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Research Article

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The effect of materials and curing system on the behavior of self-compacting geopolymer concrete

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Abstract: The aim of the present work was to investigate and achieve the optimum compressive strength of self-compacting geopolymer concrete (SCGC). Fly ash (FA) and ground granulated blast furnace slag (GGBFS) are used at different ratios as binder materials to produce the SCGC mixes. Alkaline solution was a mix of sodium silicate and sodium hydroxide. Three different ratios of binder materials were used to produce SCGC (0FA-100GGBFS; 50FA-50GGBFS; and 100FA-0GGBFS). The total binder weight was 500 kg/m^3 within a constant alkali–binder proportion (0.5). Two curing conditions were used, at ambient environment and heat curing at 110°C for 24 h. The compressive strength and fresh properties of SCGC are evaluated. The compressive strength is utilized to demonstrate the mechanical properties of SCGC. The compressive strength is investigated at two ages (7 and 28 days). The results showed that the use of GGBFS had a negative effect on the fresh properties of SCGC. However, it has a significant impact on the mechanical behavior of the SCGC. SCGC's early strength is heavily involved in heat curing. The compressive strength of 100% GGBFS in the ambient environment after 28 days was more than that of GGBFS cured at 110°C. The optimum eco-friendly mix is 50FA-50GGBFS.

Keywords: self-compacting geopolymer concrete, curing condition, binder materials

1 Introduction

Concrete is the most often used construction material due to the availability of raw materials and the ease of its form. However, due to the use of fossil fuels and the decarbonization of limestone, the cement industry emits significant amounts of carbon dioxide (CO_2) into the environment. Furthermore, besides aluminum and steel, ordinary Portland cement (OPC) is one of the more energy-intensive materials [1,2]. As a result, the negative environmental effect of carbon dioxide, as well as the large amount of energy required, are major concerns for cement manufacturing and for the future of civilization. To solve environmental challenges, new environmentally structural resources are used as an alternative for traditional concrete [3,4]. In recent years, geopolymer has developed as an environmentally friendly alternative to traditional OPC concrete [5,6]. The significant reduction in carbon dioxide emissions, as well as the increased demand for natural resources, have increased attention in geopolymer concretes. Unlike OPC, raw material production does not require calcination, hence energy usage is minimized. The amount of CO_2 emitted by geopolymer concrete (GPC) is 5–6 times less than that of OPC concrete [7–9].

Moreover, the use of GPC not only reduces carbon dioxide emissions significantly, but also allows by-product wastes from aluminosilicate synthesis to be utilized in the development of new construction materials [10]. Self-compacting concrete (SCC) is commonly employed in civil engineering projects, especially in prefabricated industries, high-rise structures, and buildings that reinforce congestion. The main properties of SCC except segregation and/or bleeding are passing ability, filling ability, and flowability. Self-compacting geopolymer concrete (SCGC) is a unique innovation in the concrete industry. It is a new form of concrete with geopolymer and SCC characteristics [11–14]. There has not been much research done on SCGC. As with standard SCC, further study is needed to evaluate the fresh and hardened performance of SCGC for future application.

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Supplemental cementitious materials (SCM) and mineral fillers are examples of such materials. They are utilized in concrete to reduce costs while simultaneously improving the workability and the hardened state properties and are more eco-friendly materials [15–18]. Many research papers have investigated the use of fly ash (FA) and ground granulated blast furnace slag (GGBFS) as SCMs because they improved the mechanical performance of concrete, economical, and the environment-friendly green concrete [16,19]. Geopolymer, also known as alkaline concrete, is an environmentally friendly product that performs well in hardened conditions. Furthermore, it consumes less energy and emits less carbon dioxide during the manufacturing process than OPC concrete [20]. A geopolymer is a non-organic binding material that can replace OPC [21]. Instead of conventional concrete, GPC based on FA may be used, and dangerous and radioactive elements can also be absorbed and immobilized. Mechanical and long-term performance of FA-based GPC is a significant issue in the concrete industry [22]. Geopolymer raw materials such as FA, waste glass powder, phosphate sludge, and red mud have also been studied [23,24]. According to the literature [25,26], other waste materials such as granulated furnace slag and silica fumes might be utilized to replace FA in the production of GPC. FA-GPC is a common type of GPC; however, FA may be replaced by slag in the production of GPC. As a result, it is possible to conclude that more study on GPC is required. However, there is only limited research in the literature regarding the mechanical and fresh characteristics of FA/GGBFS- based SCGC. GPCs are not included in the structural design standards and applications due to a lack of understanding of the properties of their material. To develop the fresh and mechanical characteristics of SCGC, more research is required. Therefore, the aim of this study is to investigate the influence of FA/GGBFS ratios and the curing process on the performance of SCGC.

