Environment sustainable construction materials for garden-fresh and mechanical properties of high strength self-compacting concrete mixes with diverse mineral admixtures and water binder ratios

R. Lavanya*

Department of Civil Engineering,
Thiagarajar Polytechnic College,
Salem 636005, Tamil Nadu, India
Email: tptlavanyacivil@gmail.com
*Corresponding author

P. Murthi

Department of Civil Engineering,
Sri Shakthi Institute of Engineering and Technology,
Chinniyampalayam Post,
Coimbatore 641062, Tamil Nadu, India
Email: drpmurthi@gmail.com

V. Karthikeyan

Department of Civil Engineering,
Thiagarajar Polytechnic College,
Salem 636005, Tamil Nadu, India
Email: vkntpt@gmail.com

Abstract: An experimental investigation was carried out to study the properties of self-compacting concrete (SCC) prepared with different mineral admixtures and water-binder ratios. The mixes were designed for M60 grade of concrete and prepared with three steps of addition of GGBS and silica fume and were made with four steps of fly ash as partial replacement of fine aggregate. The fresh properties were studied with standard tests. Compressive strength was found at the different ages and the split tensile and flexural tests were performed at the age of 28 days. The test results of SCC mixes revealed that, the flowability increases with increase in fly ash content and the compressive strength decreases with increase in water-binder ratio. It is concluded that a combination of fly ash, silica fume and GGBS in SCC can be used to make a sustainable, eco-friendly construction material for a better tomorrow.

Keywords: self-compacting concrete; SCC; water-binder ratio; fly ash; GGBS; silica fume.

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Biographical notes: R. Lavanya is presently working as a Lecturer from the Department of Civil Engineering, Thiagarajar Polytechnic College (a government aided autonomous institution) Salem, Tamilnadu, India. She received her Master's of Engineering from the Anna University, Chennai. She has over eight years of diversified experience in teaching. She has published papers in international and national journals and conferences in the areas of self-compacting concrete and optimisation.

P. Murthi is presently a Professor and Head of the Department of Civil Engineering, Sri Sakthi Institute of Engineering and Technology, Coimbatore, India. He received his PhD from the Anna University, India. He has over 28 years of diversified experience in the area teaching and research. He has published more than 30 papers in international and national journals and conferences in the areas of self-compacting concrete and fibre reinforced concrete. He is a member of several professional bodies such as ISTE and IE.

V. Karthikeyan is the Principal of Thiagarajar Polytechnic College, Salem, a government aided autonomous institution. He has obtained his Bachelor's and Master's in Civil Engineering and acquired PhD for research on Municipal Solid Waste Management. He completed the prestigious UK-India Education and Research Initiative (UKIERI) training on Further Education Leadership Development Programme sponsored by the AICTE, New Delhi. He obtained his CMI Level 5 Certificate and has published 20 research papers in international, national journals and magazines and also presented a number of papers in international, national seminars in the field of air, water, soil, municipal solid waste and concrete.

