

Comparison of High Performance Fly Ash Concrete Using Nano Silica Fume on Different Mixes

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Abstract

This paper investigates the experimental results on the effect of nano silica fume on compressive strength development of concretes containing high volume fly ash (HVFA). The effect of various silica fumes contents such as 1%, 2% & 3% (wt. %) as partial replacement of cement on the compressive strength of cements is evaluated in the first part. The nano silica fume content which exhibits the highest compressive strength above is used in high volume fly ash concretes containing 30% and 50% class F fly ash. The results show that among three different silica fumes contents, the addition of 1% increases the compressive strength of concretes. The addition of 1% silica fume also increases the early age and 28 days compressive strengths of HVFA concretes.

Keywords

Silica Fume, Fly Ash, Compressive Strength, Concrete

1. Introduction

As a recent development, supplementary cementitious materials (SCM's) are being increasingly used in concrete for improvement in its properties and for reducing amount of cement. The commonly used SCMS such as fly ash, Calcium carbon material, metakaolin and slag are widely used because of their significant contribution and availability in improving the concrete properties. To produce environment friendly "green concrete" at low cost and in view of sustainability, the partial replacement of cement by SCMS in concrete is employed. Therefore researchers have investigated the use of high volume fly ash as partial replacement of cement in concrete that has enormous impacts in reducing the cost and enhancing its sustainability. The use of fly ash as partial replacement

of cement in concrete is limited to around 15% to 20% by mass of cement which is not adequate to make concrete more sustainable. Several studies have reported that the use of HVFA in concrete provides higher durable properties than ordinary concretes in low water-cement ratio [1]-[4]. Although high volume fly ash concretes show promising performance compared to concrete, yet its low early age strength development is still a concern for wide structural application [5] [6].

Nanotechnology is gaining widespread attention and being applied in many fields to formulate materials with novel functions due to their unique physical and chemical properties. Nano material is defined as a very small size particle in a scale of 10^{-9} meter, produced from modification of atoms and molecules in order to produce larger surface area [7]. The addition of nano particles in concrete is more effective than micro size particles and is recognized as a means to improve the strength and durability properties of concrete. Most of the work to date with nano particles has been done using nano carbon (CaCO_3), nano iron (Fe_2O_3), nano titanium oxide (TiO_2), nano-alumina (Al_2O_3), and nano clay particles. Nano particles act as nuclei for cement to accelerate the cement hydration and densify the microstructure of the matrix and the interfacial transition zone (ITZ), thereby reduces the permeability of concrete [8]. In recent years, limited studies have been conducted on the additions of nano silica fume as partial replacement of cement in concrete on the hydration and compressive strength behavior.

Using nanotechnology tool, it is easy to modify the nano/basic structure of the materials to improve the materials bulk properties such as mechanical performance, durability, sustainability and volume stability. Recently, researchers have shown enormous interest to investigate the properties of building materials such as mechanical, temperature and strain sensing, durability with nano materials [9]. Self-cleaning façade with the addition of titania nano particles to the mortar [10], self sensing cementitious composites [11] and electromagnetic interference(EMI) shielding [12] by the addition of conductive nano materials viz., carbon nano tubes, carbon nano fibers or carbon black have been explored. The application of nano-sized ingredients such as alumina and silica particles and understanding of the hydration behavior are the upcoming research areas dealing with cement and concrete materials [13]-[20].

The effect of nano silica to reduce the calcium leaching and refinement in pore structure of cement paste has been studied [21]. The addition of nano silica improved the performance of cementitious system by controlling the C-S-H degradation under aggressive condition of calcium leaching process.