2 Methodology

2.1 Materials

FA, Type-F-based ASTM C618 [27], and GGBFS were used as binder materials. The total binder amount was 500 kg/m^3 and a constant ratio of alkali/binder (0.5) were proportioned. Three different binder ratios were used in the production of SCGC (0FA-100GGBFS; 50FA-50GGBFS; and 100FA-0GGBFS). FA and GGBFS were obtained from a local supplier in Erbil, Iraq. The properties of FA and GGBFS are shown in Table 1. The fine and coarse aggregate was local sand brought from the Qara Salem area near Kirkuk City, Iraq. The maximum size of fine aggregate and coarse aggregate was 4.0 and 12 mm, respectively. Tables 2 and 3 illustrate the properties of the aggregates according to the ASTM C33 [28].

The sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) solutions are used as alkali activators. A local provider in Erbil, Iraq, provided the Na_2SiO_3 (Na_2O: 13.7%, SiO_2: 33%, and water: 53.3% by mass) [26]. The NaOH with 97–98% purity with a 12 molar concentration was used, which was the optimum concentration for SCGC mechanical efficiency [29]. For economic considerations, the optimal Na_2SiO_3/NaOH ratio was determined to be in the range of 1.5–2.5, as previously examined [29]. A polycarboxylate 3rd generation with a density of 1.096 g/cm^3 was utilized as a superplasticizer to achieve high-flowability without segregation and/or bleeding [30]. Figure 1 shows the materials used in the production of SCGC mixes.

2.2 Mix design

FA and GGBFS are used as binder materials in the production of SCGC mixtures. The total binder amount was

Table 1: The properties of FA and GGBFS

Components	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O	LOI	SG	BF (m^2/kg)
FA (%)	1.58	63.21	22.13	7.15	2.39	0.11	2.39	0.38	1.56	2.31	378
GGBFS (%)	33.93	35.42	12.38	1.68	9.29	0.48	3.64	0.36	1.63	2.78	580

LOI: loss on ignition; SG: specific gravity (kg/m^3); BF: Blaine fineness (m^2/kg).

Table 2: The sieve analysis and physical properties of fine aggregates

Sieve number (mm)	No. 4	No. 8	No. 16	No. 30	No. 50	No. 200	Specific gravity	Absorption
Fine aggregate	99	87	67	53	26	1	2.62	0.17%
Percent passing according to ASTM C33	95–100	80–100	50–85	25–60	5–30	0–3		

Table 3: The sieve analysis and physical properties of coarse aggregates

Sieve number (mm)	½	3/8	No. 4	No. 8	Specific gravity	Absorption
Coarse aggregate	95	62	3	0	2.68	0.6%
Percent passing according to ASTM C33	90–100	40–70	0–15	0–5		

500 kg/m^3 and a constant ratio of alkali/binder (0.5) were proportioned. Three different binder ratios were used in the production of SCGC (0FA-100GGBFS; 50FA-50GGBFS; and 100FA-0GGBFS). The ingredients (weight per 1 m^3 concrete) for the mix are shown in Table 4.

Mechanical behavior and fresh properties of SCGC are affected by alkaline ratio, maximum grain size, and binder type. For economic purposes, the Na_2SiO_3/NaOH ratio is produced from 1.5 to 2.5 [29]; and the ratio of 2.5 was used in the current study.

