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Experimental investigation and modelling of the layered concrete with different proportions of steel fibers

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Abstract

This study examines the effect of steel fibers (SF) in concrete with different dosages ranging from 0 to 1.5%. Hooked end steel fibers of length 35mm and diameter 0.55mm with an aspect ratio of 63.64 were used. A total of 90 specimens were cast to evaluate the mechanical properties such as compression, split and flexural strength at 7 and 28 days. At steel fiber dosage of 1.5% layered concrete specimens were cast. Layered concrete is one of the best breakthroughs because of its strength and crack resistance. The Specimens were divided into three equal portions of depth d/3 each, such as bottom layer, middle layer and top layer respectively, wherein steel fiber reinforced concrete (SFRC) was cast in the bottom layer followed by middle layer consisting of conventional concrete and above it top layer comprising of SFRC. Experimental results indicate that compressive, split tensile and flexural strengths of layered concrete compared to conventional concrete were increased by 19.14%, 100.90% and 127.25% respectively. Results obtained experimentally and analytically using ANSYS software were validated and both values have strongly correlated.

1. Introduction

Concrete, a predominant building material, accounts for half of building structures and materials for roads and bridges due to its strength, plasticity, and affordability. To improve mechanical properties of concrete, Steel Fibers (SF) are induced in the concrete, termed as Steel Fiber Reinforced Concrete (SFRC), SF have become crucial in enhancing the characteristics of concrete, including, energy absorption, toughness and strength. SF used are short, discontinuous, and randomly distributed all over concrete and they enhance tensile, flexural and shear strength, toughness, resistance to impact, fracture and frost damage. Using SF in concrete increases mechanical properties, self-weight, and unit weight of concrete [1]. SFRC is also utilized to construct machine foundations and other components subjected to dynamic loads [2]. SFRC is frequently employed in industrial sector to construct tunnel linings [3] and road pavements [4]. Micro cracks formed due to shrinkage caused by evaporation of water or applied loading intersect with SF which are randomly distributed in concrete mixture thereby limiting propagation of cracks and enhance tensile strength of concrete. Volume of fibers (V_f) and aspect ratio influence the workability and strength improvement of SFRC. SF used should be clean and free from rust. Fiber content in normal weight concrete ranges from 30 to 157 kg/m^3 with an aspect ratio of 30 to 100 and quantity of fibers that can be used without compromising strength depends on placing of steel reinforcement, fiber shapes, aspect ratio and amount of water reducing admixtures used [5]. Concrete performance is improved by fiber dosage and aspect ratio to enhance fiber matrix bond, but higher aspect ratio influences uniform distribution of fibers and also dosage of fibers of length 12 to 60 mm in addition to superplasticizer is limited to 2% by volume of concrete beyond which

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fiber balling occurs [5-6]. Compressive strength increases from minimal to 23% with 2% by volume of steel fiber and with an aspect ratio of 100 [7]. Fibers show little effect on compressive strength, increasing from 0 to 25% with fiber content less than 2% [8-12]. Higher fiber content (>2%) does not enhance compressive strength and reduces workability from achieving full compaction of concrete. A significant benefit of embedding fibers into concrete is that they enhance its tensile and flexural strength after cracking when subjected to both static and impact loads [13-15]. SF are commonly employed in Fiber reinforced concrete (FRC) as they act as a bridge at the fracture interface, leading to ductile behavior after cracking [16]. Incorporating fibers into the matrix resulted in an enhancement of the pullout characteristics, including average and identical bond strengths, as well as pullout energy, which were enhanced as fiber volume fraction, increased up to a maximum of 2%, however pullout parameters were worsened with fiber volume fraction above 2% [17]. Varying proportions of SF from 0.5%,1.0%,1.5% and 2.0% increase mechanical properties of concrete thereby concluded that feasible range of SF to be 1-1.5% [18]. Smooth SF do not develop proper bond in concrete mix [6]. Fiber distribution throughout whole volume of concrete beam renders it an economically inefficient material for beams [19]. Combination of small quantity of V_f in top layer and large quantity of V_f in bottom layer enhances performance regarding flexural load and flexural energy [20]. Fibers re-arranged in the double layer UHPFRC beams Compared to single layer (uniform distribution) UHPFRC beams gives better performance with same quantity of fibers [20]. A single-layered concrete slab exhibits three-dimensional orientation of placing of fibers, while a multi-layered concrete slab demonstrates a planar orientation of fibers; hence, the multi-layered concrete performs superiorly compared to the single-layered variant [21]. The upper layer mixture was poured into the mould after 45 minutes [20]. During the casting of the upper layer, the lower layer has sufficient strength to support upper layer matrix, thereby preventing deformation at the layer interface; concurrently, the initial setting of lower layer matrix had not yet occurred [20], leading to a robust interfacial bond. Two layered concrete beams were cast using high strength concrete and normal strength concrete which were placed in compression and tension zones respectively, to improve ductility of compression zone, fibers were introduced in this zone thereby reducing high fiber utilization and control shear failure [22]. Performance of layered beams, comprising normal concrete in upper layer and fiber-reinforced lightweight concrete in lower layer, does not affect bond between the layers [23]. A finite element analysis (FEA) model was created to predict the behavior of normal and SFRC infilled composite circular columns under axial compressive load using ANSYS software. Stress-strain relationship data was obtained by conducting compression tests on cylinders for conventional concrete and SFRC, and this is taken as input for modelling in ANSYS software and for circular steel tube, a typical stress–strain relation was simulated by an elastic-perfectly plastic model [24]**.** Finite element modelling of conventional concrete and SFRC beams were carried out using ANSYS software. Modelling results and experimental results were strongly correlated [25]. Drucker and Prager yield surface parameters were used to model the beams and simulate using ANSYS [26]. Extensive research on SF with different aspect ratios and V_f when distributed homogenously in the entire cross section is being carried out to investigate the effect of SF in the mechanical properties of concrete rather than in layered concrete.

