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TECHNICAL REPORT

Effect of Micro-Silica on Fresh and Hardened Properties of Self-Compacting Concrete Reinforced with Glass and Polyvinyl Alcohol Fibres

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ABSTRACT – Self-compacting concrete (SCC) being an innovative and environmentally friendly concrete is impressively accepted in various regions of the world. SCC is a high-performance concrete that can consolidate under its own weight without the aid of mechanical vibration, filling spaces of almost any size and shape without segregation or bleeding. In this study, experimental investigations were carried out to improve the properties of self-compacting concrete by replacing cement with various percentages of Micro silica in SCC having fixed percentages of fly ash, glass, and polyvinyl alcohol fibre. Micro silica content varied from 2% to 10% by weight. Various tests like L-Box, V- funnel, Slump flow, and uniaxial compression tests were carried out on SCC, and the results have been compared with the control mix. It is observed that the hardened properties of the SCC improved with the addition of micro silica. However, the filling ability, passing ability, and resistance to segregation of fresh concrete mix with increasing micro silica content were found to reduce.

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INTRODUCTION

Self-Consolidating concrete is a revolutionary concrete that was developed nearly three decades ago. It can consolidate under its own weight without using any mechanical vibration, filling voids of almost every size. Okamura [1] felt the necessity of this type of concrete in 1986 when there was a considerable decrease in skilled labour in Japan in the early 1980s. There is rapid progress in developing new technology in material science. Numerous studies have been conducted throughout the world in the last few decades to enhance the strength and durability potential of concrete. As a result, concrete is no longer a building material made only of cement, aggregate, and water. Nevertheless, concrete has evolved into an engineered, specifically designed material with a number of unique components to fulfil the distinct requirements of the building sector. According to studies, construction completion might go up to 40% more quickly with SCC compared with regular concrete, and there are not many differences between the elastic modulus and shrinkage of SCC and the equivalent parameters of conventional concrete [2]. Self-compacting concrete is able to flow and deform without segregating [1], [3-4]. In order to preserve deformability and flowability in the concrete, a superplasticizer is therefore essential in such concrete in order to maintain a reduction in water cement ratio. With a strong plasticizer, the paste may be made more flowable with only a slight reduction in viscosity [4], which helps the concrete achieve self-compaction under its own weight without the aid of any mechanical vibration. A concrete mix with a low water-cement ratio can achieve the required workability with the help of a superplasticizer [5].

Hardened characteristics, such as flexural strength, toughness, impact strength, resistance to fatigue, and susceptibility to cracking and spalling, are improved by the introduction of fibres in the concrete [6]–[11]. Fibre Reinforced Self Compacting Concrete offers improved resistance to cracking and higher strength, toughness, and fracture properties than plain self-compacting concrete [6], [12-13]. Glass fibre, also known as Fibreglass, is a material made from extremely fine fibres of glass. Glass fibre is used in concrete to minimize cracking, especially at the surface. Sanjeev & Sai [14] studied the effect of steel and glass fibres on SCC and found that the glass fibres were more effective in increasing the compressive strength than steel fibres even in a low quantity. In the study, it was found that a 0.9% volume of steel fibres increased the compressive strength of SCC by 20.2% whereas a small amount of 0.04% of glass fibres increased the SCC’s compressive strength by 20.4%. With the addition of high modulus polymer fibres such as PVA, the fracture energy of the concrete can be highly improved and hence the resistance to cracking of such concrete increases. Bäuml & Wittmann [15] compared SCC reinforced with polyvinyl alcohol (PVA) fibres with conventional self-compacting concrete in real structures. It was found that the surface of conventional SCC cracked after one month whereas the surface of the SCC reinforced with PVA fibres did not demonstrate any visible crack even after a year.