Composite modified asphalts with nano calcium carbonate (nano CaCO_3) and nano montmorillonite (nano MMT) were prepared by melt blending. The results demonstrate that these materials homogeneously disperse in the base asphalt, which lead to an improvement in terms of toughness, strength and thermal stability [22]. The effects of nano calcium carbonate addition on the early age properties of ultra-high-performance concrete cured at simulated cold and normal field conditions were investigated [23]. These include the development of low-maintenance structures through eliminating the risk of steel corrosion induced by chloride-based accelerating admixtures, as well as a more environmentally friendly concrete through reducing the cement factor of ultra-high-performance concrete [24]. Concluded that partial replacement of cement with nano phase Fe_2O_3 particles improves the split tensile and flexural strength of concrete but decreases its setting time. Here, it is proved that the use of nano-particles up to maximum replacement level of 2% produce concrete improved tensile strength. Partial replacement of cement with nano phase Al_2O_3 particles improves the compressive strength of concrete but decrease its workability [25]-[27]. The increased the SiO_2 nanoparticles' content more than 3 wt.% causes the reduced the split tensile strength because of the decreased crystalline $\text{Ca}(\text{OH})_2$ content required for C-S-H gel formation. SiO_2 nanoparticles could improve the pore structure of concrete and shift the distributed pores to harmless and few-harm pores. Nano clays are the new generation of processed clays of interest in a wide range of high performance composites Test results show that while nano clay changes rheological properties of bitumen and increases stiffness, it also decreases angle phase and improves ageing resistances, as well.

2. Experimental Program

2.1. Materials

Ordinary Portland cement Type-I (PC), Class F fly ash (FA) and nano silica fumes are used in all mixes in this study. The nano-silica fume is obtained from Sky spring Nano materials, Inc. of USA with average particle diameter of 15 - 30 nm. The chemical properties and physical properties of PC, FA and Silica fume are listed in Table 1 and Table 2.

2.1.1. Fly Ash

It is widely accepted that the water required for workability of mortars and concretes depends on the carbon content of fly ash; the more water is needed to produce a paste of normal consistency when carbon content of fly ash is high. Most standards limit the carbon content of fly ash to 5% while few admit values as high as 7% [5]. Some researchers [26] have indicated that in HPC fly ash must comply with ASTM C618 or AASHTO M295 that limit loss on ignition to 6% and 5%. **Table 3** & **Table 4** show the characteristic and loss on ignition of fly ash.

2.1.2. Silica Fumes

Silica fume (SF) is a byproduct of the smelting process in the silicon and ferro-silicon industry. The reduction of high-purity quartz to silicon at temperatures up to 2000 C produce SiO₂ vapours, which oxidizes and condense in

Table 1. Chemical composition and physical properties of cementitious materials.

Chemical Analysis	Cement (Wt. %)	Fly Ash (Wt. %)	Silica Fume
K ₂ O	-	0.68	-
Na ₂ O	-	0.31	-
P ₂ O ₅	-	1.39	-
TiO ₂	-	1.44	-
SO ₃	2.4	0.21	0.24
MnO	-	0.10	-
MgO	2.0	1.17	0.38
CaO	63.9	1.61	0.25
SiO ₂	20.2	51.80	92.70
Al ₂ O ₃	4.9	26.40	2.04
Fe ₂ O ₃	2.8	13.20	1.08

Table 2. Physical properties.

Partial Size	25% - 40% ≤ 7 μm	40% of 10 μm	15 - 40 nm
Specific Gravity	2.7 to 3.2	2.6	-
Surface Area(m ² /g)	-	-	40
Loss on ignition (%)	2.4	0.5	-

Table 3. Characteristics of fly ash.

Moisture (%)	0.09	Total: SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃ (%)	87.73
Loss on ignition (%)	7.03	Na ₂ O (%)	0.44
Fineness > 45 μm (%)	27.53	K ₂ O (%)	1.53
Fineness > 75 μm (%)	14.30	MgO (%)	1.45
Free CaO (%)	0.00	SO ₃ (%)	0.25
Total CaO(%)	2.25	Chloride (%)	0.00
SiO ₂ (%)	58.46	P ₂ O ₅ (%)	0.16
AL ₂ O ₃ (%)	21.47	TiO ₂ (%)	0.93
Fe ₂ O ₃ (%)	7.81	Specific Gravity	2.36

Table 4. Loss on ignition of fly ash.

Fly Ash	L.O.I. (%)
Total 'as received'	7
Particles > 75 μm	26.5
Particles < 75 μm (enhanced Fly Ash)	3.5

the low-temperature zone to tiny particles consisting of non-crystalline silica. Higher the silicon content in the alloy results in the higher silica content in silica fume. The reason is the same furnace can produce different alloys, it is necessary to know the cradle of any silica fume to be used in concrete. In scrupulous, ferrosilicon with a 50-per cent content of silicon results in a silica fume with a content of silica of only about 80 per cent emblematic silica contents are as follows: silicon metal, 94 to 98; 90 percent ferrosilicon, 90 to 96; and 75 per cent ferrosilicon, 86 to 90.

