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Structural Performance of Concrete: Exploring the Limits of Steel Fiber Reinforcement

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Abstract:
Concrete is one of the most extensively utilized construction materials today. Its popularity stems from its ready availability, ease of moulding into various shapes, cost-effectiveness, and high compressive strength. Despite these advantages, concrete is known for its low tensile strength and poor performance in harsh conditions, which is a significant drawback for any construction material. To mitigate these weaknesses, concrete is typically combined with steel reinforcement. Steel fibers are added to concrete to improve the structural properties, particularly tensile and flexural strength. Plain, straight and round fibers were found to develop very weak bond and hence low flexural strength. In this research, steel binding wires were used as steel fibers which are locally available at very cheap cost. Steel fibers were added in different percentage i.e. 0%, 0.5 %, 1%, 1.5%, 2%, 2.5% and 3%. The primary focus of the research was to calculate compressive and tensile strengths of various samples and determine the maximum amount of Steel fibers that can provide the maximum strength. To achieve this, cubes and cylinders were cast and tested using a Universal Testing Machine for their compressive and tensile strengths. The findings indicated a slight increase in compressive strength, while the addition of steel fibers resulted in a more significant increase in tensile strength.

Keywords: “construction materials”, “tensile strength”, “steel fibers”, “flexural strength”, “concrete”

I. INTRODUCTION

The backdrop for this report is the current challenges faced by the building industry, including a decline in the recruitment of skilled labor and the ongoing demand for efficiency improvements. These challenges have spurred research into more efficient construction methods, leading to a growing interest in fiber-reinforced concrete (FRC). An advantage of FRC is its ability to accommodate more complex casting mold geometries. The report begins with a literature review to highlight the various properties and behaviors of fiber-reinforced concrete. The use of SFRC mix designs aims to maintain material integrity by increasing the initial crack strength and using numerous fibers to intercept micro-cracks, thereby preventing their propagation by controlling tensile strength. Unlike rebar and welded wire fabric, fibers are distributed throughout the slab, providing isotropic reinforcement and eliminating weak planes for cracks to follow. Steel fiber reinforcement (SFR) involves adding small, discrete steel fibers to concrete to enhance its mechanical properties. These fibers are typically short, typically between 25 to 50 mm in length, and can be straight or deformed. Steel fibers improve the toughness of concrete by controlling crack propagation. They act to bridge micro-cracks that develop in the concrete, thereby enhancing its ability to resist cracking under various loading conditions. Steel fibers contribute to the flexural and impact strength of concrete. This is particularly beneficial in applications where the concrete is subjected to bending or impact loads, such as in industrial floors and pavements. The use of steel fibers provides greater design flexibility, allowing for thinner concrete sections without compromising on structural integrity.

Fibers are usually used in concrete to control plastic shrinkage cracking and drying shrinkage cracking. They also lower the permeability of concrete and thus reduce bleeding of water. Some types of fibers produce greater impact, abrasion and shatter resistance in concrete. Generally fibers do not increase the flexural strength of concrete, so it cannot replace moment resisting or structural steel reinforcement. Some fibers reduce the strength of concrete (S et al., 2022). Amit Rai et al. (2008) investigated how micro-cracks in conventional concrete develop before the structure is loaded, often due to drying shrinkage and other volume changes. The addition of fibers helps transfer the load to these internal micro-cracks. As the structure is loaded, the micro-cracks open and propagate, leading to inelastic deformation in the concrete. Fiber-reinforced concrete (FRC) consists of a cementitious concrete mixture reinforced with small fibers distributed more or less randomly. The inclusion of steel fibers can enhance structural strength, thereby reducing the need for heavy steel reinforcement. R. D. Neves and J. C. O. Fernandes de Almeida (1991) conducted an experimental study to examine the impact of matrix strength, fiber content, and diameter on the compressive behavior of steel fiber-reinforced concrete. They tested two types of matrices and fibers. The results indicated that adding fibers to concrete increases its toughness and the strain at peak stress, although it can slightly reduce the Young's modulus. Behbahani et al. (2011) defined Steel fibre as discrete, short length of steel having ratio of its length to diameter (i.e. aspect ratio) in the range of 20 to 100 with any of the several cross-sections, and that are sufficiently small to be easily and randomly dispersed in fresh concrete mix using conventional mixing procedure. The first experimental work on fiber reinforced concrete in the United States was conducted in 1963 by Romualdi and Batson (1963). Since then, the use of steel fiber reinforced concrete (SFRC) has progressively gained popularity in civil engineering constructions worldwide (Meda et al., 2012). Steel fibers are preferred over other fiber materials due to their stiffness, which enhances the ductility characteristics of reinforced concrete (Michels et al., 2012). SFRC offers improvements in fatigue resistance, shock resistance, ductility, and crack arrest, while also achieving higher tensile and flexural strengths (Kawde & Warudkar, 2017). Fibers play an important role in reaching a definite load bearing capacity after the matrix fracture, depending on allocation, orientation and embedded length (K et al., 2010).