Ahmad & Umar studied the effect of glass and PVA fibres on SCC and found that the compressive strength increased compared to conventional SCC [16]. It was found that the 28-day compressive strength initially increased by 9% and 14% on the addition of 0.1% and 0.2% of glass fibres respectively, however, with 0.3 % glass fibres the strength was found to decrease. Also, with the addition of 0.1% and 0.2% PVA, the 28-day strength was found to increase by 7.1% and 10.7% respectively which got reduced to 5.3% with the addition of 0.3% of PVA. The reason for such a trend is due

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to the fact that initially, the fibres restrain the development of tensile cracks and hence the compressive strength increases, whereas, on further addition of fibres, the effect of inhomogeneous fibre dispersion or the formation of weak zones due to high fibre content dominates which leads to a decrease in compressive strength [17].

Addition of fibres also reduces the workability of SCC. One of the possible reasons behind this is due to the large surface area of the fibres which leads to increased viscosity of the SCC [14], [18]. Ahmed & Umar [14], [17], [19] found that the filling ability, passing ability, and resistance to segregation were reduced with the addition of glass and polyvinyl alcohol fibres.

The bonding strength between cement paste and fibre is one of the elements influencing the amount of stress imparted by the fibres [20-21]. Maximum stress transmitted to the fibres increases with bond strength. The efficacy of the fibres is restricted because a good bond cannot be established between synthetic fibres and cementitious matrix. The use of micro silica may be regarded as one of the helpful alternatives to boost the fibre's efficacy in the matrix due to its good pozzolanic activity [21]. Micro-silica, also known as silica fume, is produced in an electric arc furnace while manufacturing elemental silicons or alloys containing silicon. It principally comprises of extremely small, smooth, spherical silicon oxide particles with a very large surface area. The typical cement particle is 100 times larger than micro-silica particles. Environmental problems make its management and disposal a source of attention [22].

In the present investigation, the effect of micro silica on glass and polyvinyl fibre reinforced SCC is experimented to determine the fresh and hardened properties. From literature, it is observed that the total fibre content of 0.2% is an optimum dosage [16]. Therefore, the percentage of both glass and PVA fibres is kept fixed to 2.1kg/m^3 each and the effect of the variation of micro silica content from 2% up to 10% is observed. Fresh properties of SCC such as filling ability, passing ability and resistance to segregation are investigated using tests such as Slump flow, L box, and V funnel tests. Uniaxial compressive strength of SCC is evaluated as a parameter of hardened property.

MATERIALS USED

Cement and additives

Cement

Grade 43 Ordinary Portland Cement (OPC) corresponding to IS:8112-1989 [23] has been used. The chemical and physical properties of cement used in experiments are shown in Tables 1 and 2, respectively. These chemical and physical properties are in accordance with the limit values given in the IS code.

Table 1. Physical properties of cement.

Tests	Obtained Values	Requirements of IS:8112-1989
Normal Consistency	28%	-
Initial-Setting Time	54 minutes	Min. 30 minutes
Final-Setting Time	177 minutes	Max. 600 minutes
Compressive strength (MPa)	44.8	43

Fly Ash

Class F Fly Ash (FA) obtained from Harduaganj Thermal Power Plant, state of Uttar Pradesh was used as a mineral additive in our study. Anthracite and bituminous coal that has been burnt for a longer period of time often yields class F fly ash. Class F fly ash can be used as a Portland cement replacement ranging from 20-30% of the mass of cementitious material. The quantity of fly ash used in this study is kept fixed to 12% that of OPC and micro silica content. The nature of this fly ash is pozzolanic. Table 2 shows the chemical composition of fly ash.

Table 2. Chemical analysis of cement and fly-ash.

Ingredients		CaO (lime)	SiO_2 (silica)	Al_2O_3 (alumina)	Fe_2O_3 (iron oxide)	MgO (magnesia)	Alkalies	Sulphur	Loss on ignition
Quantity (%)	Cement	60-67	17-25	03-08	0.5-6	0.1-4	0.4-1.3	1-3	-
	Fly ash	2.23	58.55	28.2	3.44	0.32	0	0.07	4.17

Fine Aggregates

In this study, locally procured sand of size below 4.75 mm confirming to IS: 383-1970 [24] was used. The properties of fine aggregate used are given in Table 3.

