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ORIGINAL RESEARCH PAPER



Effect of silica fume on the hardened and durability properties of concrete

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ABSTRACT

This paper involves the study on the hardened and durability properties of the concrete at two different grades containing silica fume (SF) with various replacement percentages. Investigation on the performance of the SF was performed for M25 and M40 grades concrete with 0, 5, 10, and 15 % replacement levels at 7, 14, 28, and 90 days. The behavior of SF on the autogenous shrinkage of the concrete was studied for both the grades of concrete in the sealed (SC) and unsealed conditions (USC). The workability of the SF concrete was examined at various levels of replacement by the slump cone test. The hardened properties of the SF concrete were investigated through the estimation of compressive strength (CS) and elastic modulus (EM) at 7, 14, 28, and 90 days, respectively. Acid attack was conducted at 28 days and autogenous shrinkage of the SF concrete was investigated using length comparator at 28 day in SC and USC. Results indicate that upon increase in the percentage of SF, the hardened properties of the concrete increases at higher ages of curing and the shrinkage of the concrete tends to increase for both the grades of concrete.

KEYWORDS

silica fume, hardened properties, autogenous shrinkage, workability, acid attack

1. INTRODUCTION

Urbanization and industrialization have increased the rate of construction activities in the developing countries in recent times. Under such circumstances, the production and the utilization of cement for construction has increased rapidly. Excessive utilization of cement may increase the strength of the concrete but conversely it increases the rate of shrinkage too [1]. Furthermore, poor compaction results in pore formation that affects the structural performance of the concrete. This necessitated the utilization of micro filler silica fume (SF) as a supplementary cementitious material that fills up the voids in the concrete thereby enhancing its performance [2]. Various researches on the utilization of SF have shown improved results over the performance of the concrete. With a constant grade of the concrete, the improvement in the compressive strength (CS) of the concrete was observed upon the addition of SF up to 10% and beyond, which the CS decreases [3]. Conversely, with variation in the w/c ratios from 0.26 to 0.42 and the percentages of SF from 5 to 25%, the CS of the concrete increases, which shows an optimal dosage of 15% of SF. The maximum CS reported for 0.42 w/c ratio mix at 28 days was 61.75 N/mm² with 15% replacement of SF [4]. But the maximum dosage of 25% of SF was achieved at 0.42 w/c ratio, which reports higher CS compared to the control concrete. The higher water absorption capacity of SF concrete may be attributed to its higher surface area [5]. The investigation on the replacement of cement with 5, 9, 12, and 15% of SF for a M35 grade concrete was performed. The maximum CS observed was 46.14 MPa for 12% replacement of SF at 28 days. Increase in the CS with SF can be observed at the age of 3 days itself due to its higher rate of pozzolanic activity (ACI 226, 1987). Such increase in the CS of the concrete upon utilization of SF can also be further related to its workability properties. Increase in the workability of the concrete up to 6% was

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found to be increased upon replacement of SF till 10% [6], whereas conversely a decreasing trend in the workability was observed at 7.5% replacement of SF [7]. Such a decrease in the workability of the concrete upon lower levels of replacement of SF is due to its higher surface area. For a high strength concrete, the maximum slump of 180mm was achieved at 5% replacement of SF beyond which it causes the reduction in the slump at constant w/c ratio and dosage of super plasticizers [2, 8]. In a study performed [9] on the behavior of SF on the steel slag powdered concrete, a decline in the CS was observed beyond 8% of addition of SF, which is due to the fact that $\text{Ca}(\text{OH})_2$ produced upon cement hydration was exhausted as a result of which no C–S–H gel could be formed increasing the CS of the concrete. Similar other findings by [10] conclude that the maximum replacement percentage of SF in the concrete as 12% beyond which it causes a decrease in the CS of the concrete. With respect to the durability properties, addition of SF reduces the permeability of the concrete [11–13]. Shrinkage at the initial ages of concrete due to volume changes should be controlled as it weakens the Interfacial Transition Zone (ITZ) leading to cracking in the concrete [14, 15]. The above summary clearly demonstrates the lack of study on the shrinkage properties of SF concrete in sealed (SC) and unsealed conditions (USC). This paper presents an experimental study on the hardened properties of SF concrete at 7, 14, 28, and 90 days. This study also encompasses the

shrinkage properties of SF concrete in SC and USC and resistance of the SF concrete against the ingress of acids at 28 days.