The aim of this study is to compare the behavior of SF when placed randomly in conventional concrete for dosages ranging from 0-1.5% and in layered concrete at optimum dosage of 1.5%. The specimens in layered concrete were divided into three equal depths of d/3 each viz., top, middle and bottom layers respectively. Top and bottom layers were cast with SFRC and middle layer was cast with conventional concrete.

2. Experimental Program

2.1 Materials

An ordinary Portland cement of 53 grade conforming to IS 269-2015 [27] of brand KCP was used. River sand with a fineness modulus of 2.56 and conforming to zone-III as per IS 383-2016 [28] having specific gravity of 2.63. Crushed stone of sizes 20mm and 10mm as per IS 383-2016 [28] with a percentage of 60% and 40% having combined specific gravity of 2.88 was used. The physical and chemical properties of cement were given in tables. Hooked end steel fibers of length 35mm and diameter 0.55mm with an aspect ratio of 63.64, super plasticizer of conplast 430 conforming to IS 9103-1999 obtained from FOSROC chemicals having specific gravity of 1.18 was used in this study.

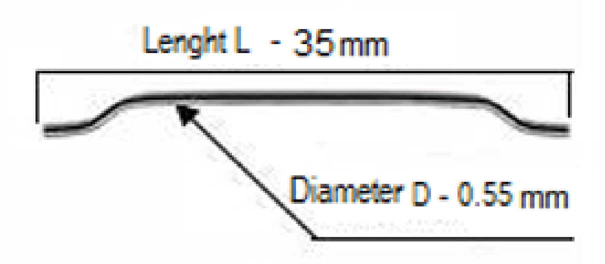


Fig. 1. Hooked-end steel fiber

Table 1. Physical properties of cement

S. No	Properties		OPC 53 grade	Requirements as per IS 269:2015
1	Fineness (m2/kg)		299	Min.225
2	Specific gravity		3.13	------
3	Normal Consistency (%)		29.5	-------
4	Setting time (Minutes)		165	Min.30
5	Soundness (mm)		0.5	Max.10
6	Compressive strength	7 days	49	
		28 days	60	

Table 2. Chemical properties of cement

S. No	Properties	OPC 53 grade	Requirements as per IS 269:2015
1	Lime Saturation Factor	0.92	0.8-1.02
2	Ratio of percentage of Alumina to that of Iron Oxide	1.24	Min. 0.66
3	Insoluble Residue (% by mass)	0.47	Max. 5.0
4	Magnesia (% by mass)	1.10	Max. 6.0
5	Sulphuric Anhydride (% by mass)	1.74	Max. 3.5
6	Total loss of ignition (%)	1.24	Max. 4.0
7	Chlorides (%)	0.002	Max. 0.1

Table 3. Quantities per cubic meter of concrete

S. No	Mix Notation	Cement (kgs)	Sand (kgs)	Coarse Aggregate (kgs)	Steel fiber dosage (kgs)	Water/Cement ratio	Super Plasticizer (Liters)
1	M30SF0.0	394	714	1213	0	0.42	3.94
2	M30SF0.5	394	714	1213	39.25	0.42	3.94
3	M30SF1.0	394	714	1213	78.5	0.42	3.94
4	M30SF1.5	394	714	1213	117.75	0.42	3.94
5	M30SF1.5-L*	394	714	1213	117.75	0.42	3.94

