UTILIZATION OF SUPER POZZOLANIC MATERIAL IN THE PRODUCTION OF SELF-COMPACTING CONCRETE

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Abstract

The study presents an experimental investigation on the properties of Self-Compacting Concrete (SCC) containing ultra-fine Ground Granulated Blast furnace Slag (GGBS) as a Super-Pozzolanic Material (SPM) in combination with class-F fly ash. Portland cement was replaced by weight with ultra-fine GGBS in the varying proportion from 0% to 10% at the rate of 2.5% whereas the fly ash was nominally fixed at 20% by weight of the total powder content in all the SCC mixtures. The properties studied include fresh state behaviour, compressive strength, ultrasonic pulse velocity, water absorption, pH of the concrete, chloride and sulfate resistance of the SCC. Results showed that the incorporation of ultra-fine GGBS positively affect the fresh, the hardened and the durability performance of the considered SCC. An increase of about 32% was observed in the compressive strength for the ternary blended SCC mixture with 10% GGBS content; when compared to the binary blended control SCC mixture. Water absorption values of the SCC showed a decreasing trend with increase in the GGBS content. Durability performance of the SCC in terms of chloride and sulfate resistance improved with addition of this ultra-fine GGBS at the later ages.

Keywords: Self-compacting concrete, Super-pozzolanic material, Fly ash, GGBS, Sulfate resistance, Chloride resistance.

1. INTRODUCTION

Self-compacting concrete (SCC), innovated in Japan in the late 1980s, is widely recognized as a high-performance concrete in terms of its productivity, durability and workability. The SCC is having wide applications in the areas of restricted zones and heavy reinforcement due to its high flowability and compactibility characteristics [1-5]. Filling ability, passing ability and segregation resistance are the essential characteristics for the SCC [6]. It is a special type of concrete that can be compacted under its own weight without any need of external vibrations. Mainly, it contains limited coarse aggregates, lower water-powder ratio, higher powder content, superplasticizer and various mineral admixtures [7]. Cement content can be decreased to make concrete more economical and sustainable [8]. Various supplementary cementitious materials (SCMs) such as fly ash, silica fume, ground granulated blast furnace slag, metakaoline, marble powder, limestone powder and rice husk ash can incorporated into concrete to improve the fresh, the hardened and the durability properties of the SCC [9-12]. Fly ash is widely used as a supplementary cementitious material in the production of the SCC to increase its paste volume and thereby improves its workability and the durability characteristics. It is by-product of coal based thermal power industries and having worldwide annual production of about 600 million tonnes. Fly ash reduces the amount of cement used in concrete production and also lowers the heat of hydration in concrete. It contributes to the strength of concrete at the later ages [13]. Ponikiewski and Golaszewski [14] reported an increase in the workability and improved rheological behaviour of the self-compacting concrete made with activated fly ash. Murai et al. [15] recommended the utilisation of fly ash to decrease the dosage of both the viscosity modifying admixtures and the high-range water reducing admixtures in the SCC. Sahmaran et al. [16] reported that fly ash incorporates self-healing property in the SCC.

Ultra-fine GGBS (Alccofine) is a new generation supplementary cementitious material with unique chemical composition and particle size distribution [17]. It is based on slag of high glass content and its high reactivity is achieved through the controlled granulation. In the Indian scenario, this is produced from the waste product of the Iron Ore Industries [18]. Due to its unique chemical composition and ultra-fine particle size (12000 cm^2/g), it exhibits superior properties than silica fume. It can also be used as high range water reducing admixture [19, 20]. Parveen et al. [21] proposed the application of Alccofine in the production of geopolymer concrete at the ambient temperature. They reported an improved microstructural property of the geopolymer concrete made with Alccofine. This Super Pozzolanic Material (SPM) termed as 'Alccofine' used in their investigation is a processed form of GGBS with ultra-fine characteristics. According to Saxena et al. [22], an increase in compressive strength was observed with the addition of Alccofine in the geopolymer mortars. They reported the positive sides of this SPM in terms of its sulfate resistance mechanism in the geopolymer mortars. Apart from these studies, several other authors recommended the utilization of ultra-fine GGBS in the production of concrete [23-26]. However, a limited number of studies have been carried out on its application in the production of the SCC and the aim of the authors is to fill this gap in the literature.

The objective of the experimental investigation is to study the effect of varying proportions (0-10%) of ultra-fine GGBS on fresh, hardened and durability behaviour of the self-compacting concrete. Various workability parameters of the SCC such as slump flow diameter, T_{50cm} time, L-box blocking ratio, U-box filling height, V-funnel time and J-ring height were determined to check self-compactibility of the concrete at its fresh state. The cube compressive strength was determined at 7, 28, 56, and 90 days of water curing. For durability performance, the cube specimens were immersed in 5% NaCl and 5% $MgSO_4$ solution to measure the strength and the weight loss at 56 and 90 days. Ultrasonic pulse velocity (UPV) values were recorded at all the respective ages to ensure the uniformity of concrete specimens. The results have been discussed in detail in the subsequent sections.