1 Introduction

Self-compacting concrete (SCC) is considered as a concrete that can be placed and compacted under its self-weight with little or no vibration, and without segregation or haemorrhage. It is sold via jumble sale to facilitate and ensure proper filling and good structural performance of restricted areas and heavily reinforced structural members (Aswathy, 2015). It has attained importance in recent years because of the advantages it offers. Such type of concrete requires a significant slump that can easily be obtained by adding a superplasticiser to a mix and by proper mix proportioning (Okamura and Ouchi, 1999). Using organic admixtures in SCC is expensive and their use may increase the cost of the materials. Savings in labour cost may offset the higher cost. Also, the use of mineral admixtures such as fly ash, blast furnace slag, or silica fume could increase the fresh properties of the concrete mixture without increasing its cost. Further, the use of fly ash enhances rheological characteristics and minimises the cracking tendency of the concrete as it reduces the heat of hydration of the cement (Anil and Chowdary, 2017). The mineral replacement of admixtures in SCC showed a significant improvement in the rheological properties of its flowing ability. The use of mineral admixtures reduces the demand for cement, fine fillers, and sand, which are mandatory in high quantities in SCC (Okamura, 1997). For concrete to be self-compacting, it is essential that it should possess filling ability, passing ability, and resistance over the segregation property (Pai et al., 2014). These features are gained by limiting the coarse aggregate content and using lower water-powder ratio together with super plasticisers (Siddique, 2011). In SCC, mineral admixtures are usually added in large amount to enhance the workability of fresh state and durability in the hardened state. A study has shown that SCC with 5% silica fume and 20% and 30% replacement of river sand by manufactured sand was considered as fresh SCC within IS 10262 (2009) guidelines (Khurana and Saccone, 2001). Silica fume is used as a simulating pozzolanic admixture in concrete. It is a product obtained by reduction of high-purity quartz together with coal in an electric arc furnace during the production of silicon or ferrosilicon alloy. Condensed silica fume is essentially silicon dioxide (more than 90%) that is present in non-crystalline form (Khayat et al., 2005). It is a very fine powder with particle size less than 1 micrometre and with an average diameter of about 0.1 micrometre approximately 100 times smaller than average cement particles. As it offers a high surface area, its bond with cement and aggregate gives better result in strength (Ahmed et al., 2017). Ground-granulated blast-furnace slag (GGBS) is obtained by quenching molten iron slag from a blast furnace in water or steam, to produce a smooth, shiny, granular product that is then dried and ground into a fine powder (Mokal et al., 2015). It has excellent pozzolanic property. In this investigation, the experiments were conducted with three mineral admixtures and three water-binder ratios were considered.

Table 1 Chemical composition of ingredients

Sl. no.	*Compound*	*Cement*	*Fly ash*	*Silica fume*	*GGBS*
		Weight (%)			
1	SiO_2	23.8	65.93	93.4	32.6
2	Al_2O_3	5.86	23.69	1.5	12.8
3	Fe_2O_3	5.47	2.82	3.0	1.3
4	CaO	63.30	3.93	0.7	4.1
5	Na_2O	0.71	0.86	0.5	0.2
6	K_2O	0.86	2.77	0.9	0.3

2 Experimental procedure

2.1 Materials

In this investigation the ordinary Portland cement with a specific gravity of 3.14 was used. Natural river sand with fraction passing through a 4.75 mm sieve and retained on a 600 µm sieve was used for this investigation as per IS 2386 (Part 1) (1963) standard (Khan, 2016). The fineness modulus of the sand used was 2.96 with a specific gravity of 2.60. Coarse aggregates of 12.5 mm were used for this investigation. In the preparation of concrete mix, locally available fly ash was used. GGBS was obtained from iron blast-furnace industry. It was collected from Jason Slag Cement (Salem, Tamil Nadu, India), and silica fume was obtained from Elkem (Mumbai, Maharashtra, India). The procured silica fume conforms to ASTM-1240 (2015) standard. In this investigation, a communally available super plasticiser was used. It was prepared from sulphonated naphthalene polymers and conformed to IS 9103 (1999), BS: 5075 Part 3, and ASTM C-494 (2017) standards. The chemical composition of the ingredients are presented in Table 1.

2.2 Mix proportions

Eleven SCC mixes were prepared, including conventional SCC. All concrete mixes were of M60 grade. In mixes FA5, FA10, FA15, and FA20, fine aggregates were replaced with 5%, 10%, 15%, and 20% fly ash, which had total powder content it contains the cement and fly ash of 550 kg/m^3. The remaining mixes were prepared with 5%, 10%, and 15% GGBS and silica fume replacing fine aggregate. Super plasticiser content was kept constant for all mix combinations (11.01 kg/m^3). In the conventional SCC mix, coarse aggregate content was maintained at 39% by volume (589 kg/m^3) of concrete and fine aggregate content at 45% by volume (910 kg/m^3) of mortar in concrete and the water-binder ratio was kept at 0.30, 0.35, and 0.40 by weight with air content being assumed to be 2%. Details of mix proportions are given in Table 2.

