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# Investigation on Flexural Behavior of HFRC with Partial Replacement of Nano Silica and Slag Cement

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## ABSTRACT

This investigation directs to understand the flexural behavior of Hybrid Fiber Reinforced Concrete (HFRC) with incorporation of Nano silica and Portland slag cement. The mechanical properties of Concrete for the grade M50 is enhanced by combining different fibers such as glass, polypropylene, and steel. Specifically, we explore the replacement of these fibers for the cement at ratios of 2%, 3%, 4%, 5% and 6%. Findings indicate that it significantly improved flexibility, as well as micromechanical support. To assess the performance of the HFRC, Specimens are cast to undergo compression, Flexure and Spilt tensile using hybrid materials with a water-cement ratio of 0.40 and made to undergo normal water curing for a period of 7, 14, and 28 days. Our comprehensive analysis reveals that the inclusion of 5% fibers along with 5% of Nano silica as a partial replacement to fine aggregate exhibits superior ductility and flexural strength compared to other fiber ratios. The addition of latex admixture enhances the flexural strength of HFRC. Comparing the flexural behavior of HFRC to conventional concrete under applied loads the remarkable load-bearing capabilities of HFRC beams under flexural conditions are highlighted furthermore emphasizing the advantages of this innovative material for use in construction applications. The results were tabulated and comparative results were presented.

**Keywords**: Hybrid Fiber-reinforced concrete; Glass fiber; Steel fiber; Nano silicon; Slag cement; Polypropylene fiber.

## 1. INTRODUCTION

One of the most widely used construction materials is concrete which has seen numerous innovations and advancements over the years to enhance its performance, sustainability, and economic viability. A key area of focus in this ongoing quest for improvement is the substitution of traditional raw materials with alternative materials that not only reduce the environmental impact but also maintain or enhance the mechanical properties of concrete. The partial replacement of nanosilica with HFRC and use of slag cement in concrete mixtures represents an intriguing avenue for exploration, particularly in terms of its influence on the flexural behavior of concrete.

The concept of using alternative materials in concrete is not new. Over the years, researchers and engineers have investigated various substitution for cementitious materials (SCMs), such as fly ash, silica fume, and slag. To maintain sustainability and flexural strength various fibers like steel fiber, polypropylene fiber were incorporated in within the concrete (Kara *et al.* 2015; Chalioris *et al.* 2019; Kumar *et al.* 2022). Nano silica is extremely reactive pozzolanic material used in concrete. The Nano silica particles are considered to be extremely small in a scale of 1 to 100 nanometers in diameter. These particles as smaller in size that allows to enhance its reactivity with cement during hydration process. Nanosilica reacts with $Ca(OH)_2$, a byproduct of cement hydration, to form additional calcium silicate hydrate (C-S-H) gel, which is the initial bonding phase in concrete (Abhilash *et al.* 2021). This pozzolanic reaction contributes to increased strength and durability. Nano-silica can improve the resistance of concrete to numerous degradation mechanisms, such as sulfate attack, alkali-silica reaction (ASR), and chloride penetration, due to its pozzolanic reactivity and densification of the microstructure (Bheel *et al.* 2024).

Slag cement, on the other hand, is a byproduct of the iron and steel industry and has been used as a substitution for cementitious material in concrete for some decades. Its utilization not only mitigates the disposal problem of steel slag but also offers benefits in terms of improved workability, durability, and sustainability of concrete (Becknell *et al.* 2011). When combined with other cementitious materials, such as Portland cement, slag cement can enhance the

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mechanical properties and enduring performance of concrete.

## 2. MATERIALS USED

The materials used for making HFRC concrete specimens include cement, coarse aggregate, fine aggregate, glass fiber, polypropylene fiber, steel fiber, and water.