2. MATERIALS

The SCCs were designed using the Portland cement which confirmed to IS 8112-2013 [27]. The properties of cement were tested according to IS 4031-1988 [28] and are presented in Table 1. Crushed stone aggregate of 10 mm maximum nominal size having fineness modulus 5.98 were used as coarse aggregate and locally available sand passing through 4.75 mm sieve was used as fine aggregate. Both coarse and fine aggregates conformed to IS 383-2002 [29] and their properties are presented in Table 2. Ultra-fine GGBS and class-F fly ash were used as supplementary cementitious materials as a binary or ternary cementitious blend. Fly ash was greyish in colour and was having a specific gravity of 1.95. Ultra-fine GGBS is a processed form of slag under controlled granulation having Blain's fineness of 12000 cm²/g with unique chemical composition. Its unique chemical composition was mainly because of presence of CaO as 30-34%, SiO_2 as 30-36% and Al_2O_3 as 18-25%. The particle size distribution of this SPM (ultra-fine GGBS) is shown in Figure 1. Polycarboxylic ether based second generation superplasticizer "Master Glenium Sky 8777" confirming to IS 9103-1999 [30] was used in the present investigation. The properties of superplasticizer are illustrated in Table 3.

Table 1: Characterization of the Portland cement

PROPERTIES	VALUE	AS PER IS 8112-2013
Specific gravity	3.15	3.15
Normal consistency	29%	-
Initial setting time (min.)	115	>30
Final setting time (min.)	165	<600
Fineness (%)	2	<10
Soundness (mm)	2	<10

Table 2: Measured physical properties of the coarse and the fine aggregates

PROPERTIES	FINE AGGREGATE	COARSE AGGREGATE
Specific gravity	2.63	2.60
Fineness modulus	3.25	5.98
Water absorption	1.7	1.2
Bulk density		
Loose (kg/m³)	1668	1453
Compacted (kg/m³)	1982	1649

Table 3: Properties of the superplasticizer

PROPERTIES	MASTER GLENIUM SKY 8777
Physical state	Liquid
Colour	Light brown
Relative density	1.10±0.01 at 25°C
pH	>6
Chloride ion content	< 0.2%

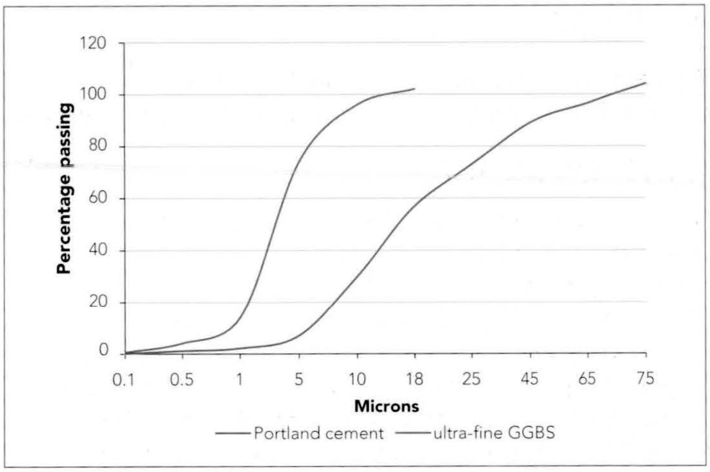


Figure 1: Particle size distribution of the ultra-fine GGBS.

3. MIX PROPORTIONS

A total of five SCC mixtures were designed including one control mix as reported in Table 4. The control mix was designed by using the fly ash as a binary blend of cement. Total powder content was fixed at 550 kg/m^3 and fly ash was used as 20% by weight of total powder content in all the SCC mixtures. The control concrete was a binary blend of fly ash and Portland cement. Other SCC mixtures were produced by replacing the Portland cement with the SPM as 2.5%, 5.0%, 7.5% and 10.0% by weight of total cement content. Water/powder (w/b) ratio was nominally fixed at 0.41 for all the considered SCCs. The superplasticizer was used a high range water reducing admixture and fixed at 0.3% by weight of total powder content. The quantities of fine aggregate and coarse aggregate were fixed at 910 kg/m^3 and 590 kg/m^3, respectively.

Table 4: Mix proportions of the SCCs

MIX ID*	MIX SYSTEM	W/B RATIO	POWDER (KG/M³)	CEMENT (KG/M³)	FLY ASH (KG/M³)	SPM (KG/M³)
Control	Binary	0.41	550	440	110	0
SCA2.5	Ternary	0.41	550	429	110	11
SCA5.0	Ternary	0.41	550	418	110	22
SCA7.5	Ternary	0.41	550	407	110	33
SCA10.0	Ternary	0.41	550	396	110	44

*Key to Mix ID: The letter in the first two place holders represents 'SCC'; the letter in the third-place holder stands for 'SPM'; the numerals represent replacement level of cement by weight the SPM.