2. MATERIALS AND MIX PROPORTIONS

Ordinary Portland cement (OPC) of 43 grades confirming to IS: 8112 (1989), river sand passing through 2.36 mm sieve, gravel passing through 20 mm sieve, SF collected from a local market and water confirming to IS 456 (2000) were used as raw materials in the study. Chemical constituents of cementitious materials like OPC and SF are given in Table 1. Various physical properties of the raw materials used in the study are presented in Table 2. Mix proportions for M25 and M40 grades of concrete used in the study are presented in Table 3. Control specimens for both grades of concrete were prepared using OPC whereas other mixtures were prepared by replacing OPC by 5, 10, and 15% of SF by its weight.

3. PREPARATION AND TESTING OF SPECIMENS

Concrete cube molds of size 150 mm × 150 mm × 150 mm, cylindrical molds of size 150 mm × 300 mm and prism molds of size 500 mm × 100 mm × 100 mm were used for casting in this study. The concrete mixes were prepared in accordance with IS 10262 (2009) for M25 and M40 grades of the concrete. The raw materials were added in the mixer and allowed to run for 3 minutes to ensure proper mixing of concrete as shown in Fig. 1. Further, the concrete mixtures were filled in the prepared molds and compacted by 25 blows in three layers and allowed to harden for 24 hours. The hardened specimens were then cured for 7, 14, 28, and 90 days at 20 °C with a relative humidity >80%. The specimens were tested for hardened properties like CS and elastic modulus (EM) in accordance with BS 1881-116 (1983) at 7, 14, 28, and 90 days with an average of three specimens for all mix combinations (Fig. 2). To determine the CS, cube specimens were loaded under universal testing machine

Table 1. Chemical constituents of cementitious materials

Se.	Constituents	Percentage of the constituents (%)	
		Ordinary portland cement	SF
1	SiO_2	17.34	89.72
2	Al_2O_3	7.62	0.80
3	Fe_2O_3	4.23	0.76
4	CaO	65.27	1.41
5	MgO	2.4	1.23
6	SO_3	3.14	0.84
7	K_2O	–	1.31
8	Na_2O	–	0.65
9	LOI	–	3.28

Table 2. Physical properties of raw materials

Se.	Raw material	Property	Tested value	BIS limits
1	Cement	Specific gravity	3.15	3.15
		Setting time (mins)	Initial – 30 Final – 600	Initial–30 Final–600
2	River sand (Fine Aggregate)	Specific gravity	2.74	2.50–3.00
		Fineness modulus	2.79	2.00–4.00
		Water absorption (%)	1.34	0.30–2.50
3	Gravel (Coarse Aggregate)	Specific gravity	2.65	2.50–3.00
		Fineness modulus	7.13	6.75–8.00
		Water absorption (%)	1.10	<2.00
4	SF	Specific gravity	2.20	2.20 to 2.30
		Surface area (m^2/kg)	18,000	>350
5	Water	pH	8.40	>6.00



Table 3. Mix proportions of concrete

Se.	Raw materials (kg/m ³)	Grade of concrete							
		Mass percentage of SF (M25 grade concrete)				Mass percentage of SF (M40 grade concrete)			
		0%	5%	10%	15%	0%	5%	10%	15%
1	Cement	336	319.2	302.4	285.6	463.5	440.32	417.14	393.96
2	Fine aggregate			834			530.27		
3	Coarse aggregate			1,114			1,153.13		
4	Water			186			185.4		
5	SF	–	16.80	33.60	50.4	–	23.18	46.36	69.54



