The Impact of Steel Fiber Content on the Durability and Mechanical Properties of Dry Lean Concrete

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Abstract

This research delves into the influence of varying steel fiber percentages on the mechanical properties and durability of Dry Lean Concrete (DLC). By incorporating steel fibers at specific ratios of 0%, 1%, 1.5%, 2.5%, 3.5% by volume, the study meticulously evaluates the resultant improvements in compressive strength, tensile strength, and flexural strength. Through a comprehensive microstructural analysis, the interactions between steel fibers and the cementitious matrix are examined, shedding light on the reinforcing mechanisms at play. The results demonstrate a notable enhancement in mechanical properties up to an optimal fiber content with diminishing returns observed beyond this threshold, likely attributable to fiber clumping and inadequate dispersion. This investigation elucidates the optimal steel fiber content necessary to maximize the mechanical performance and durability of DLC, thus providing crucial insights for its effective application in construction projects. The implications of these findings underscore the potential of steel fiber reinforced DLC in enhancing the longevity and resilience of infrastructure, making it a pivotal consideration for modern engineering practices.

Keywords: Compressive strength, Dry lean concrete, Flexural strength, Scanning electron microscopy, Tensile strength.

Introduction

Concrete has long been esteemed in the construction industry for its unparalleled strength, versatility, and durability. It forms the backbone of modern infrastructure, providing the essential framework for buildings, bridges, roads, and numerous other structures [1-4]. Its inherent capacity to bear immense loads and resist environmental stresses makes it indispensable in achieving the structural integrity required for contemporary engineering marvels. In the sphere of contemporary construction methodologies, concrete has garnered a distinguished reputation as a material emblematic of robustness, adaptability, and longevity [5-6].

Dry Lean Concrete (DLC), a specialized variant of conventional concrete, is predominantly utilized as a sub-base material in pavement construction. Unlike standard concrete, DLC is characterized by a higher aggregate-to-cement ratio, resulting in a mixture with low workability and a relatively dry consistency. The burgeoning demand for resilient, economical, and durable infrastructure has necessitated innovative advancements in construction materials [7-9]. Dry Lean Concrete (DLC), has emerged as a preferred choice due to its cost-effectiveness and structural integrity. However, conventional DLC, having low cement content faces limitations in its tensile strength and resistance to cracking. This is where the inclusion of steel fibers becomes pertinent, warranting comprehensive research to explore its multifaceted benefits. Despite its robust compressive strength and durability, conventional DLC can be susceptible to cracking and reduced tensile strength, especially under dynamic and repetitive loads [10-12]. The incorporation of steel fibers into the DLC mix is a strategic enhancement designed to counteract these deficiencies. Steel fibers, known for their high tensile strength and ductility, are dispersed uniformly within the concrete matrix, creating a composite material with significantly improved performance characteristics. The fibers bridge cracks in the concrete, providing resistance to crack propagation and enhancing the overall toughness of the material [13-17]. This modification is particularly beneficial in applications where the sub-base is subjected to heavy loads and adverse environmental conditions [18].

The aim of this research paper is to meticulously investigate the influence of varying steel fiber content at 0%, 1%,1.5%, 2.5% and 3.5% on the durability and mechanical properties of Dry Lean Concrete (DLC) through comprehensive experimental and analytical methodologies. The study seeks to elucidate the optimal fiber content that maximizes the mechanical performance, including compressive strength, tensile strength, and flexural toughness, as well as improves the durability of DLC. By integrating quantitative assessments and microstructural analyses, the research endeavours to provide critical insights into the reinforcing mechanisms of steel fibers within the concrete matrix and their practical implications for advancing construction practices and materials engineering.

Materials & Methodology

Materials

Cement

Upon obtaining the requisite approval from the Engineer, the following varieties of cement are deemed permissible: i) Ordinary Portland Cement (OPC) in accordance with IS:8112 and IS:12269 ii) Portland Pozzolana Cement (PPC) as per IS:1489 (part 1) iii) Portland Slag Cement (PSC) conforming to IS:455. In scenarios where the subgrade soil harbours soluble sulphates exceeding a concentration of 0.5 percent, it is imperative to utilize sulphate-resisting Portland cement, adhering to IS:12330, or alternatively, Portland slag cement with a slag content of up to 50 percent [20-23]. In this experiment, Ordinary Portland Cement (OPC) 43 grade JK Cement, compliant with IS 8112: 2013 is used & its physical properties are provided below in the Table 1.

Table 1. Cement properties

Material	Test Results	
Cement OPC 43 (IS 8112: 2013)	Company Name	JK Cement
	Specific Gravity	3.14
	Fineness	4%
	Normal Consistency	32%
	Initial Setting Time	71 min
	Final Setting Time	202 min
	Color	Grey

Aggregates

Aggregates utilized in dry lean concrete must adhere to the IS:383 standard and should be natural, non-alkali-reactive aggregates. The content of deleterious materials must remain within the limits prescribed by IS:383. If the aggregates are contaminated with dirt, they must be washed and allowed to drain for at least 72 hours before batching. The water absorption of the aggregates must not exceed 3 percent. The grading of fine aggregate(sand) should comply with grading zones I, II, III, or IV as per IRC:15 or IS:383. Coarse aggregate should be composed of clean, hard, robust, dense, and non-porous pieces of crushed stone or gravel, free from disintegrated stone, and should not include soft, flaky, elongated, very angular, or splintery fragments [24-26]. The maximum size of the coarse aggregate should be 26.5 mm. 20mm & 10 mm coarse aggregates are considered in this investigation. The grading of combined aggregate shall conform to Table 2.