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II. METHODOLOGY

1. Materials:

The materials used in this research included coarse aggregate (20-25 mm), fine aggregate (sand, 75 microns to 4.75 mm), cement, water, and steel fibers. Locally available coarse and fine aggregates were utilized. The coarse aggregate had a fineness modulus of 6.1, while the fine aggregate (sand) had a fineness modulus of 2.72. The steel fibers, a crucial component of the mix, were obtained by cutting locally available steel binding wires into small pieces, 80 mm in length with a diameter of 1 mm, resulting in an aspect ratio of 80. The equipment used in this study included a tamping rod for compaction, a mixing tray for concrete mixing, molds (150x150x150 mm for compressive strength tests and 300 mm height by 150 mm diameter for tensile strength tests), a universal testing machine, and a water tank for curing.

Fig. 1: cutting steel wires into 80mm length

2. Concrete mix proportions

A concrete mix ratio of 1:1.5:3 (cement: sand: aggregate) and a water-cement (w/c) ratio of 0.5 were used for all the samples. The only variable was the percentage of steel fiber. The mix proportions are detailed in Tables I and II. In total, 15 cubes and 21 cylinders were prepared for compressive strength and tensile strength tests, respectively. Seven different types, each with varying percentages of steel fibers, were created, with three samples made for each type.

Table I: Concrete Mix Proportion for cubes

S.N.	No. of samples	Cement (kg)	Sand (kg)	Aggregate (kg)	Water (kg)	Steel Fiber (%)
1	3	2.65	3.97	7.95	1.33	0
2	3	2.65	3.97	7.95	1.33	0.5
3	3	2.65	3.97	7.95	1.33	1
4	3	2.65	3.97	7.95	1.33	1.5
5	3	2.65	3.97	7.95	1.33	2

Table II: Concrete Mix Proportion for cylinders

S.N.	No. of samples	Cement (kg)	Sand (kg)	Aggregate (kg)	Water (kg)	Steel Fiber (%)
1	3	4.16	6.24	12.48	2.08	0
2	3	4.16	6.24	12.48	2.08	0.5
3	3	4.16	6.24	12.48	2.08	1
4	3	4.16	6.24	12.48	2.08	1.5
5	3	4.16	6.24	12.48	2.08	2
6	3	4.16	6.24	12.48	2.08	2.5
7	3	4.16	6.24	12.48	2.08	3

3. Mixing of concrete with steel fibers

The dry cement and aggregates were hand-mixed in a tray for five minutes. Mixing continued for a few more minutes while approximately 80% of the water was added. Afterward, mixing continued for another few minutes as the fibers were gradually incorporated into the concrete over 2–3 minutes while stirring. Finally, the remaining water was added, and mixing proceeded for an additional two minutes. This process ensured the complete distribution of fibers throughout the concrete mix.

4. Compaction

After proper mixing, the moulds were oiled to reduce friction during the moulding and de-moulding of the concrete specimens. The concrete was then cast in three layers. Each layer was compacted using a tamping rod before adding the next layer. The surface was levelled after the final layer. After 24 hours, the specimens were de-moulded.

