Effect of Silica Fume & Steel Slag on Nano-silica based High-Performance Concrete

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Abstract. This study presents strength behaviour of concrete based composites including three different ternary binders namely Nano-Silica (NS), Silica Fume (SF) & Steel Slag (SS). NS as fragmental substitution of cement, SF as the fragmental substitution for the fine aggregates and SS as fragmental substitution of coarse aggregates has been used. The study has been conducted at an optimized content of NS (2%) and by varying the content of SF (10-15%) and SS (10-30%). Cement concrete having M60 grade strength at fixed W/C (0.35) has been explored for the strength behaviour. The studies have revealed that the optimized content of NS, SF and SS can be used as a partial substitute of cement, fine aggregates and coarse aggregates respectively to obtain increased strength. Thus, NS, SF and SS can be used to obtain high performance and eco-friendly concrete structures.

Keywords: Steel Slag, Silica Fume, Nano silica, Concrete, Compressive Strength.

1. Introduction

India is a country, which is interested in leading the world in globalization, and therefore the country should continuously develop itself especially by enhancing industrialization and innovative construction technology. The growing concern over detrimental environmental impact of construction industry in terms of responsive carbon dioxide emissions as well as durability concerns of structures, researchers are looking after innovative solutions [1]. Over time, high-performance concrete (HPC) has been developed and undergone many ameliorations for improvements. The concrete with strength more than M55 grade is commonly known as high strength concrete [2]. The use of HPC is increasing day by day because of its excellent structure performance and environmental friendliness with lesser impact on energy utilization [3]. HPC can withstand the impact of high temperature and maintain its toughness and strength due to presence of strength modifiers [4]. Supplementary cementitious materials (SCMs), namely silica fume (SF) [5], nano silica (NS) [6], ground granulated blast furnace slag (GGBS) [7], steel slag (SS) [8] and fly ash (FA) [9] are the essential substances which are used for fabrication of HPC. When such ingredients are used as additives for HPC, the strength and bending characteristics of concrete are enhanced [10]. Especially, the SCMs such as pozzolans including FA, SF
and NS are highly desirable as these materials enhance the strength of the concrete by propagating the formation of additional calcium silicate hydrate (CSH) gel, the prime factor for strength enhancement [11]. With reference to worldwide concern over sustainability, the due utilization of industrial waste is highly desirable [12]. Researchers are working continuously on the performance of high strength concrete using mineral admixtures/industrial waste in place of regular main/natural ingredients [13]. The best possible route could be the utilization of such waste and conversion into a usable product that can be reused as raw materials or as strength modifying materials [12]. Ecologically sustainable HPC has been obtained by using recycled concrete aggregates in presence of fly ash and has been observed to exhibit high strength and durability in reinforced structures [14]. It has been reported that when cement is partially replaced with strength enhancers, the improved strength properties have been observed [15].

Steel slag is a by-product of steel industry that is obtained as a molten liquid when iron is converted into steel or by melting steel in an electric arc furnace [16]. The molten liquid, which is a complex silicate and oxide solution solidifies and turns into a steel slag after the cooling process. Steel slag is a non-metallic product made up of calcium and ferrite that is mixed with iron, aluminium, magnesium, calcium, magnesium oxide and is merged among steel in an electric arc or open-hearth furnace with the help of basic oxygen. Use of steel slag has been reported to produce eco-friendly HPC as demonstrated by life cycle analysis and toxicity investigations [8]. Steel slag has been used as a substituent of coarse aggregates at a lower water/cement ratio ranging in between 1.76-2.21 and coarse/fine aggregate ratio as 1.98. An early and significant strength enhancement was recorded for the specimens [17]. Silica fume is a by-product of silicon-based alloy industry and is primarily non-crystalline (amorphous) silicon dioxide (usually over 85%) with particle size < 1 μm in diameter [18]. Its particles are 100 times finer than the average cement particles. Silica fume is used in between 5-15% by the weight of the cement or fine aggregates. It is used in places where concrete with high impermeability, durability and high strength is required [19]. Incorporation of SF in concrete at a varying range of 5-25% has been observed to significantly enhance the strength aspects of concrete and best results were obtained at 10% content of SF [5]. Nano-silica is mainly used as a pozzolanic and antibleeding agent in HPC and SCC concrete. Its incorporation makes concrete more cohesive and the segregation tendency is reduced. According to literature, the addition of colloidal nano-silica (0.5-2% by weight of cement) in concrete and mortar will ultimately enhance the strength [20]. Similarly, the use of colloidal nano-silica at a range of 0.5-2.0% in HPC concrete was found to impart accelerated hydration, and improved chloride ion resistance at low water/binder ratio [21]. A remarkable decreased chloride permeability was attributed to the increased compactness of the interfacial transition zone [22].