Table 2. Aggregate progression following code IRC SP:49-2014

Sieve Designation	Percentage Passing (by Wt.)
26.50 mm	100
19.00 mm	75-95
9.50 mm	50-70
4.75 mm	30-55
2.36 mm	17-42
600micron	8-22
300micron	7-17
150micron	2-12
75micron	0-1

Table 3. Aggregate physical properties
(as per IS 383: 2016 & IS 2386)

Property	Fine aggregates Results	Coarse aggregate results	Test Method
Grading	Zone II	—	IS 2386 (Part 1)
Fineness Modulus	3.2	—	IS 2386 (Part 1)
Silt Content	1.3%	—	IS 2386 (Part 2)
Specific Gravity	2.63	2.87	IS 2386 (Part 3)
Water Absorption	0.8	0.84	IS 2386 (Part 3)
Bulk Density	1600 kg/m³	2690	IS 2386 (Part 3)
Moisture Content	As per requirement	As per requirement	IS 2386 (Part 3)
Deleterious Materials	nil	nil	IS 2386 (Part 2)
Aggregate Impact value	—	12.54%	IS 2386 (Part 4)
Flakiness Index	—	15%	IS 2386 (Part 1)
Elongation Index	—	17.1%	IS 2386 (Part 1)
Los Angeles abrasion value	—	11.80%	IS 2386 (Part 4)

Admixture

Fly ash, ranging from 15-30%, or Ground Granulated Blast Furnace Slag (GBFS), constituting 25-50% by weight of the cementitious material, may be employed as a partial substitute for Ordinary Portland Cement (OPC) in concrete. It is imperative that all materials are stored appropriately to prevent degradation or contamination by extraneous substances, thereby ensuring their quality and suitability for usage [27]. In this study, a naphthalenebased superplasticizer branded as Conplast was utilized. The specimens were cast using 420 brown in colour and specific gravity 1.185.

Water

Water employed for mixing and curing concrete must be pristine and devoid of deleterious quantities of oil, salt, acid, alkali, sugar, vegetable matter, or other substances detrimental to concrete. It must comply with IS:456 standards. Potable water is typically deemed suitable for these purposes. A pH value of up to 9 is permissible for mixing and curing water [28].The purity and quality of water used are pivotal factors that significantly influence the desired properties and long-term durability of the concrete.

Hooked end steel fibers

It has high tensile strength to provide tighter aggregate interlock which in return provides increased load carrying capacity. Steel fibre length is 60mm average, hook length of 1.5 to 5mm and wire diameter 0.75mm. Concast HSF 8060 is a high-quality, low-carbon steel wire fibre that is cold drawn and monofilament in nature. Made from premium steel bars and continuously deformed for optimal performance, it is specifically designed to reinforce concrete, mortars, and other cement-based mixtures. Tensile strength of steel fibre is 1250, numbers of fibre per kg is 3825± 5% [29].

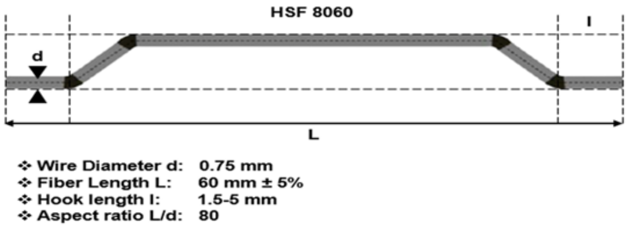

Fig.1 Steel fibre diagram

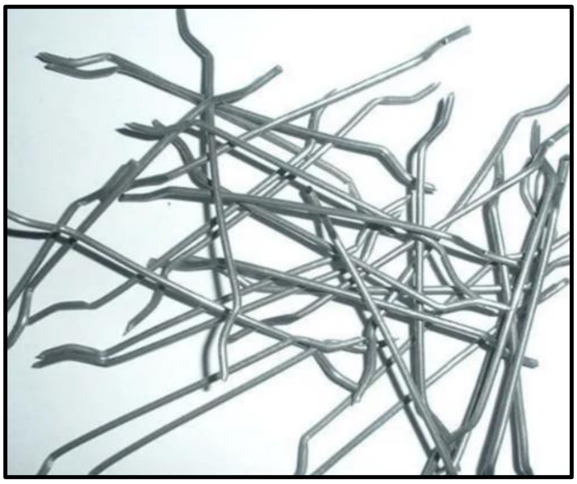

Fig 2. Hook end steel fibre

DLC Design

According to IS Code SP: 49-2014, the design mix used is M7.5, with a cement, fine aggregates, coarse aggregate as the main materials. Table shows the design mix for all specimens. Mix designing of dry lean concrete is done following specification IRC: SP:49-2014 Guidelines for the designing of dry lean concrete [30]. 'Optimum

Moisture Content'(OMC) and 'Maximum Dry Density' (MDD)is obtained by performing modified proctor test as per IS 2720 Part 8. First, physical properties of aggregates and cement are calculated. Second, conducting tests on all individual samples, including Coarse Aggregates (20mm, 10mm) and Fine Aggregates, in accordance with MORTH specifications or other designated IS sieves for DLC.