Table 2 Mix proportions of SCC

Sl. no.	*Mix ID*	*Ingredients (kg/m^3)*						*Fine aggregate (kg/m^3)*	*Water (kg/m^3)*
		C	*C A*	*F A*	*SF*	*GGBS*	*SP*		
Water-binder ratio of 0.3									
1	Conventional SCC	550	589	0.0	0.00	0.00	11.0	913.0	165
2	FA5	550	589	45.7	0.00	0.00	11.0	867.4	165
3	FA10	550	589	91.3	0.00	0.00	11.0	821.7	165
4	FA15	550	589	137.0	0.00	0.00	11.0	776.1	165
5	FA20	550	589	182.6	0.00	0.00	11.0	730.4	165
6	SF5	550	589	0.00	45.7	0.00	11.0	867.4	165
7	SF10	550	589	0.00	91.3	0.00	11.0	821.7	165
8	SF15	550	589	0.00	137.0	0.00	11.0	776.1	165
9	GGBS5	550	589	0.00	0.00	45.7	11.0	867.4	165
10	GGBS10	550	589	0.00	0.00	91.3	11.0	821.7	165
11	GGBS15	550	589	0.00	0.00	137.0	11.0	776.1	165
Water-binder ratio of 0.35									
1	Conventional SCC	550	589	0.0	0.00	0.00	11.0	867.4	192.5
2	FA5	550	589	45.7	0.00	0.00	11.0	821.7	192.5
3	FA10	550	589	91.3	0.00	0.00	11.0	776.1	192.5
4	FA15	550	589	137.0	0.00	0.00	11.0	730.4	192.5
5	FA20	550	589	182.6	0.00	0.00	11.0	867.4	192.5
6	SF5	550	589	0.00	45.7	0.00	11.0	821.7	192.5
7	SF10	550	589	0.00	91.3	0.00	11.0	776.1	192.5
8	SF15	550	589	0.00	137.0	0.00	11.0	867.4	192.5
9	GGBS5	550	589	0.00	0.00	45.7	11.0	821.7	192.5
10	GGBS10	550	589	0.00	0.00	91.3	11.0	776.1	192.5
11	GGBS15	550	589	0.00	0.00	137.0	11.0	867.4	192.5

Table 2 Mix proportions of SCC (continued)

Sl. no.	*Mix ID*	*Ingredients (kg/m³)*						*Fine aggregate (kg/m³)*	*Water (kg/m³)*
		C	*C A*	*F A*	*SF*	*GGBS*	*SP*		
Water-binder ratio of 0.4									
1	Conventional SCC	550	589	0.0	0.00	0.00	11.0	867.4	220.0
2	FA5	550	589	45.7	0.00	0.00	11.0	821.7	220.0
3	FA10	550	589	91.3	0.00	0.00	11.0	776.1	220.0
4	FA15	550	589	137.0	0.00	0.00	11.0	730.4	220.0
5	FA20	550	589	182.6	0.00	0.00	11.0	867.4	220.0
6	SF5	550	589	0.00	45.7	0.00	11.0	821.7	220.0
7	SF10	550	589	0.00	91.3	0.00	11.0	776.1	220.0
8	SF15	550	589	0.00	137.0	0.00	11.0	867.4	220.0
9	GGBS5	550	589	0.00	0.00	45.7	11.0	821.7	220.0
10	GGBS10	550	589	0.00	0.00	91.3	11.0	776.1	220.0
11	GGBS15	550	589	0.00	0.00	137.0	11.0	867.4	220.0

2.3 Preparation and casting of test specimens

For these mix proportions, required quantities of materials were weighed. Mixing of cement and mineral admixtures was carried out in the dry state. Coarse and fine aggregates were taken in dry state separately and then mixed together in a mixer to obtain homogeneous mix, after adding water. After mixing, the casting was done without any lapse of time and the test was carried out to determine fresh properties. The uppermost surface of the specimens was scraped to remove excess material and to produce a smooth finish. The samples were removed from moulds after 24 hours and cured in water till testing, as per requirement of the test. The average of the three readings was taken for all the test measurements.

2.4 Testing of the specimens

2.4.1 Properties of fresh concrete

For determining the self-compacting ability properties, slump flow, T50 cm time, V-funnel flow times, L-box block ratio, and U-box difference in height tests were performed. The fresh state properties of mixes were determined with duration of 30 min. after mixing.