### 2.1. Cement

Portland slag cement is a type of chemical binder used in construction to aid in the setting, hardening, and adherence of various materials. It is not typically used alone, but rather as a binding agent to combine sand and gravel aggregates. When mixed with fine aggregate, it produces mortar for masonry, while its combination with sand and gravel results in concrete. Which is the most commonly used as building materials and is second only to water as the most consumed resource on Earth. In the realm of engineered cementitious composites, a higher slag content is recognized for its importance in cement materials. The specific gravity of cement is in this case is 2.88, indicating a relatively dense material (Banthia *et al.* 2007). Additionally, the setting time of the concrete exhibits an initial setting period of 33 minutes and a final setting time of 544 minutes (9 hours and 4 minutes). The specific gravity of cement in this case is 3.13, indicating a relatively dense material.

### 2.2. Fine Aggregate

Fine aggregate is made up of mineral grains that result from the weathering and disintegration of rocks. For this particular study, high-silica-content Nano silica with 150-micron-sized particles was used. Fine aggregate is different from clays since it is devoid of organic elements, and it varies from gravel solely in particle size. Usually, fine aggregates are obtained by segregating and separating them from organic matter through the action of water currents or winds, which typically results in a uniform grain size. Much of the Earth's surface is covered in sandy regions, with sands primarily composed of quartz and other siliceous materials. The sand is used for various purposes, such as in concrete production, as an abrasive material in polishing and sandblasting, and in foundries to create molds when it contains a small amount of clay. Clear sands are used for water filtration. Construction sand is usually procured locally, and its quality can vary according to regional supply. The specific gravity of cement in this case is 2.64, indicating a relatively dense material.

### 2.3. Coarse Aggregate

Crushed stone that has been economically mined, crushed, and graded makes up coarse aggregates, an essential part of the concrete-making process. The three most often utilized crushed stone kinds are trap rock, limestone, and granite. In addition, a number of fine-grained, dark-colored igneous rocks, including diorite, gabbro, and basalt, are referred to as "trap rocks." Parts of graded crushed stone usually have sharp edges and are made of a single type of rock. These stones usually have a size between 0.9 and 1 inch (20 and 25 mm), while bigger sizes might be utilized as substantial concrete aggregates. The coarse aggregate utilized in this investigation was machine-crushed, annular-shaped granite with a specified size of 20 mm and 25mm. The specific gravity of Course aggregate in this study is 2.67.

### 2.4. Glass Fiber

These fibers, made of virgin polypropylene, are available in different lengths and have a melting point of 162 °C. With a specific gravity of 0.91, they are resistant to ignition up to 360 °C. They have low thermal and electrical conductivity and are highly resistant to alkalis, acids, and salts (Kene *et al.* 2012). Their diameter ranges from 19 to 40 microns, and their aspect ratio varies between 215 and 1250. These fibers are well-suited with all concrete admixtures and reflects enhancement in the building materials. The specifications for shop glass fibers for building applications are as follows: Material: Virgin Polypropylene (PP) shown in Fig. 1. Length: Available in 6, 12-, 24-, 36-, and 50-inches Melting Point: 162 °C Ignition Point: 360 °C Specific Gravity is obtained as 0.91. Electrical conductivity and thermal conductivity are low. High Resistance to alkali, salt and acid is observed whereas it is noted that the fiber is 100% alkali proof. Has a high diameter of 19 to 40 microns with respect to aspect ratio approximately varying from 215 and 1250 (Chasioti *et al.* 2017). Fibers improve the performance of construction materials and work well with all concrete admixtures.

**Fig. 1: Glass fiber**

### 2.5. Polypropylene Fiber

Polyvinyl alcohol (PVA) fibers are synthetic fibers which is shown in Fig. 2 typically used in concrete. Synthetic fibers, like PVA, have the following primary characteristics: They improve the performance of concrete, they are more durable than other types of fibers, and they strengthen hardened concrete. For semi-hardened concrete, synthetic fibers are used to manage and control cracks (Kara *et al.* 2015). Additionally, they are resistant to expansion in high-temperature conditions and contraction in low-temperature scenarios, effectively preventing cracking under such circumstances. Synthetic fibers are widely used in many industries. Some of the most common synthetic fibers include carbon, nylon, polyester, polypropylene, and polyethylene. These fibers have a larger diameter, approximately ranging from 25 to 40 microns, and exhibit an aspect ratio of approximately 215 to 1250.