Table 3. Physical Properties of fine aggregates.

Characteristic	Values Obtained
Specific Gravity	2.46
Bulk Density	1.4 kg/m^3
Fineness Modulus	2.65m^2/g
Water absorption	0.85%

Coarse Aggregate

A coarse aggregate is defined as the material that is retained on 4.75 mm IS Sieve. In most cases, crushed stone is utilized as a coarse aggregate. The maximum size of the aggregate is influenced by the type of construction. The aggregate used in this study passed through 12.5mm and was retained on 4.75 mm IS Sieve. Results of various tests on coarse aggregates performed in accordance with IS: 2386 (Part-I, III & IV)-1963 [25]–[27] are tabulated in Table 4.

Table 4. Physical properties of coarse aggregates.

Characteristic	Value obtained
Specific gravity (IS: 2386 (Part- III) - 1963	2.66
Water absorption (IS: 2386 (Part- III) -1963	0.3%
Fineness modulus (IS: 2386 (Part- I) - 1963	6.88
Impact value (IS: 2386 (Part- IV) -1963	17.5%
Crushing value (IS: 2386 (Part- IV) -1963	17%

Chemical Admixture

In this study a superplasticizer, Fosroc Chemicals' Conplast SP-430 is used to provide acceleration of strength gain at early ages and major increases in strength at all ages by reducing water demand in a concrete mix. It significantly improves the workability of site mixed and precast concrete without increasing water demand and provide improved durability by increasing ultimate strengths and reducing concrete permeability. Conplast SP430 conforms with BS 5075, BS EN 934-2 and with ASTM C494 as Type A and Type F, depending on dosage used. It is a chloride free, superplasticising admixture based on selected sulphonated napthalene polymers. It is a brown solution which instantly disperses the fine particles in the concrete mix, enabling the water content of the concrete to perform more effectively. The optimum dosage of Conplast SP430 to meet workability requirements as per EFNARC guidelines and BS standards is determined by trial mixes of concrete. The optimum dosage of Conplast SP430 is obtained as 1.2 % of cementitious material, including flyash and microsilica. Table 5 lists the characteristics of the superplastisizer.

Table 5. Characteristics of super-plasticizer.

Appearance	Brown fluid
Specific gravity	1.1-1.2 (at 25°C)
pH	8.5 to 9.5
Chloride content	Nil

Glass fibres

Generally, glass fibres do not have any capacity to resist chemical attacks in alkaline environments, so glass fibres explicitly developed to withstand high alkalinity (known as AR Glass Fibres), are generally used. Glass Fibres used in our experimental work are Cem-FIL AR fibres which are continuous-filament, alkali resistant with high durability in cement [17]. The properties of glass fibres (obtained from the manufacturer) used in our study and the chemical composition obtained from EDS analysis are given in Table 6 and Table 7. As mentioned in the introduction, a fixed optimum quantity of 2.1 kg/m^3 of glass fibres is used in all the SCC mixes for the best results [16].

Table 6. Physical composition of glass fibres.

Property	Value
Specific gravity	2.68
Modulus of elasticity (GPa)	72
Tensile strength (MPa)	1700
Diameter (micron)	14

Table 7. Chemical composition of glass fibres.

Element	Weight (%)
C	16.02
O	43.36
Na	7.92
Si	21.39
Ca	2.94
Fe	0.10
Zn	0.11
Zr	8.17

Polyvinyl Alcohol Fibres

PVA fibres are well-suited for a wide variety of applications because of their superior crack-lighting properties, high modulus of elasticity, excellent tensile and molecular bond strength, and high resistance to alkali, fatigue, and abrasion [5], [16-18], [28]. In the experimental tests, the amount of PVA fibres is also kept fixed to 2.1 kg/m^3 to have better hardened properties [16].