4. EXPERIMENTAL PROGRAM

4.1. Fresh concrete properties

Self compactibility of fresh concrete was confirmed by performing various tests such as slump flow diameter, T_{50cm} time, L-box, U-box, V-funnel and J-ring. All tests were carried out to ensure the passing ability, the filling ability and the segregation resistance of the SCC mixtures. Dimensions of various apparatus used in different tests were according to EFNARC standard [31]. The fresh concrete was poured directly into buckets from mixer and tested in the following order.

(a) V-funnel test
(b) L-box test
(c) U-box test
(d) T_{50cm} time and slump flow diameter
(e) J-ring test

The slump flow test was carried out to ensure the flowability or filling ability of SCC. The test was performed using a slump cone on a non-absorbing surface in absence of obstructions. The EFNARC standards recommend the value of 550 to 800 mm for the slump flow diameter and from 2 to 5 seconds for the T_{50cm} time. V-funnel time was determined to confirm viscosity/flowability of concrete. The V-funnel time is recommended between 6 to 12 seconds. L-box blocking ratio (BR), U-box filling height and J-ring tests were performed to determine passing ability of the fresh concrete. Higher values of the BR, lower values of the filling height and minimum difference of the J-ring heights were reported to improve the passing ability of concrete.

4.2 Compressive strength

Concrete cube specimens of size 150×150×150 mm were cast to perform the compressive strength test. All the specimens were cast at an average temperature of 24±2°C and demoulded after 24 hours. The cube specimens were tested after 7, 28, 56 and 90 days of water curing and 3 companion specimens were tested for each SCC mixture. All the specimens were tested on compression testing machine at a constant loading rate as per IS 516-1959 [32].

4.3 Water absorption

Three cube companion specimens of size 150×150×150 mm for each SCC mixture were cast to determine the water absorption at 28 days. The test specimens were kept in oven for 24 hours at 105±5°C and then allowed to dry under natural heat loss to measure the oven dried weight (A). Thereafter, they were immersed in curing tank for 48 hours and brought into saturated surface dry (SSD) moisture condition and SSD weight was noted (B). Equation (1) was used to determine the water absorption values for all the SCC mixtures.

$$Water\ absorption\ (\%) = \left(\frac{B-A}{A} \times 100\right) \quad (1)$$

where, A is weight of oven dried specimen and B is weight of saturated surface dried specimen.

4.4 Chloride resistance

The concrete cube specimens of size 150×150×150 mm were cast for each SCC mixture to determine the chloride resistance in terms of the strength and the weight loss after immersing in 5% NaCl solution. After 28 days of water curing, the test specimens were put in a chloride solution. The weight of specimens was noted after surface drying at an age of 28 and 62 days of chloride curing. Three companion specimens were used in this investigation at both the respective ages. The weight of water cured specimens at an age of 56 and 90 days were compared with the weight of cube specimens cured in 5% NaCl solution for 28 and 62 days, respectively. The percentage loss in weight was determined at the age of 56 and 90 days. Similarly, the strength loss (%) was determined by comparing the compressive strength values of the water cured sample for 56 and 90 days with 5% NaCl cured samples for 28 and 62 days, respectively.

4.5 Sulfate resistance

Sulfate resistance of SCC mixtures was determined in terms of the strength and the weight loss of cube specimens when immersed in 5% $MgSO_4$ solution. After 28 days of water curing, the test specimens were immersed in a sulfate solution. The weight of specimens was noted after surface drying at an age of 28 and 62 days of sulfate curing. Three companion specimens were used in this investigation at both the respective ages. The weight of water cured cube specimens at an age of 56 and 90 days was compared with the weight of cube specimens cured in 5% $MgSO_4$ solution for 28 and 62 days, respectively. The percentage loss in weight was determined at the age of 56 and 90 days. Similarly, the strength loss (%) was determined by comparing the compressive strength values of the water cured sample for 56 and 90 days with 5% $MgSO_4$ cured samples for 28 and 62 days, respectively.

4.6 pH of concrete

The alkalinity of test specimens was measured using a pH meter at 56 and 90 days of chloride curing. A total of 10 g powdered sample of concrete was mixed with 100 ml of distilled water and placed in the incubator at 20±2°C for 24 hours. Thereafter, the concrete powder was separated from the water using a filter paper. The pH values were determined as per ASTM method using a digital pH meter [26].

4.7 Ultrasonic pulse velocity

Ultrasonic pulse velocities were determined to check internal flaws or homogeneity of concrete specimens. The UPV values were noted at all ages (7, 28, 56 and 90 days) for the water cured samples. For chloride and sufate cured samples, the UPV values were noted at an age of 56 and 90 days. The transmitter and receiver were positioned in direct transmission mode on the cube specimens.

