concrete containing ground glass causes an increase in workability at constant water to binder ratio. For that reason, the amount of SP was decreased to achieve the desired workability in all GWG concrete mixtures. The dosage of SP for each mix was carefully selected as over dosage may induce bleeding and strength retardation. The SP dosage of 1.1–1.4% by weight of cementitious has been employed to obtain the targeted slump flow values of $680 \pm 30 \text{ mm}$. A suitable procedure should result in the greatest efficiency of its action. There are two methods of adding SP to the mix, direct addition and delayed addition. For the direct addition, water and SP were poured into the mixer first, and then the cement, mixing was started, and then fine aggregate was added. This method aimed to let the cement contact the SP first. For the delayed additions, all constituent materials except SP were mixed with part of the total mixing water and the remaining mixing water blend with SP several minutes after the start of mixing. The mixing sequence and duration are important issues to produce stable and self-compactable concrete. In order to supply similar homogeneity and uniformity in all concrete groups, the batching sequence consisted of homogenizing the fine and coarse aggregates for 30 s in a rotary planetary mixer, then adding about half of the mixing water into the mixer and continuing to mix the mixture for one more minute. Thereafter, the aggregates were left to absorb

Table 4 Properties of the SP.

Items	Standards quality	Testing results	Regulatory
Density (20°C)	0.938 - 1.146	1.1 ± 0.02	ASTM C494
PH (20°C)	5.4 - 7.4	7	—
Chlorine (ppm)	≤ 2400	500	ASTM C494
Color	—	Dark green	—

Table 5 Concrete design mix proportions.

Detail mix	Mix	Aggregates (kg/m^3)		Cementitious material (CM) (kg/m^3)		W/CM	SP ^a (%)
		Coarse	Fine	GWG	Cement		
0% GWG+100%C	SCCG-0	700	950	0	400	0.51	1.4
5% GWG+95%C	SCCG-5	700	950	20	380	0.51	1.4
10% GWG+90%C	SCCG-10	700	950	40	360	0.51	1.4
15% GWG+85%C	SCCG-15	700	950	60	340	0.51	1.4
20% GWG+80%C	SCCG-20	700	950	80	320	0.51	1.4
25% GWG+75%C	SCCG-25	700	950	100	300	0.51	1.2
30% GWG+70%C	SCCG-30	700	950	120	280	0.51	1.1

^aPercent by mass of CM.

the water in the mixer for 1 *min*. After the cement and mineral admixtures were added, mixing was resumed for another minute. Finally, the SP with remaining water was introduced, and the concrete was mixed for 3 *min* and then left to rest for 2 *min*. Eventually, the concrete was mixed for an additional 2 *min* to complete the mixing sequence (Guneyisi *et al.* 2012).

4. Background on the workability of SCC

According to the EFNARC committee, a concrete mixture can only be classified as SCC if the requirements for filling, passing, and segregation resistivity characteristics are fulfilled. The most important advantage of SCC over conventional concrete is its flowability. Other advantages of using SCC include shorter construction periods, lower labor cost, and better compaction in the structure especially in confined zones where compaction is difficult. The highly flowable nature of SCC is due to very careful mix proportioning, usually replacing much of the coarse aggregate with fines and cement, and adding chemical admixtures. Many different test methods have been developed in attempts to characterize the properties of SCC. The deformability and flowability of fresh SCC were evaluated using V-funnel and slump flow tests. The final diameter was determined in the slump flow test, and the time required for the concrete to spread to a diameter of 500 *mm* (T_{500}) was recorded using a video tape recorder. The L-box test was conducted to evaluate passing ability (the ability of SCC to flow around obstructions) (Hassan *et al.* 2012). So far, no single method or combination of methods has achieved universal approval although most have their adherents. Therefore, no single method has been found to characterize all the relevant workability

to characterize all the relevant workability aspects. Consequently, each mix design should be tested by more than one test method in order to obtain different workability parameters. For site quality control, two test methods are generally sufficient to monitor production quality of SCC. Typical combinations are slump flow and V-funnel, or slump flow and J-ring. However, filling and passing ability cannot be evaluated sufficiently by a slump-flow test alone. Both L-box and U-box tests may be used as a passing ability indicator (Felekoglu *et al.* 2007). **Table 6** shows test methods being developed that measure characteristics of SCC. The typical workability acceptance criteria for SCCs based on EFNARC, JSCE (Japan Society of Civil Engineers) (2007) and IMSCCPM (Inspection Manual for Self-Compacting Concrete in Precast Members) (2007) are listed in **Tables 7 to 9**, respectively.