The introduction of binary pozzolanic systems at optimized content has been found to impart better results ascribed to the enhanced pozzolanic reaction [23]. Hence, a combination of three SCMs, namely NS, SF and SS to partially substitute the binders in HPC can produce better results. With this consideration, the main objective of this study is partial replacement of cement as well as fine and coarse aggregates by NS, SF and SS respectively to develop high strength and ecologically sustainable concrete. The compressive strength, split tensile strength, and flexural strength has been investigated. The research provides a systematic scientific analysis utilizing admixtures and analyzing their effects.

2. Materials and Methods

This examination was carried out using Ordinary Portland Cement (OPC) 43 grade (Ultra Tech Cement) from a solitary batch. NS, SF and SS as well as the fine and coarse aggregates were procured from the
local suppliers. The physical properties and chemical composition of the components has been listed in Table 1 and Table 2 respectively. Steel Slag and Silica Fume are similar in size to coarse and fine aggregates respectively making the concrete mixture to be operational or workable. However, the use of Steel Slag and Silica Fume may negatively impact the workability of the concrete combination, and consequently, water-reducing admixtures were mixed. The mix composition has been listed in Table 3 for the seven mix specimens at water/binder ratio of 0.35 and in presence of superplasticizer. The specimens were prepared as control specimen with only 2% NS (C0), specimen with 2% NS and 10% SF with incorporation of 10% SS (M1), 20% SS (M2), 30% SS (M3) and specimen with 2% NS and 15% SF with incorporation of 10% SS (M4), 20% SS (M5), 30% SS (M6). The strength analysis including compressive strength, flexural strength, and split tensile strength was carried out at 7, 28 and 56 days [15].

### Table 1. Physical Properties of Components

| Aggregate Type | Bulk Density (kg/m³) | Fineness modulus | Specific gravity |
|----------------|----------------------|------------------|-----------------|
| NS             | <100                 | -                | 1.25            |
| SS             | 1620                 | 5.43             | 2.90            |
| SF             | 1465                 | 2.36             | 2.22            |
| Fine aggregates| 1615                 | 2.83             | 2.55            |
| Coarse aggregates| 1527               | 5.52             | 2.74            |

### Table 2. Chemical Composition of Binder Materials

| Oxides | % by mass | OPC | % by mass | NS | % by mass | SF | % by mass | SS | % by mass |
|--------|-----------|-----|-----------|----|-----------|----|-----------|----|-----------|
| SiO₂   | 19.46     | 99.9| 98        | 26.4|
| Al₂O₃  | 4.22      | -   | 0.03      | 4.84|
| Fe₂O₃  | 3.56      | -   | 0.02      | 43.4|
| CaO    | 65.92     | -   | 0.3       | 16.9|
| MgO    | 1.08      | -   | 0.2       | 1.86|
| K₂O    | 0.67      | -   | 0.3       | 0.11|
| Na₂O   | 0.21      | -   | 0.3       | 0.15|
| TiO₂   | 0.24      | -   | -         | 0.22|
| SO₃    | 2.6       | -   | -         | 2.58|

### Table 3. Mix proportion of Binders per m³

| Designation | Cement (g) | NS (g) | SF (g) | SS (g) |
|-------------|------------|--------|--------|--------|
| C0          | 1000       | 20     | -      | -      |
| M1          | 980        | 20     | 100    | 100    |
| M2          | 980        | 20     | 100    | 200    |
| M3          | 980        | 20     | 100    | 300    |
| M4          | 980        | 20     | 150    | 100    |
| M5          | 980        | 20     | 150    | 200    |
| M6          | 980        | 20     | 150    | 300    |

3. Results and Discussions
3.1. Compressive Strength

Concrete compressive strengths of specimens C0, M1, M2, M3, M4, M5 and M6 at 7, 28, and 56 days has been illustrated in fig.1. All the ternary specimens were found to exhibit higher strength as compared to the control specimen. The increased compressive strength on substituting the fine aggregates with SF and coarse aggregates with SS is due to the densification of the structure of the matrix because of the accelerated pozzolanic action [4]. The fine silica particles of SF occupy the pores in the concrete matrix and also react with calcium hydroxide to generate additional CSH gel. Likewise, the calcium oxide and silica particles in steel slag are strength enhancing in nature and improve the strength. Further, there is a decrease in fine aggregates and coarse aggregates content, in turn increasing the content of SCMs. This leads to better binding between the binder materials with reduced porosity of the matrix. The synergistic effect of SF in presence of SS provide better results as compared to C0 [16].