Table 5. Combined particle size Distribution of 20 mm coarse aggregate Sample

Sieve size (mm)	**Cumulative % of passing**		**Average Cumulative % of passing**	**Range**
	Sample-1	**Sample-2**		
26.5	100	100	100	100
19.0	89	84	86.5	75-95
9.5	67	64	65.5	50-70
4.75	0	0	0	30-55
2.36	0	0	0	17-42
0.600	0	0	0	8-22
0.300	0	0	0	7-17
0.150	0	0	0	2-12

Table 6. Combined Particle Size Distribution of 10 mm coarse aggregate

Sieve size (mm)	**Cumulative % of passing**		**Average Cumulative % of passing**	**Range**
	Sample-1	Sample-2		
26.5	100	100	100	100
19.0	10	100	100	75-95
9.5	94.7	94.13	94.41	50-70
4.75	14.85	16.06	15.45	30-55
2.36	6.69	6.67	6.68	17-42
0.600	1.75	1.82	1.785	8-22
0.300	0	0	0	7-17

0.150	0	0	0	2-12

After grading of individual aggregates, blending all individual items in suitable proportions and try to result will be near to the mid value of upper and lower limit as specified in the code. Blending different sizes of aggregates helps achieve a well-graded mix, which minimizes voids and ensures better packing. This process produces denser and more durable concrete. A well-blended aggregate mix improves the workability of concrete, making it easier to mix, place, and finish. This is crucial for achieving a smooth and uniform surface. Proper blending ensures that the concrete has a balanced distribution of coarse and fine aggregates, which improves its compressive and tensile strength. A well-graded aggregate mix reduces the risk of segregation and bleeding, leading to more durable concrete. By minimizing voids, a well-blended aggregate mix reduces the amount of cement paste required to fill the gaps, leading to cost savings.

Table 7. Blending for Dry Lean Concrete

Ratio of blending	**20 mm**			**10 mm**	**sand**	
	32%			**34%**	**34%**	
Sieve size (mm)	**Avg % of passing**			**% of passing**	**Acceptable limit**	
	20 mm	**10 mm**	**sand**		**Lower limit**	**Upper Limit**
26.5	100	100	100.00	100.00	100	100
19.0	86.5	100	100.00	88.65	75	95
9.5	65.5	94.41	100.00	61.84	50	70
4.75	0	15.45	98.80	35.64	30	55
2.36	0	6.68	94.70	30.65	17	42
0.600	0	1.785	48.40	17.07	8	22
0.300	0	0	31.40	11.63	7	17
0.150	0	0	26.60	9.40	2	12
0.075	0	0	15.30	5.28	0	10

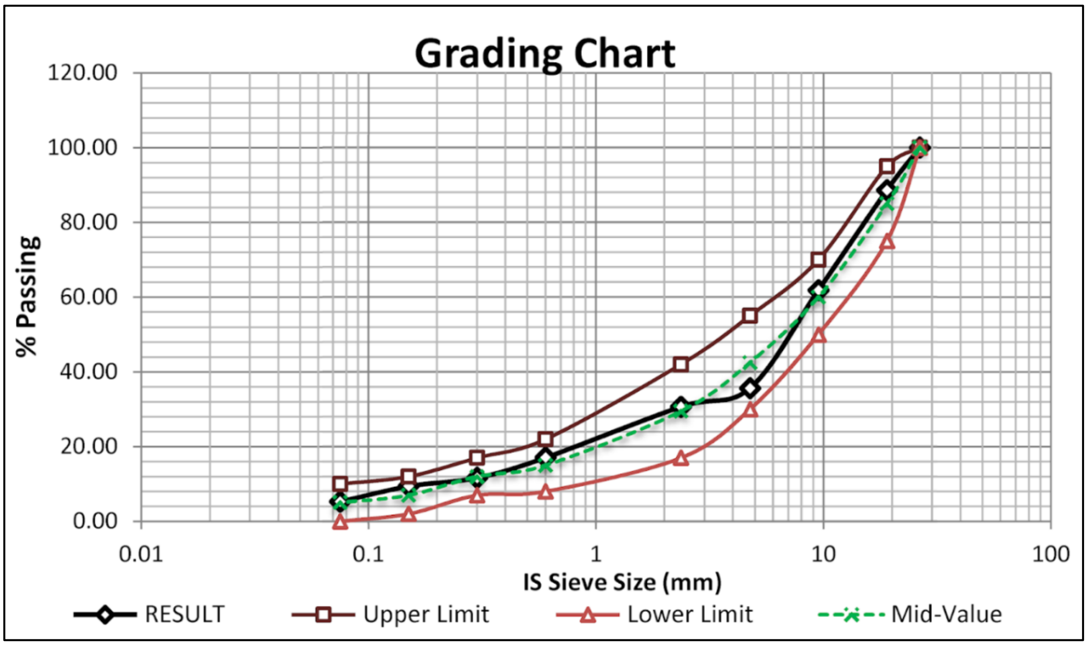

Fig. 3. Gradation Chart of Aggregates

This chart indicates that the results of the percentage of passing lie in between the upper limit and the lower limit.

