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Original Article

Sustainable Concrete Composites: Evaluation Of Structural Performance of Egg Shell Powder and Silica Fume Replaced Steel Fibre Added Concrete

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Abstract - *Concrete plays a critical role in infrastructure development, but its heavy reliance on cement contributes significantly to global carbon emissions. Simultaneously, the need for improved mechanical performance and sustainability has driven research into alternative cementitious materials and advanced reinforcement strategies. In response to these challenges, this study explores the use of Eggshell Powder (ESP) and Silica Fume (SF) as partial replacements for cement, combined with Corrugated Steel Fibres (CSF) for mechanical enhancement. Concrete specimens were prepared with varying proportions of ESP (5–15%), SF (2.5–10%) and CSF (0–1.5%) and tested for 28-day compressive, split tensile and flexural strength. The optimized mix of 5% ESP, 2.5% SF and 1% CSF demonstrated superior performance, achieving 35.01 MPa in compressive strength, 5.37 MPa in split tensile strength and 5.97 MPa in flexural strength, compared to 31.93 MPa, 4.59 MPa and 4.75 MPa, respectively, in the control mix. These improvements highlight the effectiveness of combining industrial byproducts and bio-waste with steel fibre reinforcement to develop a cost-effective, high-strength and environmentally sustainable concrete solution.*

Keywords - *Steel fibre reinforced concrete, Silica fume, Egg shell powder, Sustainable concrete, Mechanical properties, Cement replacement.*

1. Introduction

Concrete is the most commonly used construction material, recognized for its versatility, durability, and ability to be molded into nearly any shape [1]. It forms the backbone of modern infrastructure, from residential buildings to bridges and highways. Despite its widespread use, conventional concrete has inherent limitations that affect structural performance and durability, particularly under dynamic loads or adverse environmental conditions. One of the primary challenges lies in its brittle nature and low tensile strength, which often necessitate additional reinforcement to prevent premature failure [2]. To overcome these limitations, the construction industry has increasingly turned to material innovation and technological improvements.

Modern research and engineering practices emphasize the need to enhance concrete's mechanical properties like tensile strength, compressive strength and flexural performance, while also improving its durability, sustainability and cost-effectiveness. Innovations in materials science have led to the development of various advanced concretes that integrate supplementary components and reinforcing agents to address specific performance requirements. Fiber-Reinforced Concrete (FRC) is one such advancement that has garnered significant attention [3]. The inclusion of discrete fibers within the concrete matrix has been shown to substantially improve resistance to cracking, impact, shrinkage and fatigue. By bridging microcracks and redistributing stresses, fibers help maintain the structural integrity of concrete elements under demanding conditions. The orientation and distribution of these fibers throughout the matrix allow for multidirectional reinforcement, enhancing not only strength but also ductility and toughness.

In parallel with the development of high-performance concrete composites, sustainability has become a critical consideration in construction practices. The global construction trade is a major natural resource consumer and an important contributor to carbon emissions, largely due to the energy-intensive production of Portland cement. As environmental regulations tighten and awareness grows about ecological impacts, researchers and practitioners are seeking ways to decrease the environmental impacts of concrete. One approach involves the partial replacement of traditional cementitious materials with alternative binders or waste byproducts that possess cementitious or pozzolanic properties [4]. These alternative materials are often sourced from industrial waste, agricultural residues or natural minerals and offer the dual benefit of reducing reliance on virgin resources while diverting waste from landfills. Additionally, when these materials respond with the hydration products of cement, they contribute to improved microstructure development and long-term strength gain. The incorporation of such alternatives not only addresses sustainability goals but also enhances the durability and mechanical performance of concrete, especially when used in conjunction with advanced reinforcement strategies [5]. The evolution of concrete technology is thus characterized by a multidisciplinary effort to balance performance, economy and sustainability. By employing waste utilization, material engineering and advanced design approaches, modern concrete solutions aim to meet the growing demands of resilient infrastructure while minimizing environmental impacts. The present study investigates the potential of integrating innovative materials and reinforcement techniques to produce a concrete composite that meets contemporary engineering requirements. The major objectives of the study are listed below.

- Introduced a sustainable concrete mix using agricultural waste and industrial byproduct as partial cement replacements.
- Optimized the blend of ESP and SF to improve split tensile, compressive and flexural strength of concrete without increasing cement content.
- Compared performance with control mixes, showing measurable improvements over conventional concrete in all mechanical properties.
- Validated the feasibility of using waste materials in structural concrete applications without compromising strength or durability.
- Contributed to sustainable construction practices by reducing cement usage and promoting a circular economy through material reuse.

The remaining portion of the study is organized as follows: Section 2 provides an overview of recent studies on sustainable cement replacements and fibre-reinforced concrete, emphasizing the potential of using eggshell powder, silica fume and steel fibres.

Section 3 describes the materials used, mix design, specimen making and the procedures followed for mechanical testing. Section 4 analyses the data obtained from the tests and compares the performance of various concrete mixes. Section 5 summarizes the key findings of the research and highlights the practical implications of using waste materials in structural concrete.

2. Literature Review

Research into sustainable cementitious materials has gained momentum as the construction industry seeks to reduce environmental impact while maintaining or improving mechanical performance. This review highlights past efforts involving ESP, SF, and various types of fibre-reinforced concrete to support the formulation of more environmentally responsible composites.

2.1. Eggshell Powder and Cement Replacement

Hailemariam et al. [6] analyzed cement's partial replacement in alkali-activated mortars using ESP and Steel Slag (SS) as supplementary binders. The research examined the effects of incrementally replacing ESP with SS (10–50%) in a system containing 50% ordinary Portland cement, activated with NaOH and Na_2SiO_3. The methodology included mechanical and microstructural testing after curing, with strength measured up to 56 days. The results indicated that increasing SS improved compressive strength, density, and resistance to thermal and sulfate exposure while reducing porosity and water absorption. However, higher SS content negatively affected workability, requiring additional water or admixtures. The study was limited to 50% OPC-based systems and lacked exploration of long-term durability under real environmental conditions. Soman et al. [7] examined the mechanical behavior of steel Fibre-Reinforced Concrete (FRC) modified with ESP and Nano-Silica (NS) as partial cement replacements. The research involved replacing OPC with 0–15% ESP and NS, along with 1.5% steel fibres by weight. Samples were tested for compressive, flexural, and split tensile strength after curing for 7 and 28 days. The results showed that 10% replacement with ESP or NS provided optimal strength gains. ESP contributed through pozzolanic reactions and particle packing, while NS enhanced matrix densification. Despite these improvements, the study was limited by reduced workability at higher replacement levels and did not assess the influence of these materials under environmental exposure conditions.

Safayet et al. [10] examined the influence of ESP and Nylon Fibres (NF) on the characteristics of Self-Compacting Concrete (SCC) for workable construction. Concrete mixes were prepared with ESP replacing 5–15% of cement and NF added at 0.05–0.10% by weight. Fresh, mechanical, durability, and microstructural properties were tested alongside machine learning models to predict performance outcomes. The mix with 5% ESP and 0.10% NF showed optimal strength and workability, improving compressive and tensile strength by 6% and 4%, respectively. However, higher ESP content minimized strength due to low silica content and the dominance of the filler effect. A key limitation was the lack of variability in curing conditions.