Concrete Mixture M2 with 2.0% NS, 10% SF and 20% SS was found to exhibit the maximum compressive strength at all the studied ages. Increasing the amounts of SS from 10% to 20% at constant SF content was found to increase the compressive strength. However, further increase of SS content to 30% at constant SF content was found to result in a comparative decrease in the strength. The percent increase in compressive strength as compared to C0 was observed as 3.0%, 10% and 6.0% at 28 days for M1, M2 and M3 specimens. On the other hand, the percent increase in compressive strength for M4, M5 and M6 specimens at 28 days was observed as 2.0%, 6.0% and 3.0% respectively as compared to C0. The slight reduction in strength at increasing content of SS and SF is possibly due to increase in friction among the particles.

![Figure 1. Compressive Strength of Specimens](image)

3.2. Split Tensile Strength

Splitting tensile strength of the concrete specimens was measured at 7, 28 and 56 days and the results have been illustrated in fig.2. Splitting tensile strength of C0 was observed as 4.10 MPa on 7 days, 5.36 MPa on 28 days and 6.13 MPa on 56 days. With the presence of Silica Fume & Steel Slag at all ages, the splitting tensile strength was found to increase as compared to C0. The behavior was similar
to compressive strength results with presence of SF and SS. The percent increase in split tensile strength as compared to C0 was observed as 6.0%, 13% and 9.0% at 28 days for M1, M2 and M3 specimens. On the other hand, the percent increase in split tensile strength for M4, M5 and M6 specimens at 28 days was observed as 5.0%, 9.0% and 6.0% respectively as compared to C0. The slight decrease in strength was attributed to the loss of binding at higher concentration of SF and SS due to increased repulsive forces between the finer particles [10]. However, the results were significantly improved as compared to C0 indicating the suitability of SF as a partial substitute of fine aggregates and SS as a partial substitute of coarse aggregates.

3.3. Flexural Strength

Flexural strength of the concrete specimens was measured at 7, 28 and 56 days and the results have been illustrated in fig.3. Flexural strength of C0 was observed as 7.26 MPa on 7 days, 7.91 MPa on 28 days and 8.23 MPa on 56 days. The flexural strength of all specimens were found to increase with presence of SF and SS as compared to C0. The percent increase in flexural strength as compared to C0 was observed as 5.0%, 8.0% and 7.0% at 28 days for M1, M2 and M3 specimens. On the other hand, the percent increase in flexural strength for M4, M5 and M6 specimens at 28 days was observed as 6.0%, 7.0% and 5.0% respectively as compared to C0. The substitution of fine aggregates with SF upto 10% in presence of 2.0% NS and 20% SS as a partial substitute of coarse aggregates was found to exhibit the maximum flexural strength at all the studied ages. The increase in SF and SS content beyond this content was found to cause slight decrease in strength. The amount of air voids in the matrix is one of the crucial elements of the concrete mixture [5]. Air voids help water to drain into pores, reducing high internal stress and structural micro cracking. As the air voids are occupied at higher content of steel slag and silica fume, the decreased availability of water may decrease the hydration reaction causing negative impact on the concrete strength [22].
Figure 3. Flexural Strength of Specimens

4. Conclusion

The goal of this research was to study the strength behaviour of high-performance concrete, by replacing the coarse aggregates and fine aggregates by two industrial waste products namely silica fume (SF) and steel slag (SS). Enhanced compressive strength, flexural strength and split tensile strength was observed for these specimens indicating their effectiveness as a partial substitute in the concrete mixes. Hence, the use of SS and SF as a partial substituent of natural aggregates not only reduces the environmental impact of these wastes, but also reduces the global carbon dioxide emission. The findings showed that the strength characteristics of high-performance concrete by using these industrial wastes exhibit significant results up to 10% SF and 20% SS, as compared to conventional concrete with no negative impact on workability in presence of superplasticizer. Thus, an optimized use of SS and SF in presence of NS can significantly improve the strength aspects of concrete structures as well as help in sustainable construction practices.

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