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Original Research Article

Fibre reinforcement strategies for enhancing ductile behaviour in concrete elements

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Abstract: Steel is costly and detrimental to the environment when used as a reinforcement. Another technique for reinforcing concrete is fibre reinforcement. Fibre is a small amount of reinforcing material with specific properties. Fibre-reinforced concrete has several uses and is available in several shapes. Cellulose fibre, glass fibre, steel wire fibre and steel raw material have the following percentages: 0.5%, 0.7%, and 1%; 0.3%, 0.6%, and 1%; and 0.5%, 1%, and 1.5%, respectively. Specific percentages of different fibres, ranging from 0.3% to 1.5%, are employed in this study to assess the ductile behaviour of concrete since the primary objective of utilising these fibres is to enhance the ductile qualities of concrete. The fibre-added specimens are subjected to four distinct kinds of tests. It has been demonstrated that concrete's flexural strength, split cylinder strength, and double punching strength have increased by up to 28%, 60%, and 93%, respectively, compared to the control mix concrete. Steel and raw material fibre exhibited no detrimental impacts on compression at certain percentages; however, glass fibre and cellulose fibre reinforcements had detrimental effects, reducing the compressive strength by up to 33.5% and 49.3%, respectively.

Keywords: Double punching strength, Split cylinder strength, Ductility, Steel, Glass fibre, Raw material, Elasticity.

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1. Introduction

Concrete is one of the most often used building materials. Its global usage is double that of aluminium, steel, wood, and plastics combined, ton for ton. Plain concrete buildings and reinforced concrete buildings are the two primary types of concrete construction (Thomassen, 2013; Baker, 2018; Soni *et al.*, 2022; Zhao *et al.*, 2022). PCC may be poured and cast without the need for reinforcement. This is used when the structural component is not bent and is solely exposed to compressive stresses (Mali & Datta, 2019). Reinforcements are required to withstand tension stresses when the component is bent since a structural element is far weaker in tension than in compression (Lee *et al.*, 2016). The tension strength of concrete is typically just 10% of its compression strength (Fehling *et al.*, 2011). Concrete dwellings, industrial buildings, roadways, tunnels, skyscrapers, bridges, walkways, superhighways, dams, and multistorey buildings are just a few of the structures that use it. The Hoover Dam, Panama Canal, and Roman Pantheon are famous examples of enormous concrete structures. Concrete is the most considerable material used in the construction that has been produced by the mankind (Lorinc, 2022).

Sales of ready-mix concrete, which accounts for the largest share of the worldwide concrete industry, are predicted to reach over $600 billion by 2025. The ecology suffers from this widespread use in several ways. Most notably, cement manufacture generates a considerable quantity of greenhouse gas emissions, which comprise about 8% of global emissions. Many studies are being conducted to try to reduce emissions or make concrete a source of carbon sequestration (Kajaste & Hurme, 2015; Miller *et al.*, 2021). Additional environmental problems include widespread illicit sand mining, environmental impacts including increased surface runoff or the urban heat island effect, and potential health concerns to the general population from toxic components. Concrete may also aid in lowering pollution from other sources by absorbing contaminants such as coal fly ash or bauxite tailings and residue.

Fibres are typically used in concrete to stop plastic shrinkage cracking and drying shrinkage cracking. They also reduce concrete permeability, preventing water leaks (Islam & Gupta, 2016; Kayondo *et al.*, 2019; Aghaee & Khayat, 2021; George & Paul, 2021). Certain types of fibres provide concrete with greater resistance to impact, abrasion, and breaking. Fibres can't replace structural steel reinforcement or moment-resisting reinforcement since they frequently don't increase the flexural strength of concrete. Certain fibres reduce the strength of concrete (Shah & Ribakov, 2011; Mobasher *et al.*, 2015; Al-Osta *et al.*, 2016). The volume fraction typically ranges from 0.1 to 3% and represents the percentage of fibres added to a concrete mix about the overall volume of the composite (concrete and fibres). An analogous diameter is used to compute the aspect ratio for fibres with a non-circular cross-section.

Fibres with a higher modulus of elasticity than the matrix (concrete or mortar binder) assist support the weight by increasing the material's tensile strength. As the fibber's aspect ratio rises, the matrix's flexural strength and toughness are frequently divided. However, very long fibres might "ball" in the mixture, making it difficult to work with. According to several recent investigations, adding fibres to concrete has little effect on the materials' resistance to impacts. This finding is important since fibre-reinforced concrete is commonly believed to become more ductile.