Abdellatief et al. [11] studied the performance of lightweight geopolymer foam concrete (LWGFC) integrating fly ash, ESP, and ground granulated blast furnace slag, activated using alkali solutions. ESP was added in proportions of 5–20%, and the silicate modulus (SiO_2/Na_2O) was varied between 1.0 and 1.5 to assess effects on expansion, strength, porosity, and thermal conductivity. Results showed that 10%

ESP and higher silicate modulus improved compressive strength and reduced porosity, but also increased thermal conductivity. Although strength improved with moderate ESP content, higher levels (≥20%) reduced performance due to high water absorption and weak pozzolanic reactivity.

A limitation of the study was the trade-off between insulation properties and mechanical strength, challenging the optimization of both durability and thermal efficiency. Fahad et al. [12] analyzed the environmental and mechanical performance of concrete modified with ESP and Sawdust Ash (SDA) as partial cement replacements. Using Life Cycle Assessment (LCA) via Ecoinvent and the SimaPro database, the study assessed mixes with 10–40% cement replacement. Mechanical testing was conducted over a 56-day period, and the peak compressive strength gain was detected at 20% replacement. Environmental benefits included reduced resource depletion, emissions, and energy use. However, replacements above 20% showed limited strength development due to low calcium oxide content and weaker pozzolanic activity. A key limitation was the trade-off between environmental gains and mechanical performance at higher replacement levels, which remains a key challenge in balancing sustainability with structural integrity.

Paul et al. [13] inspected the use of Rice Husk Powder (RHP) and ESP as partial sand replacements in M30 grade mortar to enhance sustainability. Mortar mixes were set by replacing natural fine aggregates with RHP (3–15%) and ESP (3–7%) at a constant water–cement ratio. Tests included compressive and split tensile strength, water absorption, pore structure, and electrical resistivity, supported by XRD, SEM, and EDS analyses. Results showed that 5% RHP and 7% ESP maintained strength near control levels while improving resistivity by up to 80%. Water absorption and porosity remained unaffected. However, higher RHP and ESP levels reduced strength due to dilution of hydration products. A key limitation was the short observation period, which did not capture the long-term pozzolanic activity of the filler materials.

2.2. Silica Fume and Concrete Enhancement

Paruthi et al. [9] examined the durability performance of concrete incorporating SF as a partial cement replacement under chemically aggressive conditions. Concrete specimens containing 10%, 20%, and 30% SF were exposed to sodium chloride and sulfuric acid solutions for 90 days. Durability was assessed through sorptivity, strength loss, porosity, and chloride penetration tests. The findings showed that 20% SF replacement optimized durability, improving resistance to chemical attack and reducing permeability. However, the study noted limitations related to higher costs, reduced workability at elevated SF dosages, and challenges with large-scale implementation due to supply variability and processing demands. Paruthi et al. [9] explored the performance of Date Palm Fibre (DPF)-based concrete reinforced and modified with SF as a supplementary cementitious material.

The research assessed concrete mixes containing up to 3% DPF and 15% SF, tested under both ambient and elevated temperatures (200–800 °C). Mechanical properties were evaluated alongside Multivariable Regression Analysis (MRA) and Multi-Criteria Decision-Making (MCDM) techniques to predict and rank mix performance. Results showed that while DPF alone reduced compressive strength, the addition of 10% SF mitigated these effects and improved thermo-mechanical behavior. Mix M7 (1% DPF, 10% SF) was consistently identified as optimal. However, limitations included reduced workability due to fibre addition and a lack of validation of the prediction models across diverse environmental and material conditions.

Olivia et al. [14] examined the effect of SF and precipitated silica on the performance of Palm Oil Fuel Ash (POFA)-based concrete as partial cement replacements. Four mixes, including a control and combinations of POFA with either SF or precipitated silica, were assessed for mechanical strength, porosity, and microstructure. The inclusion of precipitated silica improved compressive and tensile strength, strength activity index, and microstructure more significantly than silica fume. SEM and FTIR analyses confirmed enhanced densification and reactivity with precipitated silica. However, all POFA-based mixes exhibited lower initial strength than control concrete, attributed to the porous nature of POFA. A key limitation was the reduced early-age strength.

2.3. Combined Use of Waste-Based Cement Replacements and Fibres

Zaid et al. [8] explored the incorporation of Mine Tailings Sand (MTS) and Mine Tailings Powder (MTP) as partial replacements for cement and quartz sand in Ultra-High-Performance FRC (UHPFRC). The research evaluated various parameters, including workability, strength, sulfate resistance, thermal behavior, shrinkage, porosity, hydration kinetics, and microstructure. The optimal mix with 60% MTS and 15% MTP improved compressive strength, reduced shrinkage by nearly half, and enhanced resistance to sulfate and thermal exposure. However, higher mine tailings content adversely affected workability and fibre dispersion and increased porosity. The study also noted the challenge of chemical variability and potential contaminants in mine tailings.

2.4. Research Gaps

Although numerous studies have explored cement replacement using materials like ESP, SS, NS, and industrial byproducts, several research gaps remain. Key limitations include reduced workability at higher replacement levels, inconsistent material quality, and lack of validation under varied environmental conditions [6]. Additionally, many studies focus on short-term performance, overlooking long-term durability and degradation behavior in aggressive environments [13]. While environmental and mechanical benefits are evident, optimal balancing of strength, durability, and sustainability is still underexplored, especially in large-scale or real-world applications [10, 12]. These gaps highlight the need for more comprehensive, long-term investigations into the performance of sustainable cementitious approaches.

3. Materials and Methods

3.1. Materials Used

3.1.1. Cement

According to IS 12269:1987, OPC of 53 Grade was utilized in this research. To ensure quality and performance, the following laboratory tests were conducted as per relevant Indian Standards: standard consistency, initial and final setting time and the fineness of cement. These tests were performed in accordance with IS 4031 and IS 269 standards.

Standard consistency is the percentage of water essential to make a cement paste of standard plasticity [15]. It was determined using the Vicat apparatus as per IS 4031 (Part IV):1988. Equation (1) is used to calculate the required water.

$$Standard\ Consistency\ (\%) = \frac{W_2}{W_1} \times 100 \quad (1)$$

Where W_1 represents the weight of cement (g) and W_2 is the weight of water added (g). The test was performed to determine the standard consistency of cement as per IS 4031 (Part IV):1988 using the Vicat apparatus. As the amount of water augmented, the penetration depth of the needle decreased. From the bottom of the mould, a penetration of 6 mm corresponds to the standard consistency point, which was achieved at 148 g of water for 400 g of cement, resulting in 37% water by weight, as shown in Table 1.