Table 6 Test methods being developed that measure characteristics of SCC.

	ACI 237R-07 (2007)	EFNARC
Test name	Characteristic	Characteristic
Slump flow	Filling ability	Filling ability
Slump flow T_{500}	Filling ability	Filling ability
J-ring	Passing ability	Passing ability
L-box	Passing and filling ability	Passing ability
Visual stability index (VSI)	Resistance to segregation	Resistance to segregation
V-funnel	—	Filling ability
V-funnel at $T_{5 \text{ minutes}}$	—	Segregation resistance

Table 7 Acceptance and conformity criteria for the properties of SCC according to EFNARC (2002) and EFNARC (2005).

Acceptance criteria for SCC according to EFNARC (2002) ²⁹ .				Conformity criteria for the properties of SCC according to EFNARC (2005) ³⁰ .	
Method	Unit	Typical range of values		Property	Criteria
		min	max		
Slump flow	mm	650	800	Slump flow class SF1	550 - 650 (mm)
T_{500} slump	sec	2	5	Slump flow class SF2	660 - 750 (mm)
J-ring	mm	0	10	Slump flow class SF3	760 - 850 (mm)
V-funnel	sec	6	12	V-funnel class VF1	≤ 8 (s)
V-funnel at T_{5min}	sec	0	3	V-funnel class VF2	9 - 25 (s)
L-box	(h_1/h_2)	0.8	1	L-box class PA1 (with two rebars)	≥ 0.8
				L-box class PA1 (with three rebars)	≥ 0.8
GTM	%	0	15	Sieve segregation resistance class SR1	≤ 23 (%)
—	—	—	—	Sieve segregation resistance class SR2	≤ 18 (%)

Table 8 Acceptance criteria for SCC according to JSCE.

Rank	1	2	3
Construction condition minimum gap between reinforcement (mm)	30 - 60	60 - 200	≥ 200
Amount of reinforcement (kg/m ³)	≥ 350	100 - 350	≤ 100
Filling height of U-box test (mm)	≥ 300	≥ 300	≥ 300
Absolute volume of coarse aggregates per unit volume of SCC (m ³ /m ³)	0.28 - 0.30	0.30 - 0.33	0.30 - 0.36
Flowability slump flow (mm)	650 - 750	600 - 700	500 - 650
Segregation resistance ability time required to flow through V-funnel (s)	10 - 20	7 - 20	7 - 20
Time required to reach 500 mm of slump flow (s)	5 - 25	3 - 15	3 - 15

Table 9 General acceptance criteria for SCC workability according to IMSCCPM.

Method	Typical range of values	Application Requirements
Slump flow	525 - 600 (mm)	Appropriate for members with light or no reinforcement, short lateral flow distances, or high placement energy (e.g. panel, barriers, coping)
	610 - 675 (mm)	Ideal for most applications
	675 - 750 (mm)	Appropriate for members with light congested reinforcement, long lateral flow distances, or low placement energy (e.g. U-beams, I-beams, and other beams)
T ₅₀₀ slump	< 2 (S)	Poor stability
	2 - 7 (S)	Acceptable, should not vary over range of 3 s between batches
	> 7	Possible, may reduce placeability
J-ring	< 1.25 (mm)	Appropriate for members with light congested reinforcement, long lateral flow distances, or low placement energy (e.g. U-beams, I-beams, and other beams)
	1.25 - 2.5 (mm)	Appropriate for members with moderately congested reinforcement.
	> 2.5	Appropriate for unreinforced or lightly reinforcement members (e.g. panel, coping)

5. Test procedure

In this study, the workability test results of fresh concrete, tested by the slump flow (Diameter, T₅₀₀ and T-Final), V-funnel (T₀), J-ring (step height, diameter, T₅₀₀ and T_{final}), GTM screen stability and L-box (h₁/h₂, T₂₀₀, T₄₀₀ and T_{final}) tests were performed according to the recommendations of the EFNARC code. Visual stability index (VSI) test was also conducted according to ACI-237R-07 code provisions. Additionally, some fresh tests were also conducted. The above-mentioned tests are described below.

