Experimental study on steel fiber reinforced concrete modified with egg shell powder and nano silica

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Abstract. This work presents the mechanical characteristics of concrete enhanced with egg shell powder (ESP) and nano-silica (NS) along with steel fibres. Steel fibre reinforced concrete (SFRC) offers several benefits, including prevention of macro cracks, improving ductility and residual strength and increasing toughness. These benefits make SFRC a valuable choice for structural applications requiring enhanced durability, crack resistance, and resilience to mechanical stresses. To develop the modified concrete mixture the Ordinary Portland Cement (OPC 53 grade) was partially replaced with varying percentage such as 0%, 5%, 10%, and 15% of ESP and NS by weight of the total binder content. Steel fibers were merged into the concrete at a volume fraction of 1.5% by weight of concrete to boost the engineering characteristics of concrete. The effect of ESP and NS were observed on compressive, flexural and split tensiles trength of the concrete. The test was conducted after 7 and 28days of curing period. The inclusion of 10% and 15% percentage of ESP and NS gives high mechanical properties. The findings validated the suitability and efficacy of employing ESP and NS as partial substitutes for OPC, leading to substantial enhancements in the engineering characteristics of SFRC.

Keywords : Concrete , Steel Fibre, Egg shell powder, Nano silica

1. Introduction

Cement-based materials (CBMs) are in high demand to meet the growing needs of the construction industry. CBMs primarily consist of aggregates, cement, and water. Cement production is energy-intensive and releases substantial amounts of carbon dioxide, a major greenhouse gas. As a result, the production of building materials, particularly CBMs, has a significant impact on the natural environment. The reliance on cement as a key ingredient in construction materials underlines the importance of exploring sustainable alternatives and adopting practices that reduce environmental harm while meeting construction demands. Industrial leftovers and agricultural trash are two types of solid waste materials that can be transformed into cement substitutes, reducing cement consumption and mitigating

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environmental harm from open trash disposal [1]. Eggshells are currently disposed of in landfills worldwide in significant quantities, and by 2030, global egg production is expected to increase by about 90 million tons., it is crucial to explore alternative technologies for converting eggshells into components for other applications. Due to the similar chemical composition of cement, the eggshell powder (ESP) is employed as a fractional alternative for Ordinary Portland Cement (OPC) in concrete [3].

One of the most widely used type of alternative of cement in concrete industry is nano silica (NS). Lately, many types of nano materials are used in concrete (e.g., nano-titanium dioxide, nano-zinc oxide, nano-calcium carbonate, nano-silicon dioxide, and nano clays) upgraded engineering properties of concrete. Nano silica has been investigated extensively and is considered one of the most efficient nano materials, yielding promising outcomes in various applications [6].

Steel fibers are recognized for their significant enhancement of concrete's mechanical properties in contrast to fibers such as carbon, nylon, glass, and polypropylene [7].This improvement is attributed to the strong connection of steel fibres with the cementitious matrix. Moreover, the development of crimped steel fibres has further enhanced bonding strength and effectiveness compared to straight steel fibres. However, the main challenge remains the high initial costs and environmental impact due to the high usage of Ordinary Portland Cement (OPC), especially in Fiber Reinforced Concrete (FRC) with admixtures like steel fibres [8]. One approach to mitigate these challenges is by incorporating globally capable Supplementary Cementitious Materials (SCMs) as partial substitutes for OPC, which can reduce the carbon footprint of concrete production and contribute to sustainable Waste Management Practices [3].

A range of fibres, such as carbon fibre, basalt, nylon, glass, polyvinyl alcohol, polypropylene, fibres are employed in fibre reinforced concrete (FRC). While also the addition of steel fibres in suitable proportion also enhances the impact resistance and reduces the shrinkage in concrete [10].The optimal volume content for achieving superior mechanical properties in SFRC admixtures typically ranges between 0.5% and 2.0% according to prevailing studies [5].It is proved that adding short, discontinuous fibres significantly enhances concrete's mechanical properties by increasing elastic modulus, reducing brittleness, controlling crack formation and growth, and improving toughness and fracture resistance, especially in fibre reinforced concrete (FRC) subjected to cyclic and dynamic loads.