The slump flow represents the mean diameter of the mass of concrete after the release of a standard slump cone. The diameter was measured in two perpendicular directions. A slump flow ranging from 500 mm to 700 mm is considered as the slump required for a concrete to be self compacted (Bharali, 2015). At more than 700 mm the concrete might segregate, and at less than 500 mm the concrete is considered to have an insufficient flow to pass through highly congested reinforcement. The stability of the SCC mixes was evaluated through the V-shaped funnel test. A funnel test flow time less than six seconds is recommended for a concrete to qualify for an SCC.

2.4.2 Mechanical properties

Compressive strength was computed at 1 day, 3 days, 7 days, 14 days, 28 days, and 90 days as per Bureau of Indian Standards, IS 516 (1959) guidelines. Splitting tensile and flexural tests were carried out at the age of 28 days. Cubes of 100 mm in size, cylinders of 100 mm × 300 mm, and prisms of 100 mm × 100 mm × 500 mm were cast for to determine the compressive strength, split tensile strength, and flexural strength respectively.

3 Results and discussion

3.1 Properties of fresh concrete

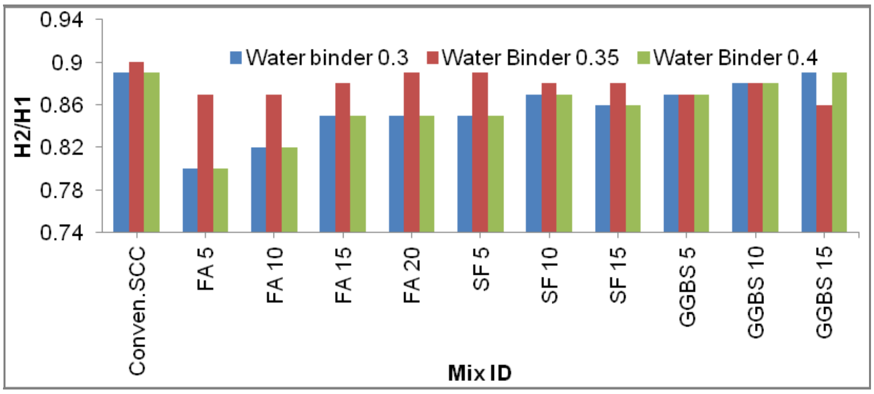
The fresh properties of the concrete are graphically represented in Figure 1, which shows the slump flow values for all mixes fall in the range of 624 mm to 880 mm. The *European Guidelines for Self-compacting Concrete* recommends that the slump flow range value should range from 550 mm to 850 mm. Mix FA20 shows the highest value of slump flow with 880 mm diameter with water-binder ratio of 0.4.

Mix SF15 with water-binder ratio of 0.3 shows the least slump flow of 624 mm. The increase in water-binder ratio increases the slump flow value. The value decreases gradually with the increase of percentages of mineral admixtures. The reduction in the flow is due to the presence of mineral admixtures that influence the workability of the fresh properties of the concrete. The slump flow time for the concrete to reach the diameter of 500 mm for most of the mixes was between 2.4 and 7.2 seconds. The slump time for fly ash and silica fume mixes was about 6 s and for GGBS mix, it was six to seven seconds. Compared to GGBS, the flowability of fly ash is higher followed by that of silica fume.