Aggregates, FA, and GGBFS were first mixed for 2.5 min. The alkali activator was added gradually for 1 min, and then a superplasticizer was mixed with extra water and added for 2 min. For adequate homogeneity and uniformity, the mix was mixed for additional 3 min.

2.3 Fresh properties tests

All fresh characteristics testing is conducted in accordance with the European specification for SCC development established by the EFNARC committee [31]. The slump flow value is used to determine the free flowability of a mixture. The SCC is used in several building parts. Therefore, EFNARC standard classify the slump flow into three classes. Figure 2 shows the slump test for the SCGC mix. Furthermore, the V-shaped funnel time, which is the elapsed time of mixture's flow through the V-funnel opening, was utilized to evaluate the V-funnel flow test. The L-box test determines the ability of fresh concrete to flow through narrow gaps and restricted locations, such as areas with congested reinforcement, without losing homogeneity or regularity.

2.4 Curing method for the SCGC specimens

The specimens were covered with plastic sheets for 24 h after the concrete was cast to prevent the alkaline solution from evaporation. On the other hand, the samples are divided into two groups depending on the curing type. The first group was stored at room temperature

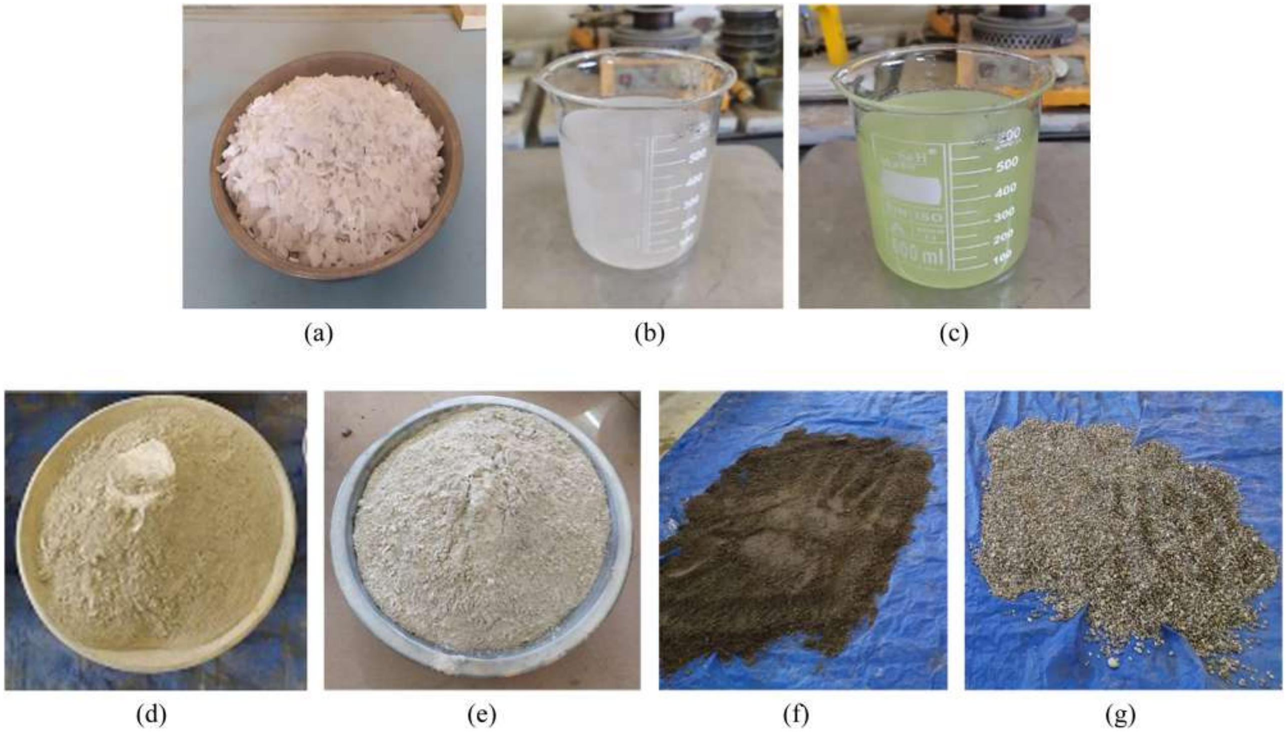

Figure 1: Materials used in the production of SCGC specimens: (a) sodium hydroxide, (b) alkaline solution, (c) superplasticizer, (d) FA, (e) GGBFS, (f) fine aggregate, and (g) coarse aggregate.