2 Experimental Procedures

2.1 Materials used

2.1.1 Cement

OPC of grade 53 was used in this investigation. Subsequently, Materials underwent laboratory testing to ascertain their consistency, initial setting time, specific gravity, and fineness modulus.

2.1.2 Fine Aggregate & Coarse aggregate

In the study, manufactured sand having a fineness modulus of 3.75 and a specific gravity of 2.46, meeting the Zone 2 grade specifications of IS: 383-2016 used as fine aggregate.

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In this study, coarse aggregate consisting of crushed natural stone with a particle size of 20mm was utilized. Also, the specific gravity of aggregate is 2.62 and fineness modulus is 6.9. The coarse aggregate is used in accordance with IS: 383-2016.

2.1.3 Steel fibre

The steel fibre used for the present study is rounded crimped steel fibre with dimensions of 30mm length, 0.5mm diameter, and 60 aspect ratio.

Fig. 1. Round crimpled steel fibre

2.1.4 Eggshell powder (ESP)

In eggshell powder there are many layers of calcium carbonate is presented. It is the major component required to generate binder mix. Also, the usage of eggshell powder instead of cement is a feasible alternative for creating environmentally friendly concrete [3].

Fig. 2. Eggshell powder

Table 1. Chemical composition of ESP used.

Component %	C	Na_2O	MgO	P_2O_5	SO_3	K_2O	CaO	Fe_2O_3	SrO
Eggshell powder	21.12	0.10	0.92	0.41	0.32	0.05	76.99	0.01	0.03

2.1.5 Nano-silica

Incorporating nano-silica into the cement accelerates hydration rates, resulting in early strength gain, and enhances the thermal stability of the cement matrix [6]

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Fig 3. Nano-silica

Table 2. Chemical composition of NS used in the study

Component %	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O
Nano silica (%)	92.5	7.39	0.08	0.06	0.21	0.02	0.04

2.1.6 Water

Drinking water and quality municipal water was utilized for both combining and curing the concrete specimens.

2.2 Mix Proportion

The concrete mixture was formulated according to the guidelines outlined in IS 10262 – 2009 and IS 456-2000 for normal concrete, with a designated grade of M30 and a water-cement ratio of 0.45.

Table 3. Mix proportion

Grade of concrete	Mix proportion			
	Cement	**Fine aggregate**	**Coarse aggregate**	**water**
M30	1	1.46	2.52	0.45

2.3 Test Specimens

Standard moulds were used to prepare cubes of size 150 mm × 150 mm × 150 mm, cylinders measuring 150 mm diameter × 300 mm height, and prisms of dimension 100 mm × 100 mm × 500 mm. The samples are cast using the four different combinations as, control mixes of SFRC and SFRC with ESP and NS separately. After 24 hours of casting, the samples were removed from the moldand placed in a water tank for a curing period of 28 days. A total of 84 specimens were cast to assess the mechanical properties of the specimen.In this experiment, 7 types of concrete mixtures including one control mix for steel fibre reinforced concrete were made, where the percentage of replacement of cement by the ESP and NS was 5%, 10%, and 15% [1]. From literature survey, previous studies have shown that the optimum dosage of steel fibre was 1.5 % by weight of concrete [1]. So, in this study the volume fraction of steel fibre was fixed at 1.5% [1]. The mix designations are given below in the Table 4.