Silica fume has been recognized as pozzolanic admixture that effective in enhancing the mechanical properties by using silica fume along with super plasticizers, it is defined easier to obtain compressive strengths of order of 100 - 150 MPa in laboratory. Adding silica fume to concrete improves the durability of concrete through reduction in the permeability, refined pore structure, leading to a reduction in the diffusion of harmful ions; reduce calcium hydroxide content which results in a higher resistance to sulphate attack Improvement in durability will also improve the ability of silica fume concrete in protecting the embedded steel from corrosion.

Figure 1 shows the schematic diagram of silica fume production. The silica fume is collected a very large filters in the bag house and then made available for use in concrete

2.1.3. Properties of Silica Fume

1) Physical Properties

Silica fume particles are extremely small, with more than 95% of the particles finer than 1 μm . Its typical physical properties are given in **Table 5**. Silica fume colour is either premium white or grey shown in **Figure 2**.

2) Chemical Composition

Silica fume is composed primarily of pure silica in non-crystalline form. X-ray diffraction analysis of different silica fumes reveals that material is essential.

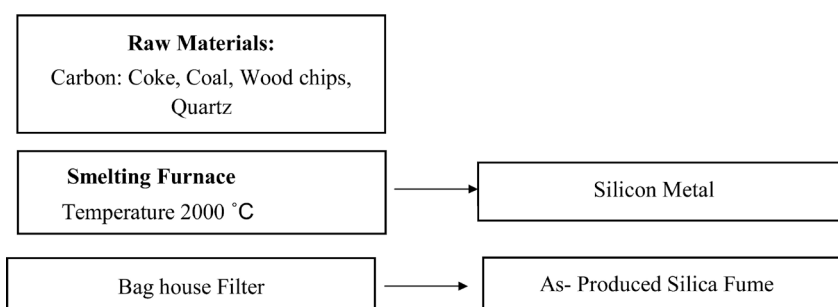


Figure 1. Schematic diagram of silica fume production.



Figure 2. Silica fume.

Table 5. Typical physical properties of silica fume.

Property	Value
Particle size (typical)	<1 μm
Bulk density As Produced	130 - 430 kg/m^3
Slurry	1320 - 1440 kg/m^3
Densified	480 - 720 kg/m^3
Specific gravity	2.2
Surface Area	13,000 - 30,000 m^2/Kg

2.2. Mixture Proportions

The mixture proportion is shown in **Table 6** respectively. The effects of different nano-silica fumes contents on compressive strength development of HVFA cement are evaluated. The first series is the control cement. The effects of high fly ash content 30% and 50% as partial replacement of cement on compressive strength of cements are evaluated in second series. The third series investigates the effects of different nano-silica fumes contents (e.g. 1%, 2% and 3%) as partial replacement of cement on compressive strength of cements. The nano silica fume content that exhibits the highest compressive strength in the third series is used in the fourth series to study its effect on the compressive strength of cements containing 30% and 50% class F fly ash (by wt) as partial replacement of cement.

2.3. Mixing Methods

The concrete mixes are prepared in a pan mixer with water/binder ratio of 0.4 and sand/binder ratio of 2.75. Dry mixing time of cement, fly ash, Nano-silica fume and aggregates are extended to 4 - 5 minutes due to higher volume of mix and presence of coarse aggregates. Standard cylinders having diameter of 100 mm and height of 200 mm are cast and cured in water at room temperature. The compressive strengths of concretes are determined at 3, 7 and 28 days according to ASTM C873 standard. **Figure 3** shows casting of specimens for cube and cylinder. **Figure 4** shows compressive strength test.

3. Results and Discussion

3.1. Effect of Silica Fume on Workability of Concretes

The effect of silica fume on workability of control cement concrete is evaluated using flow table test according to ASTM C1437 (2012). It can be seen from **Figure 5** that the concrete containing nano silica fume exhibited

Table 6. Mixture proportions of concretes.

Series	Mix Designation	Cement (kg/m ³)	Class F Fly ash (kg/m ³)	Nano Silica Fume (kg/m ³)	Sand (kg/m ³)	Coarse Aggregate (kg/m ³)	Water (kg/m ³)
1	PC	300	-	-	513	888	123
2	FA 30	210	90	-	513	888	123
	FA 50	150	150	-	513	888	123
3	NS1	297	-	3	513	888	123
	NS2	294	-	6	513	888	123
	NS3	291	-	9	513	888	123
4	FA29%NS1%	210	87	3	513	888	123
	FA49%NS1%	150	147	3	513	888	123



Figure 3. Casting of specimens.