Table 1. Determination of the standard consistency of cement

Weight of Cement (g)	Water Added (g)	Penetration (mm)	% of Water ($W_2/W_1 \times 100$)
400	120	38	30%
400	128	27	32%
400	136	19	34%
400	144	12	36%
400	148	6	37%

The Initial Setting Time (IST) determines the onset of cement stiffening and was measured using a Vicat needle, as specified in IS 269:1989. The paste was prepared using 85% of the water content established for standard consistency, as shown in Equation (2).

$$Water\ for\ IST = 0.85 \times 37\% = 31.45\% \quad (2)$$

The needle failed to penetrate beyond 5 mm at 55 minutes after mixing, indicating the initial setting time. According to the IS code, this value must be greater than or equal to 30 minutes, and the obtained result thus confirms acceptable workability. The final setting time was also recorded via the Vicat apparatus. This denotes the time at which the cement paste loses its plasticity completely.

In this research, the final setting time was found to be 300 minutes, which lies well within the IS-prescribed maximum of 600 minutes (10 hours). This ensures that the cement has adequate time to be placed and compacted before hardening. Fineness affects the rate of hydration and strength gain. It was analyzed using the dry sieve method with a 90 µm sieve, as per IS 4031 (Part I):1996. The percentage retained on the sieve was calculated using Equation (3).

$$Fineness\ (\%) = \frac{W_2}{W_1} \times 100 \quad (3)$$

Where $W_1 = 100g$ is the sample weight, and $W_2 = 9g$ is the weight of residue. Table 2 shows fineness test results from three samples. The average fineness was found to be 9%, which is within the permissible limit of 10% for OPC, indicating that the cement is adequately ground and suitable for high early strength development.

Table 2. Fineness of cement using a 90 µm sieve

Sample No.	Weight of Sample (g)	Weight of Residue (g)	Fineness (%)
1	100	9	9%
2	100	9	9%
3	100	8	8%

3.1.2. Fine Aggregate

Manufactured sand (M-sand) was utilised as the fine aggregate in this research, conforming to IS 383:2016 specifications. Fine aggregate has a main role in the strength, workability and overall concrete performance [16].

To ensure its suitability, the fine aggregate was tested for bulk density, specific gravity and particle size distribution. These properties are essential for mix design calculations and ensuring uniform gradation and compaction in concrete. Bulk density indicates the mass of aggregate in a given volume and is expressed in kg/L and is calculated using Equation (4).

$$Bulk\ Density = \frac{W_2 - W_1}{V} \quad (4)$$

Where W_1 is the weight of the empty container and W_2 is the weight of the container with aggregate, and $V = W_4 - W_1$ is the volume of the container (by displacement method). Table 3 and Figure 1 provide the fine aggregate's bulk density analysis.

The obtained bulk density value of 1.74 kg/L lies within the standard range of 1.2 to 1.8 kg/L (IS 2386 Part III:1963), indicating that the M-sand is appropriately graded and compacted.

Fig. 1 Determination of fine aggregate's bulk density

Table 3. Bulk density of fine aggregate

Parameter	Value
Weight of Empty Container (W_1) (kg)	3.382
Weight with Aggregate (W_2) (kg)	8.610
Weight with Water (W_4) (kg)	6.386
Bulk Density (kg/L)	1.74

Specific gravity is a critical property used in mix design to calculate the volume occupied by the aggregates [17]. It was determined using a pycnometer in accordance with IS 2386 (Part III):1963 and is computed by Equation (5).

$$Specific\ Gravity = \frac{W_2 - W_1}{(W_4 - W_1) - (W_3 - W_2)} \quad (5)$$

Where W_1 is the weight of the empty pycnometer, W_2 is the weight with dry aggregate, W_3 is the weight with dry aggregate and water and W_4 is the weight with water only. The specific gravity of fine aggregate is illustrated in Table 4. The specific gravity of 2.355 is slightly lower than the typical range of 2.6 to 2.8, but it is still suitable, depending on the type of sand and local source variations. It indicates moderate density, which is suitable for M25 grade concrete.

Table 4. Specific gravity of fine aggregate

Weight Description	Measured Value
Empty Pycnometer (W_1) (kg)	3.382
Pycnometer + Dry Aggregate (W_2) (kg)	8.610
Pycnometer + Aggregate + Water (W_3) (kg)	9.394
Pycnometer + Water Only (W_4) (kg)	6.386
Specific Gravity	2.355

Sieve analysis was performed using IS standard sieves of the following sizes: 4.75 mm, 2.36 mm, 1.18 mm, 600 µm, 300 µm, and 150 µm. Equation (6) computes the Fineness Modulus (FM).

$$Fineness\ Modulus = \frac{Sum\ of\ cumulative\ weight\ retained}{100} \quad (6)$$

From the sieve analysis, as illustrated in Figure 2, the total cumulative weight retained was 399.35 g out of 2000 g of sample. Table 5 illustrates the fine aggregates' particle size distribution and FM.

Fig. 2 Sieve analysis setup

The FM of 3.99 indicates that the fine aggregate is moderately coarse, suitable for medium- to high-strength concrete mixes. This grading helps achieve desirable workability and packing density.

Table 5. Particle size distribution and FM of fine aggregate

Sieve Size (mm)	Weight Retained (g)	Cumulative Retained (g)	Cumulative %
4.75	55.90	55.90	2.80
2.36	298.45	354.35	17.72
1.18	491.15	845.50	42.28
0.60	483.95	1329.45	66.47
0.30	347.60	1677.05	83.85
0.15	322.30	1999.35	99.97
Pan	0.65	2000.00	100.00

The tested M-sand meets the physical criteria required for quality concrete production. It has 1.74 kg/L bulk density, a 2.355 specific gravity and 3.99 FM, all within acceptable limits specified in IS 383:2016. These characteristics ensure that the fine aggregate contributes positively to the concrete's durability and strength.

3.1.3. Coarse Aggregate

Crushed granite aggregate with a nominal maximum size of 20 mm was utilized as the coarse aggregate in compliance with IS 383:2016. Coarse aggregate significantly influences the durability, dimensional stability and strength of concrete [18]. To evaluate its quality, tests were conducted to govern specific gravity, bulk density, particle size distribution, abrasion resistance and aggregate crushing value. These tests were conducted as per IS 2386 (Parts I–IV):1963. Bulk density is a significant parameter used in mix design to assess the volume occupied by aggregates in a unit volume of concrete. It was determined using the relation, as shown in Equation (7).

$$Bulk\ Density = \frac{W_2 - W_1}{(W_4 - W_1)} \quad (7)$$

Where W_1 is the weight of the empty container, W_2 of the container with aggregate and W_4 is the weight of the container with water. The bulk density of coarse aggregate is demonstrated in Figure 3 and Table 6.

Fig. 3 Experimental setup for determining the bulk density of coarse aggregate

The obtained bulk density lies within the typical range of 1.2–1.8 kg/L, confirming that the coarse aggregate is well-compacted and suitable for concrete production.

Table 6. Bulk density of coarse aggregate

Parameter	Value
Weight of Empty Container (W_1) (kg)	13.4
Weight with Aggregate (W_2) (kg)	39.6
Weight with Water (W_4) (kg)	29.1
Bulk Density	1.668 kg/L

Specific gravity reflects the aggregate's density relative to water and is used in proportioning the concrete mix. As shown in Table 7, a specific gravity of 2.65 falls within the standard range of 2.6 to 2.8, indicating a dense, strong aggregate ideal for high-strength concrete applications.