5. RESULTS AND ANALYSIS

5.1. Fresh properties

The fresh properties of all the SCC mixtures were evaluated and are compiled in Table 5. The effect of addition of various proportions of the SPM (ultra-fine GGBS) was studied on fresh properties of concrete. T_{50cm} time and slump flow diameter tests were conducted to examine the filling ability of the SCCs and were found within the limits as suggested by Domone and Jin [34]. The minimum and the maximum value of T_{50cm} was observed as 2 and 3.8 seconds, respectively. Slump flow diameter was in the range of 550 to 700 mm for all the considered mixtures and was found highest for the mix SCA7.5. V-funnel test measured the flowability of concrete. The greater flowability is indicated by the shorter time. The mixture SCA10 was highly flowable with a minimum value of V-funnel time. Highest blocking ratio of the L-box test was found for the concrete mix SCA10 with 10% replacement with ultra-fine GGBS. Filling height of the U-box was found between 0 to 30 mm for all the SCC mixtures. J-ring test was conducted as another check for the passing ability of self-compacting concrete. The minimum step height was found as 2 mm for the mix SCA10. The fresh properties of all the SCC mixtures were found in compliance with as suggested by EFNARC standard [31].

Table 5: Measured fresh state properties of the SCCs

MIX ID	SLUMP (MM)	T_{50cm} (S)	V_f (S)	L-BOX	U-BOX (MM)	J-RING (MM)
Control	670	3.0	9.0	0.82	17	0
SCA2.5	638	2.0	11.0	0.70	9	11
SCA5.0	550	3.8	5.8	0.76	35	22
SCA7.5	688	2.0	6.0	0.76	30	33
SCA10.0	624	2.8	5.5	0.86	30	44

5.2. Compressive strength

Figure 2 shows variations in the compressive strength values of SCC mixtures at various replacement levels of the SPM. It was observed that strength values were highest for the mix SCA10.0 at all the respective ages of testing. For example, the compressive strength of binary blended control SCC mix was 31.64 MPa after 28 days of curing, which increased to 41.64 MPa for the ternary blended mix SCA10.0. For mix SCA10.0, the percentage increase in strength with respect to control SCC mixture was 21.52%, 26.48%, 31.10% and 26.58% after 7, 28, 56 and 90 days of curing, respectively. As illustrated in Figure 2, the maximum gain in strength was observed between 7 to 28 days. For example, the percentage increase in strength between 7 to

28 days was 24% and 30% for the mix SCA5.0 and SCA10.0, respectively. The increase in strength properties with increase in the SPM content can be attributed to unique particle size distribution and inbuilt CaO content which lead to formation of dense pore structure of the concrete.

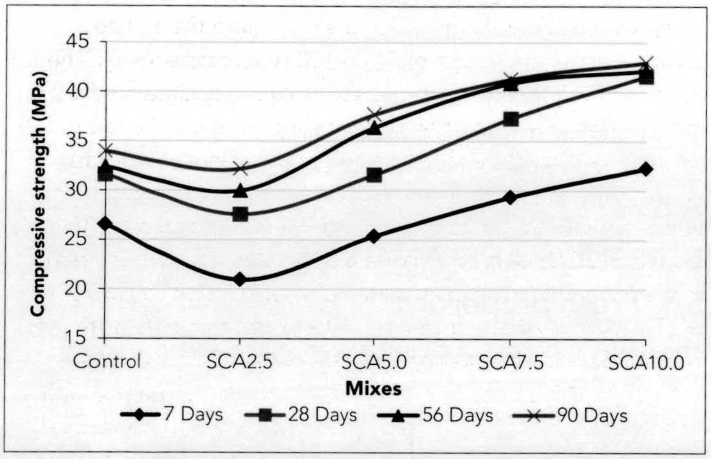


Figure 2: Compressive strength of the designed SCCs.

5.3. Water absorption

The water absorption values for the considered SCC mixtures after 28 days of moist curing are shown in the Figure 3. In spite of having high surface area (12000 cm^2/g) of the ultra-fine GGBS, the water absorption of SCC mixtures decreased as compared to the control mix. It can be seen in the figure, as the percentage of SPM increased, the water absorption tends to decrease gradually. The water absorption was highest as 4.43% for the control SCC mix and lowest as 3.41% for the mix SCA10.0. The decrease in water absorption with increase in the addition of SPM can be attributed to the presence of high glass content in the SPM.