Figure 4. Compressive strength test.

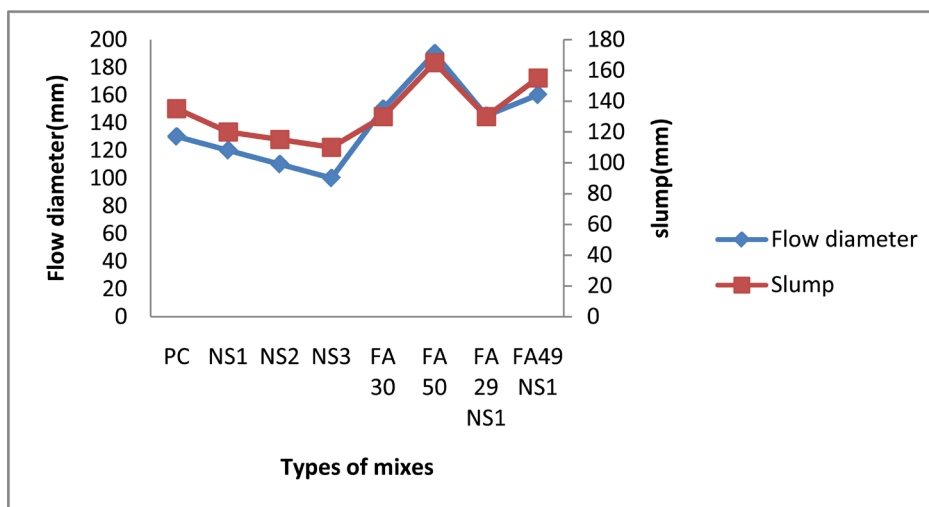


Figure 5. Effect of nano silica fume on workability of concrete.

slightly lower workability than the control cement concrete and the flow values decreases with increase in nano-silica fumes contents as partial replacement of cement. The effect of 1% (by wt.) silica fumes on workability of HVFA concretes can also be shown in Figure 5.

Similar to control concrete, the use of 1% silica fume also reduced the workability of HVFA concrete. For instance, the FA30 yielded a flow diameter of 140 mm while this flow is reduced to 135 when 1% nano-silica fume is used as partial replacement of fly ash (e.g. FA 29NS1 concrete). Similar behavior is observed in FA49NS1 concrete. This can be explained due to high specific surface area of nano-silica fume. This shows that workability of concrete containing HVFA and combined HVFA with nano-silica fumes are also measured to evaluate the effect of nano-silica fume. The high surface area of nano-silica fume can be attributed to the reduced workability of concrete and their HVFA counterparts.

3.2. Effect of Nano-Silica Fume on Compressive Strength of Cement

Figure 6 shows the effect of 1%, 2% & 3% nano-silica fume on 3, 7 & 28 days compressive strength of ordinary concrete.

It can be seen in Figure 7(a) that the concretes containing 1%, 2% & 3% Nano-silica fumes exhibited higher compressive strength at all ages than the ordinary concrete and among the three Nano-silica fume contents the 1% Nano-silica fume exhibited the highest compressive strength at all ages. Therefore 1% Nano-silica fume is used in HVFA concretes to evaluate its synergistic effect with fly ash on the compressive strength development. It can be seen in Figure 7(b), that the 1% Nano-silica fume significantly improved the 3 & 7 days compressive strength of HVFA concrete containing 29% fly ash, where about 47% and 44% improvement is observed respectively. At 28, the improvement is even higher (about 87%) for the concrete containing 29% fly ash.