The subsequent objectives pertaining to the research is to investigate the characteristics of conventional concrete utilising fibre reinforcing and to conduct a comparative analysis and also the study follows the determined impact of fibre reinforcing on concrete parameters such as tensile strength, flexural strength, compressive strength, and split tensile strength. Glass fibre comprises small glass fibres dispersed inside a cementitious matrix consisting of cement, sand, water, and additives. It has been widely employed in the construction industry for non-structural elements such as channels, pipelines, and façade panels. GRC has several advantages such as durability, aesthetic appeal, fire resistance, and lightweight properties. This study conducts trial tests with cubes of varying dimensions to assess the compressive and flexural strengths of concrete with and without glass fibre.

GFRC exhibits significant potential as an alternative construction material, as evidenced by the study's diverse applications, experimental findings, techno-economic evaluations against other materials, and financial analyses (Shakor & Pimplikar, 2011). The study aims to evaluate the impact of cellulose fibre on fibre-reinforced mortar composites' mechanical properties. The influence of fibre length and content on mechanical properties was evaluated by a factorial design with a central point. The results indicated that the composites improved their flexural strength. The exceptional interaction between cellulose fibre and cement resulted in the most significant modulus of elasticity (De Pellegrin *et al.*, 2019). This pertains to polymer concrete, a composite material composed of aggregates and resin. The aggregates in the present study were adhered to using epoxy adhesive. The cellulose fibres were included in the mixture adjacent to the fly ash, which served as filler. The mechanical parameters of Fibre-Reinforced Polymer (FRP) concrete, such as split tensile strength, flexural strength, and compressive strength, were analysed. Although the filler dosages and epoxy resin varied, the fibre ratio remained the same.

Compared to polymer concrete devoid of cellulose fibres, the mechanical characteristics of the former were not improved by the inclusion of cellulose fibres (Barbuta & Harja, 2008). The major objective of the research is to investigate the effects of steel and glass fibres in concrete. FRC's fire resistance and high tensile strength result in less damage during fire events. This study conducts strength tests to compare concrete composed of steel fibres with that made of glass fibres. For M20 grade concrete, the Fibre Reinforcement Concrete (FRC) is included at 0.5%, 1%, 2%, and 3% concentrations. The results indicate the 28-day percentage increase in split tensile strength, flexural strength, and compressive strength (Arunakanthi & Kumar, 2016). This provides methods for predicting fracture widths and deflections in GFRP-reinforced beams. The impact of FRP reinforcement ratios and the elastic modulus of FRP were incorporated into the exponent m of Branson's equation to apply the effective moment of inertia for concrete beams reinforced with GFRP bars. A formula for forecasting deflections was developed utilising the flexural stiffness of GFRP-reinforced concrete. A theoretical correlation for predicting fracture breadth was proposed based on this and other experiments. Experiments were performed on six concrete beams reinforced with different amounts of GFRP. The proposed models were compared with their observed fracture widths and deflections. The models' predictions and the experimental results strongly correlate (Toutanji & Saafi, 200).

Various supplementary research has enhanced the properties of concrete while reducing its cost relative to ordinary concrete by the use of diverse chemicals. Cement ratios have been substituted with other additives, such as glass, marble, bentonite, and several other substances (Ullah *et al.*, 2021; Khan *et al.*, 2021; Anas *et al.*, 2022; Zaheer *et al.*; 2024; Shafiullah *et al.*, 2024. The research paper's conclusion indicates that the study examined the cracking patterns and analysed unreinforced concrete's tensile and compressive strength. This study investigated blocked beams and columns. Unreinforced concrete and reinforced concrete masonry are evaluated for compressive and tensile strength variations. This unreinforced concrete masonry has inferior compressive and tensile strengths compared to reinforced concrete masonry. Incorporating fibre reinforcement into concrete improves its ductility. Comparable to conventional tensile and stirrup reinforcement, it was demonstrated that the fibres exhibit significant reinforcing efficacy at the initiation of matrix fractures. The study's application of several fibre kinds, volumes, lengths, and orientations illustrates its effectiveness in both contemporary and traditional contexts. It is more economical than steel bar reinforcement and has superior strength compared to traditional unreinforced concrete.

2. Methodology and material

The subsequent topics include all facets of the material and approach. Many research articles were analysed to choose the sorts of fibres suitable for concrete reinforcement, considering their availability in Pakistan. Consequently, the most relevant publications from prior research undertaken by diverse scholars were analysed for this study's literature review. The selected fibres are:

- Steel fibre (wire)
- Raw material fibre
- Glass fibre
- Cellulose fibre

The selected fibres and requisite aggregates were produced and procured in the required quantities in compliance with the study's specifications. Subsequently, the fibre-reinforced concrete was cast with control mix specimens of beams and cylinders, followed by specimens incorporating varied percentages of different fibres.