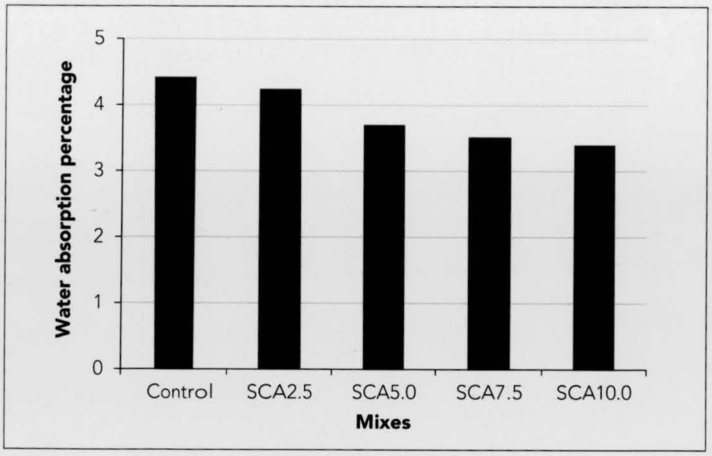


Figure 3: Water absorption for the various SCCs.

5.4. Chloride resistance

The chloride resistance of various SCC mixtures was determined in terms of the weight and the strength loss of cube specimens. The results of the percentage weight loss (%) of cube specimens immersed in 5% NaCl solution at the age of 56 and 90 days are shown in Figure 4. As illustrated from the Figure, the percentage loss in weight was highest at 90 days of chloride curing as compared to 56 days of curing. The weight loss was observed to be highest for the control SCC at both the curing ages whereas the mix containing highest amount of ultra-fine GGBS, showed minimum weight loss. It was observed that resistance to chloride attack increased with increase in the percentage addition of the SPM. The weight loss was 0.52% and 2.26% for the control SCC and 0.29% and 1.28% for the mix SCA10.0 at the 56 and 90 days of chloride curing, respectively. At both the ages, the weight loss was minimum for the SCC mixture which contained 10% ultra-fine GGBS.

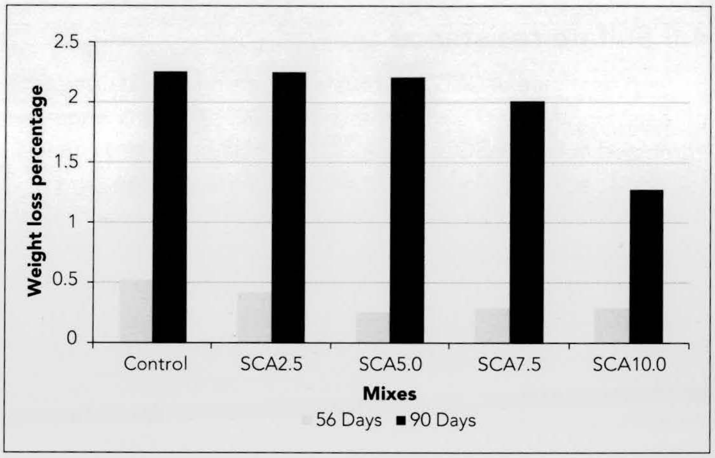


Figure 4: Percentage loss in weight for the specimens immersed in 5% NaCl solution.

Figure 5(a) and 5(b) shows the comparison of cube compressive strength values for the water cured and the chloride cured samples at the age of 56 and 90 days, respectively. The decrease in compressive strength values for the chloride cured samples as compared to the water cured samples may be attributed to the leaching of calcium hydroxide in NaCl solution which caused change in chemical composition of the mixes. As illustrated in the figure, the SPM has not contributed to the chloride resistance at 56 days while at the period of 90 days, it showed a marked reduction in the strength loss. The strength loss for the control SCC was 0.24% at 56 days which increased to 5.71% at 90 days. The strength loss for the mix SCA10.0 was 9.62% at 56 days which improved to 2.81% at 90 days. This improvement is attributed to the packing effect of the SPM and its unique particle size distribution which caused pore refinement at the later ages. Also, the increase in chloride resistance may occur due to the chloride chemical binding and physical binding. The chloride chemical binding was due to the high alumina content of the ultra-fine GGBS and the fly ash which leads to the formation of calcium chloroaluminate and ultimately reduced free available chloride ions [35]. In addition, the SPM and the fly ash leads to increase in the amount of C-S-H (calcium silicate hydrate) content due to their pozzolanic nature which causes physical binding of the chloride ions [36]. It may be concluded that the SPM react positively to the chloride attack at the later ages and a better chloride resistant SCC can be obtained with increase in the strength.