Table 8. Properties of Polyvinyl Alcohol Fibres.

Appearance	Yellowish white
Specific gravity	1.3
Tensile strength (MPa)	1500
Modulus of elasticity (GPa)	41.7

Micro-Silica

Silica fume, also known as micro silica, is an amorphous (non-crystalline) polymorph of silicon dioxide. It is an ultrafine powder collected as a by-product of silicon and ferrosilicon alloy production and consists of spherical particles with an average particle diameter of 150 nm [22]. Silica fume, which is an industrial waste, is also one of the contributors to air pollution. Adding micro-silica to the concrete mix helps in the reduction of air pollution. Concrete voids are also reduced by the addition of micro silica [29]. With the inclusion of micro-silica in the concrete mix, the capillarity, porosity, and absorption decrease because microscopic silica fume particles react with the lime in the cement. Silica fume enhances the concrete mix through the Pozzolanic Effect and the Micro-filler Effect [30]. In this study 2%, 4%, 6%, 8% & 10% of micro silica is used as cement replacement. Physical and chemical properties of micro silica are mentioned in Table 9.

Table 9. Physical and chemical properties of micro silica.

Compound	Value	Unit
SiO_2	94.68	%
$CaCO_3$	1.83	%
FeS_2	0.44	%
MgO	1.09	%
MAD-10 Fieldspar	1.95	%
Loss on Ignition (LOI)	1.59	%
Specific Gravity	2.2	-
Bulk density	620	Kg/m^3

EXPERIMENTAL PROGRAM

Mix proportions

A number of trial mixes were formed by modifying the super-plasticizer and water-powder ratios. Since the quantity of fine and coarse particles in self-compacting concrete is almost equal [7], the fine aggregate content is kept as 725 kg/m^3 and the coarse aggregate content is kept as 775 kg/m^3. When 1.2 percent of superplasticizer was added to the water to powder ratio of 0.35, self-compactibility was attained. The mix proportions are given in Table 10.

Table 10. Mix proportions of different mixes.

Material	SCC-GP	SCC-GPM2	SCC-GPM4	SCC-GPM6	SCC-GPM8	SCC-GPM10
Cement (kg/m^3)	530	519.4	508.8	498.2	487.6	477
Fly Ash (kg/m^3)	70	70	70	70	70	70
Fine Aggregate (kg/m^3)	725	725	725	725	725	725
Coarse Aggregate (kg/m^3)	775	775	775	775	775	775
Water (kg/m^3)	225	225	225	225	225	225
Super plastisizer %	1.2	1.2	1.2	1.2	1.2	1.2
Glass Fibres (kg/m^3)	2.1	2.1	2.1	2.1	2.1	2.1
PVA fibres (kg/m^3)	2.1	2.1	2.1	2.1	2.1	2.1
Micro Silica(kg/m^3)	0	10.6	21.2	31.8	42	52.6

***SCC-GP**: Self Compacting Concrete with Fixed Amount of Glass and Polyvinyl Alcohol Fibres.
***SCC-GPM2, SCC-GPM4, SCC-GPM6, SCC-GPM8, SCC-GPM10**: Self Compacting Concrete with fixed amount of Glass and Polyvinyl Alcohol Fibres and 2%, 4%, 6%, 8% & 10% micro-silica respectively.

Testing of specimens

Fresh properties of Self consolidating concrete

The workability of the SCC specimens was assessed as per the EFNARC guidelines [31]. The filling ability, passing ability, and resistance to segregation of concrete were measured from the tests given below and these results are shown in Table 11. The passing ability was determined using the slump flow test [32]. The freshly made concrete was poured into the slump cone and gently raised up. A slump flow of concrete is defined as the average of the two diameters at which the concrete spreads horizontally on the test instrument. The slump flow is then determined by measuring the diameters of the flow spread in two perpendicular directions and rounding the mean value to the closest 10. T_{500} time is the amount of time that has passed between the cone's upward movement and the moment the concrete has flowed to a diameter of 500 mm.