M30SF0-M-Mix;30-Compressive strength of concrete; SF0-Steel fibers of dosage 0%; SF1.5-Steel fibers of dosage 1.5%; L*- Layered concrete;

2.2 Preparation of Samples

The concrete Mixes were prepared using Indian standard codes of IS 456-2000 [29] and 10262-2019 [30]. A total of 30 Cubes of dimensions 150x150x150mm, 30 cylinders of dimensions 150x300mm and 30 prisms of dimensions 100x100x500mm were cast. Conventional concrete was prepared using constituent materials i.e. cement, sand, aggregates, water, and super plasticizer. SFRC was prepared using above mentioned materials in addition to steel fiber dosages ranging from 0-1.5%. The SF were added in small amounts to avoid fiber balling and improve workability of concrete.

The layered concrete has three equal layers, viz., top, middle, and bottom layers, each having of uniform depth. Initially the bottom layer was cast using SFRC for a depth of d/3 measured with a ruler and left undisturbed for 45 minutes, not more than its initial setting time. The bottom layer was laid upon middle layer of depth d/3, measured using a ruler, was cast, comprising conventional concrete. After 45 minutes, the top layer was cast with SFRC following the aforementioned process.

3. Numerical Analysis

Finite Element Analysis (FEA), utilized in structural engineering, assesses the overall behavior of a structure by partitioning it into numerous elements, each possessing clearly defined mechanical and physical properties. Modelling the intricate behavior of reinforced concrete, characterized by its non-homogeneity and anisotropy, is a significant difficulty in the finite element analysis of civil engineering constructions. A competent modelling of concrete on a finite element (FE) platform necessitates the utilization of an acceptable element type, sufficient mesh size, suitable boundary conditions, a realistic loading environment, and proper time stepping, alongside the provision of relevant concrete properties.

3.1 Finite Element Formulation

Numerical method such as finite element method was used for the complex problem, in this study prism specimens were modelled using ANSYS 2024R2 for the validation of the experimental results. The prisms of size 100x100x500mm were modelled in ANSYS using CPT 215 element to get ultimate load and deflection.

3.2 Element Description

CPT215 is a 3-D eight-node coupled physics solid element capable of modelling coupled physics phenomena such as structural-pore-fluid-diffusion-thermal analysis and prevents volumetric mesh locking in nearly incompressible cases. Furthermore, the CPT215 element, when coupled with damage-plastic micro plane models, helps to reduce numerical instability and mesh sensitivity for strain-softening materials. The element is defined by eight nodes as shown in Fig. 15 and can have UX, UY, UZ, Pressure and Temperature degrees of freedom at each node.

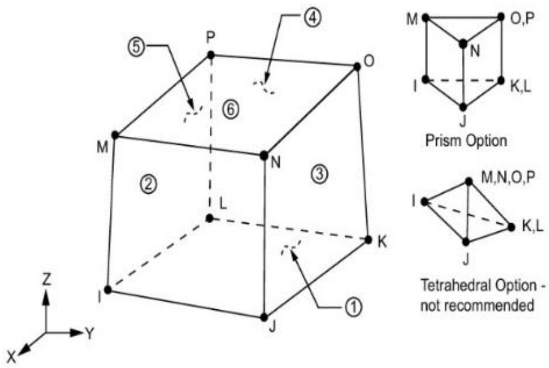


Fig. 15. Structural solid geometry

3.3 Material properties for the prism model

The prisms were modelled in ANSYS and for the analysis of the prisms the following material properties were considered as shown in Table 4.

Table 4. Parameters for various types of concretes

Parameters	Symbol	Mix Notation				
		M30SF0.0	M30SF0.5	M30SF1.0	M30SF1.5	M30SF1.5-L*
Modulus of elasticity (MPa)	E	27920	28720	30530	31700	31800
Poisson's ratio (Unit less)	μ	0.20	0.21	0.22	0.22	0.22
Uniaxial compressive strength (MPa)	f_{uc}	40.59	43.11	46.52	47.85	48.36
Bi-Axial Compressive Strength (MPa)	f_{bc}	46.68	49.57	53.49	55.02	55.61
Tensile strength (MPa)	f_t	3.32	4.05	5.02	5.95	6.67
Tension cap hardening constant (unit less)	R_t	1	1	1	1	1
Compressive hardening constant (MPa^2)	D	20000	30000	60000	90000	110000
Intersection points between the compression cap and the Drucker–Prager yield function (unit less)	σ_V^C	-31.11	-33.04	-35.66	-36.68	-37.07
Compression cap ratio constant (unit less)	R_C	2	2	2	2	2
Tensile damage threshold (unit less)	Γt	0	0	0	0	0
Compressive damage threshold (unit less)	Γc	2e-5	2e-5	2e-5	2e-5	2e-5
Compression damage evolution (unit less)	βc	4000	2000	2000	2000	2000
Tension damage evolution (unit less)	βt	6000	3000	3000	3000	3000
Nonlocal range parameter (mm^2)	c	900	1225	1225	1225	1225
Over-nonlocal parameter (unit less)	m	2.5	2	2	2	2