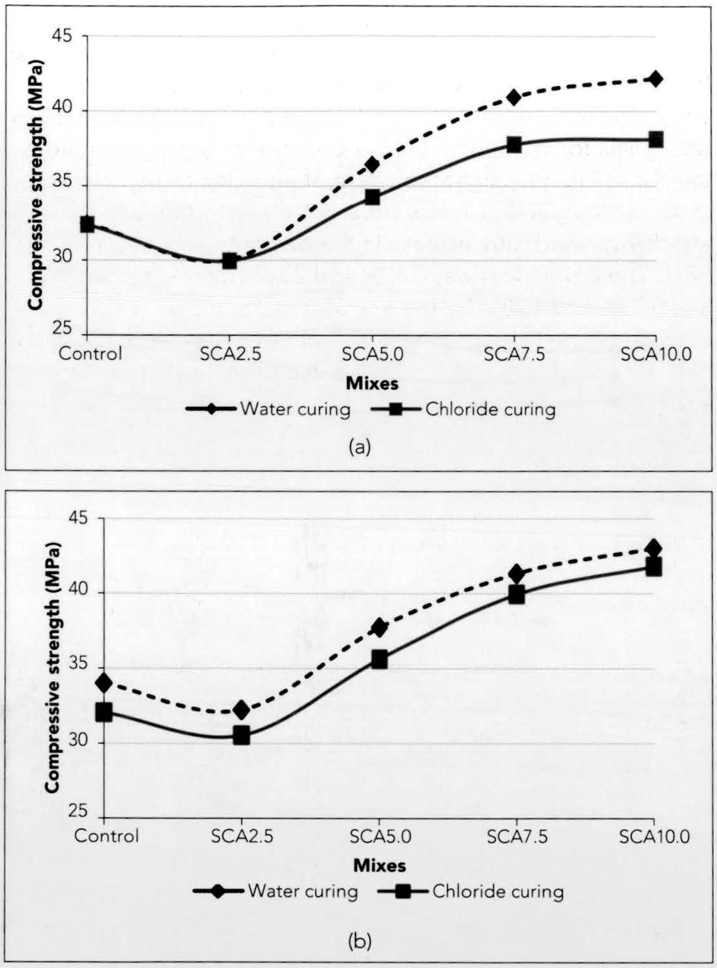


Figure 5: Comparison of the strength values of the water and the chloride cured specimens at (a) 56 days and (b) 90 days.

5.5. Sulfate resistance

The sulfate resistance of various SCC mixtures was determined in terms of the weight and the strength loss of the cube specimens. Figure 6 shows the weight loss in percentage for the cube specimens immersed in 5% magnesium sulfate solution. In general, the percentage loss in weight was highest for the 90 days of sulphate curing as compared to the 56 days of sulfate curing. The percentage loss in weight was 0.15% at 56 days which increased to 1.18% at the age of 90 days for the mix SCA10.0.

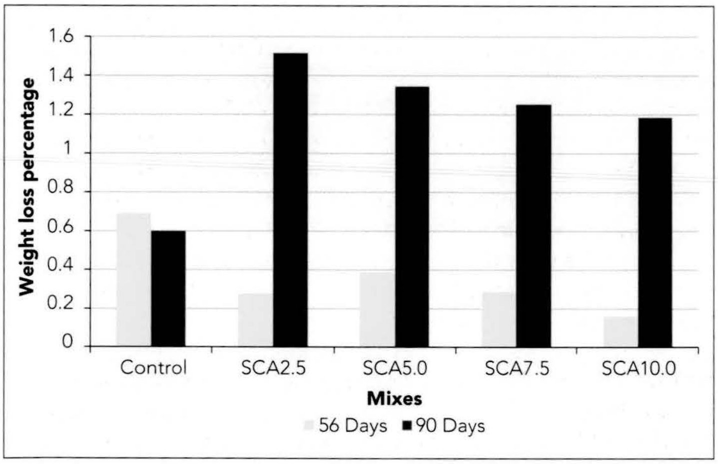
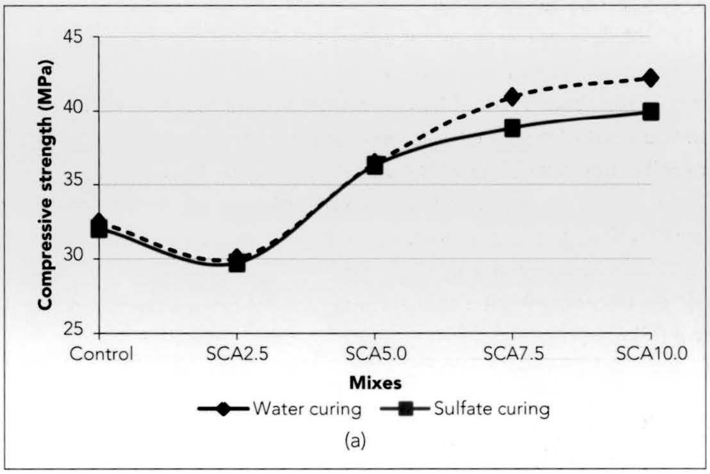


Figure 6: Percentage loss in weight for the specimens immersed in 5% $MgSO_4$ solution.