5. Curing

The specimens were kept in water tank for next 28 days and compressive strength and tensile strength test were performed.

In case of compressive strength test, the ultimate load was noted for every sample of each type of concrete and the ultimate strength calculated. The ultimate load from UTM was noted in tons which later converted to MPa (Mega Pascal). In case of tensile strength test, Ultimate loads were noted for each specimen of every category of concrete. Load was then applied (recorded in tons). The formula used for calculation of tensile strength is:

Tensile Strength = 2P/ (pi*l*d)

Where, Ultimate load = P

Diameter (d) = 150 mm

Length (l) = 300mm

Fig. 2: Splitting tensile test of cylinder

Fig.3: cylinder in two halves at failure

III. RESULT AND DISCUSSION

Table III: Compressive strength of cubes

Steel Fiber (%)	Compressive Strength (Mpa)	Average Compressive Strength (Mpa)	Coefficient of Variance (%)
	18.9		
0	19.4	19.2	1.38
	19.3		
	20.12		
0.5	20.05	20.36	2.35
	20.91		
	20.8		
1	21.88	21.39	2.55
	21.48		
	21.9		
1.5	20.9	21.7	3.32
	22.3		
	18.6		
2	19.87	19.39	3.56
	19.7		

Table IV: Splitting tensile strength of cylinders

Steel Fiber (%)	Tensile Strength (Mpa)	Average Tensile Strength (Mpa)	Coefficient of Variance (%)
	2.28		
0	2.33	2.29	1.57
	2.26		
	2.6		
0.5	2.55	2.55	9.55
	2.5		
	2.75		
1	2.68	2.76	2.74
	2.85		
	2.9		
1.5	3.2	3.07	2.98
	3.1		
	3.4		
2	3.45	3.42	4.20
	3.4		
	3.6		
2.5	3.6	3.65	1.69
	3.75		
	3.15		
3	3.1	3.18	3.27
	3.3		

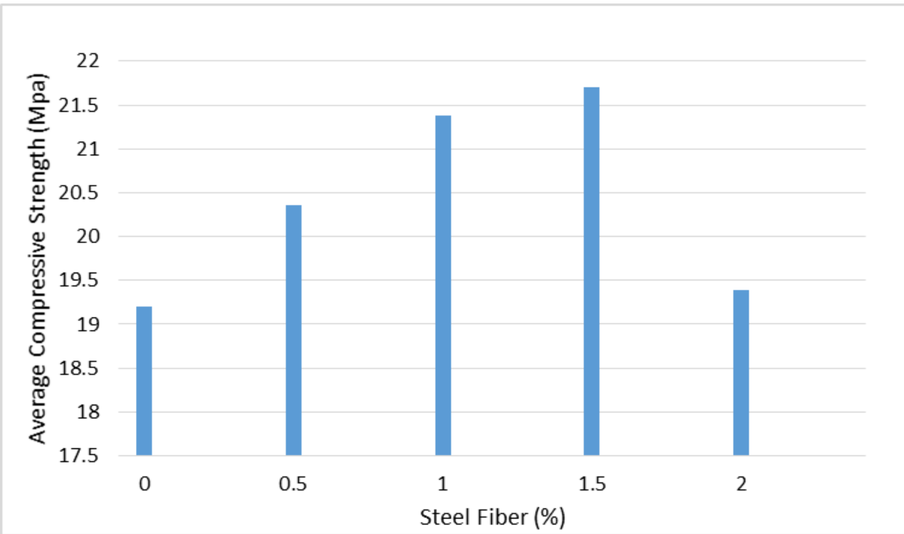

Fig.4: Steel fiber (%) vs Average Compressive strength (Mpa)