4. Results and Discussions

4.1 Workability of Concrete

Slump cone of dimensions 100x200x300mm was used to measure the concrete workability. The slump value is decreased with increasing fiber volume fractions, aspect ratio and decreasing fiber diameter [31]. The M30SF0.0 means conventional concrete of grade 30MPa without SF obtained a slump of 160mm, for M30SF0.5, M30SF1.0 and M30SF1.5 with varying steel fiber dosages of 0.5%,1.0% and 1.5% the slump values were recorded as 145mm,125mm and 90mm respectively as shown in Fig. 2. The steel fiber quantity ranging from 0.5% to 1.5% gradually reduces the workability beyond which it leads to less compaction and create more pores in the concrete.

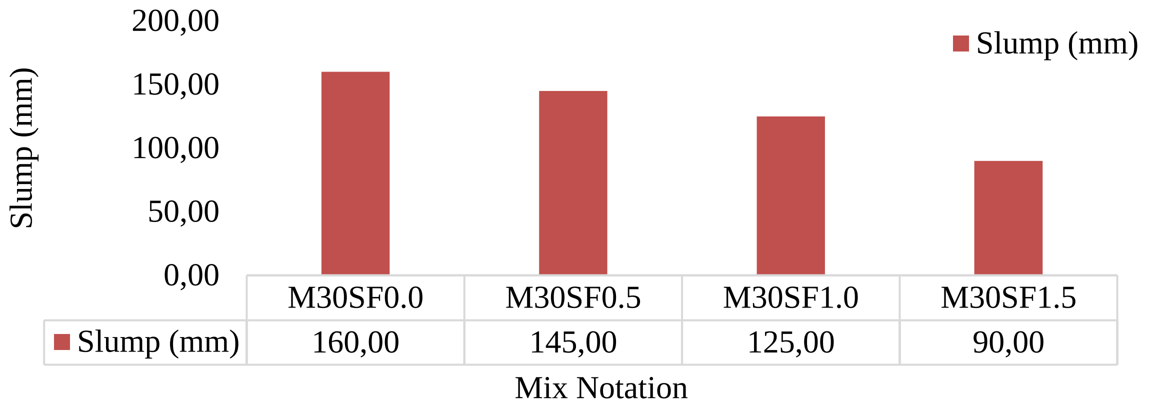


Fig. 2. Slump values of various mixes

4.2 Compressive Strength

The compressive strength values of specimens were determined using 300 Ton Compression testing machine (CTM) as shown in Fig. 3. The inclusion of SF of length 35mm, diameter 0.55mm with an aspect ratio of 63.64, enhance the compressive strength from 6.21% to 17.89% with fiber dosage varying from 0.5% to 1.5%. The ultimate strength of concrete was improved by arresting the crack growth which depends on the bond strength of steel fiber and matrix.