Aggregate Impact Value Test (IS:2386 Part 4)

The test sample comprises aggregates that pass through a 12.5 mm sieve while being retained on a 10 mm sieve. These aggregates are dried in an oven at 100-110°C for four hours, after which they are allowed to cool. The measure is initially filled about one-third with the aggregate and compacted 25 times using the rounded end of a tamping rod. An equivalent quantity of aggregate is then added and again tamped 25 times. Finally, the measure is filled to the brim, tamped 25 times, and the surplus aggregate is levelled off using the tamping rod as a straight-edge. The net weight of the aggregate in the measure is subsequently determined to the nearest gram (weight A). A cup with an internal diameter of 102 mm and a depth of 50 mm is securely fixed on the machine's base. The entire sample is placed into the cup and compacted with 25 strokes of the tamping rod. The hammer is lifted until its lower face is 380 mm above the top surface of the aggregate in the cup and then allowed to fall freely onto the aggregate. The test sample undergoes a total of 15 blows, each delivered at intervals of no less than one second.
The crushed aggregate is removed from the cup and sieved using a 2.36 mm IS sieve until no substantial amount passes through in a minute. The portion that passes through the sieve is weighed with an accuracy of 0.1 g (denoted as weight B), and the portion retained on the sieve is also weighed (denoted as weight C). If the combined weight of B and C is more than one gram less than the initial weight (A), the result is disregarded, and the test is repeated. Two trials are carried out.

Table 8. Aggregate Impact value

Sample ID	**Initial Weight (A) (g)**	**Wt. passing 2.36 mm sieve(B) (g)**	**Weight Retained on Sieve (C) (g)**	**Total Weight (B + C) (g)**	**Agg. Impact Value (%)**
Sample 1	500	62.8	436.9	499.7	12.56
Sample 2	500	62.5	437.0	499.7	12.54
Sample 3	500	62.7	437.2	499.7	12.52

Average value of AIV = B/ (B +C) × 100 = 12.54%

Hence, it is a strong aggregate.

Aggregate Abrasion Value Test (IS: 2386 (Part 4))

The abrasive charge comprises cast iron or steel spheres, each approximately 48 mm in diameter and weighing between 390 and 445 grams. The test sample consists of clean aggregates, dried in an oven at 105-110°C to attain a nearly constant weight. The test sample and abrasive charge are placed in the Los Angeles abrasion testing machine, which rotates at a speed of 20 to 33 revolutions per minute.

Upon completion of the test, the material is expelled from the machine, and a preliminary separation is conducted using a sieve coarser than 1.70 mm. The finer fraction is then sieved on a 1.70 mm sieve. The material retained on the 1.70 mm sieve is washed, oven-dried at 105-110°C to a near-constant weight, and accurately weighed to the nearest gram. The difference between the original and final weights of the test sample, expressed as a percentage of the initial weight, indicates the percentage of wear.

The Los Angeles Abrasion Value (LAAV)is calculated by:

$$LAA = \frac{\text{Weight of material passing 1.7 mm sieve (B)}}{\text{Initial weight of Sample (A)}} \times 100$$

Table 9. Los Angeles Abrasion Value

Sample ID	Initial Weight (A) (g)	Weight Retained on 1.7 mm Sieve (g)	Weight Passing 1.7 mm Sieve (B) (g)	Los Angeles Abrasion Value (%)
Sample 1	5000	4400	600	12
Sample 2	5000	4450	550	11
Sample 3	5000	4380	620	12.40
Average	-	-	-	**11.80**

Subsequently, trial mixes of dry lean concrete are formulated according to code IRC SP: 49-2014 with water contents of 5.0, 5.5, 6.0, 6.5, and 7.0 percent of the aggregate's total weight. Optimum moisture content and density are determined by casting cubes with varying moisture levels and plotting a moisture-density curve. Here in this experiment, each sample comprises five cubes, casted with water contents of 4.50, 5.62, 6.57 and 7.67 percent.

Table 10. Findings of the Maximum Dry Density and optimum Moisture Content

Particular	Trial-I	Trial-2	Trial-3	Trial-4
Wt. of Mould + Wet Sample gm	12210	12303	12248	12244
Wt. of Wet Sample gm	5883	5976	5921	5917
Wet Density of Sample gm	2.615	2.656	2.632	2.630
Wt. of Container + Wet Sample gm	152.60	140.85	153.46	187.00
Wt. of Container + Dry Sample gm	147.40	135.00	146.00	176.00
Wt. of Container gm	31.81	30.98	32.44	32.60
Wt. of Water gm	5.2	5.8	7.5	11.0
Wt. of Dry Sample gm	115.6	104.0	113.6	143.4
Moisture Content gm	4.50	5.62	6.57	7.67
Dry Density of Sample gm/cc	2.502	2.515	2.469	2.442