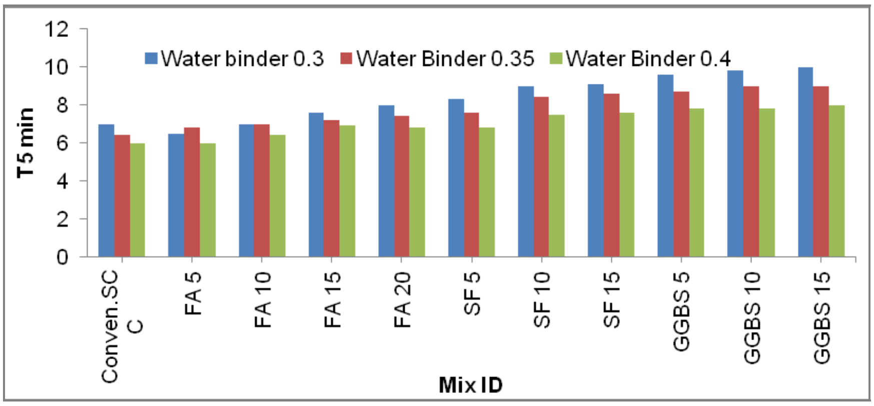
Besides the slump flow test, V-funnel test was also performed to assess the flowability and stability of the SCC. The V-funnel flow time is the elapsed time in seconds among the opening of the lowest vent confide in the time after which opened (T10 seconds and T5 minutes) and the time when the light becomes striking from below when observed from the top. As per The European Federation of Specialist Construction Chemicals and Concrete Systems (EFNARC, 2005), the time was considered from 6 to 12 seconds to adequate for an SCC. The duration of six to ten seconds was taken for V-funnel flow test.

The test results revolve that all SCC mixes met an acceptable value in the requirements of allowable flow time. The L-box ratio H2–H1 for the SCC mixes was above 0.8, which is as per the EFNARC standards. U-box difference in the height of concrete in two compartments was in the range of 20 mm to 30 mm. Self-compacting concrete should have higher powder content and a lower coarse aggregate volume ratio than vibrated concrete to ensure its fresh properties (Bharali, 2015). The test results confirmed that the water-binder ratio helps to improve the fresh properties.

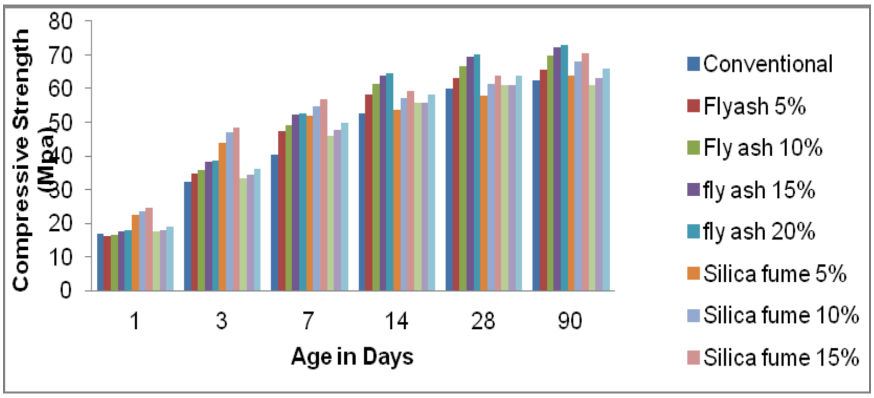
Figure 1 Fresh properties of SCC mix (a) L-box various water-binder ratio (b) T_5 min slump various water-binder ratios (c) U-box various water–binder ratios (see online version for colours)



(a)

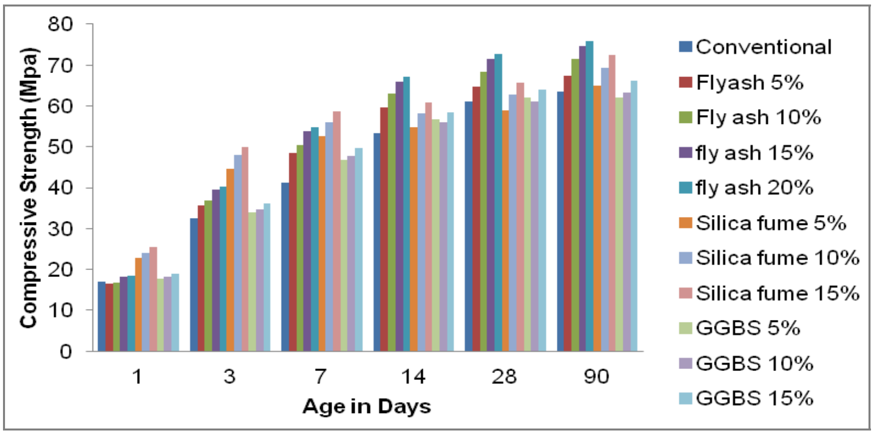


(b)