**Fig. 2: Polypropylene fiber**

**Table 1. Mix proportion**

| Mix ratio | Glass fibre (%) | Polypropylene fibre (%) | Steel fibre (%) | Nano silica (%) |
|---|---|---|---|---|
| **M0** | - | - | - | - |
| **M1** | 5% | 2% | 5% | 5% |
| **M2** | 5% | 3% | 5% | 5% |
| **M3** | 5% | 4% | 5% | 5% |
| **M4** | 5% | 5% | 5% | 5% |
| **M5** | 5% | 6% | 5% | 5% |

### 2.6. Steel Fiber

Steel fibers are typically made of cold-drawn wire or cut from steel sheets. These fibers are shown in Fig. 3. They can have different cross-sectional shapes, such as straight, hooked, crimped, or twisted, to improve their anchorage and bonding with the concrete matrix (Hilles, M.M. and Ziara, M.M 2019). The aspect ratio (length-to-diameter ratio) of steel fibers typically ranges from 20 to 100, with common values between 50 and 80. Steel fibers have lengths ranging from 6 mm (0.24 in) to 60 mm (2.36 in), with typical lengths between 12 mm (0.47 in) and 50 mm (1.97 in). The diameter of steel fibers commonly ranges from 0.15 mm (0.006 in) to 1.0 mm (0.04 in). A typical size ratio for steel fibers ranges from 0.2 to 0.6, with higher values indicating a greater surface area for bonding.

### 2.7. Nano Silica

Nano Silica is highly pozzolanic materials. Nano silica are the particles refers to silica particles having an average particle size ranging from 1 nm to about 100 nm. Due to their extremely small particle size, Nano-silica particles have greater specific surface area, typically ranging from 50 to 600 m²/g. The specific gravity of Nano-silica is 2.33. It also has a bulk density of 2190 kg/m$^3$, a fineness of 638 m$^2$/g.

**Fig. 3: Steel fiber**

### 2.8. Nominal mix design for HFRC

As there is no specific mix design available for HFRC, our research required the formulation of various mixes with different components, including fibers, fine aggregate, and super plasticizer. Mix design were designed in accordance with IS 10262-2009 standards to arrive at an M50-grade concrete mix. In which Nano silica is partially replaced with fine aggregate and various fibers were added to the mix which is represented in the below Table 1. The goal is to produce concrete with a maximum required strength and durability.

## 3. EXPERIMENTAL WORK

### 3.1. Mix Procedure

The process of mixing plays an important role in concrete preparation, especially when dealing with Engineered Cementitious Composite (ECC). It is essential to ensure thorough mixing before casting due to the presence of coarse aggregates. The interaction between fibers and other cementitious materials depends on several constituents within the concrete mix. Since bendable concrete varies from regular concrete, a meticulous mixing sequence is crucial to achieving a workable mix. To achieve a well-rounded mixture, initially dry mix was carried out then the dry ingredients were combined with water and superplasticizer based on requirements and stirred further. The hybrid fibers were then added according to the mix proportion that was designed (Glavind *et al.* 1990).

### 3.2. Compressive Strength of Standard Cubes

In this study, concrete mixes were designed and cast based on various mix proportions incorporating hybrid fibers and nano-silica as partial replacements. The typical size of the concrete cube specimens is said to be 0.15 m x 0.15 m x 0.15 m. Upon completion of 28-day curing process, the specimens were subjected to compression testing to evaluate their compressive strength characteristics (Glavind *et al.* 1990; Almusallam *et al.* 2016). This testing procedure was performed to determine the optimum ratio of HFRC with partial replacement of nanosilica. After conducting compression tests on all six sample mixes, it was recorded that the M4 mix proportion, comprising 5% hybrid fibers and 5% nano-silica, exhibited superior compressive strength performance compared to the other mixes.