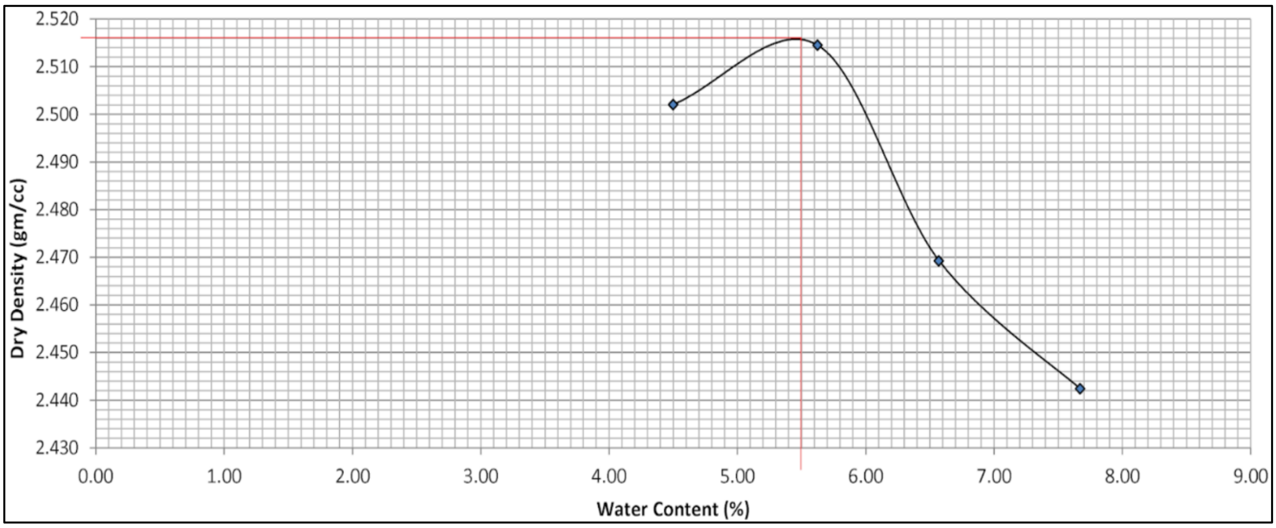

Fig. 4. OMC curve for Maximum Dry Density

From the graph, it is found that **MDD = 2.515** & **OMC = 5.5%.**

Table 11. DLC Mix Proportions

Adopted Aggregate cement ratio = 14:1	Aggregate Blending ratio	Quantity of Individual Aggregate in Mix (kg)
Cement content = 170 kg Total Aggregate = 2380 kg Total Mix weight = 2550 kg	20 mm = 30% 10 mm = 35% sand = 35%	20 mm = 714 kg/m3 10 mm = 833 kg/m3 Sand = 833 kg/m3

Result & Discussion

Compressive strength

Three cubes of each steel fibre content are casted total 15 cubes and then average strength of the three cubes were evaluated after 7 days, 14 days and 28 days respectively given in Table 10. IS 516:1959 guidelines were followed to determine the compressive strength of concrete cubes. The samples were prepared and tested according to the specifications, and the acceptance criteria were followed. At 0% steel fibre content compressive strength was 7.58 MPa. When 0% steel fibre was added in DLC, compressive strength was 8.5 MPa. When 1.5% steel fibre was added to DLC compressive strength increases up to 9.2 MPa which is 8.23% more as compared to conventional DLC i.e. at 0% steel fibre. Similarly, at 2.5 % steel fibre content, compressive strength evaluates up to 10.3 MPa which is 21.17% more as compared to 0% steel fibre reinforced DLC. Ultimately, Compressive strength increase up to its maximum compressive fortitude at 3.5 % steel fibre addition limiting up to 11.5 MPa which is 35.29% more as compared to conventional or 0% steel fibre content DLC cube.

Table 12. Compressive strength

Steel Fibre	Compressive strength, MPa		
	7 days	**14 days**	**28 days**
0%	8.5	10.8	13.0
1%	9.2	11.5	14.0
1.5%	10.3	12.9	15.6
2.5%	11.5	14.1	17.0
3.5%	11.2	13.6	16.4

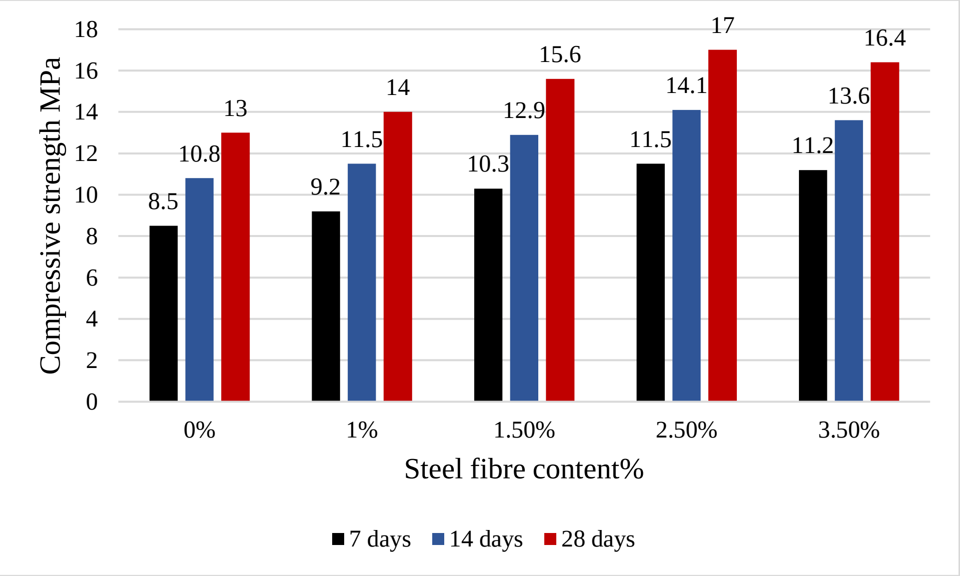

Fig. 5. Graph Comparison of compressive fortitude

Fig 6. DLC cubes before test, during test on CTM and specimen after failure

Flexural strength

The concrete mix is meticulously prepared in accordance with the procedures established for the compressive strength test. The concrete is subsequently deposited into a mould of dimensions 150 × 150 × 700 mm and compacted with a 2 kg tamping bar, 400 mm in length, possessing a 25 mm square ramming surface. The specimen is then positioned in the testing apparatus on two rollers, each measuring 38 mm in diameter and spaced 600 mm apart from centre to centre. The load is applied through two additional rollers of identical diameter, situated at the third points, 200 mm apart from centre to centre. The specimens are immersed in water maintained at 27±3°C for a period of 48 hours prior to testing and are evaluated while still wet. The load is applied continuously and without sudden impact, at a rate of 0.7 N/mm² per minute, until the specimen fails.

