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High strength sustainable concrete using silica nanoparticles

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HIGHLIGHTS

- SNPs accelerate the hydration process and shorten the dormant period.
- With the incorporation SNPs, initial and final setting is decreased significantly.
- Optimum dosages of SNPs depend on the w/b ratio of mix.
- Strength gain in case of SNPs incorporated specimens were found to be predominant at early ages.
- The mechanical and durability properties of SNPs incorporated mixtures enhanced by 20–30% at 28 days.

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ABSTRACT

This study deals with the effect of silica nanoparticles (SNPs) in high volume fly ash (40% replacement) cement paste, mortar and concrete. The content of SNPs (0.5–3.0%) was added by the weight of binder and w/b ratio (0.23, 0.25 & 3.0) was optimized in paste and mortar system. The calorimetric results reveal that the hydration process was accelerated as a result of SNPs incorporation and the dormant period was shortening by 4 h with 2% SNPs as compared to the control. The effect of optimum dosages of SNPs addition on concrete in terms of mechanical and durability properties was studied at 0.25 w/b ratio. The compressive strength results of SNPs added mixtures showed an improvement of 61% at 3 days and 25% at 28 days of hydration as compared to control. The durability studies at 28 day showed that, with the incorporation of SNPs, the porosity, sorptivity and water absorption reduced up to 25–40% and densify the interfacial transition zone (ITZ).

1. Introduction

Increased environmental concerns like global warming, pollution, depletion of natural resources have led various sectors of the industry to think towards sustainability in their respective fields. In the construction sector, concrete constitutes the major part of the constructional materials owing to its low-cost and good mechanical properties. It is reported that its rate of consumption is almost 1 m^3 per person per year. With this increasing rate of consumption due to its superior qualities, its consequences have also become predominant. The main constituent of concrete responsible for its carbon foot-print is cement, whereas the cement industries contribute about 5% of the total global CO_2 emission. In order to address this issue and make concrete more sustainable, various attempts have been made. One of the major researches is to replace cement with supplementary pozzolanic materials such as fly ash (FA), ground granulated blast furnace slag (GGBS), metakolin, rice husk ash etc. Though these materials served the purpose to a large extent, there have been issues regarding delayed setting time and early age strength when used in large quantities.

Nanotechnology is an emerging field in the construction sector, wherein different types of nanomaterials are used to enhance desired properties of concrete. For example, nano-TiO_2 particles for self-cleaning property, carbon nanotubes for flexural strength enhancement, nano-$CaCO_3$ particles for self-healing property and silica nanoparticles (SNPs) for high performance concrete have been explored. SNPs are widely used in concrete, owing its superior performance such as high early age strength due to nucleation effect, later age strength increment due to additional C-S-H gel formation and filler effect, reduction in segregation and bleeding, reduction in setting time, better thermal behaviour [1–11]. Further, SNPs incorporation makes the concrete more durable in terms of reduced water absorption, improved porosity, lower calcium content and better resistance to chloride and sulphate ingression [12–16]. However, there have been some reports indicating issues with later age strength development [17–19] and strength retrogression at later ages [20–22]. These issues have not been dealt

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in detailed, however, some literature reports that it might be because of autogenous shrinkage or conversion of C–S–H gel to tobermorite or due to thick dense layer formation on the surface of FA particles and thus, degrading or retarding the FA reactivity [23]. In the present work, a systematic study on paste, mortar and concrete was carried on high volume fly ash system (HVFA) system with incorporation of SNPs. The dosages of SNPs and water to binder ratio were optimized in paste and mortar studies and these optimized dosages were used in the concrete study.

2. Materials and methods

2.1. Materials

The ordinary Portland Cement (OPC) with Blaine fineness of 390 m^2/kg conforming to IS 8112:1989 [24] and class F fly ash (FA) with surface area of 252 m^2/kg confirming to IS 3812(Part-2):2003 [25] were used for the study. The chemical composition of cement and FA are given in Table 1.The laboratory synthesised dispersed SNPs with surface area of 116 m^2/g and fourth generation superplasticiser (SP), polycarboxylic ether were used for the present study.