Figure 7(a) and 7(b) shows the comparison of the cube compressive strength values for the water and the sulfate cured samples at the age of 56 and 90 days, respectively. The trend in strength loss for the concrete cube specimens cured in magnesium sulfate solution was similar to that of chloride cured specimens. The decrease in compressive strength values for the sulfate cured specimens may be attributed to the formation of ettringite which caused deterioration of the concrete [37]. Ultra-fine GGBS and fly ash due to high alumina content lead to the formation of calcium sulfoaluminate (ettringite) which is expansive in nature and caused deterioration and strength loss in the concrete. The strength loss for control SCC was 6.94% at 56 days which increased to 12.36% at 90 days. The strength loss for the mix SCA10.0 was 5.42% at 56 days which improved to 3.25% at 90 days. This might be due to pore refinement and dense microstructure of concrete which increased resistance to ingress of sulfate ions into concrete and ultimately reduced the formation of ettringite.



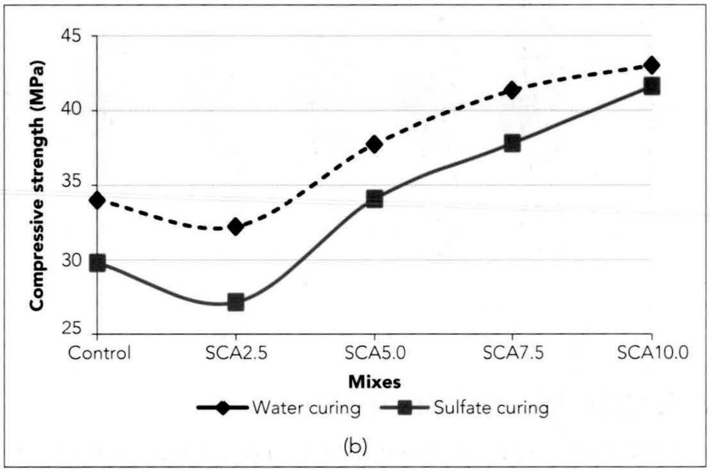


Figure 7: Comparison of the strength values of the water and the sulfate cured specimens at (a) 56 days and (b) 90 days.

Figure 8 shows the comparison between compressive strength values of the water, the chloride and the sulfate cured cube specimens at the period of 90 days. The loss in strength was highest for the cube specimens immersed in 5% $MgSO_4$ solution as compared to the 5% NaCl cured specimens for all the SCC mixtures. The strength loss decreased with increase in the SPM addition and observed to be lowest for the mix SCA10.0.

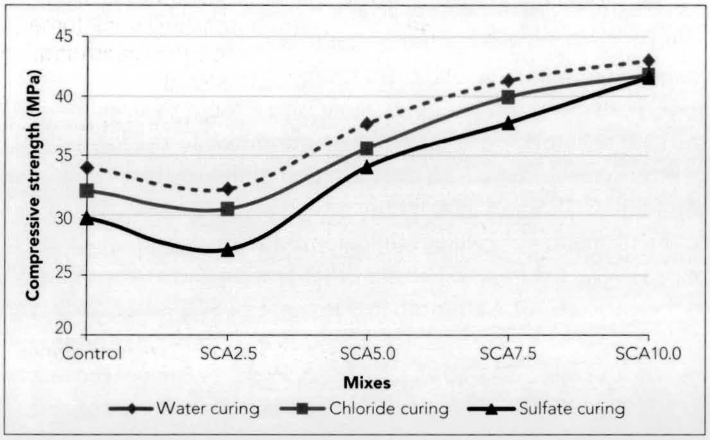


Figure 8: Comparison of the strength values for the chloride and the sulfate cured specimens.

5.6 pH of concrete

Figure 9 show the pH values of the concrete samples collected after 56 and 90 days of the chloride curing in 5% NaCl. As illustrated in the figure, the pH of concrete decreased with increase in the time of exposure. For example, the pH value for the control SCC was 12.05 at 56 days which decreased up to 11.44 at 90 days. The pH for the mix SCA10.0 was 11.92 at 56 days which decreased to 11.24 at 90 days. Also, all the pH values were noted to be greater than 11.

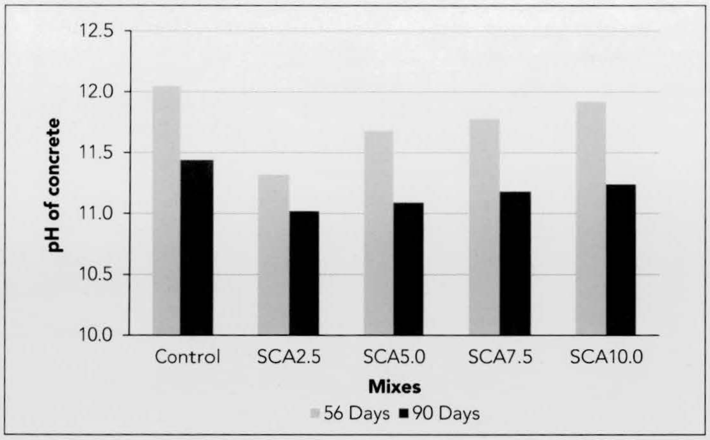


Figure 9: pH values for the various concrete samples after the chloride curing.