Table 4. Mix designation with varying percentage of ESP and NS

Type of concrete	Steel fibre (% volume of concrete)	ESP (% weight of cement)	NS (% weight of cement)	Mix designation
Control	1.5%	0%	0%	SFRC
SFRC	1.5%	5%	0%	SFESP1
	1.5%	10%	0%	SFESP2
	1.5%	15%	0%	SFESP3
	1.5%	0%	5%	SFNS1
	1.5%	0%	10%	SFNS2
	1.5%	0%	15%	SFNS3

2.4 Fresh properties

The workability of different mixes was evaluated by measuring the slump value and compacting factor in accordance with IS 1199:1959 specifications. Table 5 and Table 6 shows the values of slump and compacting factor for varieties of concrete mixes.

Table 5. SFRC with varying percentage of ESP

Mix	SFRC	SFESP1	SFESP2	SFESP3
Slump(mm)	100	90	50	30
Compaction factor	0.93	0.88	0.86	0.73

Table 6. SFRC with varying percentage of NS

Mix	SFRC	SFNS1	SFNS2	SFNS3
Slump	100	75	70	40
Compaction factor	0.93	0.85	0.72	0.76

3 Experimental Results

3.1 Hardened Properties

3.1.1. *Compressive strength results*

For each mix of the control sample, SFRC with ESP, SFRC with NS, three cube specimens of size 150mm×150mm were tested according to the I.S specifications, on the 7 and 28days. The values obtained varying of ESP and NS are given in fig 4 and fig 5.

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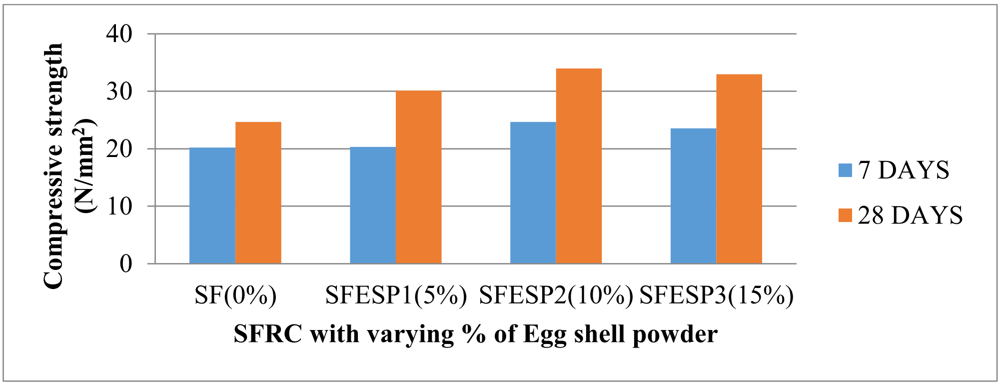

Fig4. 7, 28 days compressive strength of SFRC with varying percentage of ESP

It is evident that adding ESP compressive strength increased up to a marginal amount of 10% and above it will reduce. The negligible enhancement in the compressive strength because of the ESP is caused due to the raised number of calcium from the calcium carbonate of the ESP in the binder's matrix. The presence of calcium oxides in ESP initiates a pozzolanic reaction which causes improvement in the compressive strength at later curing [1]. Similarly, by adding nano-silica compressive strength increased up to 10% and above it will reduce. The increment justified that the high surface area of nano-silica particles improves the pore structure of concrete and reduce the porosity, final improve the compressive strength [7].