Table 7. Specific gravity of coarse aggregate

Weight Description	Measured Value
Empty Pycnometer (W_1) (kg)	13.4
Pycnometer + Dry Aggregate (W_2) (kg)	39.6
Pycnometer + Aggregate + Water (W_3) (kg)	45.4
Pycnometer + Water Only (W_4) (kg)	29.1
Specific Gravity	2.65

Sieve analysis was performed using sieves of sizes 40 mm, 20 mm, 10 mm and 6.3 mm. The total cumulative weight retained was 335.5 g out of a 10 kg sample. The fineness modulus of 3.35 indicates a well-graded aggregate, suitable for dense and durable concrete mixes, as revealed in Table 8.

The Los Angeles abrasion test evaluates the aggregate's resistance to wear and tear [19]. According to IS 2386 (Part IV): 1963, it is calculated as shown in Equation (8).

Table 9 shows the Los Angeles abrasion test result. With a low abrasion value of 3.6%, the aggregate exhibits excellent wear resistance, making it suitable for pavement, road, and structural applications.

Table 8. Particle size distribution and FM of coarse aggregate

Sieve Size (mm)	Weight Retained (g)	Cumulative weight Retained (g)	Cumulative %
40	0.0	0.0	0.00
20	250.0	250.0	25.00
10	510.0	760.0	76.00
6.3	240.0	1000.0	100.00

$$Abrasion\,Value = \frac{W_1 - W_2}{W_1} \times 100 \quad (8)$$

Table 9. Los Angeles abrasion test result

Initial weight (kg)	Final weight (kg)	Weight Loss (kg)	Abrasion Value (%)
5.00	4.82	0.18	3.6

The Aggregate Crushing Value (ACV) test assesses the capability of coarse aggregate to resist crushing under progressively applied compressive load, as calculated using Equation (9). Table 10 demonstrates the aggregate crushing value test result. The ACV of 20.04% is well within acceptable limits (<30% for structural concrete), confirming the aggregate's sufficient mechanical strength.

$$ACV = \left(\frac{W_3}{W_1}\right) \times 100 \quad (9)$$

Table 10. ACV test result

Initial weight (kg)	Retained weight (kg)	Crushed weight (kg)	ACV (%)
2.939	2.350	0.589	20.04

All the properties of the coarse aggregate, including a 1.668 kg/L bulk density, 2.65 specific gravity, abrasion value of 3.6% and ACV of 20.04%, fall within the permissible limits prescribed by IS standards. These results confirm that the selected coarse aggregate is mechanically sound, well-graded, and suitable for producing M25-grade concrete.

3.1.4. Water

Water plays a major role in the hydration process of cement, influencing the workability, strength progress and durability of the concrete [20]. Local freshwater sources were used for mixing concrete and curing procedures. The pH value was tested, and the value should not be less than 6 to confirm its suitability for use in concrete without causing adverse reactions or affecting the strength development.

3.1.5. Steel Fibres

Corrugated steel fibres were employed to improve the flexural and tensile characteristics of the concrete. The mechanical performance and crack resistance of the concrete is thereby improved. Table 11 shows the fibre properties.

Table 11. Properties of the steel fibres

Property	Value
Length	5 cm
Mean Diameter	0.75 mm
Aspect Ratio	66.67
Young's Modulus	200 GPa
Specific Gravity	7850 kg/m³
Tensile Strength	1100

3.1.6. Eggshell Powder

The sustainability and environmental responsibility of the study were enhanced by utilizing ESP as a partial replacement for cement. Eggshells, a typical household and commercial waste product, were carefully gathered, cleaned to remove contaminants, and allowed to air dry for two to three days. To achieve a uniform particle size suitable for mixing with cement, the shells were dried, crushed into a fine powder, and sieved, as shown in Figure 4. Approximately 95% of eggshells are made of calcium carbonate ($CaCO_3$), with smaller amounts of magnesium, aluminum and phosphorus compounds. ESP is a good supplemental cementitious material due to its high calcium content. ESP improves early-age strength, decreases Alkali-Silica Reaction (ASR) expansions and speeds up cement hydration by offering more nucleation sites. The application of ESP improves the strength properties of concrete and encourages the recycling of biowaste.

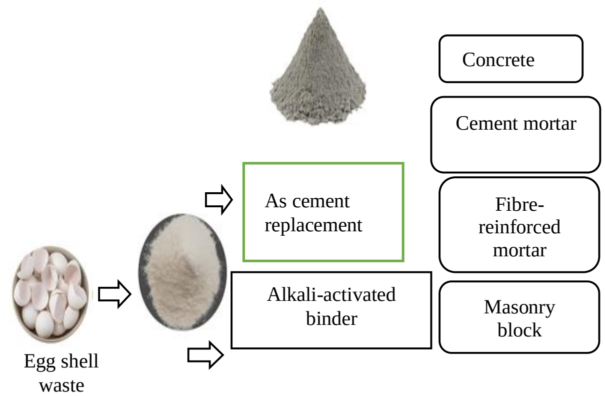


Fig. 4 Conversion of eggshell waste into eggshell powder

3.1.7. Silica Fume

The highly pozzolanic byproduct known as silica fume or microsilica is obtained during the production of ferrosilicon alloys or silicon metal. In this research, silica fume was used in small amounts as a partial replacement for cement. Its high amorphous silica content and ultrafine particle size make it an excellent additive for filling microvoids in the cement matrix, thereby increasing packing density and reducing porosity.

Table 12. Chemical composition and properties of cement, eggshell powder and silica fume

Component / Property	Cement	Eggshell Powder	Silica Fume	Remarks / Role in Concrete
Aluminium oxide (Al_2O_3)	6.6%	0.03%	0.43%	• Contributes to setting and strength development through the formation of calcium aluminates.
Silicon dioxide (SiO_2)	21.8%	0.08%	99.886%	• Major source of pozzolanic activity. • Improves long-term strength and durability.
Iron oxide (Fe_2O_3)	4.1%	0.02%	0.03%	• Enhances hardness and contributes to cement color and minor hydration reactions.
Calcium oxide (CaO)	60.1%	55.85%	0.001%	• Reacts with silica and alumina to form C-S-H and C-A-H, which is critical for strength development.
Specific Gravity	3.15	1.01	2.24	• Influences the mix proportioning. • ESP's low density affects workability and water demand.
Water Demand / Workability	Moderate	Water reduced by ~3%	Increases water demand	• ESP improves workability slightly. • SF requires more water or the use of superplasticizers.
Pozzolanic Activity	Moderate	Low (mainly filler effect)	Very High	• SF actively reacts with $Ca(OH)_2$. • ESP acts more as a nucleation site and filler.
Cost (INR/kg)	350	No cost (waste product)	75	• Use of ESP and SF significantly reduces material cost and enhances sustainability.
Environmental Impact	High (CO_2 intensive)	Negligible	Medium	• Cement has a high carbon footprint. • ESP helps reduce clinker usage

When added to concrete, SF reacts with the calcium hydroxide released during cement hydration to get additional Calcium Silicate Hydrate (C–S–H) gel, which improves resistance to chemical attack, reduces permeability and increases long-term strength. Silica fume, when combined with steel fibers and eggshell powder, improved the concrete's overall durability and mechanical properties.