- Steel fibre (wire) (0.5%, 1%, and 1.5%)
- Raw material (0.5%, 1%, 1.5%)
- Glass fibre (0.3%, 0.6%, 1%)
- Cellulose fibre (0.5%, 0.7%, 1%)

Upon concluding the casting and drying procedures, beams and cylinders were placed in the curing tank. The conduct of the experiment on the cast specimens was succeeded by a 28-day curing time in the water tank.

The specimens underwent four different types of testing: compression, flexural strength, split cylinder, and double punching tests. After the experimental implementation of the 28-day concrete strength test, findings were generated.

2.1. Fibres of different types

Various types of fibres used in our research have been briefly described below:

2.1.1. Steel fibre (wire)

Steel fibre is a metallic reinforcement characterised as a distinct, small segment of steel. The use of steel fibres in concrete can significantly enhance its physical qualities, markedly improving resistance to cracking, impact, fatigue, bending, tenacity, durability, and other characteristics. The steel fibre utilised was locally sourced steel wire with a length of 25 mm ± 5 mm (Figure 1).

Figure 1: Steel fibre (wire) sample

2.1.2. Raw material

The raw material we used in our project was extracted from the lathe machine and purchased from a local factory (Figure 2).

Figure 2: Raw material sample

2.1.3. Glass fibre

Glass fibre is a material consisting of numerous extremely fine fibres of glass. The length of glass fibre ranges from 35 to 50 mm. It was purchased locally but basically imported from China (Figure 3).

Figure 3: Glass fibre sample

2.1.4. Cellulose fibre

Sugarcane Bagasse was purchased from Kashmir Sugar Mill, Shorkot. It was used to prepare cellulose fibre (Figure 4).

Figure 4: Cellulose fibre sample

2.2. Preparation of cellulose fibre

The residue was set to air dry for a whole day. The bagasse was stored in plastic bags throughout the project's duration. The desiccated bagasse underwent a water bath with a solid-liquid ratio of 1:10 at 70 ± 10°C for 120 minutes to extract the cellulose fibres. The bagasse was subsequently immersed in a 15% weight solution of sodium hydroxide (NaOH) at 98 ± 5°C for 90 minutes. After a 24-hour water bath to remove residual sodium hydroxide (NaOH), the fibres were set to air dry for 48 hours.

2.3. Collection of material

2.3.1. Sand, aggregate and cement

The description of sand, aggregate and cement are (a) The sand used was locally available; (b) The crush used was Sargodha, Pakistan crush; and (c) Cement was used of the Maple Leaf brand.

2.3.2. Mixing, casting and curing

The combination ratio utilised is 1:2:4. The components have been blended with an appropriate mixer. The slurry is subsequently poured into the moulds in three stages, with each layer being tamped 25 times. This produces a seamless surface and prevents the formation of air bubbles. Following a day, the mould is removed and placed in the curing tank. Before testing, each sample was properly cured for 28 and 56 days.

2.3.3. Casting of control mix specimen

Cement sand and aggregates are mixed with certain proportions to cast the specimens (Table-1).

- Volume of 1 Cylinder = Area (A) x Height (H) = 3.14 x r^2 x 300 = 3.14 x 5625 x 300 = 5.29 x 10^6 mm^3 = 0.00529 m^3
- Volume of 18 Cylinder = 0.09522 m^3
- Volume of 1 Beam = Length x width x Depth = 510 x 105 x 105 = 5.623 x 10^6 mm^3 = 0.005623 m^3
- Volume of 6 Beams = 0.03374 m^3

Table-1: Specifications of control mix specimens

Control Mix Specimen				
	28 Days	56 Days		
Double Punching	3	3	Total Cylinder	18
Split Tensile Strength	3	3		
Compressive Strength	3	3	Total Beams	6
Flexural Strength	3	3		
Volume of 1 Cylinder	0.00529 m^3	Total Volume		0.12896m3
Volume of 12 Cylinders	0.09522 m^3	Concrete		309.504kg
Volume of 1 Beam	0.005623 m^3	Concrete after 10% Addition		340.45kg
		Cement	Sand	Coarse Aggregate
The volume of 6 Beams	0.03374 m^3	48.64kg	97.27kg	194.54kg

2.3.4. Casting of different additives concrete specimens

Cement sand and aggregates are mixed with certain proportions of different additives like steel fibre (wire), raw material, glass fibre and cellulose fibre with different percentages to cast the specimens (Table-2).