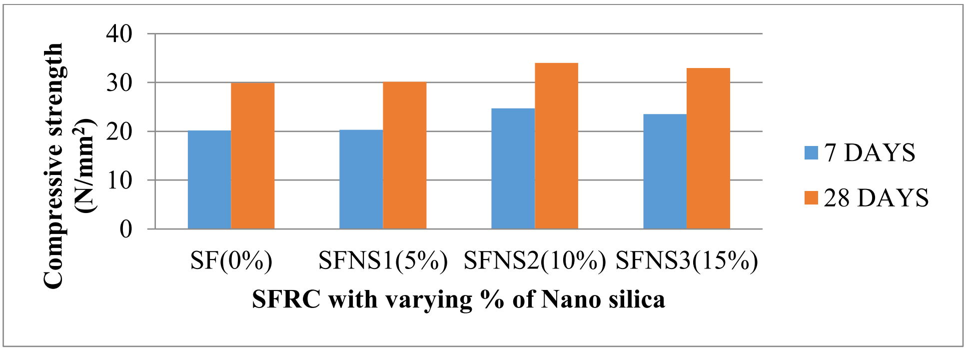

Fig 5 .7, 28 days compressive strength of SFRC withvarying percentage of NS

3.1.2. Splitting tensile strength

This experiment was carried out on cylindrical samples of size 150mm x 300mm to indirectly determine the tensile strength of concrete. The values obtained varying of ESP and NS are given in fig 6 and fig 7. It was examined that the control samples without eggshell powder and nano silica content have less split tensile strength than SFRC with ESP and NS. Also, the splitting tensile strength was maximum at 10 % for eggshell powder and 10% NS.

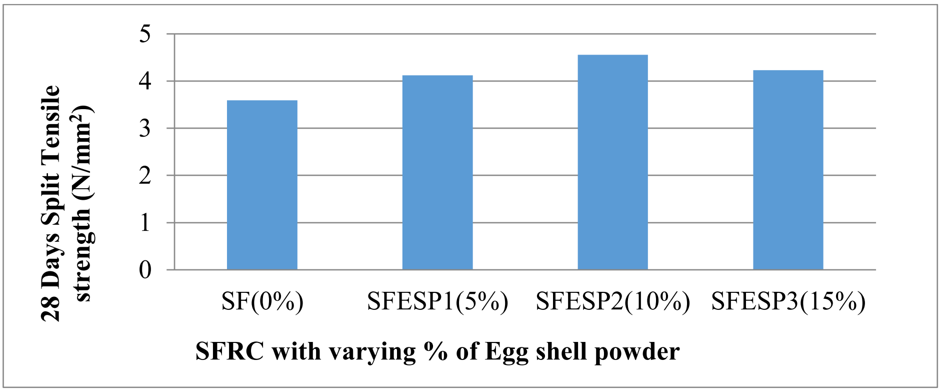

Fig 6. Split Tensile strength of varying percentage of ESP

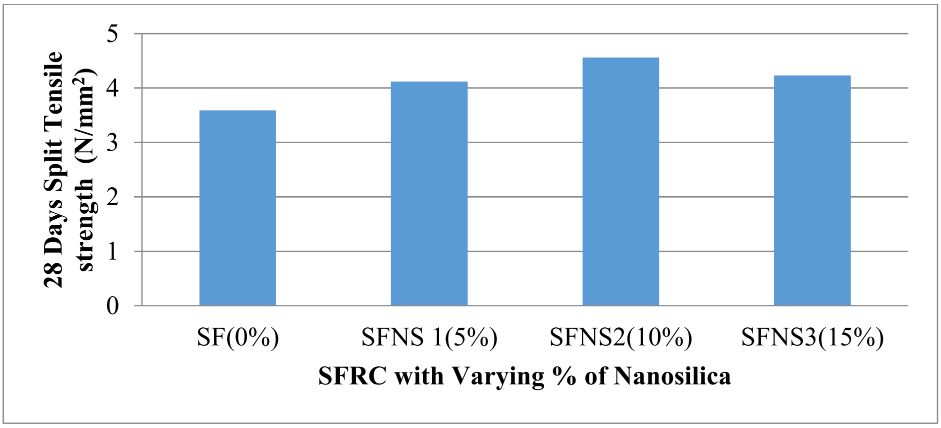

Fig 7. Split Tensile strength of varying percentage of NS

3.1.3.Flexural strength

The flexural strength tests were performed on beam specimens of size 100x100x500 mm as per ASTM C1018. Three specimens were taken from each sample mix. The findings showed that the flexural strength increased with the percentage of eggshell powder and nano silica. The results of the flexure test are as shown in fig 8 and Fig 9. The improvement justified as the ESP and NS acts as a plaster material in concrete enhances the densification of concrete this densification improves the interfacial transition zone between the cement matrix and steel fibres resulting in enhanced bond strength. Improved bond strength between the matrix and fibres can lead to increased flexural strength [5].