3.2. Chemical Composition of Cementitious Materials

The material's chemical composition was analyzed to understand its potential reactivity and compatibility in concrete. Table 12 presents the key oxide contents, specific gravities and relative costs of the three materials.

3.3. Mix Design

IS 10262:1982 describes methods for developing typical concrete mixes for the progress of the mix design for the concrete employed in this research. For M25 concrete, the typical nominal mix proportions for cement, fine aggregate and coarse aggregate were decided to be 1:1.5:3. A water-to-cement (w/c) ratio of 0.45 was preserved to offer the required strength properties and sufficient workability. This ratio was selected to strike a balance between the need to maintain adequate hydration and the requirement to reduce porosity and potential durability issues. ESP and SF were used in this experimental program to partially substitute cement in several batches of concrete. While silica fume was continuously employed at a 5% replacement level in all pertinent mixes, ESP was substituted for the cement at different weight percentages of 5%, 10%, and 15%. To isolate the effects of ESP and SF, corrugated steel fibers were added to all mixes at a consistent ratio, guaranteeing consistent reinforcement across samples.

3.4. Experimental Programme

The experimental programme was structured to assess the mechanical performance of steel FRC when a portion of the cement is replaced with ESP and SF. The examination focused on assessing the effect of supplementary materials on the split tensile, compressive and flexural strengths of concrete.

3.4.1. Specimen Preparation

All concrete specimens were prepared using a standardized procedure to ensure repeatability and uniformity across all batches. The dry materials, including OPC, ESP, SF, M-sand, and coarse aggregate (crushed granite), were weighed using a precision digital balance and thoroughly mixed in a clean, dry mixing pan for approximately 2–3 minutes to achieve a uniform blend. Corrugated steel fibres were then gradually added to the dry mix and hand-mixed for another 1–2 minutes to prevent fibre clumping and ensure even dispersion throughout the matrix. Once the dry mixture was homogeneous, water (as per the designed water-to-cement ratio of 0.45) was added incrementally while continuously mixing for 3–4 minutes using a mechanical mixer until the mix reached a consistent and workable state. Concrete was cast into standard moulds corresponding to each test type (as detailed in Table 13). Moulds were filled in three equal layers. Each layer was compacted either manually using a tamping rod (25 strokes per layer, as per IS 516:1959) or via a vibrating table to minimize air voids and ensure full compaction. After casting, the specimens were covered with plastic sheets to prevent moisture loss and left undisturbed for 24 hours at room temperature (27 ± 2°C). Upon demolding, all specimens were transferred to a curing tank containing potable water and maintained at the same temperature (27 ± 2°C) for 28 days. All materials and procedures followed Indian Standard specifications where applicable, and each batch was prepared fresh immediately prior to casting to ensure consistency. The casting of the specimens alongside the materials used is depicted in Figure 5.

Table 13. Specimen types and dimensions for mechanical strength tests

Test Type	Specimen Shape	Dimensions (mm)
Compressive Strength	Cube	150 × 150 × 150
Split Tensile Strength	Cylinder	150 (diameter) × 300 (height)
Flexural Strength	Rectangular Beam	150 × 150 × 700

Every mould was filled in layers, each of which was compacted with either a tamping rod or vibrated to remove air pockets and achieve proper consolidation. The specimens were subsequently protected with plastic sheets to retain moisture and removed from the moulds after 24 hours. The casting of the specimens alongside the materials used is depicted in Figure 5.

Fig. 5 Stages of concrete specimen preparation

3.4.2. Curing

Following demoulding, all specimens were immersed in a curing tank containing potable water at room temperature. The curing procedure was extended for 28 days to ensure proper hydration of cementitious ingredients and the full development of mechanical strength. Proper curing was required to prevent early-age cracking, promote the full hydration of both cement and pozzolanic materials and simulate normal field conditions.

3.4.3. Testing Procedures

After the 28-day curing period, the specimens were tested using standard laboratory procedures and calibrated testing equipment, as revealed in Table 14. The experimental setup for each type of test is shown in Figure 6. All testing was carried out under controlled environmental conditions to ensure accuracy and reproducibility. The test results were then compiled and analyzed to decide the effect of SF and ESP on the mechanical performance of steel fibre reinforced concrete.

Table 14. Mechanical testing methods and standards followed

Test Type	Specimen Dimensions (mm)	Testing Method	Standard Followed	Remarks
Compressive Strength	150 × 150 × 150 (Cube)	Load applied gradually to failure using the Compression Testing Machine (CTM)	IS 516:1959	Average of 3 specimens used per mix
Split Tensile Strength	150 (Diameter) × 300 (Height) (Cylinder)	Diametral compressive load causing vertical split	IS 5816:1999	Measures indirect tensile strength; average of 3 specimens
Flexural Strength	150 × 150 × 700 (Rectangular Beam)	Third-point loading method using a universal testing machine	IS 516:1959	Assesses crack resistance and bending behavior; average of 3 specimens

Fig. 6 Testing concrete specimens

4. Results and Discussion

The mechanical strength properties of steel FRC were evaluated using diverse percentages of ESP and a constant percentage of SF. The samples were cured for 28 days prior to testing and the analysis of the impact of these additional cementitious materials on split tensile, compressive and flexural strength.

4.1. Compressive Strength

The results of the compressive strength test at 28 days, shown in Table 15, indicate that the integration of ESP and SF significantly influenced the mechanical performance of the concrete mixes. The control mix (E0-S0), which contained neither ESP nor SF, achieved a baseline compressive strength of 31.75 MPa. When 5% ESP was added without silica fume (E5-S0), the strength improved slightly to 32.25 MPa. Further, it increased to 34.27 MPa with 10% ESP (E10-S0), confirming that ESP enhances hydration and contributes to early strength development. However, increasing ESP to 15% (E15-S0) led to a decline in strength (31.45 MPa), suggesting that excessive ESP may dilute the binder matrix and reduce reactivity. Figure 7 demonstrates the visualization of compressive strength results.