5.1 Slump flow

One way to quantify the SCC flowing characteristics is to conduct a slump flow test. The slump flow value describes the flowability of a fresh mix in unconfined conditions. The slump flow test was used to evaluate the free deformability and flowability of SCC. It is a sensitive test that will normally be specified for all SCCs (Bingol and Tohumcu 2013). This test is performed similarly to the conventional slump test using the standard slump cone (ASTM C 143 2012; ASTM A993 1998). The standard slump cone was used for the test and the concrete was poured in the cone without compaction. The slump flow value represented the mean diameter (measured in two perpendicular directions) of concrete after lifting of the standard slump cone. The upper and lower limits of slump flow classes (SF) can be classified as SF1-slump flow from 550 to 650 mm, SF2-slump flow from 660 to 750 mm, and SF3-slump flow from 760 to 850 mm based on the EFNARC provisions. At slump flow >700 mm, the concrete might segregate, and at <500 mm, the concrete might have insufficient flow to pass through highly congested reinforcement. During the slump flow test, the required time of SCC to reach 500 mm slump flow radius and the final time and diameter of the concrete circle through four directions were measured.

5.2 Visual Stability Index (VSI)

The VSI test involves the visual examination of the SCC slump flow spread resulting from execution of the slump flow test. This test method is intended to provide the user with a procedure to determine the stability of SCC mixtures. It is used to evaluate the relative stability of batches of the same or similar SCC mixtures (ACI 237R-07 2007). This can be assessed by visually evaluating the distribution of the coarse aggregate within the concrete mass after the spreading of the concrete has stopped. Typically, once the slump flow test has been completed, a visual stability index value is assigned to the concrete. A VSI number of 0, 1, 2 or 3 is given to the spread to characterize the stability of the mixture, as defined according to ACI-237R-07 in **Table 10**. Because the VSI rating is determined visually, it can be subjective. Therefore, the VSI rating is an excellent quality control tool for producing SCC, but should not be used for acceptance or rejection of a given mixture (Madandoust and Mousavi 2012). VSI values of 0 or 1 indicate acceptable SCC. a VSI value of 3 clearly indicates SCC that should be rejected. The VSI value of 2 indicates that the concrete is unstable and the mix design should be immediately modified to obtain a VSI value of 0 or 1 (i.e. site addition of viscosity modifying admixtures, etc.).

Table 10 VSI rating of SCC mixtures according to ACI-237R-07 (2007).

VSI value	Criteria
0 = highly stable	No evidence of segregation in slump flow spread
1 = stable	No mortar halo or aggregate pile in the slump flow
2 = unstable	A slight mortar halo (< 10 mm) or aggregate pile, or both, in the slump spread.
3 = highly unstable	Clearly segregating by evidence of a large mortar halo (> 10 mm) or a large aggregate pile in the center of the concrete spread, or both.

5.3 V-funnel

The V-funnel test measures the flowability and segregation resistance of concrete. The deformability rate of concrete flowing through an restricted area and the stability of SCC mixtures were evaluated through the V-shaped funnel test, too. First, the test assembly is set firmly on the ground and the inside surfaces are moistened. The trap door is closed and a bucket is placed underneath. Then the apparatus is completely filled with concrete without compacting and the top is struck off with the straight edge so that the concrete is flush with the top of the funnel. After a delay of (10 ± 2) s from filling the funnel, the gate is opened and the time to 0.1 s from opening the gate to when light is seen from above through the funnel is measured. This time is the V-funnel flow time. It is the time of concrete flowing from the opening at the bottom of the funnel (Akram *et al.* 2009; Aghabaglou *et al.* 2013). A funnel test flow time less than 6 s is recommended for a concrete to qualify as SCC. Slump flow and V-funnel time are to some degree related to viscosity, both giving indications of flowability of concrete (Liu 2011). As per EFNARC, time ranging from 6 to 12 s is considered adequate for a SCC.

5.4 J-ring

The J-ring test is conducted in the same manner as the slump flow test; however, a J-ring consisting of 16 equally spaced bars in a 300 mm diameter ring is placed around the slump cone. After the slump cone is lifted, the concrete flows through the bars in the J-ring. Instead of measuring the slump flow, the difference in height of concrete immediately inside and outside of the J-ring (step height) is measured. Lower J-ring step height measurements are associated with increased passing ability. The size and spacing of the reinforcement bars is constant for all tests while the maximum value for the change in height should be established for the application (Eric *et al.* 2007). The passing ability and the blocking behavior of SCC were tested using a J-ring apparatus according to the procedure described in EFNARC. This test can be used in conjunction with the slump flow, or eventually even in conjunction with the V-funnel. These combinations test the flowing ability and (for the J-ring test) the passing ability of the concrete (EFNARC 2002).