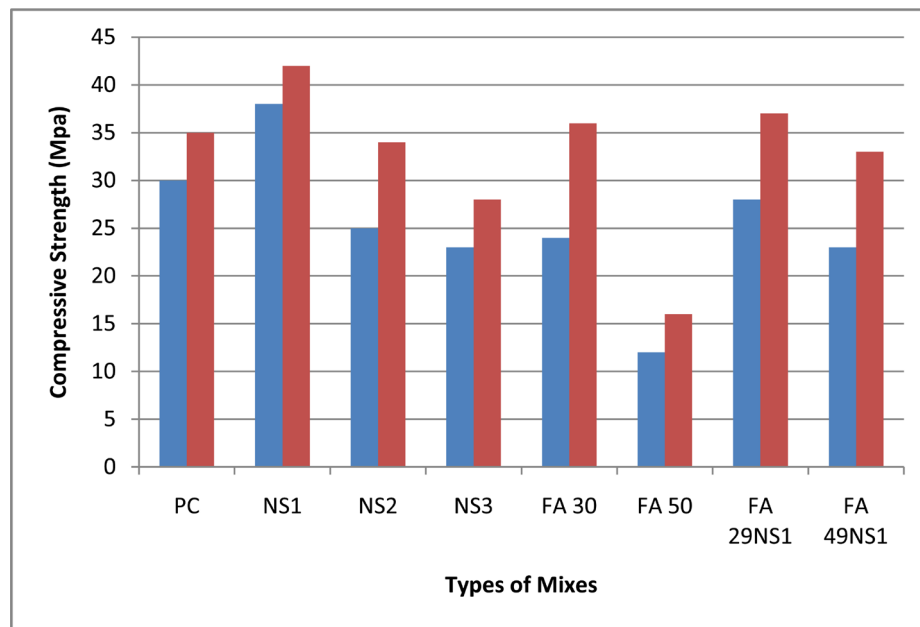


Figure 6. Effect of nano-silica fume on compressive strength of concrete & high volume fly ash concrete (7 days, 28 days).

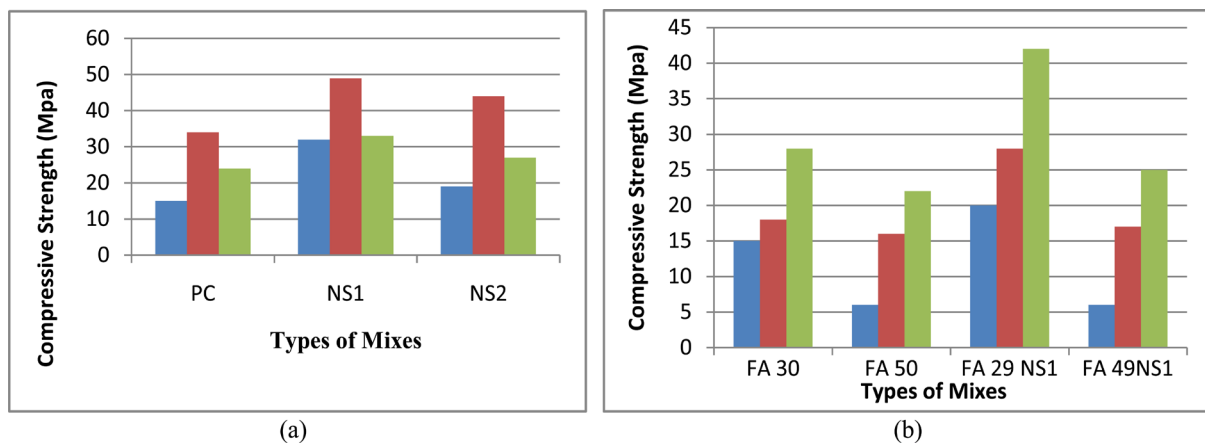


Figure 7. (a) Concretes containing nano-silica fume (3 days, 7 days, 28 days); (b) HVFA concrete containing silica fume (3 days, 7 days, 28 days).

4. Conclusions

Based on workability 3, 7 & 28 days compressive strength results on the effect of nano-silica fume in high volume fly ash concrete, the following conclusions can be drawn.

- 1) Nano-silica fume slightly reduced the workability of both ordinary & HVFA concretes.
- 2) Concrete containing 1% Nano-silica fume as partial replacement of cement exhibited about 140% improvement of early age compressive strength (e.g. at 3 & 7 days) as compared to control concrete. At 28 days, the improvement was 62%.
- 3) The addition of 1% Nano-silica fume increased the compressive strength at early ages (e.g. 3 & 7 days) of HVFA concrete containing [28].
- 4) 1% fly ash by about 44% - 46%. At 28 days, the improvement was about 53%.
- 5) The compressive strengths of FA29 NS1 concrete at all ages exceeded the ordinary Portland cement concrete.
- 6) This shows that sustainable concrete with 40% less cement can be produced by adding 1% nano-silica fume.

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