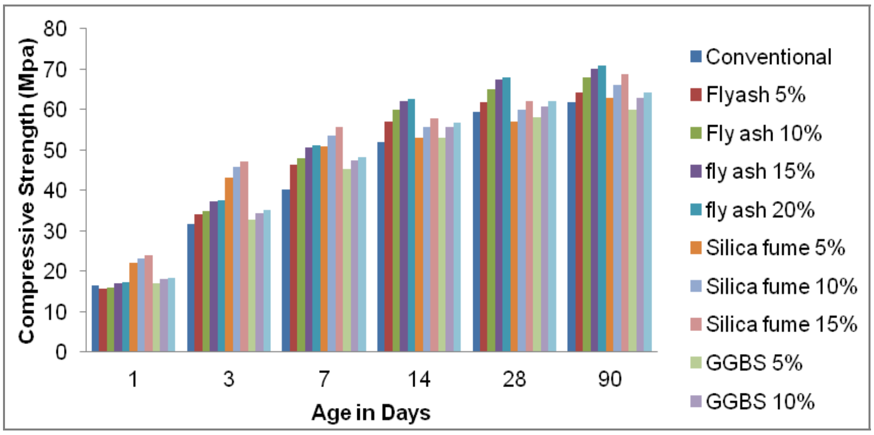


(c)

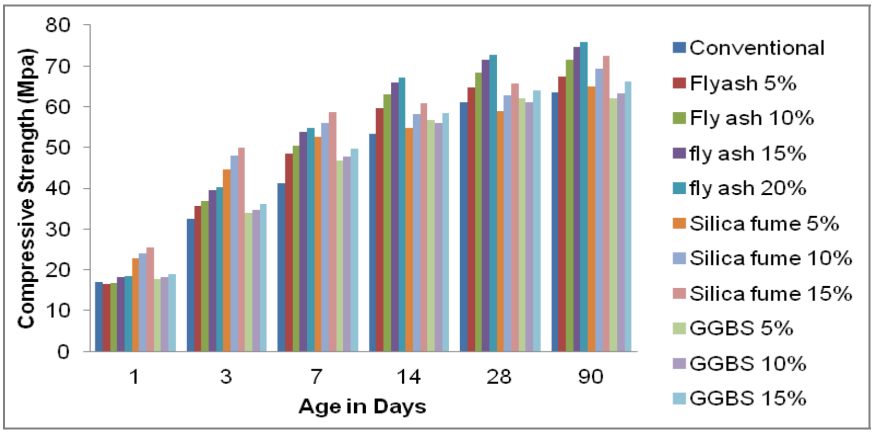
Figure 2 Results of compressive strength of various water-binder ratios (a) water-binder ratio 0.3 (b) water-binder ratio 0.35 (c) water-binder ratio 0.4 (see online version for colours)



(a)



(b)



(c)

3.2 Mechanical properties

3.2.1 Compressive strength

The experiments were carried out with a water-binder ratio of 0.3, 0.35 and 0.45 with a duration of 1 day, 3 days, 7 days, 28 days, and 90 days. It is clearly seen from the chart, FA20 produces the maximum compressive strength under water-binder ratio of 0.3. Further, it is observed that the addition of silica fume increases the strength in the initial period of up to 7 days. Though FA and SF are pozzolanic materials, silica fume reacts faster than fly ash because of its finest particle size, which is 100 to150 times finer than the cement particles. SF15 shows 27.86% higher strength than controlled mix. The addition of GGBS shows least rate of strength improvement compared to all other mineral admixtures at all ages. At the water-binder ratio of 0.3, the 90 days strength values are 19.5%, 15.96%, and 10.63%, which are higher than those of controlled mix with the maximum addition of fly ash, silica fume, and GGBS respectively, whereas at the water-binder ratio of 0.4, the 90-day strength values are 15.9%, 13. 3%, and 7.3% higher than those of the controlled mix. It implies that increase in water-binder ratio decreases the 90-day strength.