5.5 L-box

As the test name implies, the apparatus consists of an L-shaped box. Concrete is initially placed in the vertical portion of the box, which measures 600 mm in height and 100 mm by 200 mm in section. A door between the vertical or horizontal portions of the box is opened and the concrete is allowed to flow through a line of vertical reinforcing bars and into the 700 mm long, 200 mm wide, and 150 mm high horizontal portion of the box. There are two variations; two and three bar tests. The three bar test simulates more congested reinforcement. In the

most common arrangement of reinforcing bars, three 12 mm bars are spaced with a clear spacing of 35 mm. The test assesses the confined flow of SCC and the extent to which it is subject to blocking by reinforcement (ACI 237R-07 2007). The height of the concrete left in the vertical section (h_2) and at the end of the horizontal section (h_1) is measured. The ratio of h_1/h_2 is calculated as the blocking ratio (EFNARC 2002). The ratio is usually between 0.8 and 1.0. If the ratio is less than 0.8, the viscosity of the SCC mixes is too high, which would cause blockage around the reinforcement (Kou and Poon 2009). The horizontal section of the box can be marked at 200 mm and 400 mm from the gate and the times taken to reach these points measured. These times are known as the T_{200} and T_{400} times. The T_{200} and T_{400} times can give some indication of ease of flow, but these are not suitable parameters for evaluating the concrete flowability.

5.6 GTM screen stability test

The GTM screen stability test method, developed by French contractor GTM, was adopted to assess the segregation resistance of the fresh SCC mixtures. The method consisted of taking 10 L of concrete and allowing concrete to stand for 15 min in a bucket covered with a lid to prevent evaporation. After that, half of the concrete was poured onto a 5 mm sieve of 350 mm diameter, which sat on a sieve pan on a weighing scale. After 2 min, the mass of mortar that passed through the sieve was measured and expressed as a percentage of the weight of the original sample on the sieve (Siddique *et al.* 2012).

5.7 Air content

Air content tests were carried out by using a modified procedure of the ASTM C231 (2014) standard (pressurizing method). The volume of fresh concrete used in the test was approximately 7 L. Two samples were carried out for each batch, taking the arithmetic mean of the two values obtained as the result. The molded fresh concrete was not compacted, it was poured into the air-meter mold and consolidated by its own weight (Felekoglu *et al.* 2007). Air bubbles formed by hydrophilic surface active compounds should not adhere to cement and grains of the aggregate, being uniformly dispersed in the concrete mix. Moreover, these bubbles are slightly bigger than those formed as a result of the functioning of the air-entraining admixture, but their stability is lower (Litvan 1983). The increased plastic viscosity causes the air content of mortar to decrease. This is because the increased plastic viscosity tends to collapse some of the air voids with higher internal pressure (Khayat and Assaad 2002).

5.8 Setting time test

Knowledge of the setting characteristics of concrete is rather important in the field of concrete construction. These will help in scheduling the various stages in-

involved in concrete construction operations such as transporting, placing, compacting and finishing of concrete. This information is a necessity when deciding whether or not to use a retarding admixture or accelerator (Brooks *et al.* 2000). The setting times of the concrete mixtures were determined in accordance to ASTM C 403 (2008). The test was performed on mortar that was obtained by sieving freshly mixed concrete through a 5 mm sieve, and measuring the force required for a needle to penetrate 25 mm into the mortar. Initial and final setting times are defined as the times at which the penetration resistance reaches values of 3.5 (500 psi) and 27.6 MPa (4000 psi), respectively.

6. Results and discussion

6.1 Slump flow test

The slump flow values of SCCs with GWG immediately after the mixing process are presented in Fig. 4. As can be seen from Fig. 4, the slump flow diameters of the mixes ranged from 670 to 702.5 mm, which classified as SF2 based on EFNARC recommendations. Slump flows of 650 to 800 mm are typically required for SCC and all the mixtures under investigation fall into this category. Utilization of GWG increased workability of the fresh concrete and as mentioned, all groups with GWG were determined to be in the SF2 class, which is suitable for many normal applications (e.g. walls, columns). The SCCG-0 mixture (control mix), which contains no GWG, showed the lowest slump flow (670 mm) compared with the other mixtures. The water content was kept constant for all of the mixtures in this study and the authors tried to keep the slump flow diameters for all mixes in a constant number to allow exact comparison. Therefore, the SP dosage should be adjusted so that the slump flow of SCCs is approximately constant. As the water absorption of GWG is lower than that of cement, the free water of the mixes increased as GWG increased, resulting in greater slump flow. In general, it can be concluded that the addition of GWG improves the workability of the concrete mix, primarily due to an increase in effective w/c and the negligible water absorption of the glass powder. This characteristic can be beneficially employed to reduce the w/c for a given workability (Schwarz *et al.* 2007). This increase in workability may