Fig. 1. Casting of concrete specimens

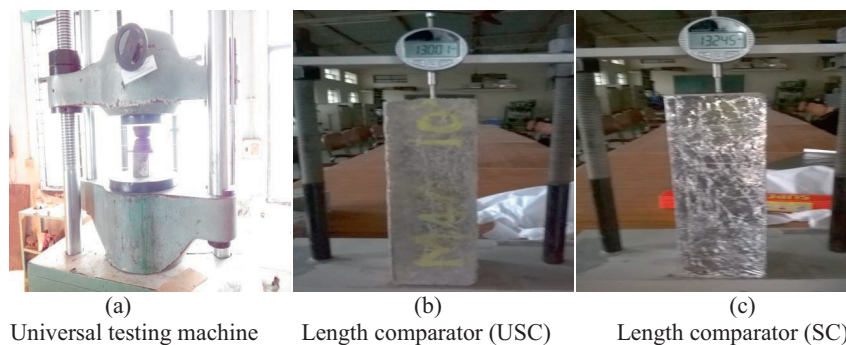


Fig. 2. Testing of concrete specimens

(UTM) at a rate of 140 kg/cm² till the specimen fails and the maximum load at failure of the specimens was noted. To determine the EM, cylindrical molds were mounted on the UTM having load measurement accuracy of $\pm 0.5\%$ and position measurement accuracy of $\pm 0.01\%$ affixed with compressometer, and the applied stress and measured loads were determined. For acid attack, hardened cube specimens were demoulded after 24 h and immersed in the acidic solution having 5% of 0.1M HCl for 28 days. The specimens were then dried and tested to determine the percentage reduction in the CS. Demoulded beam specimens of 3 No's for mix combinations in both SC and USC were subjected to shrinkage study regularly till 28 days and the volume change was measured using length comparator and an average of three readings were measured (Fig. 2). In both the cases of strength and shrinkage measurements, the relative difference in the strength and shrinkage of 3 samples for each mix combination

was found to be less than 5%, which is acceptable as per IS 456: 2000. Fewer specimens were sealed and kept in controlled condition of 20 °C for the entire 28 days [16].

4. RESULTS AND DISCUSSIONS

4.1. Fresh property study

Workability study for the M40 grade concrete performed in accordance with BS 1881-102 (1983) with various replacement percentages of SF is shown in Fig. 3. From the results, it could be observed that the slump value reduces with the increase in the percentage of SF. Higher percentages of SF tend to absorb more water. This attribute is due to the finer particle size of the SF that absorbs more water as a result of its increased surface area [8, 17–19].

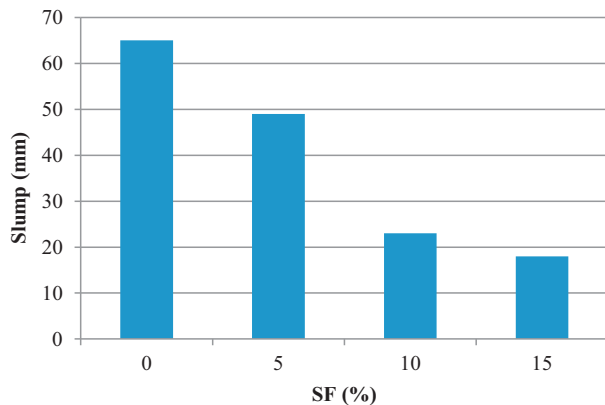


Fig. 3. Slump of the concrete mixtures

Table 4. Compressive strength at different ages

Se.	Grade of the concrete	SF (%)	Compressive strength (MPa)			
			7 days	14 days	28 days	90 days
1	M25	0	23.47	30.06	33.41	36.69
2		5	25.58	33.16	36.84	40.34
3		10	26.17	34.50	38.11	41.64
4		15	26.56	35.31	39.13	42.48
5	M40	0	31.86	43.23	48.04	52.91
6		5	34.61	47.49	52.61	57.72
7		10	35.72	48.83	54.15	59.21
8		15	36.14	49.67	55.21	60.26

4.2. Compressive Strength (CS)

The CS for both grades of concrete at different ages of curing is given in Table 4. Percentage improvement in the CS of the concrete upon different replacement percentages of SF compared to control concrete is shown in Fig. 4. For M25 grade concrete, the maximum improvement in the strength of 14.68% was observed at 14 days and 13.62% at 90 days. Similarly for M40 grade concrete, the maximum improvement in the strength of 13.01% at 14 days and 12.19% at 90