Table 13. Flexural Strength

Steel Fiber	**Flexural Strength, MPa**		
	7 days	**14 days**	**28 days**
0%	2.5	3.1	3.8
1%	3	3.5	4.2
1.5%	3.2	3.7	4.5
2.5%	3.4	3.9	4.7
3.5%	3.3	3.8	4.4

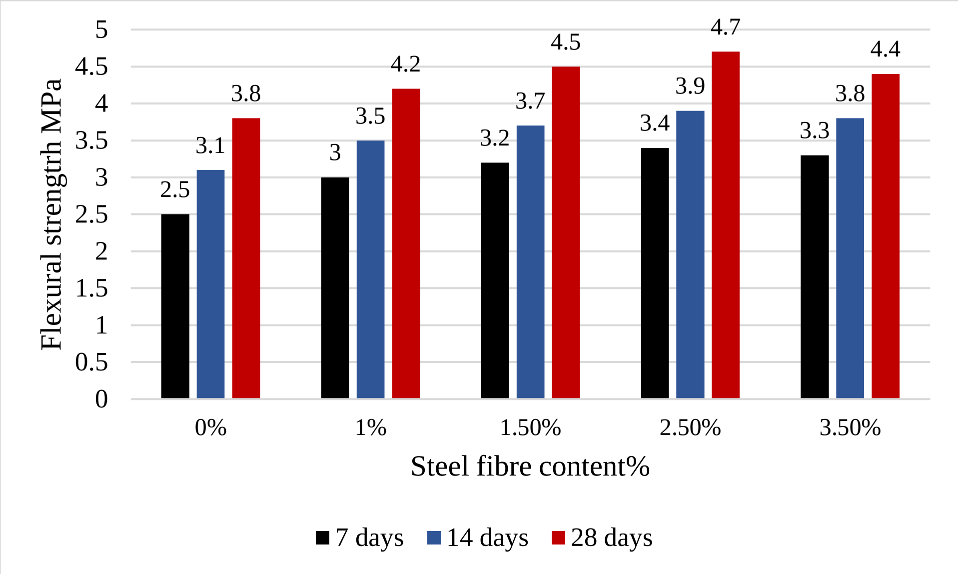

Fig 7. Graph Comparison of Flexural strength

Split Tensile strength

The test involves applying a compressive force to the concrete specimen such that the specimen fails due to induced tensile stresses. The specimen is cylindrical, with a diameter not less than four times the maximum size of the coarse aggregate and not less than 150 mm. The test cylinder has a diameter of 150 mm and a length of 300 mm.

Table 14. Split tensile strength

Steel Fibre	**Split Tensile Strength (MPa)**		
	7 days	**14 days**	**28 days**
0%	1.3	1.9	2.5
1%	1.6	2.2	2.8
1.5%	1.8	2.4	3.1
2.5%	2.0	2.6	3.3
3.5%	1.9	2.3	3.2