Fig. 4 Slump flow diameters of SCGWGC mixtures.

have a beneficial effect on concrete in the sense that concrete mixes with low water-to-cement ratios, for the same amount of cement materials replaced, can be produced which may have good workability, greater strength and improved durability than the control mix (i.e. SCCG-0). SCCG-25 and SCCG-30 have slump flow diameter lower than SCCG-20, the reason being a lesser SP dosage, which decreased from 1.4% to 1.2% for SCCG-25 and 1.1% for SCCG-30. Therefore, the SP dosage has a remarkable effect on the flowability of fresh concrete.

T_{500} time is measured to determine the viscosity of mixes. According to the test results, all of the SCCs are in the VS2 class, except SCCG-20. The upper and lower limits of EFNARC for T_{500} are 5s and 2s, respectively. However, it was reported in France that successful SCC mixtures were prepared with T_{500} time of 1s without any segregation and bleeding (Felekoglu *et al.* 2007). As presented in Fig. 6, the T_{500} flow times were measured in the range of 1.68 to 4.96s. The lowest slump flow time of 1.68s was measured for SCCG-20 while the mixture with 0% GWG (control mix) had the highest flow time of 4.96s. The addition of GWG improves the workability of the concrete mix, primarily due to the smooth surface texture and low moisture absorption of the GWG. Related to the various parameters, such as the dosage, the reactivity of the GWG and the w/p control the volume of the entrapped voids in the system, the total volume of voids in the fresh system and the required volume of fine particles. With increased GWG content, T_{500} flow time decreased. The reasons for this behavior seems to be the lack of cohesion and could be attributed to the fact that the paste had free water content as the result of the low moisture absorption of the GWG, which caused the SCC to be of low viscosity. Due to the lower SP for SCCG-25 and SCCG-30 compared with SCCG-20, these concretes have greater T_{500} than SCCG-20. T_{final} increase up to 15% GWG content, but SCCG-0 has a lower T_{final} compared with other SCCs (Fig. 6). This is due to an increase in workability and slump diameter. However, in the mix containing 20% GWG, the existing free water may have caused T_{final} to decrease.

Fig. 6 T_{500} and T-final slump flow test versus V-funnel time of SCGWGC mixtures.

6.2 VSI test

During the slump flow test, aggregate segregation and bleeding were visually checked. Generally, a VSI of 0 or 1 was attained for all mixes, which indicates suitable stability of the mixes. The results showed SCCG-0, SCCG-5, SCCG-10, SCCG-15, SCCG-25 and SCCG-30 to be highly stable (VSI = 0), while SCCG-20 was stable (VSI=1). It should be noted that when the SP increased over the normal dosage, segregation occurred and the VSI of the concrete mix increased. The decrease of VSI for SCCG-25 and SCCG-30 might be due to the decreased dosage of SP. The results of this test indicate acceptable SCCs (Table 11). The pictures of the VSI test for the various mixes are presented in Fig. 5.

6.3 V-Funnel test

The V-funnel test measures the time required for concrete to flow down through a funnel so as to evaluate cementing paste viscosity in concrete and resistance to material segregation. A longer flow time indicates higher viscosity of the mixture and it directly relates to better resistance to segregation (Aghabaglou *et al.* 2013). Based on the V-funnel test results (Fig. 6), all the SCCs have provided successive performance in terms of stability. All mixes displayed a V-funnel flow time of less than 9 s and according to the EFNARC guide, all the groups can be classified as VF1 in terms of their viscosity. The time measured using the V-funnel was in the range of 5.87–8.15 s depending mainly on the GWG% used. The lowest V-funnel flow time of 5.87 s was measured for the SCCG-30 while the mixture with 0% GWG (control mix) had the highest flow time of 8.15 s. Also, the V-funnel flow time for SCCG-15, SCCG-20, SCCG-25 and SCCG-30 did not show significant variation. According to the EFNARC recommendations, viscosity should be specified only in special cases such as best surface finish and in limiting the formwork pressure or improving the segregation resistance. As obvious in Fig. 6, the SCCG-20 can be classified as VS1/VF1. VS1/VF1 has good filling ability even with congested reinforcement. It is capable of self-levelling and generally has the best surface finish. However, it is more likely to suffer from bleeding and segregation (EFNARC 2002). The results presented in Fig. 6 also indicated that, irrespective of W/CM ratio and SP dosage, the V-funnel time shows a distinct tendency to decrease with increasing GWG content. For instance, SCCG-0 had a V-funnel time of 8.15 s, which decreased to 5.87 s as GWG was introduced up to 30% by mass. The variation in the T_{500} slump flow against the V-funnel times showed that a good correlation can be achieved as shown in Fig. 7. An acceptable relationship between T_{500} and V-funnel times has been reported for SCC containing GWG.