### 3.3. Split Tensile Strength Test

Following a similar procedure as with the standard cube specimens, cylindrical specimens were also cast and cured. After the completion of the 28-day curing process, these cylindrical specimens were subjected to split tensile strength testing. This test was carried out on six different sets of specimens, each representing a unique mix proportion incorporating hybrid fibers and nanosilica as partial replacements. Upon testing all six sets of specimens, it was observed that the M4 mix proportion exhibited superior split-tensile strength performance when compared to the other mix proportions investigated. This finding suggests that the M4 mix design could be an optimal choice for applications requiring enhanced split tensile strength in HFRC with partial replacement of nano silica.

**Table 2. Stress vs strain**

| Specimen | % hybrid fibers | Peak load in (mPa) | Maximum displacement (mm) |
|---|---|---|---|
| Prism 1 | 2% | 4.96 | 6.3 |
| Prism 2 | 3% | 5.62 | 6.9 |
| Prism 3 | 4% | 6.14 | 7.8 |
| Prism 4 | 5% | 7.37 | 8.1 |
| Prism 5 | 6% | 6.84 | 7.2 |

### 3.4. Modulus of Elasticity on Concrete Cylinder

Concrete's Modulus of Elasticity measures how stress is distributed within the material in relation to the strain it undergoes. To determine this value accurately, a compression test is performed on a cylindrical concrete specimen in a laboratory. During this test, the deformation of the specimen is analyzed under various loads, generating a Stress-Strain graph (also known as a load-deflection graph) as shown in Fig. 4 (Banthia *et al.* 2007; Banthia *et al.* 2014). The Stress-Strain graph shown in the Table 2 is then used to calculate the Modulus of Elasticity of the concrete.

The Modulus of Elasticity is determined by finding the slope of a line drawn on the stress-strain curve, starting from zero stress and extending to the maximum compression stress of 0.45f'c (representing the working stress) (Soroushian *et al.* 1998). This value delivers a precise measurement of the Modulus of Elasticity for concrete.

### 3.5. Flexural Strength of Prism

The extreme fiber stresses in a beam under flexural load are measured by the modulus of rupture. This holds true for scenarios with both balanced two-point loading and one-point loading. Tensile stresses are applied to the lower part of a simply supported beam during bending. At the point of maximum bending, cracks start to form if the beam's flexural strength is exceeded. The crack is caused by the load applied. The following, Table 3 shows the various values for Stress-Strain for respective loading condition.

**Table 3. Maximum displacement**

| Load | Gauge reading | Stress | Strain |
|---|---|---|---|
| 0 | 0 | 0 | 0 |
| 10 | 0.16 | 0.00063 | 0.000202 |
| 20 | 0.29 | 0.00126 | 0.000505 |
| 30 | 0.043 | 0.00189 | 0.000731 |
| 40 | 0.049 | 0.00252 | 0.000933 |
| 50 | 0.07 | 0.00315 | 0.00109 |
| 60 | 0.081 | 0.00378 | 0.001286 |
| 70 | 0.096 | 0.00441 | 0.001438 |
| 80 | 0.112 | 0.00503 | 0.001614 |
| 90 | 0.122 | 0.00566 | 0.001776 |
| 100 | 0.139 | 0.00629 | 0.001942 |
| 110 | 0.151 | 0.00693 | 0.002099 |
| 120 | 0.164 | 0.00755 | 0.00228 |
| 130 | 0.192 | 0.00828 | 0.002421 |
| 140 | 0.202 | 0.00881 | 0.002626 |
| 150 | 0.217 | 0.00944 | 0.002885 |
| 160 | 0.229 | 0.01007 | 0.002991 |
| 170 | 0.246 | 0.011 | 0.003202 |
| 180 | 0.262 | 0.01274 | 0.003456 |
| 190 | 0.288 | 0.01388 | 0.003697 |
| 200 | 0.289 | 0.01456 | 0.003883 |

The study on flexural behaviour of the optimum mix design M4, the cracking is absorbed along with their deflection and the crack pattern is determined using the records and depicted in Fig. 5.