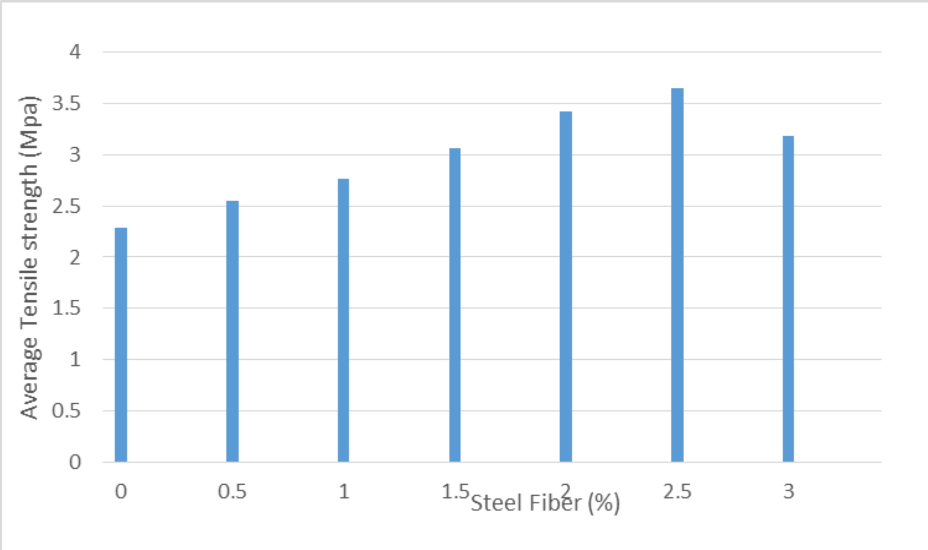

Fig.5: Steel fiber (%) vs Average Tensile strength (Mpa)

Fig.4 shows increase in compressive strength while increasing percentage of steel fibers to 1.5 % and decrease after that. When the samples of 0.5% fibers are compared with the samples with no steel fibers, it can be easily assessed that there is an increase in compressive strength, though the increase is not so prominent. Comparing the samples of 1.5% fibers and no steel fibers, there is increase in strength by 13 %.

Fig. 5 shows increase in tensile strength while increasing Percentage of steel fibers to 2.5% and decrease after that. When the samples of 0.5% fibers are compared with the samples with no steel fibers it was observed that there is increase in Tensile strength by 11.4%. While increasing the percentage of fibers from 0 to 2.5% significant increase of 59.4 % in Tensile strength is observed.

IV. CONCLUSION

Following conclusions were determined in this study:

- Fiber reinforced concrete cubes exhibited higher compressive strength compared to normal concrete.
- The compressive strength increased by 6.04% to 13% with the addition of steel fibers in the concrete mix, ranging from 0.5% to 1.5%.
- Tensile strength of concrete cylinders showed significant improvement, ranging from 11.4% to 59.4%, with steel fiber content increasing from 0.5% to 2.5% in the mix.
- Steel fibers in fiber reinforced concrete cubes and cylinders provided a robust mechanical interlocking force, enhancing matrix cohesion. Concrete samples with steel fibers remained intact even after failure loading, while those without fibers split into large pieces post-failure.
- The optimal steel fiber content was found to be 1.5%, effectively enhancing tensile properties without compromising compressive strength.
- Steel binding wires demonstrated considerable impact in tensile testing similar to steel fibers and are also cost-effective.

Many researches have different approach to steel fiber reinforcement and majority proposed that adding steel fibers with hooked ends to regular concrete typically improves various strengths noticeably. But it has been found in this research that the highest gain in concrete strength depends on the fiber content. Depending on the strength, a different amount of fiber should be added for that strength. As the fiber content rises, the failure mode shifts from brittle to ductile when squeezed and bent. Therefore, the study encouraged the use of fiber reinforcement in place of the conventional steel bars in low cost structural construction.

In over site concrete, it can be applied successfully to minimize the effects of thermal cracking, short columns, short beams, and narrow spanning slabs with fewer loads to transport. Further study on the use of steel fiber for reinforcing high-rise building structural elements, such as long columns, long beams, and broader spanning slabs, is advised.

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