The V-funnel (T_o) and V-funnel test at T_5 minutes measure the SCC's capacity for filling and resistance to segregation. The V-funnel test measures how quickly a container can be emptied after being filled with concrete. First, the V funnel is poured fully with concrete, then the shutter is opened and the time taken to empty the funnel is noted. This time is known as T_o. However, when the concrete for the V-funnel is placed for 5 minutes before being poured then the passage of time is called T_5. L-box test [33] test measures the SCC's capability to pass through tight openings such as the spacing between the reinforcements. The value of the L-box result is represented by the ratio H2/H1. In the current experiment, a three-bar L box test is conducted as it can mimic congested reinforcements.

Mechanical property

Uniaxial Compression Test (or more commonly known as compressive strength test) is one of the most widely used test for the evaluation of hardened mechanical properties. The compressive strength was evaluated for a concrete cube of dimension 15 cm x15 cm x 15 cm. The specimens were tested at 3 days, 7 days and 28 days of curing. The results of the test are given in Figure 7.

EXPERIMENTAL RESULTS

Fresh properties

As mentioned above, the fresh properties were determined by the results obtained from Slump flow test with T_{500}, V-funnel, and L- box tests whereas the hardened properties were determined by uniaxial compression tests.

It is observed that the filling ability decreased with the addition of glass and polyvinyl alcohol fibres and micro silica. The best filling ability was obtained for SCC-GP and the lowest was obtained for the mix SCC-GPM10. As the percentage of micro silica is increased in the SCC, this filling ability decreases further. This shows that the cohesiveness of the concrete rises with the rise of silica fume content and hence the flow is reduced [34]. The range of slump flow obtained is within the prescribed limits as shown in Table 12. In the L-box test, H2/H1 ratio was found maximum for SCC-GP and minimum for SCC-GPM10 as shown in Figure 2. The blocking ratio decreased with the addition of micro silica content. The findings of the V-funnel flowtime test also confirmed the mechanism seen in the slump flow for the decrease of plasticity. Both T_o and T_5 were found to increase with the increase of micro-silica content as shown in Figure 3. Fresh properties of various mixes are also tabulated in Table 11. Acceptance conditions for self-consolidating concrete [35] with a upper limit cap of aggregate size of 20 mm are given in Table 12.

Table 11. Fresh properties of self-consolidating concrete.

No.	Characteristic	Test & Parameter	SCC-GP	SCC-GPM2	SCC-GPM4	SCC-GPM6	SCC-GPM8	SCC-GPM10
1	Flowability	Slump Flow Test (SF)	753 mm	740 mm	725 mm	715 mm	710 mm	685 mm
		T500 Slump flow	3.2 sec	3.5 sec	4 sec	4.5 sec	4.5 sec	4.9 sec
2	Passing Ability	L-Box Test (H2/H1)	0.96	0.95	0.92	0.90	0.84	0.86
3	Filling Ability and Resistance to Segregation	V- Funnel Test, T_0	6.4 sec	6.5 sec	7 sec	7.5 sec	8 sec	9 sec
		T_5	6.7 sec	7 sec	7.4 sec	8.1 sec	8.5 sec	9.5 sec

Table 12. Acceptance standards for SCC.

Method	Unit	Typical values	
		Minimum Value	Maximum Value
Slump Flow	mm	600	800
T500 slump flow	seconds	2	5
V- funnel T_0	seconds	6	12
V- funnel T_5	seconds	0	3
L-box	H2/H1	0.8	1.0

The above table shows that for each mix all the fresh properties are inside the range as approved by EFNARC [31].