6.4 Blocking ratio test

The L-box test was performed in accordance with the EFNARC standards. The EFNARC guide states a blocking risk of the mixture when the L-box blocking ratio is

Fig. 5 Pictures of VSI for various SCGWGC mixtures.

Table 11 Unit costs of materials in analysis.

		Cement	GWG	FA	CA	Water	SP	Total	Reduction (%)
Unit cost	(R/kg)	1972	207	1150	840	40	74600	—	—
	(\$/kg)	0.062	0.006	0.036	0.027	0.0012	2.375	—	—
SCCG-0	(R/m ³)	788800	0	109250	58800	816	417760	1375426	0
	(\$/kg)	18	0	3.42	1.89	0.02448	13.3	36.6345	0
SCCG-5	(R/m ³)	749360	4140	109250	58800	816	396872	1319238	4.09
	(\$/kg)	17.1	0.12	3.42	1.89	0.02448	12.635	35.1895	3.94
SCCG-10	(R/m ³)	709920	8280	109250	58800	816	375984	1263050	8.17
	(\$/kg)	16.2	0.24	3.42	1.89	0.02448	11.97	33.7445	7.89
SCCG-15	(R/kg)	670480	12420	109250	58800	816	355096	1206862	12.26
	(\$/kg)	15.3	0.36	3.42	1.89	0.02448	11.305	32.2995	11.83
SCCG-20	(R/kg)	631040	16560	109250	58800	816	334208	1150674	16.34
	(\$/kg)	14.4	0.48	3.42	1.89	0.02448	10.64	30.8545	15.78
SCCG-25	(R/kg)	591600	20700	109250	58800	816	313320	1094486	20.43
	(\$/kg)	13.5	0.6	3.42	1.89	0.02448	9.975	29.4095	19.72
SCCG-30	(R/kg)	552160	24840	109250	58800	816	292432	1038298	24.51
	(\$/kg)	12.6	0.72	3.42	1.89	0.02448	9.31	27.9645	23.67

*(R/kg) = riyal /kg

Fig. 7 Correlation between T_{500} Slump and V-funnel time of SCGWGC mixtures.

below 0.8 and thus the blocking ratio (h_1/h_2) should be between 0.8 and 1.0. The blocking ratios of SCCs produced with GWG are given in **Fig. 8**. This ratio was determined to be between 0.84 and 0.99 for all mixtures and the test results were within this target range without any tendency of blockage. The results presented in **Fig. 8** also indicated that, at a constant W/CM ratio, the blocking ratio (h_1/h_2) shows a distinct tendency to increase with increasing GWG content. For instance, SCCG-0 had a ratio (h_1/h_2) of 0.84, which increased to 0.99 as GWG was introduced up to 20% by mass. According to EFNARC, all SCCs were ranked as the PA2 class. These results indicate that the SCGWGC mixes prepared here achieved adequate passing ability and maintained sufficient resistance to segregation around congested reinforcement area. As presented in **Fig. 8**, the highest blocking ratio was achieved for SCCG-20, due to more free water compared with the other mixes. When performing the L-box test, the authors did not observe any blockage or segregation. The reason for the low h_1/h_2 value for SCCG-25 and SCCG-30 compared with

Fig. 8 Blocking ratio (h_1/h_2) of SCGWGC mixtures.

the other mixes might be attributed to the lesser SP dosage of these mixtures. The T_{200} and T_{400} times, as mentioned before, are the time required for the mixture to reach a distance of 200 mm and 400 mm along the horizontal section from the sliding door of the L-box. The T_{200} and T_{400} times are presented in **Fig. 9**. These results give some indication about the easy flow of the concrete mixtures with GWG compared with the control mixture. T_{400} of the SCCG-0 (control mix) was about 1.73s while SCCG-20 had T_{400} of 0.94s. SCCG-0 has the highest T_{400} and T_{200} of all the mixtures. Also, T_{200} of SCCG-15, SCCG-20, SCCG-25 and SCCG-30 did not show significant variation. On the other hand, SCC mixtures with GWG percentages of 15% and 25% showed equal values of about 0.6s or 0.61s, whereas the 20% and 30% replacements showed values of 0.56s and 0.58s. According to EFNARC, all mixtures have a good filling ability.