5.7 Ultrasonic Pulse Velocity

Figure 10 represents the ultrasonic pulse velocities (UPV) for the various water cured SCC cube specimens at different curing period. The UPV values were in the range of 4523 to 5098 m/s for all the considered mixtures. All test values were above 4500 m/s and observed to increase with increase in the SPM addition. Results were in a good agreement with the literature and the concrete can be classified as of excellent quality [38, 39]. Figure 11 shows a comparison between UPV values of water cured, chloride cured and sulfate cured cube specimens at the period of 90 days. The decrease in UPV values of the chloride and the sulfate cured cube specimens is attributed to the deterioration of concrete due to the chloride and the sulfate attack.

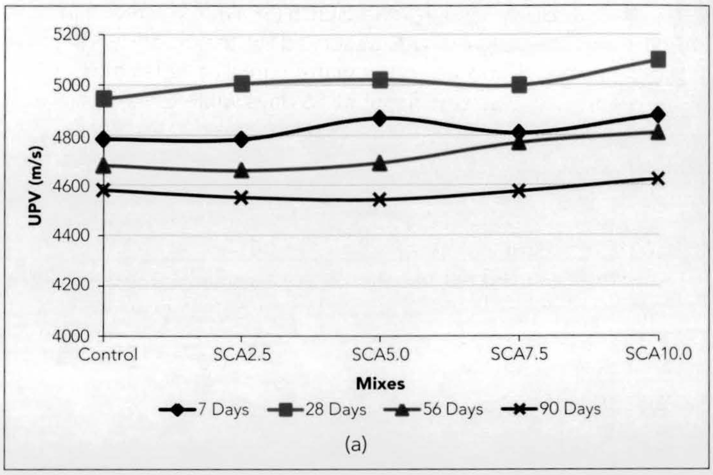


Figure 10: UPV values of the water cured cube specimens at various curing ages.

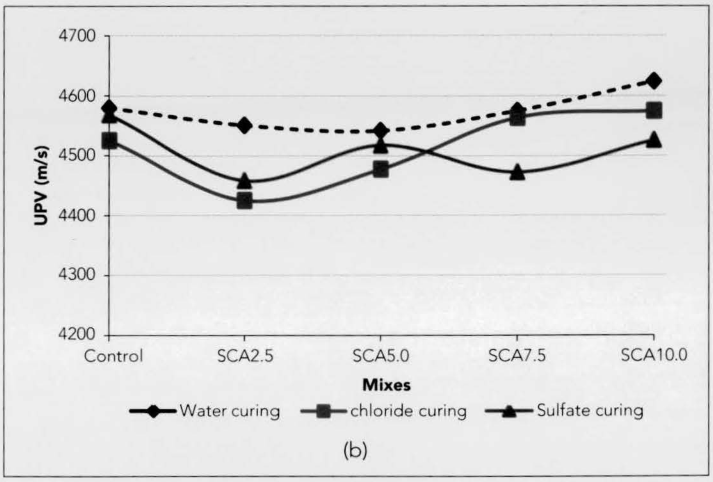


Figure 11: UPV values of water, chloride and sulfate cured cube specimens at 90 days.

6. CONCLUSIONS

1) All designed concrete mixtures were found to satisfy the norms that were set to qualify the mixes as a self-compacting concrete. The fresh properties of the considered mixtures were found within the limit as suggested by EFNARC standard. The slump flow diameter was in the range of 550 to 700 mm for all the SCC mixtures and was found highest for the mix SCA7.5.

2) Compressive strength for the various SCC mixtures increased with the increase in the SPM addition at all the respective ages of testing. For mix SCA10.0, the percentage increase in strength with respect to control SCC mixture was 21.52%, 26.48%, 31.10% and 26.58% after 7, 28, 56 and 90 days of curing, respectively.

3) Water absorption values for the SCC mixtures decreased gradually with increase in the SPM addition due to its high glass content and water repelling properties.

4) For chloride cured specimens, weight loss was observed highest for the control SCC at both ages and further a decrease in the percentage weight loss was observed with an addition of ultra-fine GGBS (SPM). A decrease in compressive strength was observed for the chloride cured samples as compared to the water cured samples and this decrease was significant at 56 days while a marked reduction in the strength loss was observed at 90 days.

5) For SCC mixtures, the percentage loss in weight was highest at 90 days of sulphate curing as compared to the 56 days of curing. The trend in strength loss for the test specimens cured in magnesium sulfate solution was similar to that of chloride cured specimens. The loss in strength was highest for the specimens immersed in 5% $MgSO_4$ solution as compared to the 5% NaCl cured specimens for all the SCC mixtures.

6) The alkalinity of all the SCC mixtures was found to be more than 11. For all the water cured concrete test specimens, the UPV values were in the range of 4523 to 5098 m/s and concrete was designated as of excellent quality at all the respective ages of curing.

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