Table 15. Compressive strength of concrete mixes combining ESP and SF at 7 and 28 days

Sl No.	Mix	7th day	28th day
1	E0-S0	17.5	31.75
2	E5-S0	17.9	32.25
3	E10-S0	17.93	34.27
4	E15-S0	17.5	31.45
5	E5-S2.5	18.57	34.95
6	E5-S5	17.52	34.32
7	E5-S7.5	17.9	32.75
7	E5-S10	16.72	32.1
8	E10-S2.5	17.5	31.5
9	E10-S5	17.1	31.13
10	E10-S7.5	16.9	31.95
11	E15-S2.5	17.39	30.57
12	E15-S5	17.25	30.39
13	E15-S7.5	16.9	29.52

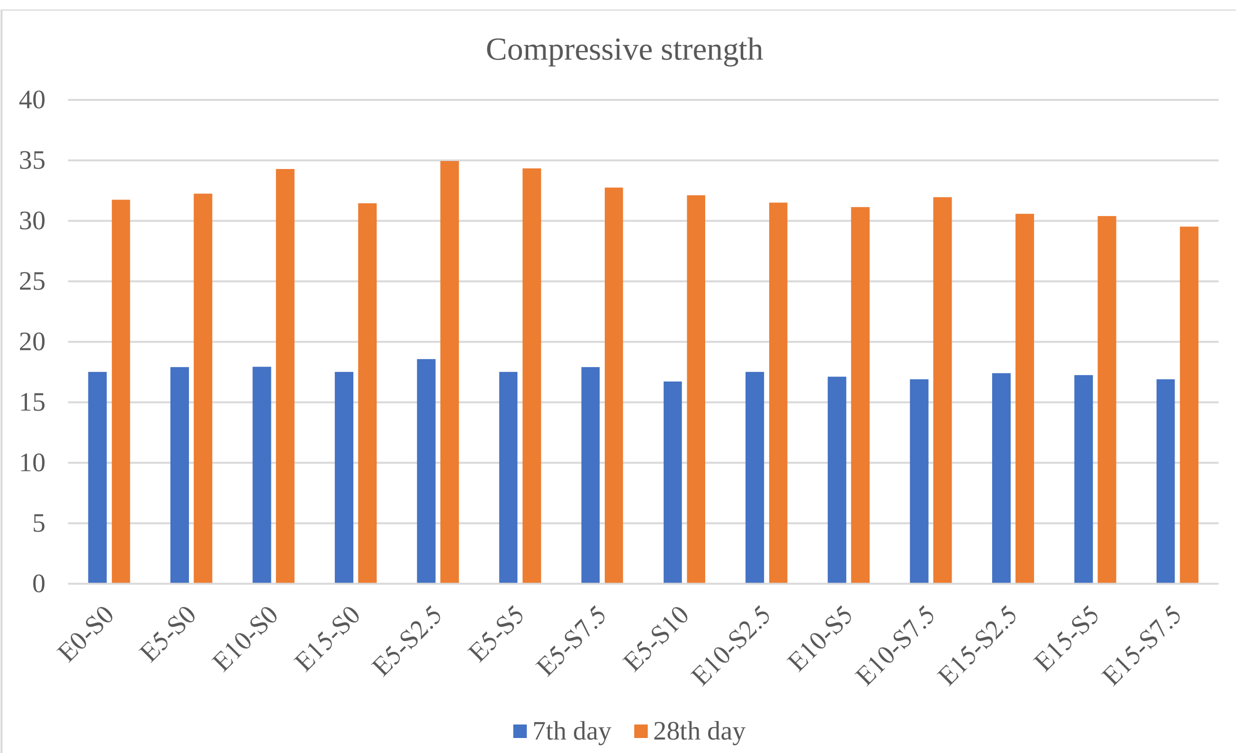


Fig. 7 Compressive strength results

The addition of silica fume yielded even more significant improvements. The mix with 5% ESP and 2.5% SF (E5-S2.5) recorded the highest strength of 34.95 MPa, outperforming all other mixes. This demonstrates the synergistic effect of ESP and SF, where ESP provides calcium for hydration and SF, due to its high pozzolanic reactivity, contributes to the formation of additional C-S-H gel. At 5% SF (E5-S5), the strength remained high at 34.32 MPa, but began to decline with further SF addition, reaching 32.1 MPa at 10% SF (E5-S10). A similar trend was observed in mixes with 10% and 15% ESP, confirming that the optimum combination for compressive strength enhancement is 5% ESP with 2.5–5% SF. Beyond this range, both ESP and SF show diminishing returns, likely due to reduced cement content and oversaturation of fine particles, which negatively affect workability and matrix continuity. These results confirm that eggshell powder and silica fume can be effectively combined to enhance compressive strength, with clearly defined optimal dosage limits.

4.2. Split Tensile Strength

The findings of the 28-day split tensile strength test in Table 16 demonstrate that there are significant variations in the tensile performance of concrete mixes that contain SF and ESP. The strength of the control mix (E0-S0) was 4.57 MPa. 10% ESP (E10-S0) resulted in a slightly lower value of 4.45 MPa, whereas 5% ESP without SF (E5-S0) generated just a slight increase to 4.59 MPa. The mix containing 5% ESP and 2.5% SF (E5-S2.5) demonstrated the highest performance, reaching a compressive strength of 4.95 MPa and significantly outperforming the control. This suggests that when combined with ideal ESP levels, silica fume improves tensile capacity.

Table 16. Split tensile strength of concrete mixes combining ESP and SF at 7 and 28 days

Sl No.	Mix	7th day	28th day
1	E0-S0	3.25	4.57
2	E5-S0	3.71	4.59
3	E10-S0	3.53	4.45
4	E15-S0	3.25	4.39
5	E5-S2.5	3.95	4.95
6	E5-S5	3.72	4.63
7	E5-S7.5	3.27	4.57
7	E5-S10	3.205	4.52
8	E10-S2.5	2.99	4.75
9	E10-S5	2.94	4.74
10	E10-S7.5	2.95	4.71
11	E15-S2.5	2.97	3.79
12	E15-S5	2.9	3.67
13	E15-S7.5	2.75	3.62

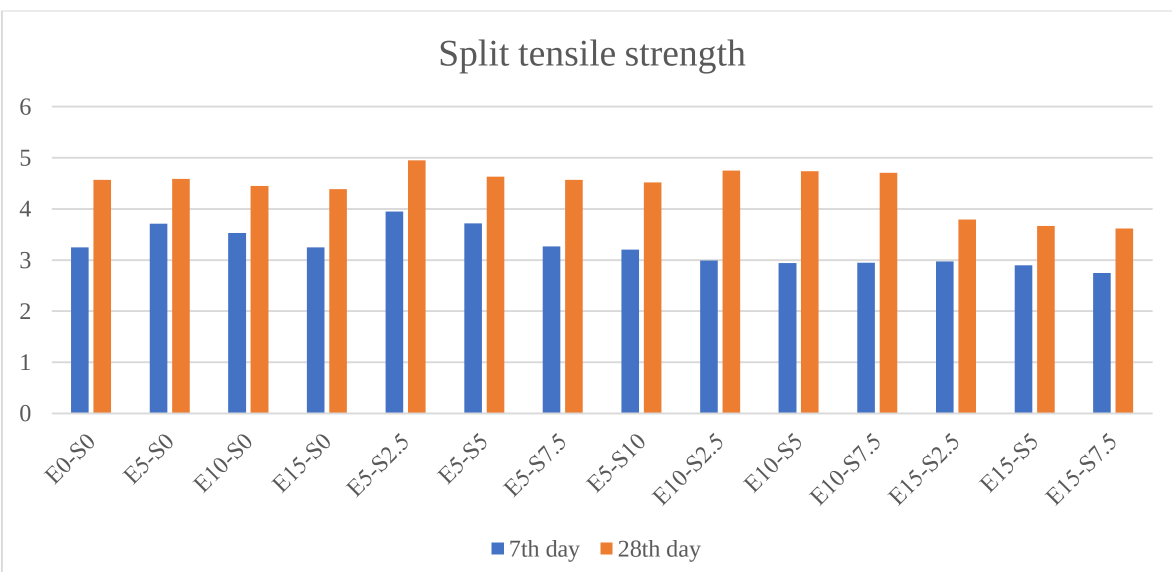


Fig. 8 Split tensile strength

However, mixes with higher ESP content (15%) consistently displayed lower split tensile strength. For example, E15-S0 and E15-S7.5 achieved only 4.39 MPa and 3.62 MPa, respectively. The decline in tensile performance at higher ESP replacements is likely due to reduced binder reactivity and poor matrix bonding. Among all mixes, the synergistic effect of 5% ESP with 2.5% to 5% SF produced the best tensile properties, demonstrating that a balanced proportion of ESP and SF enhances crack resistance and internal bonding in concrete. Figure 8 demonstrates the visualization of split tensile strength results.