Fig. 3. Testing of cube

Fig. 4. Casting of layered cubes

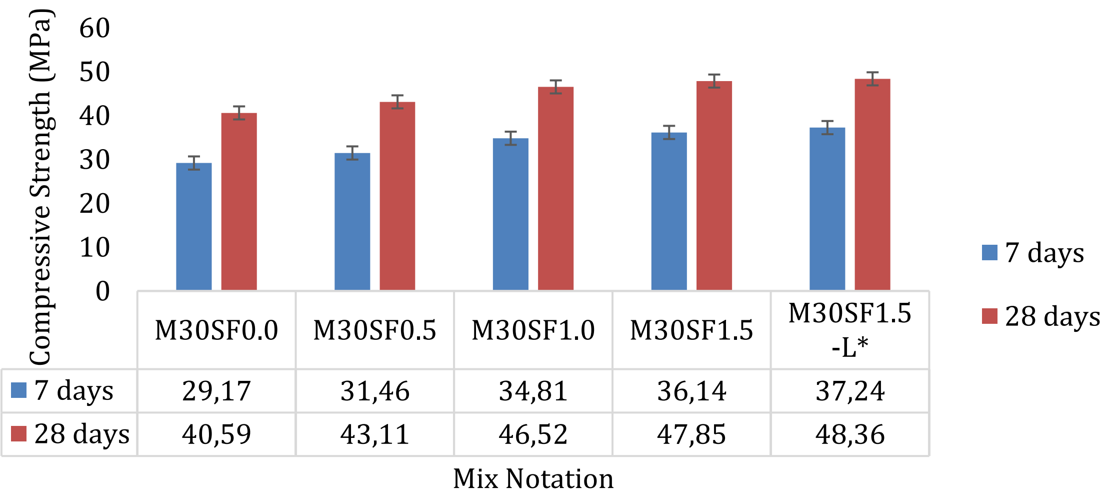


Fig. 5. Compressive strength values of various mixes

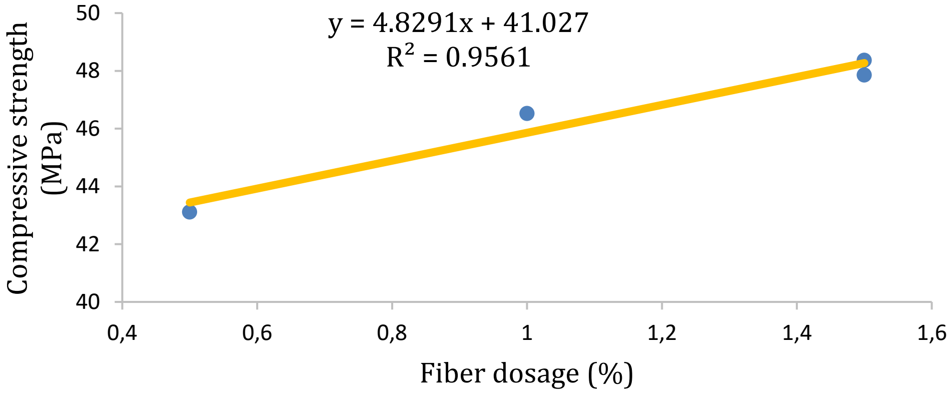


Fig. 6. Relationship between compressive strength vs Fiber percentage

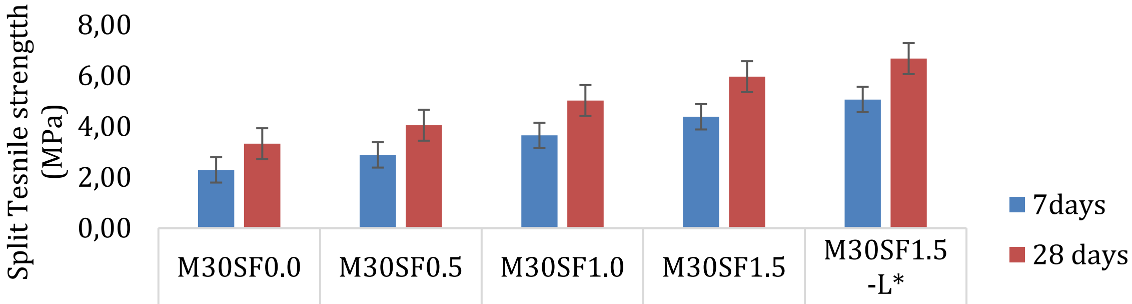
The fiber dosage of 1.5% gives maximum strength which was considered as optimum dosage with which layered concrete cubes were prepared. The cube of depth 150mm was divided into three equal layers of 50mm each. The cubes were cast from the bottom layer with SFRC and each layer was left undisturbed for a duration of 45min [20] before casting the consequent layer. The above procedure was followed for the middle layer with conventional concrete and the top layer with SFRC and the depths were measured using a Ruler as shown in Fig. 4. The strengths of the cube specimens were 37.24 MPa and 48.36 MPa at 7 and 28days respectively as shown in Fig. 5. The illustration depicts the correlation between fiber dosage and compressive strength. The R^2 value of 0.9561 as shown in Fig. 6. Signifies the prediction of compressive strength and fiber dosage of the SFRC.

4.3 Split Tensile Strength

The split tensile strength values of conventional concrete without SF and SFRC were measured using a 300 Ton CTM, as depicted in the Fig. 7. The split tensile strength of conventional concrete without SF was measured at 2.29 MPa and 3.32 MPa for specified time periods. When SF were added at varying dosages of 0.5% to 1.5%, the strength values improved from 21.98% to 79.52% at 28 days. ~~and at 1.5% dosage, maximum strength was attained~~ At 1.5% steel fiber dosage, the cylinders of depth 300mm were cast and partitioned into three levels, each measuring 100mm. The cylinders were fabricated using a three-layer approach, starting with a bottom layer of SFRC, followed by a middle layer of conventional concrete, and then topped with another layer of SFRC and each layer was left undisturbed for a duration of 45min before casting the consequent layer and not more than the initial setting time [20] and the depth was measured using a ruler as shown in Fig. 8. The split tensile strengths of layered concrete were measured to be 5.06 MPa and 6.67 MPa at 7 and 28 days, respectively as shown in Fig. 9.