6.5 J-ring test

For assessing the passing ability of SCC, the J-ring test was conducted for all the mixtures according to EFNARC. SCC with higher J-ring slump flow produces

Fig. 9 T_{200} , T_{400} and T_{final} L-box test of SCGWGC mixtures.

Fig. 10 H-h (step height) and slump flow with J ring of SCGWGC mixtures.

farther travel of SCC through a reinforcing bar under its own weight from a given discharge point, and it can fill a steel reinforced form or mold faster. The effect of GWG variation on the J-ring slump flow is represented in **Fig. 10**. As shown in this figure, with increasing GWG%, the difference in height between the concrete inside the bars and that outside the bars increased. The step height of the J-ring test changed from 10 mm (SCCG-0) to 15 mm (SCCG-15) for SCC with SP=1.4%, but this parameter for the SCCG-25 and SCCG-30 mixes measured 13.7 mm and 16 mm, respectively. From **Fig. 10**, it was observed that the J ring flow (slump flow with J ring) increased with increases in GWG content, but this trend does not hold for SCCG-25 and SCCG-30. This can be attributed to the decrease of the dosage of SP in these mixes. From **Fig. 11**, the T_{500} time for this test increased with increases in GWG content but for SCCG-15, SCCG-20, SCCG-25 and SCCG-30, this time is lower than for SCCG-0. This may be due to the increase in free water content and decrease in cohesion. The difference between the J-ring slump flow and the unconfined slump flow is an indication of the degree to which the passage of SCC through reinforcing bars is restricted (ACI 237R-07 2007). This parameter is sometimes called blocking assessment (Nanthagopalan and Santhamnam 2009). The results indicated that the difference in flow varied between 15 and 36 mm, corresponding to no

Fig. 11 T_{500} and T_{final} of J-ring test of SCGWGC mixtures.

Fig. 13 Segregation index of SCGWGC mixtures.

visible blocking and minimal blocking, respectively.

All of the SCGWGC mixtures do satisfy the EF-NARC requirement in this case. **Figure 12** shows photos of the slump flow, L-box and J-ring tests that were performed at the Institute for Concrete Research (ICR) of Rafsanjan University. **Figure 12** shows that there was no bleeding and segregation in mixes, and that all of the mixes have good workability for practical applications.

6.6 Segregation index (GTM) test

The segregation index is the percentage of laitance passing through a 5 mm sieve to the total weight of the sample. Segregation index SCC mixtures ranged from 5.6 to 8.7% in accordance with ACI-237R-07. As presented in **Fig. 13**, with increases of GWG%, the segregation index decreased by up to 10%. However, due to increase in free water content and decrease in cohesion, the segregation index for SCCG-15 and SCCG-20 increased. SCCG-25 and SCCG-30 have the lowest segregation index among the SCCs. The combined influences of an increase in glass content and decrease in SP dosage could lead to the increased viscosity and hence result in lower segregation. The laboratory sieve segregation test is presented in **Fig. 14**.

Fig. 12 SCGWGC mixtures featuring different replacement levels of GWG: (a) slump-flow, (b) L-box, and (c) J-ring tests.

Fig. 14 Sieve segregation test.

6.7 Air content

The air content in the tested mixtures amounted to 1.2% - 3.8% (**Fig. 15**). As can be seen from **Fig. 15**, increasing GWG content caused air content to decrease. This may be attributed to increase in free water content and filling ability of concrete mixes with GWG. SCCG-20 has the lowest air content of all the mixes. Therefore, more GWG improved the concrete quality in term of decreasing air content. Vice versa, increasing the SP dosage caused air trapping to decrease during mixing as a side effect, and the air content of the mixes increased. The air content test is presented in **Fig. 16**.

6.8 Wet density test

The wet density of fresh SCC was determined using BS EN 12350 Part 6⁵⁸ test method. The density of all the mixes is shown in **Fig. 17**. It is evident that density decreased with increases in the content of GWG. This can be attributed to the lower specific density of glass (2.50

Fig. 15 Air content of SCGWGC mixtures.