4.3. Flexural Strength

As shown in Table 17, the flexural strength test shows similar trends to tensile strength, further highlighting the influence of ESP and SF combinations. The control mix (E0-S0) achieved 4.75 MPa at 28 days, while mixes with 5% ESP (E5-S0) and 10% ESP (E10-S0) reached 4.57 MPa and 4.27 MPa, respectively. The highest flexural strength was again observed in E5-S5 (4.73 MPa) and E5-S2.5 (4.72 MPa). These values suggest that silica fume, when used in small percentages with ESP, significantly improves the flexural capacity of concrete, likely due to refined pore structure and enhanced bonding at the fiber–matrix interface.

Table 17. Flexural strength of concrete mixes combining ESP and SF at 7 and 28 days

Sl No.	Mix	7th day	28th day
1	E0-S0	3.1	4.75
2	E5-S0	3.16	4.57
3	E10-S0	3.43	4.27
4	E15-S0	3.05	3.79
5	E5-S2.5	3.94	4.72
6	E5-S5	3.79	4.73
7	E5-S7.5	3.76	4.61
7	E5-S10	3.09	4.27
8	E10-S2.5	3.25	4.73
9	E10-S5	2.97	4.31
10	E10-S7.5	2.93	4.25
11	E15-S2.5	2.95	4.29
12	E15-S5	2.37	3.95
13	E15-S7.5	2.09	3.91

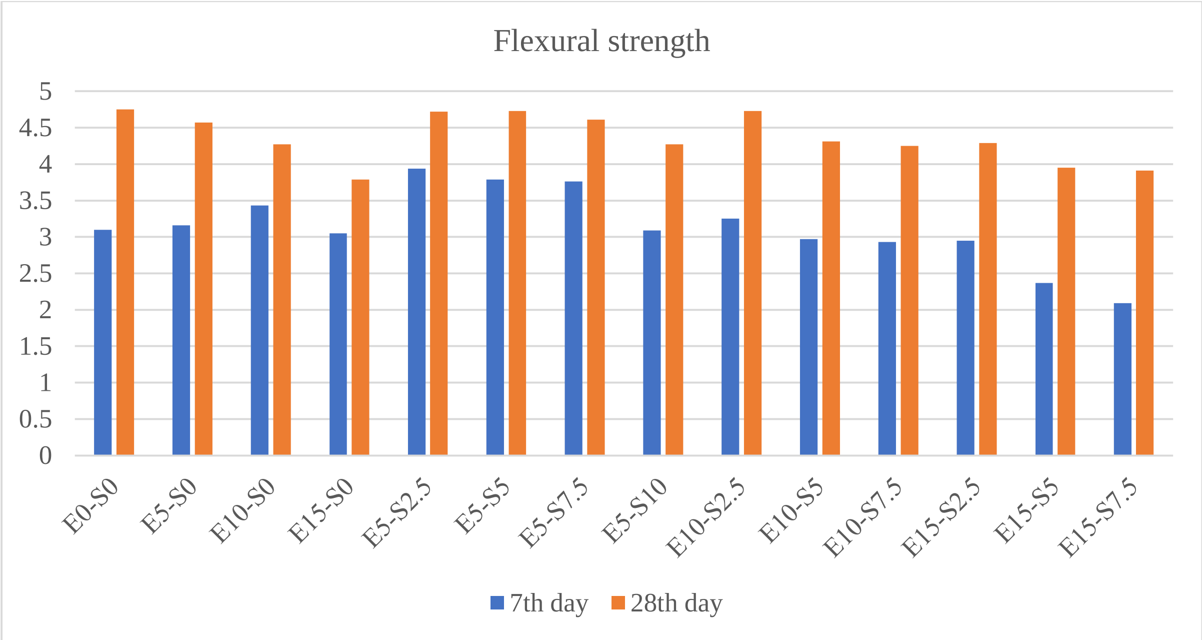


Fig. 9 Flexural strength

In contrast, mixes with 15% ESP exhibited a steady reduction in flexural strength. E15-S0 recorded only 3.79 MPa, while E15-S7.5 dropped to 3.91 MPa. The progressive decline reinforces the observation that ESP beyond 10% may negatively impact the matrix cohesion and limit performance under bending stresses. Figure 9 demonstrates the visualization of flexural strength results. Mixes incorporating 5% ESP and up to 5% SF showed the most favorable results, confirming their potential in producing sustainable concrete with enhanced flexural resistance.

4.4. Effect of Steel Fibre on Mechanical Properties

The 28-day mechanical performance of concrete incorporating varying percentages of steel fibre was evaluated through split tensile strength, compressive strength and flexural strength tests, as given in Table 18. The results reveal that increasing the steel fibre content enhances all three strength characteristics up to an optimal level, beyond which the benefits start to plateau or decline. For compressive strength, the base mix without steel fibres achieved a value of 31.50 MPa. Strength increased steadily with the addition of fibres, peaking at 32.97 MPa with 1% steel fibre. A slight drop was observed beyond this point, as the mix with 1.25% and 1.5% fibres recorded 32.39 MPa and 32.27 MPa, respectively. This indicates that 1% fibre dosage provides the optimal compressive strength, after which increased fibre volume led to fibre clumping, increased voids or reduced workability, ultimately affecting performance.

Table 18. Steel fibre reinforced concrete strength test results

Sl No	Steel fibre	Compressive strength (N/mm^2)		Split tensile strength (N/mm^2)		Flexural strength (N/mm^2)	
		7days	28days	7days	28days	7days	28days
1	0%	17.25	31.5	2.5	4.59	3.1	4.79
2	0.25%	17.7	31.49	2.52	4.67	3.25	4.94
3	0.5%	17.94	32.37	3.37	4.69	3.75	5.25
4	0.75%	18.09	32.9	3.54	4.75	4.12	5.23
5	1%	18.27	32.97	3.83	5.21	4.74	5.75
6	1.25%	18.59	32.39	3.58	4.9	4.35	4.57
7	1.5%	17.21	32.27	2.52	4.32	3.57	4.12

In terms of split tensile strength, there was a substantial gain with fibre addition—from 4.59 MPa at 0% fibre to a maximum of 5.21 MPa at 1% fibre content. Similarly, flexural strength followed a rising trend, increasing from 4.79 MPa (0% fibre) to 5.75 MPa at 1% fibre. These improvements are attributed to the crack-bridging ability of steel fibres, which delay crack propagation and improve post-cracking behavior. However, a decline in both tensile and flexural strength was noticed at 1.5% fibre dosage, suggesting over-reinforcement effects, where excess fibres may disrupt matrix integrity or hinder uniform mixing. The results confirm that steel fibre addition significantly enhances concrete's tensile and flexural capacities, with the most efficient and balanced performance observed at 1% dosage. This level provides the optimal synergy between ductility, strength and fibre dispersion.