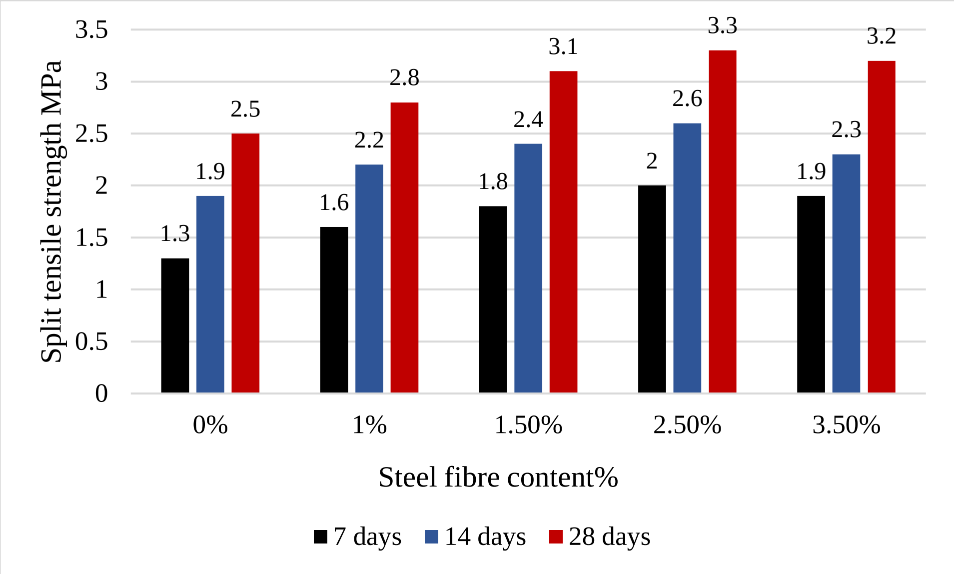

Fig 8. Graph Comparison of Split tensile strength

SEM Study

Scanning Electron Microscopy (SEM) is a powerful tool used to study the microstructural properties of materials, including steel fiber reinforced concrete. SEM uses a focused beam of high-energy electrons to scan the surface of a sample. When the electron beam interacts with the sample, it generates various signals, including secondary electrons, backscattered electrons, and characteristic X-rays. These signals are collected and processed to form highly detailed images of the sample's surface topography and composition. SEM provides high-resolution images that reveal the surface features of the concrete, including the distribution and orientation of steel fibers within the matrix [31]. By examining the microstructure, SEM helps in understanding the bonding between the steel fibers and the concrete matrix, which is crucial for assessing the material's mechanical properties. Coupled with Energy-Dispersive X-ray Spectroscopy (EDS), It can analyse the elemental composition of the concrete, detecting any impurities or variations in the material.

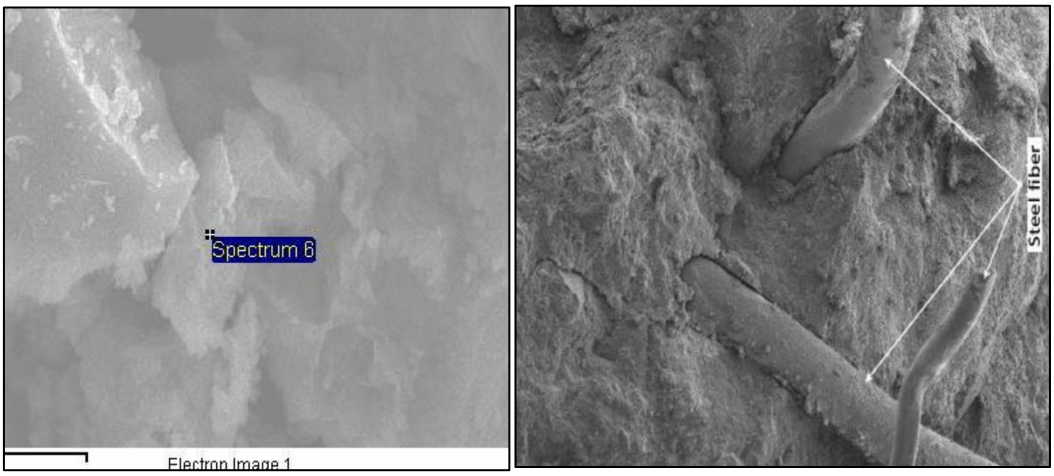

Fig. 9. SEM view at 1 µm

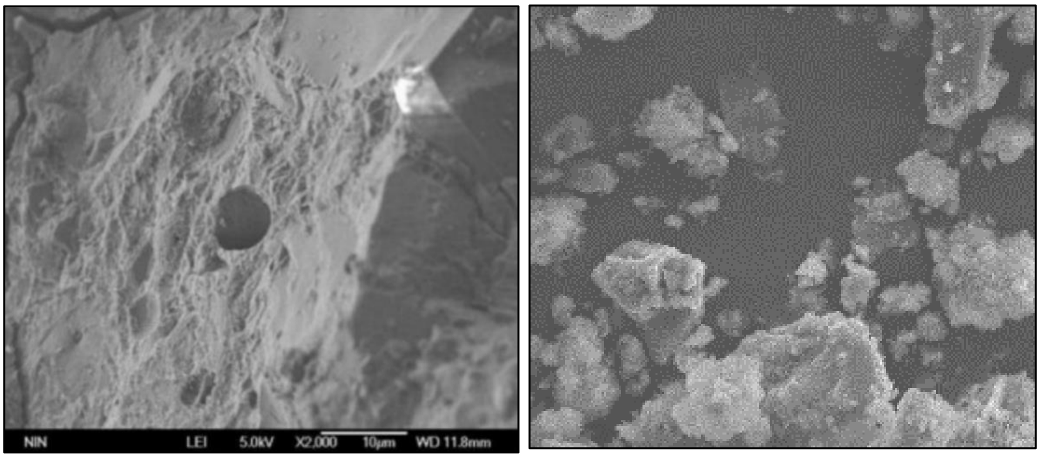

Fig 10. SEM view at 10 µm

Conclusion

This study demonstrated that the inclusion of steel fibers in DLC significantly increases its compressive strength, at minimum fibre content found as 3.5%. In addition to this percentage, no significant gain in strength was observed. This research demonstrates that steel fibre reinforcement significantly advances the mechanical properties and durability of DLC. The SEM study provide valuable insights into the microstructural mechanisms responsible for these improvements. The study contributes to the understanding of fibre-reinforced DLC and highlights the potential of advanced characterization techniques in concrete research.

The presence of steel fibers improves the material's resistance to erosion, freeze-thaw cycles, and other environmental stressors. This makes it an ideal candidate for applications in regions with harsh climates or high traffic volumes. Furthermore, the incorporation of steel fibers can potentially reduce maintenance costs and extend the service life of pavement structures, thereby offering long-term economic benefits.

Future research could investigate the effects of blending steel fibers with synthetic and natural fibers, potentially uncovering synergies that could further enhance the mechanical properties of DLC. Conduct a series of experiments where dry lean concrete specimens are prepared with steel fibers of varying percentages along with incorporating nano materials such as nano silica, nano alumina. Further studies can delve deeper into the use of advanced machine learning algorithms, like neural networks, to refine the prediction models for DLC's mechanical performance, enabling more accurate and efficient mix design optimizations.