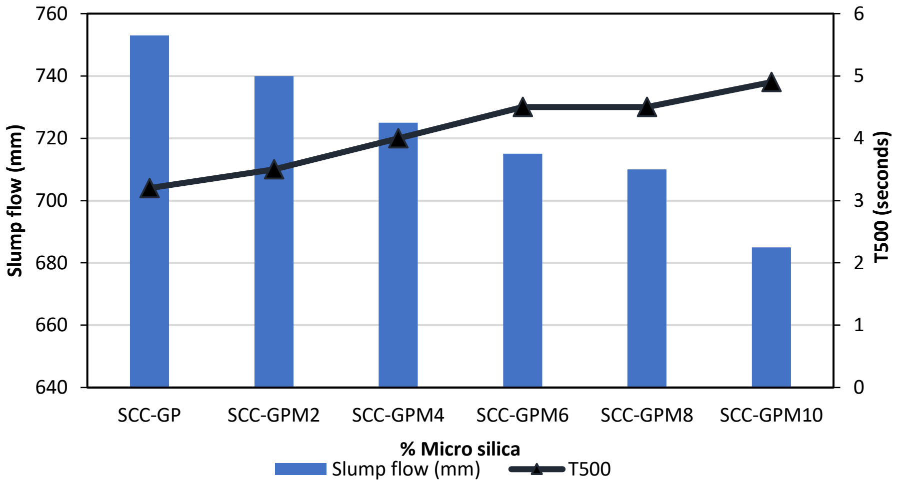

Figure 1. Slump flow and T_{500} time.

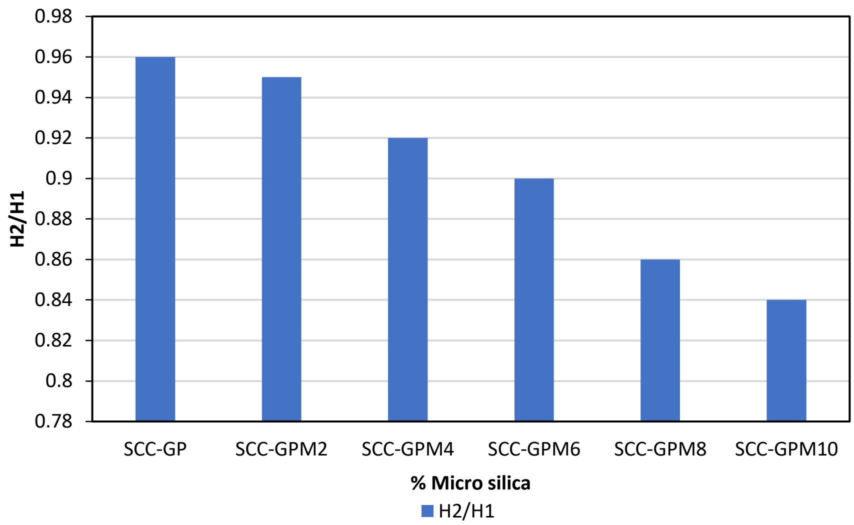

Figure 2. L-Box test.

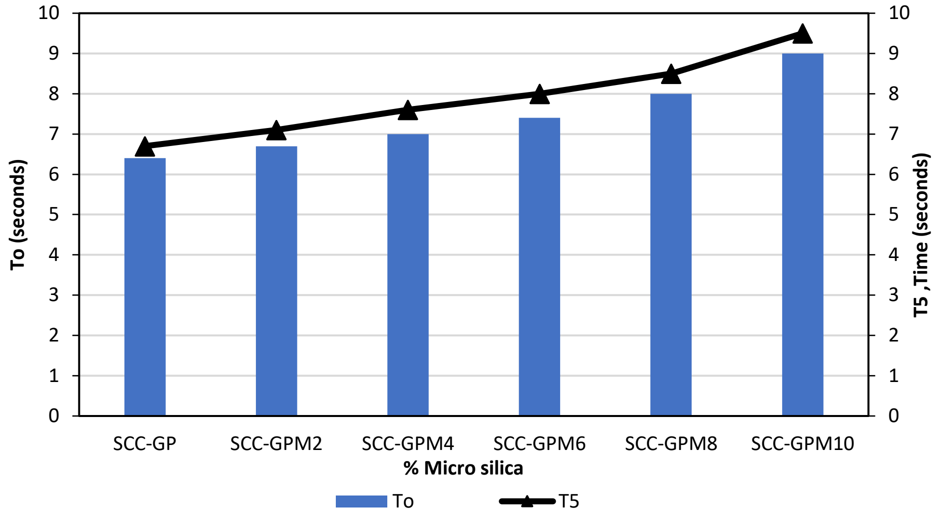

Figure 3. V-Funnel test (T_o and T_5).