Fig. 7. Testing of cylinder

Fig. 8. Casting of layered cylinder



	M30SF0.0	M30SF0.5	M30SF1.0	M30SF1.5	M30SF1.5 -L*
7days	2,29	2,88	3,65	4,38	5,06
28 days	3,32	4,05	5,02	5,96	6,67

Fig. 9. Split tensile strength of various mixes

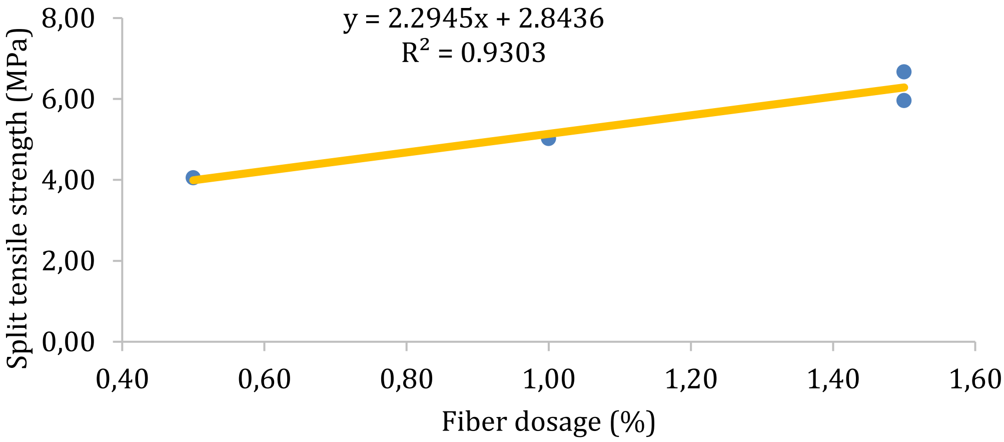


Fig. 10. Relationship between Split tensile strength vs Fiber percentage

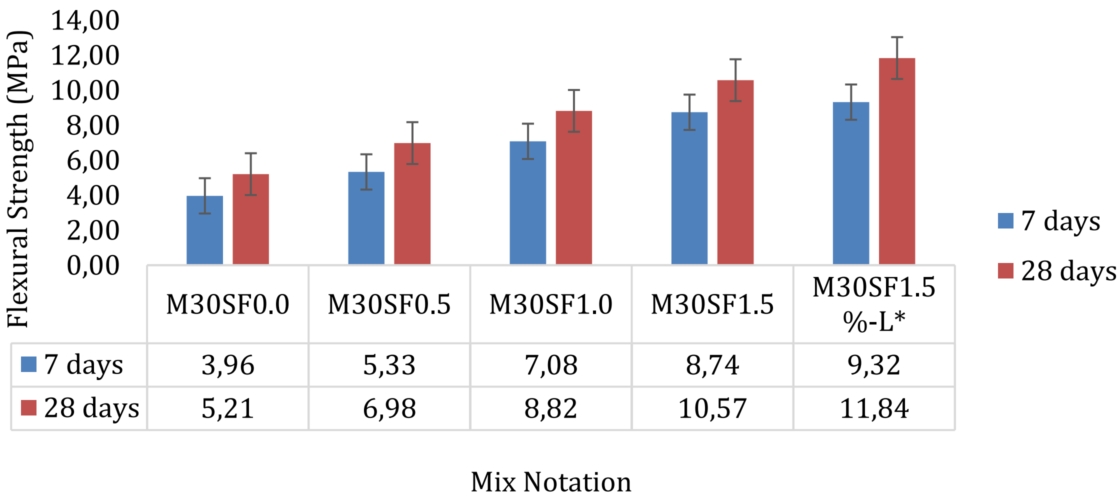
The Fig10. shows the relationship between fiber dosage and split tensile strength. The R^2 value of 0.9303 as shown in Fig. 10. indicates a better prediction of split tensile strength and fiber dosage of the SFRC.