Fig. 16 Air content test.

gr/cm^3) compare with the cement specific density ($3.15 gr/cm^3$). The density of SCCG-30 compared with SCCG-0 decreased about 1.4 %. As the self-weight of SCC and the dead weight of the structure are decreased using SCGWGC, these mixes are good candidates for the construction of building components.

6.9 Setting time test

According to ASTM C 403⁵⁴, **Fig. 18** shows typical trends of penetration resistance of concrete as a function of time. Here, the penetration resistance method has been investigated in order to evaluate setting phenomena and observe the development of connected hydration products (Gamsa and Trtnik 2013). Increasing the GWG content led to considerable increase of the initial and final sets. For instance, from **Fig. 18**, it is observed that for a given W/CM ratio and SP dosage, the initial and final sets of SCCG-20 are greater than those of SCCG-0. This can be attributed to the increasing of free water in SCCs and smooth surface texture and the low moisture absorption of glass. However, a decrease in SP dosage could lead to the decrease of the initial and final setting times of concrete for SCCG-25 and SCCG-30. Compared with SCCG-0, the initial and final setting times of SCCG-30 decrease 20 min and increase 57 min, respectively. The maximum initial and final setting times were obtained for the specimen made with 20%

Fig. 17 Unit weight of SCGWGC mixtures.

Fig. 18 Setting time of SCGWGC mixtures.

Fig. 19 Setting time test.

GWG. The setting time test is presented in **Fig. 19**.

7. Comparison of cost analysis

Because of the used SPs and additional cement in SCC, the cost of SCC is higher than that of conventionally vibrated concrete. SCC can only be cost effective if more economical mixture ingredients are introduced on the market (Uysal and Yilmaz 2011). Incorporation of inert, pozzolanic/hydraulic additions or waste and recycling materials as substitutions for high amounts of cement may significantly improve the material cost effectiveness of SCC. GWG being a waste material, its cost is either nil or negligible, making its use as a cement replacement in SCC applications economically attractive. The change to the overall cost of concrete production, i.e. transportation, handling, placement and quality control, was not taken into account in this study. Cost analysis of the materials used was analyzed based on the purchase price from the market (as of July 2014). In order to compare the costs of the seven investigated SCCs, the local unit costs of materials were collected and are presented in **Table 11**. The costs of 1 m^3 of each mixture is presented in **Table 11**, which shows that the cost of SCGWGC decreases with increased GWG content, owing to the decreased dosage of SP and ordinary Portland cement. For example, the cost of the ingredients of SCCG-30 replacing 30% of cement with GWG is 23.67% less compared with the control concrete.

7. Concluding Remarks

The present paper considers the feasibility of employing GWG as a supplementary cementing material for producing SCC. Based on the experimental results, the following conclusions have been drawn:

- 1- In general, incorporating GWG as a cementing material increases the workability properties of SCC, maybe due to the smooth glassy surface texture and low moisture absorption of GWG.
- 2- Increasing the GWG content as cement replacement caused the slump flow to increase, which can be attributed to the low water demand of glass compared

with cement. Another effect is that the amount of admixture has a significant effect on the workability of SCC, especially slump flow. Using an appropriate admixture could improve the workability of SCC remarkably, as observed in this study.

- 3- Viscosity decreased dramatically as the GWG content as cement replacement increased. V-funnel time and T500 slump flow are two important viscosity measurement tests. The results from both tests show that utilizing GWG as cement decreased the times, meaning that viscosity was decreased.
- 4- Passing ability increased as GWG content increased. The L-box and J-ring tests are two important tests that assess the passing ability of fresh SCC. From the obtained results it can be concluded that as GWG increased, the L-box and J-ring ratios increased, meaning that passing ability increased. This can be attributed to the low water demand of GWG compared with cement, resulting in more free water and increased rheology and flowing characteristics.
- 5- The bleeding and segregation phenomena of SCGWGCs were seen to be in acceptable ranges. This made the aggregates and paste work together and homogenize
- 6- Air content decreased as the GWG percent increased, and consequently this led to a dense concrete. But densities measurements of the mixes showed that wet densities decreased as GWG increased.
- 7- The setting times increased as cement was replaced by GWG in different quantities, confirming the expectation that the addition of pozzolan slag such as GWG to cementing material would increase the setting time.
- 8- The improvement in the fresh properties of concrete mixtures incorporating GWG as cement indicates that GWG can be used beneficially as cementing material for SCC. However, additional experimental results are needed with regard to the properties of hardened concrete and long-term behavior.

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