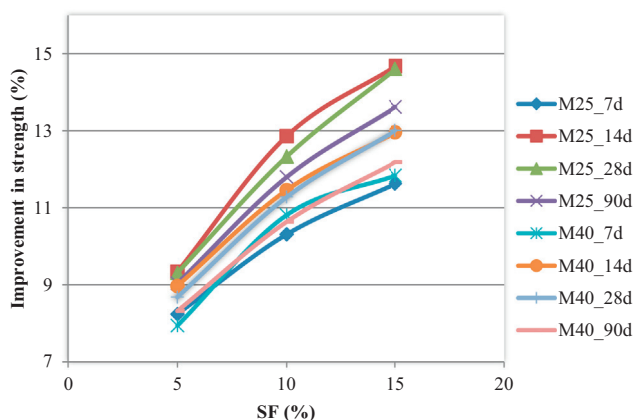


Fig. 4. % improvement in strength of concrete at different ages

days was observed. This attribute is due to the increase in the fineness of the SF particles. In spite of increased surface area of the SF, the particles tend to fill up the voids in the concrete during mixing and compaction. This in turn results in the formation of a closely packed structure with lesser porosity, thereby improving the strength of the concrete [20–22]. But the improvement in the strength of the concrete was not linear beyond 28 days, as the percentage of improvement compared to control concrete at 90 days is lesser compared to that of 28 days. This is because of the formation of an inhibiting product after 28 days preventing further reaction of SF with the Ca(OH)_2 . Also, the reactivity of the SF was much effective till 28 days due to its pozzolanic activity, later on which it decreases, thereby affecting the strength improvement in the concrete at later ages [18, 23].

4.3. Elastic modulus

The EM for both the grades of concrete at different curing periods is shown in Fig. 5. It can be observed as the percentage of the SF is increased, the EM of the concrete tend to increase. Maximum improvement of 7.06% at 15% replacement of SF for M25 grade concrete and 6.29% at 15% replacement of SF for M40 grade concrete was observed at 90 days. No significant variation in the improvement of EM at different grades of concrete was observed at 90 days. The micro-filler SF tends to fill up the voids in the concrete forming a closely packed structure. Upon loading, the grain to grain transfer of load occurs as a result of which strain increases eventually at the rate of stress, thereby increasing the EM of the concrete.

4.4. Autogenous shrinkage

The autogenous shrinkage for both grades of concrete at 28 days in both SC and USC is shown in Fig. 6. Maximum decrease in the shrinkage strain was observed for the concrete specimens in SC compared to USC. Also, as the percentage of SF increases, the rate of shrinkage strain increases for both grades of the concrete [24–26]. For M40 grade concrete, the rate of shrinkage strain is more compared to

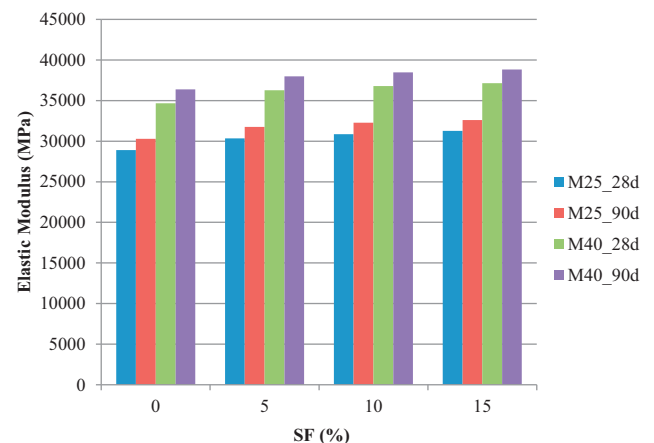
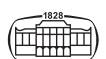