Table 4: The SCGC mixture proportions

Mixture	Binder kg/m^3	Na_2SO_3 + NaOH kg/m^3	GGBFS kg/m^3	FA kg/m^3	Curing °C	Fine agg. kg/m^3	Coarse agg. kg/m^3	SH concentration	SP %	Extra water %
S50FA50	500	250	250	250	Ambient	865.61	742.88	12	6	5
S100FA0	500	250	500	0	Ambient	862.65	740.34	12	6	5
S0FA100	500	250	0	500	Ambient	859.69	737.80	12	6	5
S50FA50	500	250	250	250	110	865.61	742.88	12	6	5
S100FA0	500	250	500	0	110	862.65	740.34	12	6	5
S0FA100	500	250	0	500	110	859.69	737.80	12	6	5

FA: fly ash, GGBFS (S): ground granulated blast furnace slag, SH: sodium hydroxide, SP: superplasticizer, both SP and extra water are a ratio percent of the binder weight materials.

(ambient curing) in the lab until the test day, and the other group was left in an electric oven for 24 h at 110°C and then left in the lab till the day of the test. For each test, three identical specimens were used for each experiment, and the mean value was taken.

2.5 Compressive strength of SCGC

The hardened tests were carried out to investigate the combined effects of using GGBFS and FA at various ratios, and curing methods on the behavior of SCGC specimens. Compressive strength testing on cubic specimens (100 mm × 100 mm × 100 mm) was carried out in accordance with the ASTM C39 standard [32].

3 Experimental results

3.1 Fresh properties of SCGC

The flow ability and passing ability of SCGC mixes are within the EFNARC specifications [31]. In addition, the slump flow diameters fulfilled the EN 12350-8 standard [33], which specifies a minimum slump flow diameter of 600 mm. The fresh properties showed that there is no segregation and bleeding for SCGC mixes. One of the research goals is to investigate the effect of GGBFS/FA ratio on the fresh properties of SCGC. The effects of these variables on the flowability and passing-ability properties of SCGC were investigated in detail.

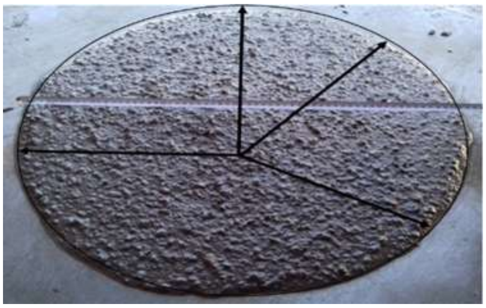

Figure 2: Slump flow diameter of SCGC.

3.2 Effect of GGBFS on the fresh performance of SCGC

Table 5 represents the effect of GGBFS on the fresh state of SCGC. The mixture of 0% GGBFS and 100% FA achieved the maximum slump flow diameter (720 mm). The slump flow diameter was reduced from 720 mm (0% GGBFS) to 685 and 665 mm after adding 50 and 100% GGBFS, respectively. All slump flow values were in the SF2 interval, which is appropriate for a wide range of reinforced members (slab, beam, and column) according to the EFNARC specification [31]. It was also shown that GGBFS content improved both bleeding and segregation resistance, and that greater GGBFS mixes were more cohesive than lower GGBFS mixes.