3.2.2 Split tensile strength

Table 3 shows the 28-day split tensile strength results. It is observed that FA20 produces maximum split tensile strength when compared with all other mix combinations. As the compressive strength increases, the split tensile strength also increases irrespective of water-binder ratio and percentage replacements of mineral admixtures. In SF and GGBS combinations, all the ratios except those of SF5 and GGBS5 impart higher strength. The addition of FA increases the strength. At the water-binder ratio of 0.3, the 28-day strength values of SF5, SF10, and SF15 are 2.53%, 9.47%, and 14.42% higher than those of conventional SCC mix. At the water-binder ratio of 0.35, the 28-day strength values of SF5, SF10, and SF15 are 2.43%, 8.72%, and 12.86% higher than those of controlled mix. At the water-binder ratio of 0.40, the 28-day strength values of SF5, SF10, and SF15 are 1.83%, 6.92%, and 10.99% higher than those of conventional SCC mix. The improvement in split tensile strength is due to the pore-filling effect between silica fume and GGBS.

3.3 Flexural strength

Table 3 presents the 28-day flexural strength results. It can be seen that FA20 produces maximum flexural strength at the water-binder ratio of 0.3. At the water-binder ratio of 0.4, the 28-day flexural strength values of GGBS10 and GGBS15 are 2.38% and 4.33% higher than those of conventional SCC mix. At water-binder ratio of 0.35, the 28 days flexural strength values of GGBS5, GGBS10, and GGBS15 are 1.36%, 1.59%, and 6.39% higher than those of conventional SCC mix. At the water-binder ratio of 0.30, the 28-day strength values of GBBS5, GGBS10, and GGBS15 are 1.66%, 0.35%, and 8.18% higher than those of the conventional SCC mix.

Table 3 Results of split tensile strength and flexural strength at day 28

Sl. no.	Mix ID	Water-binder ratio					
		Split tensile strength (Mpa)			Flexural strength (Mpa)		
		0.3	0.35	0.4	0.3	0.35	0.4
1	Conventional SCC	4.2	4.1	4.1	11.2	11.0	10.9
2	FA5	4.4	4.3	4.2	11.9	11.6	11.4
3	FA10	4.7	4.5	4.4	12.6	12.2	11.9
4	FA15	4.9	4.7	4.6	13.2	12.7	12.4
5	FA20	5.0	4.8	4.6	13.4	12.9	12.5
6	SF5	4.0	3.9	3.9	10.8	10.6	10.5
7	SF10	4.3	4.2	4.1	11.5	11.3	11.0
8	SF15	4.5	4.3	4.2	12.1	11.7	11.4
9	GGBS5	4.2	4.2	4.0	11.4	11.2	10.7
10	GGBS10	4.2	4.2	4.2	11.2	11.2	11.2
11	GGBS15	4.5	4.4	4.2	12.1	11.7	11.4

4 Conclusions

The SCC mixes slump flow range between 624 mm and 800 mm, a flow time less than six seconds, and V-funnel time in the range from 2.4 to 7.2 seconds. L-box ratio is greater than 0.8 for all mixes and difference in the height of concrete in two compartments in U-box lies in the range of 20 mm to 30 mm. The flow ability of fly ash-added mixes is significantly higher compared to GGBS and silica fume mixes. The mix FA20 possess the improved mechanical properties compared to all other mixes at all the ages followed by GGBS15 and SF15. The improvement in split tensile strength is due to the pore-filling effect between silica fume and GGBS. The SCC mixes compressive strengths ranging from 41.1 MPa to 72.25 MPa. The mineral admixtures contribute much to the fresh and hardened state properties of the SCC. The results indicate that it is possible to produce a good performing SCC using locally available fly ash, GGBS, and silica fume. The rheological characteristics were within the limits specified in (EFNARC, 2005) guidelines. It is concluded that the experimental results are shows the possibility to use fly ash, silica fume, and GGBS in the manufacturing of SCC. The potential benefits to society to build with green concrete using fly ash, silica fume, and GGBS at large-scale include saving the environment and achieving sustainability.

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