Fig. 5. Elastic modulus of SF concrete



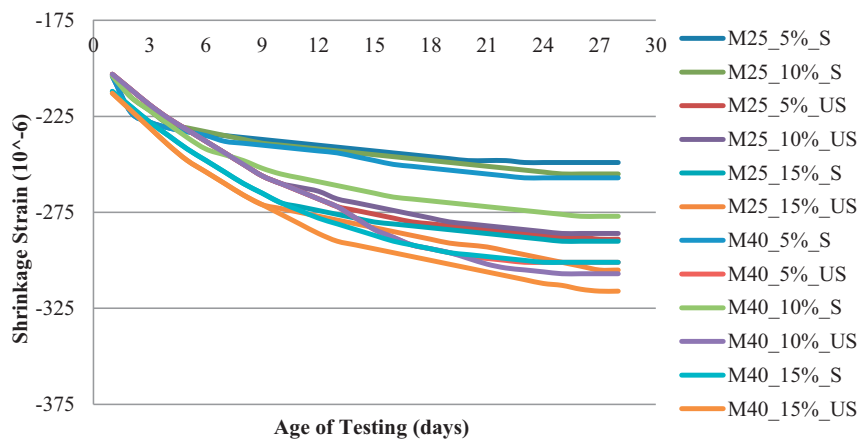


Fig. 6. Shrinkage strain at 28 days

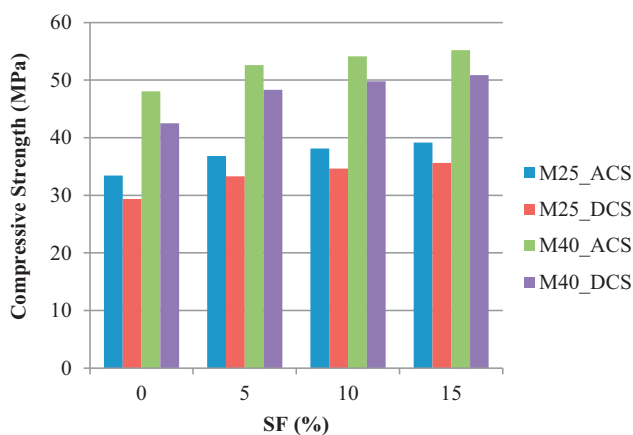


Fig. 7. Resistance to acid attack.

*ACS – Actual Compressive Strength; DCS – Decreased Compressive Strength

M25 grade under all levels of replacement of SF. This is due to the attribute of the increased cement content and reduced volume of aggregates. When the volume of aggregates in the mix was reduced, the restraining ability of aggregates against shrinkage of cement matrix reduces, thereby increasing the rate of shrinkage strain in the concrete [18]. Also, increase in the percentage of SF increases the shrinkage of the concrete. At higher grades, SF tends to fill up the voids in the cement paste. This in turn increases the stress over the cement paste and leading to further expansion of cement matrix. Such expansion of the cement matrix may cause micro-cracks in the concrete affecting the durability of the concrete.

4.5. Acid attack

The acid resistance of the concrete with different percentages of SF for both grades of the concrete is shown in Fig. 7. The maximum resistance to penetration of acids was observed at 15% replacement of SF for both M25 and M40 grades of concrete. Upon increase in the percentage of the SF, the rate of resistance to acid penetration was reduced. This is due to the pore filling ability of SF, which fills up the voids in the concrete, thereby decreasing the rate of

ingression of harmful acids into the concrete. Also, higher content of SiO_2 in SF reacts with Ca(OH)_2 forming an impermeable C-S-H gel, that reduces the rate of penetration of harmful acids thereby enhancing the durability of the concrete [27].

5. CONCLUSION

Based on the investigations on the performance of SF at different levels of replacement, the following recommendations were put forth:

1. Increase in the percentage of SF decreases the workability of concrete as the finer SF having higher surface area tends to absorb more water reducing the slump value of the concrete.
2. As the percentage of SF increases, the strength of the concrete increases irrespective of the grades of the concrete. Conversely, the percentage improvement in the strength of concrete upon addition of SF was reduced due to its lesser pozzolanic reactivity at later ages.
3. The elastic modulus of the concrete is not much dependent on the percentage of SF as no significant variation was observed.
4. The shrinkage of the concrete increases with the increase in the percentage of SF and it is more dependent on the grade of the concrete.
5. Resistance of the concrete to acid increases with the increase in the percentage of SF.

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