Mechanical property

Compressive Strength

Compressive strength of concrete cubes of 15cm x 15cm x 15cm is determined at 3 days, 7 days and 28 days age of concrete under uniaxial compressive strength testing machine as shown in Figure 4. Average compressive strength of 3 cubes at 3, 7 and 28 days for each mix is shown in Table 13 and the results are compared in Figure 5, Figure 6, and Figure 7. There is an increase in compressive strength of the concrete with increasing percentage of micro silica up to 10%.

Table 13. Compressive Strength of Control Mix.

Mix	Average compressive strength of concrete cubes (MPa)		
	3 days	7 days	28 days
SCC-GP	25.76	31.19	49.52
SCC-GPM2	26.45	31.91	50.95
SCC-GPM4	26.83	32.23	51.45
SCC-GPM6	27.39	32.86	52.35
SCC-GPM8	27.95	33.14	52.87
SCC-GPM10	28.34	33.43	53.54


(a) Cube under testing (b) Cube at the failure

Figure 4. Compressive strength test.

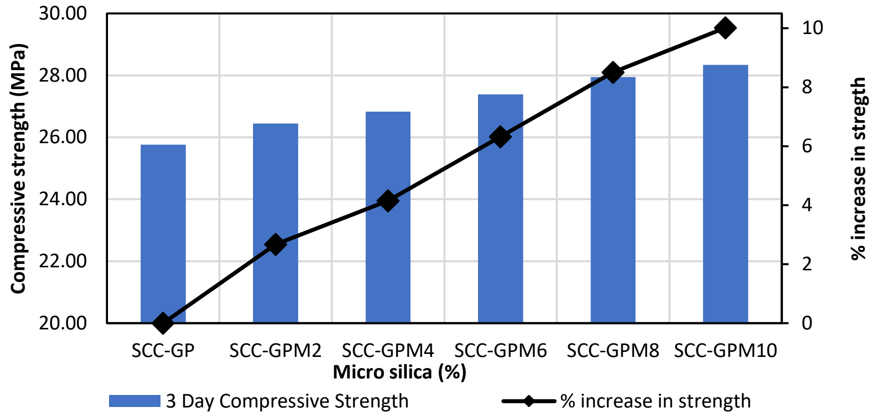

Figure 5. 3-day compressive strength for different percentages of micro silica.

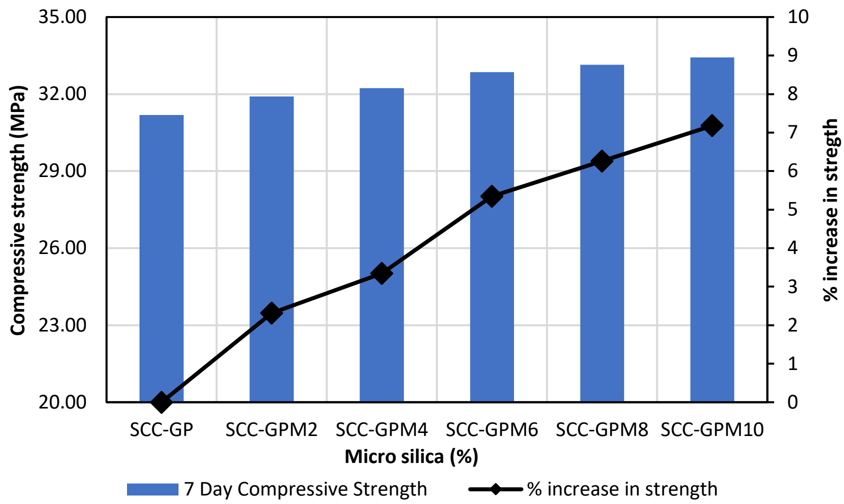

Figure 6. 7-day compressive strength for different percentages of micro silica.