4.4 Flexural Strength

The flexural strength values of conventional concrete and SFRC were using a 100 Ton Universal Testing Machine, as depicted in the and Fig. 11. The flexural strength of conventional concrete without SF was found to be 3.96MPa and 5.21MPa for 7 and 28 days respectively. The inclusion of SF at different dosages of 0.5%, 1.0% and 1.5% resulted in a rise in flexural strength with a percentage of 33.97% to 102.88% at 28 days. The optimum dosage for prisms made with layered concrete is 1.5%, which leads to the highest flexural strength at 7 and 28 days. The prism, which had a depth of 100mm, was divided into three levels, with each level measuring 33.33mm. The prism was constructed utilizing a layered method, beginning with a bottom layer with SFRC, followed by a middle layer with conventional concrete, and then top layer with SFRC and each layer was left undisturbed for a duration of 45min before casting the consequent layer [20] and the depth was measured using a ruler as shown in Fig. 12. The flexural strengths of layered concrete were determined to be 9.32 MPa and 11.84 MPa after 7 and 28 days, respectively as shown in Fig. 13. The Fig14. shows the relation between fiber dosage and flexural strength. The R^2 value of 0.9359 indicates a better prediction for the flexural strength and fiber dosage of the SFRC.

Fig. 11. Testing of Prism

Fig. 12. Casting of layered Prism



	M30SF0.0	M30SF0.5	M30SF1.0	M30SF1.5	M30SF1.5 %-L*
7 days	3,96	5,33	7,08	8,74	9,32
28 days	5,21	6,98	8,82	10,57	11,84

Fig. 13. Flexural strength of various mixes

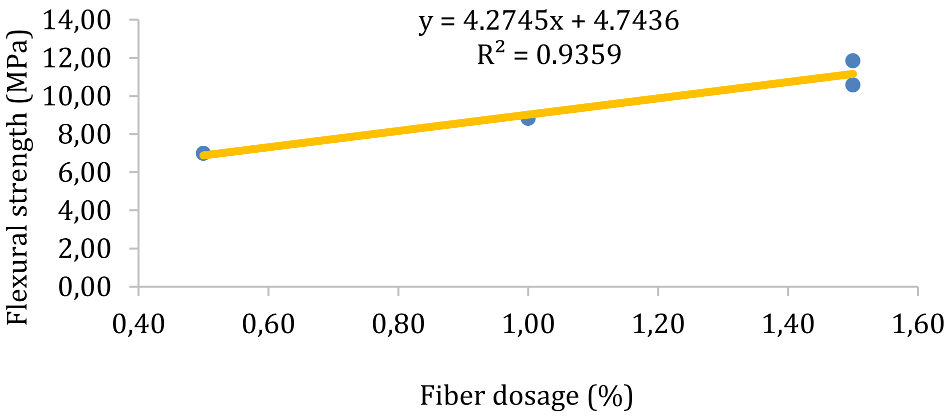


Fig. 14. Relationship between flexural strength vs fiber percentage

4.5 Numerical Validation

FRC is considered as a quasi-homogeneous material which means the fibers are not arranged homogeneously in reality during filling the construction form work, fibers added to concrete mix obtain non-homogeneous distribution. In spite of randomly mixing of fibers, to facilitate modelling it was assumed that the fibers were mixed homogeneously [25].

For the linear analysis of concrete, the modulus of elasticity and Poisson's ratio of the materials are sufficient. However, for the non-linear analysis, the two elastic constants are insufficient; hence, the Drucker-Prager yield parameters are extremely useful for understanding the non-linear behavior of the concrete. The researcher [26] proposed a damage-plasticity micro plane model for analyzing concrete's non-linear behavior, which uses the Drucker-Prager yield parameters listed in the table and includes formulas to calculate these parameters.

Table 5. Load-Deflection values of different types of concretes

S. No	Mix Notation	ANSYS			EXPERIMENTAL	
		Ultimate Load (N)	Deflection (mm)	stiffness	Ultimate Load (N)	Deflection (mm)
1	M30SF0.0	13040	0.31	42420	13025	0.30
2	M30SF0.5	17461	0.41	42944	17445	0.40
3	M30SF1.0	22062	0.48	45630	22051	0.48
4	M30SF1.5	26446	0.56	47343	26425	0.56
5	M30SF1.5-L*	29630	0.61	48733	29600	0.60