The composition and fineness of the binder compounds, the structure and concentration of alkaline activators, and

Table 5: The test result of fresh properties of SCGC

Mixture	GGBFS	FA	Slump flow (mm)	V-Funnel (s)	T50 (s)	L-Box (%)
S0FA100	0	100	720	13.26	2.33	1
S50FA50	50	50	685	13.8	3.5	0.99
S100FA0	100	0	665	23.1	4.8	0.95

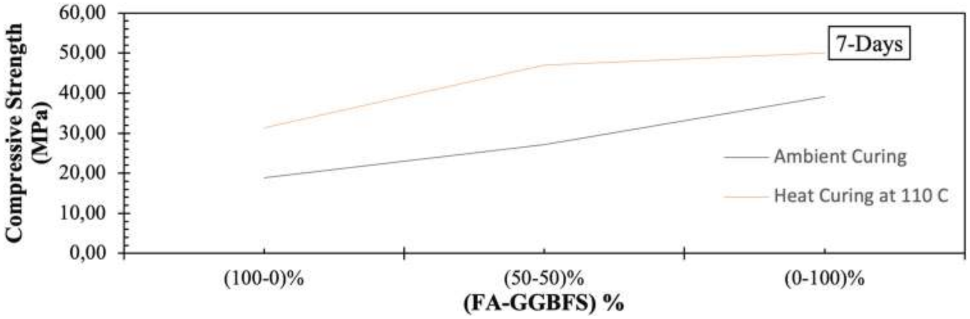

Figure 3: The effect of binder ratio and curing condition on the compressive strength at 7 days.

the curing condition all have an effect on the SCGC setting time [34,35]. GGBFS particles are smaller than FA particles. According to studies, GGBFS has a specific surface area of 580 m^2/kg. SCGC's rheological activity and flowability are influenced by its high specific surface area. GGBFS absorbed a significant amount of water on the surface due to its high specific surface area, resulting in lower flowability of SCGC due to the reduced amount of water required for lubrication [36–38].

The better T50 time and V-funnel flow time were detected using 100% FA-0% GGBFS based SCGC and increased with the addition of GGBFS, similar to slump flow results. However, according to EFNARC requirements, all V-funnel and T50 values in the current study were deemed acceptable [29]. Furthermore, the T50 duration findings indicated that the quantity of GGBFS ratios had a negative impact on the flowability of SCGC; mixes containing 100% GGBFS had the longest T50 duration and V-funnel flow time.

The incorporation of GGBFS in the mix causes an increase in plastic viscosity, while reducing the L-Box ratio and slump test value. Moreover, when the ratio of GGBFS in the mixture increases, the viscosity and cohesiveness of the mixtures increase, while the flowability and fluidity decrease. Since the specific surface area of FA is lower than GGBFS, more free water is available for lubrication, and therefore superior workability was achieved. Mixes containing (100% GGBFS-0% FA) exhibited superior workability properties. However, all SCGC mixes, according to EFNARC, satisfied the SCGC characteristics.

3.3 Compressive strength of SCGC

The influence of GGBFS and FA on the compressive strength of SCGC specimens exposed to ambient temperature and/or 110°C oven curing is shown in Table 5 and Figures 3–7. The specimens containing 100% FA had lower compressive strength than the specimens containing 50 and 100% GGBFS. This may be because unreacted FA particles cause severe self-dehydration, resulting in cracks and decreased the compressive strength [39]. Furthermore, increasing the GGBFS ratios improved the compressive strength of SCGC. Previous studies investigated that specimens including GGBFS0-FA100 had the lowest compressive strength due to lower FA activity [40] and low calcium [41,42]. Different types of binder are investigated by the researchers and they indicated that the compressive strength was improved by the use of FA, GGBFS, and FA/GGBFS as a binder in the production of GPC [41–44]. The researchers studied in detail the XRD patterns of

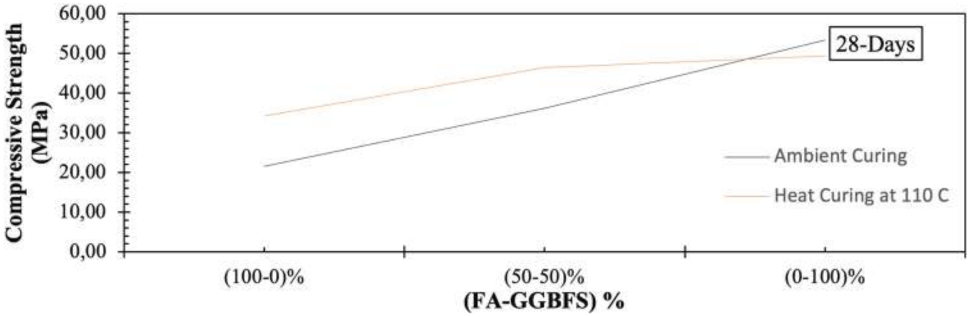

Figure 4: The effect of binder ratio and curing condition on the compressive strength at 28 days.