Two types of sand, the first one is the standard Ennore sand having the specific gravity 2.60 and fineness modulus of 2.77 was used for mortar studies, whereas, second one being river sand having specific gravity of 2.57 and fineness modulus of 2.98 was used for concrete samples. The angular crushed aggregates having maximum size of 10 mm were used as coarse aggregates, having specific gravity of 2.62 and fineness modulus being 7.34. The aggregates were found to be satisfying the specifications of IS 383:1970 [26].

2.2. Mix proportioning

In the entire study, 40% FA content was used as a constant amount of replacement with cement and the mix proportioning used for the paste and mortar casting were given in Table 2. The content of SNPs (0.5%, 1.0%, 2.0% & 3%) was added by the weight of binder and three different w/b ratio (0.23, 0.25 & 3.0) were used to optimize the SNPs dosage and w/b ratio in paste and mortar study. The optimized mixed (based on compressive strength of cement paste and mortar samples) were used for concrete studies. The concrete mix proportioning was based on Fuller and Thompson gradation curve for aggregate grading, while w/b ratio and cement content were based on the requirement for high strength fly ash concrete (Table 3).

2.3. Testing

The compressive strength test of paste and mortar samples were carried out on 25 × 50 mm cubes, respectively, while for the concrete samples, compressive and tensile strength test were performed on 100 × 200 mm cylinders. The compressive strength testing was done on 1, 3, 7, 28, 56 and 90 days aged samples for paste and mortar studies, while for the concrete samples, it was done till 56 days only. The test was carried out in accordance with IS 516:1959 for compressive strength [27] and ASTM C 496-11 for tensile strength [28]. Flexural strength testing was performed on 100 × 100 × 500 mm prism according IS 516:1959 [27] with a loading rate of 1.8 KN/min after 28 days of curing using four point bending test procedure. For the determination of elastic moduli, 150 × 300 mm cylinders were used for the preparation of samples and test were carried out according to ASTM C 469-14 [29]. Further, the water absorption and permeable voids of concrete samples were measured according to ASTM C-642-13 [30] on 7 and 28 days cured samples and sorptivity of concrete samples was measured according to DI manual for concrete durability index testing [31] at 28 days of maturity. The test was carried out on 30 × 70 mm disks and the mass gain was measured at 3, 5, 7, 9, 12, 16, 20 and 25 min after placing oven dried sample in water front of 2–3 mm. For the determination of pH, finely grounded

Table 2
Mixtures cast for paste and mortar studies.

Binder	w/b ratio	SNPs content as addition (bwob)	Notation
60% cement + 40% FA	0.23	0%	0.23-Control
		0.5%	0.23–0.5% SNPs
		1.0%	0.23–1.0% SNPs
		1.5%	0.23–1.5% SNPs
		2.0%	0.23–2.0% SNPs
		3.0%	0.23–3.0% SNPs
	0.25	0%	0.25-Control
		0.5%	0.25–0.5% SNPs
		1.0%	0.25–1.0% SNPs
		1.5%	0.25–1.5% SNPs
		2.0%	0.25–2.0% SNPs
		3.0%	0.25–3.0% SNPs
	0.3	0%	0.3-Control
		0.5%	0.3–0.5% SNPs
		1.0%	0.3–1.0% SNPs
		1.5%	0.3–1.5% SNPs
		2.0%	0.3–2.0% SNPs
		3.0%	0.3–3.0% SNPs

Table 3
Mix proportions used in concrete casting.

Material	Control	0.5% SNPs	2.0% SNPs
Cement (kg/m^3)	360	360	360
Fly ash (kg/m^3)	240	240	240
Nano silica (kg/m^3)	–	3	12
Fine aggregate (kg/m^3)	627	627	627
Coarse aggregate (kg/m^3)	1023	1023	1023
Water content (kg/m^3)	150	150	150
SP (kg/m^3)	5.4	5.73	6.12
w/b ratio	0.25	0.25	0.25

Table 1
Chemical composition of OPC and FA.

	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Alkalis ($K_2O + Na_2O$)	Others	LOI
Cement (%)	64.3	19.3	5.8	5.0	0.8	2.4	0.9	1.5	4.0
FA (%)	–	56.8	30.2	5.0	0.7	0.2	1.4	5.7	3.6