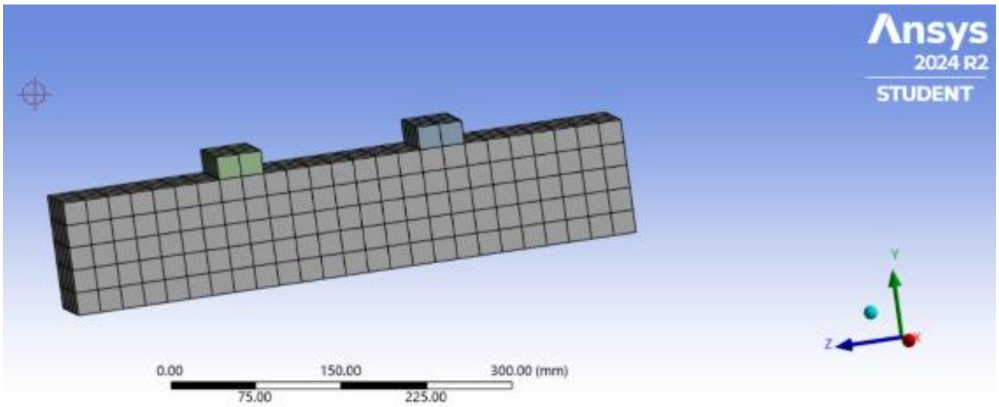


Fig. 16. Meshing of the Prism M30SF0.0

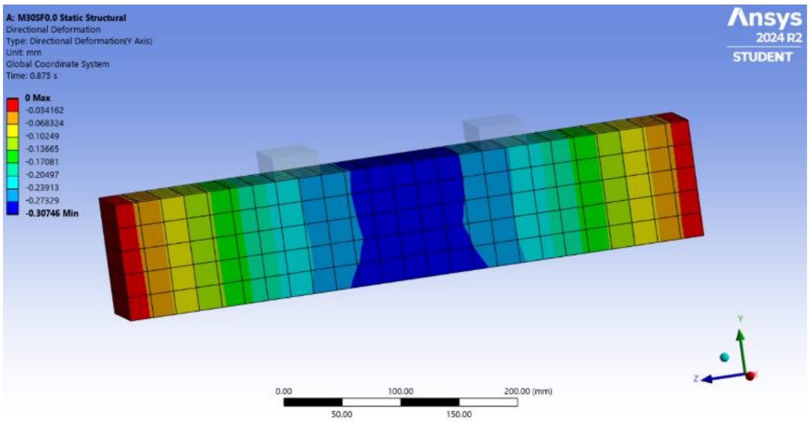


Fig. 17. Deformation of the Prism M30SF0.0

Prisms were tested under four-point loading. The Boundary conditions of the prisms were simply supported, the meshing was done perfectly, all the elements in the meshing are an 8-noded hexahedral elements, and no other element shapes are involved in the meshing. The element metrics reach 1.0 and consist of 1008 nodes and 645 elements as shown in Fig. 16. This analysis is static, and the time step is required to be completed in 1 second.

The M30SF0.0 prisms tested under four-point loading achieves maximum load recorded was 13040 N at a time step of 0.875 s, and the corresponding deflection at that point was 0.31 mm as shown in Fig. 17. Similarly, for M30SF0.5, M30SF1.0, M30SF1.5, and M30SF1.5-L*, the maximum loads were 17461 N, 22062 N, 26446 N and 29630 N at time steps of 0.91 s, 0.915 s, 0.92 s, and 0.98 s and the corresponding deflections were 0.41 mm,0.48 mm,0.56 mm and 0.61 mm respectively as shown in Table 5. The deformation of M30SF0.0 is illustrated in Fig. 17. The boundary conditions were simply supported, exhibiting zero deformation at the supports and maximum deformation was observed near the center of the beam.

5. Conclusions

The mechanical characteristics of conventional concrete without SF were greatly improved by the inclusion of SF in various dosages. The experimental study yielded the following conclusions

- The double-hooked end steel fibers, varying from 0.5% to 1.5% slightly improved the compressive strength upto 17.89% for 28 days.
- The split tensile strength of SFRC was enhanced from 21.98% to 79.52% for fiber dosage ranging from 0.5% to 1.5% compared to conventional concrete
- The flexural strength of concrete was improved by 33.97%, 69.29% and 102.88% for varying percentages of SF. The maximum strength was attained at 1.5%.
- Layered concrete containing SFRC at top and bottom layers respectively and conventional concrete in the middle layer has a compressive strength of 48.36 MPa, split tensile strength of 6.67 MPa and flexural strength of 11.84 MPa at 28days.
- The compressive, split and flexural strengths of layered concrete were enhanced by 19.14%,100.90% and 127.25% to that of conventional concrete.
- Layered concrete subjected to load containing SFRC at bottom layer utilises to repair connections between the transition zone of the aggregate and matrix contact, hence preventing the formation of microcracks at that portion only.
- Linear relation was observed between fiber dosage and compressive strength, split tensile strength and flexural strength with R^2 values of 0.9561,0.9303 and 0.9359 respectively.
- The flexural strength values of prisms were compared both experimentally and numerically. The modelling results have aligned with that of the experimental values in terms of load and deflection.

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