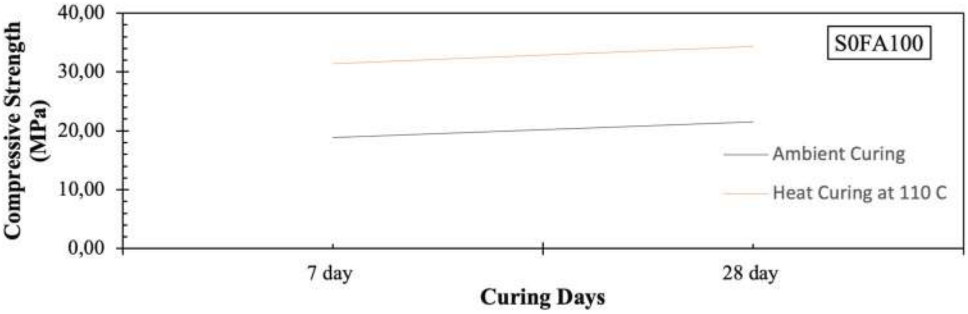

Figure 5: Compressive strength of (0GGBFS-100FA) specimens.

FA-based GPC (100% FA) to investigate how low calcium FA affected the results. Less calcium-silicate-hydrate was produced as a result of less reactive calcium (Ca) (C–S–H). The reduced volume of Ca in the FA did not contribute to the formation of calcium-silicate-hydrate, explaining why FA-based GPC specimens had lower compressive strength. They also investigated that the calcium aluminum oxide hydroxide hydrate ($Ca_6Al_2O_6(OH)_632H_2O$) is the primary hydration agent for FA-based GPC specimens [36,40].

It was illustrated from Table 6 that the heat curing also improved the compressive strength of SCGC at an early age. Each mix improved when it was exposed to heat curing; the improvement ratio was 66, 73, and 28% for the specimens including 0% GGBFS, 50% GGBFS, and 100% GGBFS, respectively, at age of 7 days. Whereas the improvement ratios at the age of 28 days were 81, 72, and 27% for the same mixes. It was noted that the compressive strength for the specimens exposed to heat curing at the age of 7 days were the highest values. This may be due to the geopolymerization process (activation process), which was almost completed at the age of 7 days. However, the specimens including 100% FA had 9% improvement at the age of 28 days compared to the age of 7 days. Hence, it is possible to use the GGBFS to improve the mechanical properties of SCGC at ambient conditions, since the maximum compressive strength was

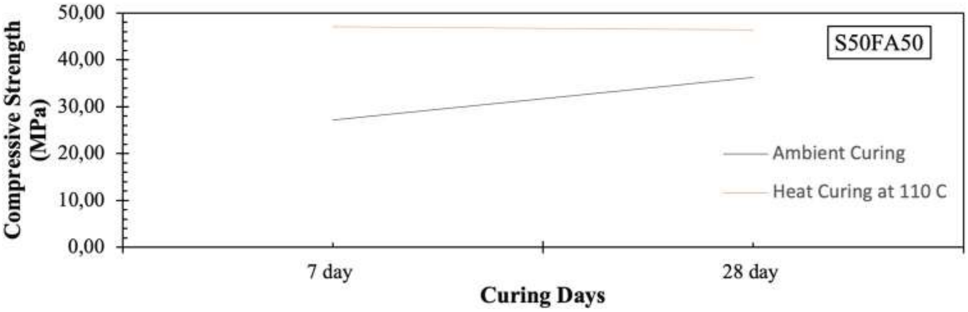

Figure 6: Compressive strength of (50GGBFS-50FA) specimens.