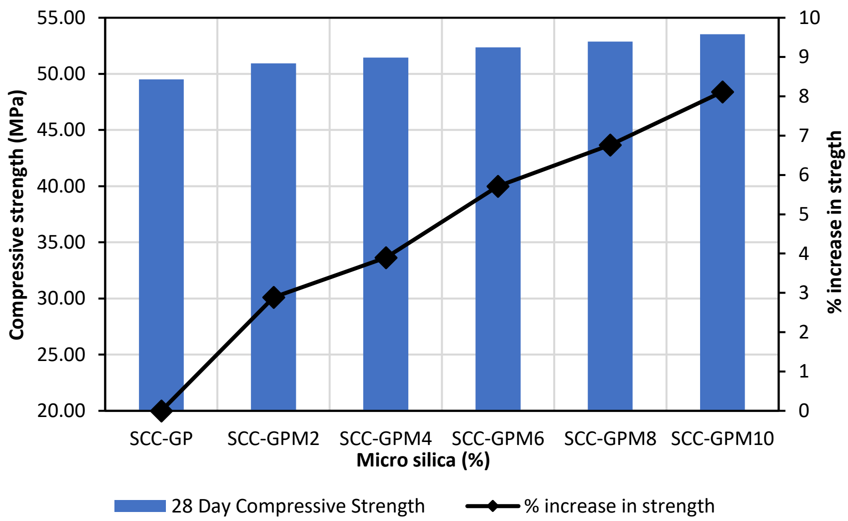

Figure 7. 28-day compressive strength for different percentages of micro silica.

In figures 5-7, the 3-day compressive strength of SCC increased from 2.6%, 4.15%, 6.32%, 8.5% and 10.01%, 7-day compressive strength of SCC increased from 2.3% 3.34%, 5.34%, 6.25% and 7.17%, and 28-day compressive strength of SCC increased from 2.88%, 3.89%, 5.71%, 6.76% and 8.11% for SCC's incorporated with 2%, 4%,6% 8% and 10% micro silica respectively when compared with SCC without micro silica content. One of the reasons for the increase in strength of SCC is the result of increase of bonding strength between the cement paste and fibres due to the good pozzolanic activity of micro silica. Due to the lower size of micro silica, the surface is for bonding becomes higher which in turn increases the efficiency of the bond [21]. The inclusion of micro silica also decreases the capillarity and porosity of the concrete mix.

CONCLUSION

The following conclusions are derived from the experimental investigations on the SCC with fly ash, glass and PVA fibres, with the varying percentage of micro silica content.

Fresh properties

All the fresh concrete properties (Filling ability, passing ability, and resistance to segregation) had an adverse effect on the addition of micro silica because of increased. However, all the SCC mixes satisfy the upper and lower limits as mentioned in the EFNARC guidelines.

Hardened properties

With the addition of micro silica, there was an increase in compressive strength of the concrete mix. It is found that the compressive strength increased by 10.01%, 7.18% and 8.12% over control mix (SCC-GP) with the addition of 10% micro silica content for 3, 7 and 28 days respectively. One of the reasons of the increase in the compressive strength is due to the improved bonding between the fibres and cementitious matrix, because of which the bonding strength increases. From the above results, it can also be concluded that SCC designed with incorporating fly ash and micro-silica helps in the reduction of solid waste disposal, which adds to the advantages of SCC being an environment-friendly concrete because no compaction is required in SCC, and hence there is no noise due to the vibrators that are used for the compaction of conventional concrete.

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