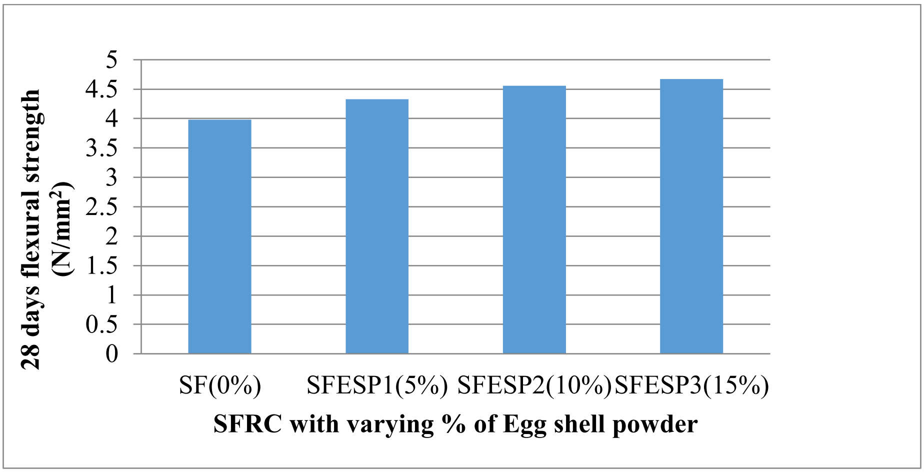

Fig 8. 28 days Flexural strength of SFRC with varying percentage of ESP

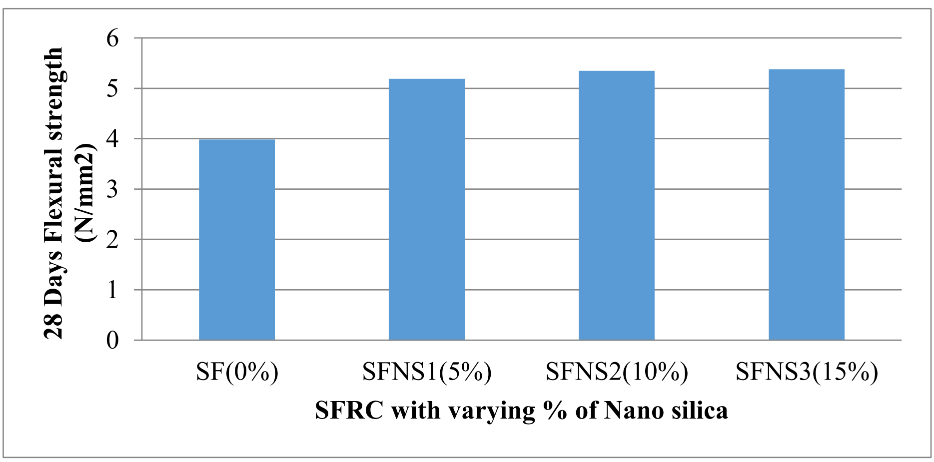

Fig 9. 28 days Flexural strength of SFRC with varying percentage of NS

4. Discussion

The current study demonstrates that incorporating ESP and NS in SFRC results in improved mechanical properties, including cube mechanical properties such as, compressive strength, split tensile strength, and flexural strength of concrete [3,4].It was clearly seen that the mechanical properties of SFRC increases with the addition of ESP and NS to a marginal amount for cube compressive strength, split tensile strength. But, the addition of ESP and NS above 10% volume fraction adversely affected the hardened properties of SFRC except flexural strength. This will due to the ESP contains calcium carbonate which reacts with calcium hydroxide forming additional calcium silicate hydrate (C-S-H) gel, this gel enhances the binding properties of concrete and improve its mechanical strength [4]. Also, when added to concrete, NS (fine particles of silicon dioxide) fills the voids between the cement particlele ading to a denser microstructure.