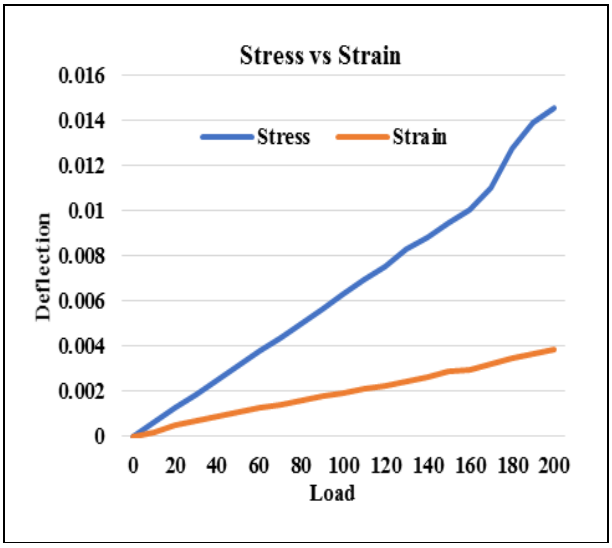

Fig. 4: Modulus of elasticity

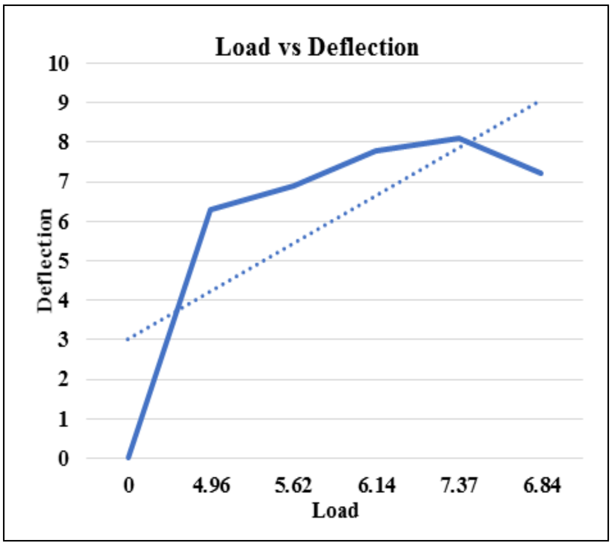

Fig. 5: Maximum displacement

Fig. 6: Reinforcement

Fig. 7: Casting of beams

## 3.6. Casting of Beam and Testing

Based on the findings from above listed mechanical testing i.e., the compression, split tensile, and flexural tests, the optimum mix proportion was determined to be the M4 mix, which contained 5% hybrid fibers and 5% Nano-silica. The reinforcement and the casting of beam for the optimum mix proportion of M4 is shown in Fig. 6 and Fig. 7 respectively. This mix exhibited superior performance in terms of mechanical testing. To further investigate the flexural behavior of this optimized mix, six beam specimens were cast using the M4 mix proportion. These beams had dimensions of 1.2 meters in length, 200 mm in width, and 150 mm in depth. After casting, the beams were subjected to a 28-day curing period. Upon completion of the curing process, the beam specimens were tested under two-point loading conditions, with the supports configured as hinged supports. The experimental setup included load and deflection indicators strategically positioned to measure the applied load and the corresponding deflection at the mid-span of the beam. During the testing, the beams were gradually loaded until failure occurred. The maximum load-carrying capacity of the HFRC beams was recorded using the load indicator. Simultaneously, the deflection indicator at the mid-span of the beam monitored and recorded the corresponding deflection values for each incremental load applied. Through this comprehensive experimental investigation, the flexural performance of the optimized HFRC mix (M4) was thoroughly evaluated. The ultimate load-carrying capacity and the equivalent deflection behavior were determined, providing valuable insights into the flexural strength and deformation characteristics of HFRC beams incorporating hybrid fibers and Nano-silica.