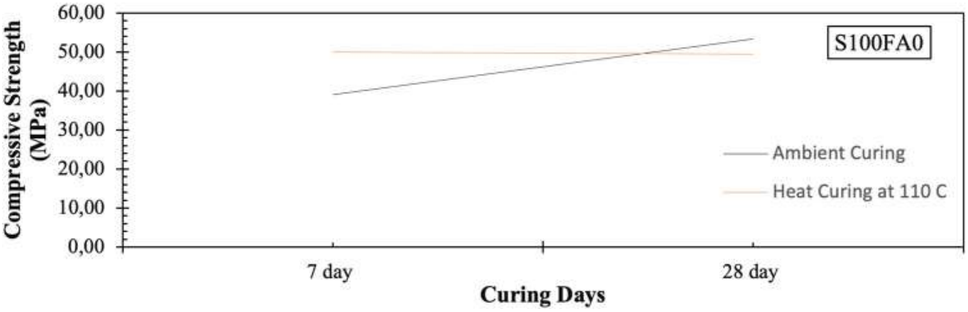

Figure 7: Compressive strength of (100GGBFS-0FA) specimens.

Table 6: The compressive strength of SCGC specimens

Mix designation	7-day compressive strength		28-day compressive strength	
	Ambient curing	Heat curing at 110 °C	Ambient curing	Heat curing at 110 °C
S0FA100	18.9	31.4	21.55	34.3
S50FA50	27.2	47	36.2	46.38
S100FA0	39.1	50	53.4	49.44

observed at ambient environment for the mix including 100% GGBFS.

The highest compressive strength was found when 100% of GGBFS was used, and the minimum compressive strength was found when 100% FA was used. In addition, SCGC mixtures cured at ambient environment have a compressive strength on the scale of normal to high, which can be noted with average values between 21.5 and 53 MPa.

Moreover, the compressive strength values showed that it continued to increase up to 28 days at ambient curing. On comparing the 7 days' compressive strength test values to 28 days' compressive strength test results for 0, 50, and 100% GGBFS, the average increase was around 14, 33, and 37%, respectively.

On the other hand, it was noted that the optimum ratio of the binder materials for SCGC at ambient environments was 50% FA-50% GGBFS according to the use of FA (eco-friendly purposes) and the values of compressive strength achieved in the current study compared to other mixes. It is worth to mention that the use of GGBFS exhibits high amounts of shrinkage and long-term durability performance as stated in previous studies.

4 Conclusion

In this study, the influence of materials and curing method on the behavior of SCGC was investigated, and the following conclusions were reached:

- The use of GGBFS substantially reduced the flowability and passing ability of fresh state tests. The mixes with the highest 0FA-100GGBFS had the maximum reduction in fresh results.
- Flowability and passing-ability requirements for all SCGC mixes have met the specifications of EFNARC standard requirements.
- The use of GGBFS increased the plastic viscosity, and decreased the L-box ratio and slump flow values.
- Mixtures with high amounts of GGBFS become more cohesive and viscous. The resistance to bleeding and segregation was improved. However, the flowability and fluidity are decreased when the ratio of GGBFS increased. All the tested mixes fell into the VS2/VF2 category according to the EFNARC standard.
- Compressive strength is affected by the replacement ratio of the GGBFS, where the compressive strength increased as the GGBFS ratio increased up to 100%. When cured at 110°C, SCGC achieves the highest compressive strength at an early age (7 days). On the other hand, ambient curing has a progressive impact on compressive strength.
- The compressive strength of the specimens exposed to ambient environment was shown to grow with time up to 28 days, in comparison to compressive strength after 7 days of ambient curing.
- The highest compressive strength was found when 100% of GGBFS was used, and the minimum compressive strength was found when 100% FA was used. In addition, SCGC mixtures cured at ambient environment having a compressive strength on the scale of normal to high with average values between 21.5 and 53 MPa can be noted.
- It was noted that the optimum ratio of the binder materials for SCGC at ambient environments was 50% FA-50% GGBFS according to the use of FA (eco-friendly purposes) and the values of compressive strength achieved in the current study compared to other mixes. It is worth to mention that the use of GGBFS exhibits high amounts of shrinkage and long-term durability performance as stated in previous studies.

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