References

1. Bentur, A., & Mindess, S. (1990). Fibre Reinforced Cementitious Composites. CRC Press.
2. Banthia, N., & Gupta, R. (2006). Influence of polypropylene fiber geometry on plastic shrinkage cracking in concrete. Cement and Concrete Research, 36(7), 1263-1267.
3. Li, V. C. (2003). On engineered cementitious composites (ECC). Journal of Advanced Concrete Technology, 1(3), 215-230.
4. Markovic, I. (2006). High-performance hybrid-fibre concrete: Development and utilisation. Doctoral dissertation, Delft University of Technology.
5. Mo, Y. L., & Peng, L. (2001). Fiber-reinforced concrete containing steel fibers under dynamic impact. Cement and Concrete Research, 31(6), 931-936.
6. Ganesan, N., Indira, P. V., & Santhakumar, A. (2007). Engineering properties of steel fiber reinforced geopolymer concrete. Construction and Building Materials, 23(6), 2180-2187.

7. Thomas, J., & Ramaswamy, A. (2007). Mechanical properties of steel fiber-reinforced concrete. Journal of Materials in Civil Engineering, 19(5), 385-392.
8. Aghdasi, P., Alhosseini, S., & Yazici, H. (2017). Performance of steel fiber-reinforced concrete under impact loading. Materials and Structures, 50(5), 229.
9. Khaloo, A. R., & Afshari, M. (2005). Flexural behavior of small steel fiber reinforced concrete slabs. Cement and Concrete Composites, 27(1), 141-149.
10. Yazıcı, Ş., İnan, G., & Tabak, V. (2007). Effect of aspect ratio and volume fraction of steel fiber on the mechanical properties of SFRC. Construction and Building Materials, 21(6), 1250-1253.
11. Mazaheripour, H., Ghanbarpour, S., Mirmoradi, S. H., & Hosseinpour, I. (2011). The effect of polypropylene fibers on the properties of fresh and hardened self-compacting concrete. Construction and Building Materials, 25(6), 3510-3517.
12. Beaudoin, J. J., & Ramachandran, V. S. (1996). Handbook of analytical techniques in concrete science and technology: principles, techniques, and applications. William Andrew.
13. Balaguru, P., & Shah, S. P. (1992). Fiber reinforced cement composites. McGraw-Hill.
14. Aoude, H., Belghoul, Y., & Mamdouh, H. (2017). Durability of steel fiber reinforced concrete containing different levels of recycled concrete aggregate. Construction and Building Materials, 147, 446-456.
15. Naaman, A. E. (1994). Fiber Reinforced Cement and Concrete Composites. CRC Press.
16. Çavdar, A. (2012). A study on the effects of silica fume and steel fibers on the mechanical properties of high strength concrete. Materials & Design, 33, 267-274.
17. Zhang, J., & Stang, H. (1998). Application of stress crack width relationship in predicting the flexural behavior of fiber-reinforced concrete. Cement and Concrete Research, 28(3), 415-422.
18. Sharma, A., Siddique, R., & Gupta, T. (2018). Durability properties of concrete made with high-volume bottom ash as fine aggregate. Journal of Cleaner Production, 170, 808-818.
19. Shah, S. P., & Rangan, B. V. (1970). Fiber reinforced concrete properties. Journal Proceedings, 67(8), 539-551.
20. Alsadey, S. (2013). Effect of polypropylene fibers on fresh and hardened properties of concrete. Journal of Engineering Research and Applications, 3(5), 66-69.
21. Zollo, R. F. (1997). Fiber-reinforced concrete: an overview after 30 years of development. Cement and Concrete Composites, 19(2).
22. IRC: SP:49-2014 Guidelines for the use of Dry Lean Concrete as sub-base for rigid pavement.
23. Gettu, R., & Marikunte, S. (1998). *Mechanical Properties of High-Strength Steel Fibre-Reinforced Concrete*. *ACI Materials Journal*, 95(6), 611-617.
24. IS 8112-2013: 43 grade Ordinary Portland Cement-Specification (Second Revision).
25. IS 383: Coarse and fine aggregate for concrete – specification, Bureau of Indian Standards (2016).
26. IS 456: Plain and Reinforced Concrete - Code of Practice, Bureau of Indian Standards (2000).
27. IS 2720-8 (1983): Methods of test for soils, Part 8: Determination of water content-dry density relation using heavy compaction.
28. Lee, Seunghye, et al. "Super learner machine-learning algorithms for compressive strength prediction of high-performance concrete." *Structural Concrete* 24.2 (2023): 2208-2228.
29. Błaszczyński, Tomasz, and Marta Przybylska-Fałek. "Steel fibre reinforced concrete as a structural material." *Procedia Engineering* 122 (2015): 282-289.
30. Kang, Min-Chang, Doo-Yeol Yoo, and Rishi Gupta. "Machine learning-based prediction for compressive and flexural strengths of steel fiber-reinforced concrete." *Construction and Building Materials* 266 (2021): 121117.
31. Lee, Seunghye, et al. "Super learner machine-learning algorithms for compressive strength prediction of high-performance concrete." *Structural Concrete* 24.2 (2023): 2208-2228.