This densification results in increased strength and durability of concrete. The reduction in strength is justified as, by the replacement of cement with ESP or NS leads to a very large reduction of cement which adversely affects the strength of the concrete. But flexural strength increases with the addition of ESP and NS, and the maximum value obtained at 15% for ESP and 15% for NS. That means the effect of fibre combinations overcome the effect of the pozzolanic activity of ESP and NS. It can be clearly seen that, the optimum dosage of ESP for improved behavior of mechanical properties of SFRC at 10% and the optimum dosage of nano silica at 10% . The same has been observed in past studies [16-18]

From the previous recearch reports, compressive strength of conventional concrete M30 mix was 30.82 N/mm^2 at 28 days [2]. In the present study, by adding steel fibres of 1.5%, compressive strength at 28 days is found to be increased by 2.2%. Also with eggshell powder and nano silica, compressive strength of steel fibre reinforced concrete increased by 5.8 % and 7.9% respectively. That means by the inclusion of sustainable waste materials enhance the mechanical properties of conventional concrete and steel fibre reinforced concrete effectively.

5. Conclusions

In this research, the focus was on investigating the impact of environmentally sustainable supplementary cementitious materials (SCMs) like egg shell powder and nano-silica, derived from solid waste, on the strength properties of steel fiber-reinforced concrete. From the research findings, the subsequent conclusions are deduced

- The inclusion of eggshell powder and steel fibre in concrete decreases the workability of concrete mixes [3].
- By using steel fibres, it improves the compressive, tensile strength, and flexural strengths of the material while also improving its ductility [10, 11].
- Using waste eggshells in construction materials will contribute to sustainability by addressing environmental considerations associated with the disposal of eggshell waste, conserving raw materials, creating cost-effective materials, and reducing CO2 emissions [3].
- Eggshell powder can optimize the particle packing of concrete mixtures, promoting better interlocking between particles and enhancing the mechanical properties of the hardened concrete [3,4]
- The nano-scale filling effect of nano-silica reduces the porosity of the concrete, resulting in a significant improvement in compressive strength [1]
- The highest mechanical properties were observed when 10% of the cement was replacement with eggshell powder [5].
- The maximum inclusion of eggshell powder to use is 10%, which results in improved compressive strength of 33.33 N/mm^2, as well as increased flexural and split tensile strengths of 5.35 N/mm^2 and 4.56 N/mm2 respectively after 28 days.
- Eggshell powder enhances the compressive strength of fiber-reinforced concrete by facilitating a pozzolanic reaction with calcium hydroxide, leading to the formation of additional calcium silicate hydrate gel. Additionally, the fine particles of eggshell powder act as microfillers, optimizing particle packing and promoting better interlocking within the concrete matrix, thereby increasing its compressive strength

[1,4]

- The highest mechanical properties were observed when 10% of the cement was replacement with Nano silica.
- The maximum inclusion of nano silica to use is 10%, which results in improved compressive strength of 33.99 N/mm^2, as well as increased flexural and split tensile strengths of 5.38 N/mm^2 and 5.27 N/mm^2 respectively after 28 days.
- Nano silica enhances the compressive strength of fiber-reinforced concrete by filling in the voids between cement particles, resulting in a denser and more compact concrete matrix. Additionally, nano silica promotes the formation of additional calcium silicate hydrate gel during hydration, leading to improved interfacial bond strength between the fibers and the concrete matrix, ultimately increasing compressive strength[1,15]
- Comparing with OPC, by adding steel fibres of 1.5%, compressive strength at 28 days is found to be increased by 2.2%. Also with eggshell powder and nano silica, compressive strength of steel fibre reinforced concrete increased by 5.8 % and 7.9% respectively[10]

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