4.5. Statistical Analysis

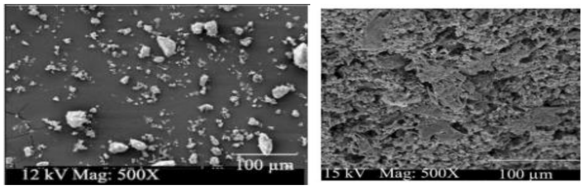
To assess the statistical significance of differences in strength among the various concrete mix designs, one-way Analysis of Variance (ANOVA) tests were performed for 28-day compressive strength, split tensile strength, and flexural strength. The analysis was conducted using strength values from three replicate specimens per mix. The results of the ANOVA tests are summarized in Table 19. All three mechanical strength properties exhibited p-values well below the significance threshold of 0.05, confirming that the observed differences between mix designs are statistically significant and not due to random variation. The high F-statistics for each test indicate strong between-group variability relative to within-group noise, suggesting that the varying proportions of eggshell powder, silica fume, and steel fibre had a reliable influence on mechanical performance.

Table 19. One-way ANOVA results

Test Type	F-Statistic	p-Value	Significance ($\alpha = 0.05$)
Compressive Strength	49.54	0.00012	Significant
Split Tensile Strength	38.83	0.00021	Significant
Flexural Strength	85.56	0.00004	Significant

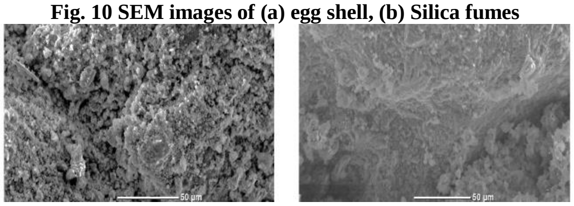
4.6. Microstructure Analysis

SEM analysis was performed on concrete samples with different ESP replacement levels to assess microstructural evolution. Figure 10 provides the SEM images of eggshell and silica fumes. As shown in Figure 11, the sample with 15% ESP displayed a relatively porous matrix with microcracks and disconnected hydration products. In contrast, the sample with 5% ESP revealed a denser microstructure with more compact C–S–H gel and improved matrix integrity. This suggests that excessive ESP may dilute binder reactivity, while moderate levels synergize with SF to refine pore structure and enhance strength.



(a) (b)

Fig. 10 SEM images of (a) egg shell, (b) Silica fumes



(a) (b)

Fig. 11 SEM micrographs of hardened concrete at 28 days with varying ESP content: (a) Mix with 15% ESP, (b) Mix with 5% ESP

4.7. Optimum Mix Performance

The results from the test comparing a control mix with no additives to a modified mix containing 5% eggshell powder, 2.5% silica fume and 1% steel fibre clearly demonstrate the enhanced performance potential of sustainable material substitutions in concrete, as shown in Table 20.

The control mix (0% ESP + 0% SF + 0% CSF) attained a 31.93 Mpa compressive strength, a 4.59 MPa split tensile strength and a 4.75 MPa flexural strength at 28 days. In contrast, the optimized mix (E5-S2.5 + 1% CSF) exhibited a significant increase across all parameters: compressive strength improved to 35.01 MPa, split tensile strength rose to 5.37 MPa and flexural strength reached 5.97 MPa.

Table 20. Test on optimum percentage of ESP replaced CSF reinforced hardened concrete

Sl No	Egg shell powder + silica fume	CSF	Compressive strength 28days (N/mm^2)	Split tensile strength 28days (N/mm^2)	Flexural strength 28days (N/mm^2)
1	0%	0%	31.93	4.59	4.75
2	E5-S2.5%	1%	35.01	5.37	5.97

These enhancements are attributed to the combined effects of the materials: eggshell powder contributes additional calcium for hydration, silica fume increases C-S-H gel formation due to its pozzolanic nature and steel fibres improve crack resistance and post-crack strength. The synergy among these materials results in better matrix density, bond strength and overall ductility. This data supports the conclusion that the combination of E5-S2.5 with 1% steel fibre offers an optimum formulation for high-performance, sustainable concrete. The optimized mix developed in this study, comprising 5% eggshell powder, 2.5% silica fume, and 1% corrugated steel fibre, demonstrated superior mechanical performance compared to both the control mix and previous research. With compressive, split tensile, and flexural strengths of 35.01 MPa, 5.37 MPa, and 5.97 MPa respectively, the proposed mix outperformed results reported in studies by Soman et al. [7], Safayet et al. [10], and Paruthi et al. [9], which focused on either ESP, SF, or fibre individually but not their combined effect. This study is distinct in its integrated approach, systematically combining ESP, SF, and steel fibres to achieve enhanced strength without compromising workability or sustainability. Additionally, it includes statistical validation and microstructural analysis, strengthening the reliability of its findings. The results affirm the viability of using agricultural and industrial waste along with fibre reinforcement to produce cost-effective, high-performance, and environmentally sustainable concrete.

5. Conclusion

This study evaluated the mechanical performance of concrete when cement is partially replaced with ESP and SF, combined with varying dosages of steel fibres. The experimental results consistently demonstrated that the strategic use of these supplementary materials can significantly enhance the strength properties of concrete, provided the dosage is optimized. The incorporation of eggshell powder up to 10% by weight improved both compressive and flexural strength due to its high CaO content, which contributes to enhanced hydration and matrix densification. Additionally, the use of silica fume at 2.5% to 5% further enhanced mechanical properties by contributing pozzolanic reactivity, reducing porosity and producing additional C–S–H. When used together, ESP and SF showed a synergistic effect, with the most effective mix identified as 5% ESP and 2.5% SF, which yielded the highest compressive, tensile and flexural strength values among all the combinations tested. The inclusion of steel fibres further improved the ductility and post-cracking behavior of concrete.

The optimum performance was observed at 1% steel fibre content, where maximum gains were achieved in all mechanical properties, compressive strength (35.01 MPa), split tensile strength (5.37 MPa) and flexural strength (5.97 MPa). The outcomes confirm that the partial replacement of cement with ESP (5%) and SF (2.5%), in combination with 1% steel fibres, provides an effective and sustainable alternative to conventional concrete, enhancing all key strength characteristics. This combination not only improves the mechanical performance but also contributes to sustainability by utilizing waste materials and reducing cement usage.

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