**Fig. 8: Testing of Beam**

## 4. RESULT AND DISCUSSIONS

From these experimental investigations, beam specimens were subjected to two-point loading conditions as are shown in Fig. 8. The loading was applied gradually, and for every 10 kN increment in the applied load, the corresponding deflection of the beam was recorded using a LVDT. The LVDT is a highly accurate sensor used to measure linear displacements or deflections in structural elements. It was strategically positioned at the midspan of the beam to capture the vertical deflection as the load was incrementally increased. As the load was applied in 10 kN increments, the corresponding deflection values were recorded by the LVDT. This process continued until the beam reached its ultimate load-carrying capacity or until a predetermined deflection limit was reached. The recorded data, consisting of the applied load and the corresponding deflection values, were tabulated and graphed in Table. 4 and Fig. 9 for further analysis.

**Table 4. Load and Displacement**

| Load (kN) | Deflection (mm) (L/2) | Deflection(mm) |
|---|---|---|
| 0 | 0 | 0 |
| 10 | 0.41 | 1.33 |
| 20 | 0.67 | 2.25 |
| 30 | 1.22 | 4.37 |
| 40 | 2.77 | 6.64 |
| 50 | 3.37 | 9.79 |
| 60 | 5.18 | 11.82 |
| 70 | 6.97 | 13.19 |
| 80 | 7.68 | 14.73 |
| 90 | 9.56 | 15.56 |
| 100 | 11.94 | 17.95 |
| 110 | 12.62 | 18.14 |

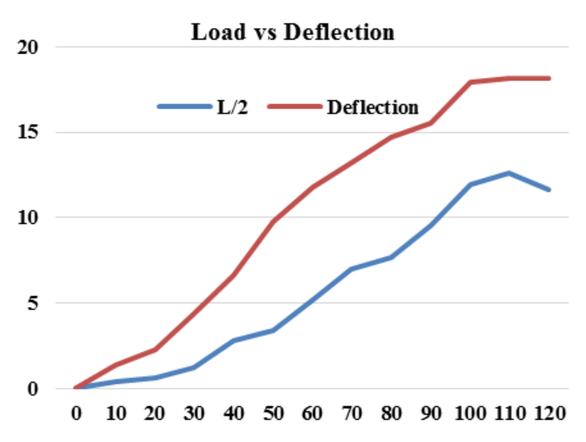

**Fig. 9: Load vs Displacement**

## 5. CONCLUSION

Based on the trial examination, it was found that increasing the volume of filaments from 2% to 6% of Polypropylene fiber with a constant replacement of Glass and Steel Fiber as 5% to that of cement and constant replacement of 5% of Nano silica resulted in an increase in the flexural strength of HFRC. The HFRC with a 5% fiber volume ratio had the best outcome in terms of flexural strength. 5% replacement of fiber volume in M50 bendable concrete observed greater compressive strength when compared with 3% and 4% replacement of fibers, whereas the compressive strength obtained is 17% less than the normal concrete. It achieved more flexural strength than 75% of regular substantial, and the modulus of the elasticity of chamber pressure strain had a value 5% greater than normal concrete. The HFRC substantial had minimal functionality and was harder than ordinary cement, thanks to the hybrid strands and the use of latex admixture. This resulted in more flexural strength and holding strength between cement and silica sand. However, the Nano silica had less holding power than normal sand or M sand. The HFR concrete achieved the highest flexural strength with partially replaced concrete with Nano silica and having 5% fiber volume.

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## CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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