Table-2: Specifications of all the additives reinforced concrete specimens

Steel Fibre (Wire)/Raw Material/Glass Fibre/Cellulose Fibre							
	28 Days			56 Days			
Testing	0.50%	1%	1.50%	0.50%	1%	1.50%	Total Cylinders
Double Punching	3	3	3	3	3	3	54
Split Tensile Strength	3	3	3	3	3	3	Total Beams
Compressive Strength	3	3	3	3	3	3	18
Flexural Strength	3	3	3	3	3	3	
Volume of 1 Cylinder		0.00529 m^3		Quantity of Concrete		928.4976 kg	
Volume of 54 Cylinder		0.28566 m^3					
Volume of 1 Beam	0.005623m^3	Total Volume	0.386874m^3	Cement		132.64 kg	
				Sand		265.28 kg	
The volume of 18 Beams		0.101214 m^3		Coarse Aggregate		530.57 kg	

2.4. Double punching test

This test is conducted on a cylindrical specimen measuring 150×150mm. The load is exerted on the upper and lower metallic punches, with the punch radius designated as “a” and the cylinder radius as “b” (Figure 5). The cylinder height is denoted as “h,” and the applied load is represented by “P.” The dimensions of the punches must satisfy the conditions a ≥ b/5 and a ≤ H/10. The punches are aligned centrally on the specimen using a circular template featuring holes that correspond to the punch diameter.

Figure 5: Cylinder before and after test for double punching test

2.5. Split cylinder test

A concrete cylinder is positioned between the platens of the testing machine, aligning its longitudinal axis horizontally. Steel strips are affixed at the upper and lower ends. This load generates lateral stress in the vertical failure plane via two strips. The failure load is determined by applying a load on the split specimen as shown in Figure 6.

Figure 6: Cylinder placed in machine for split tensile test and after test specimen failure

2.6. Flexural strength test

The strength will vary based on differences in size, preparation, moisture conditions, curing, or the method of moulding the beam to size. The outcome of this test is utilised as a foundation for mixed proportioning. As specified, the loading rate should be between 0.014 and 0.02 MPa/sec.

2.6.1. Type/size of the specimen for the test

The specimen used is a prism, square in cross-section and having a certain length. Two standard sizes of the specimen can be used for specified aggregate sizes, as given below.

150 x 150 x 750 (mm) and 100 x 100 x 510 (mm)

The size (150 x 150 x750 mm) can be used for all sizes of aggregate particles. The size (100 x 100 x 510 mm) can only be used for aggregate sizes less than 25mm. We are using this size for our test.

2.6.2. Type of loading

The loading pattern on the beam is called the third-point/two-point loading (Figure 7). The main advantage of third-point loading is that the behaviour of the beam can be studied under pure bending, as there is no shear at the central portion of the beam. The phenomenon is depicted in Figure 8 below.

Figure 7: Three-point loading on beam

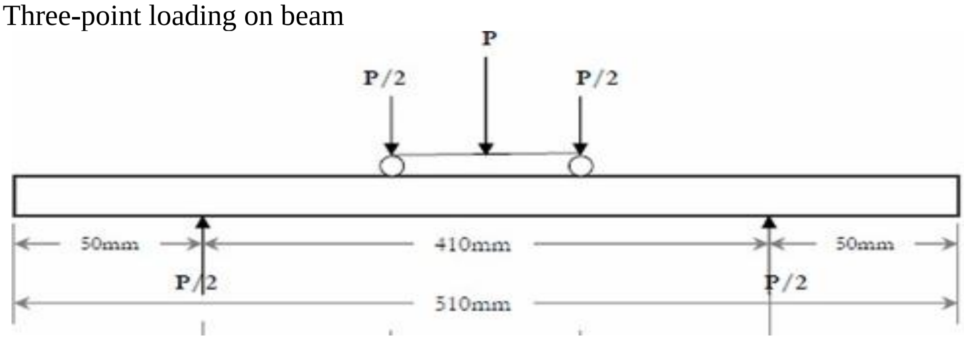


Figure 8: Beam placed in machine for split tensile test and after test specimen failure

2.7. Compression test

Compression tests are utilised to ascertain the material's behaviour under load. The maximum stress a material can endure over time under a load (constant or incremental) is ascertained. Compression testing is typically conducted until rupture or a specified limit is reached.

Figure 9: Cylinder placed in machine for split tensile test and after test specimen failure

3. Results and analysis

The results of all the experimental performances on normal and fibres reinforced concrete specimens are as follows.

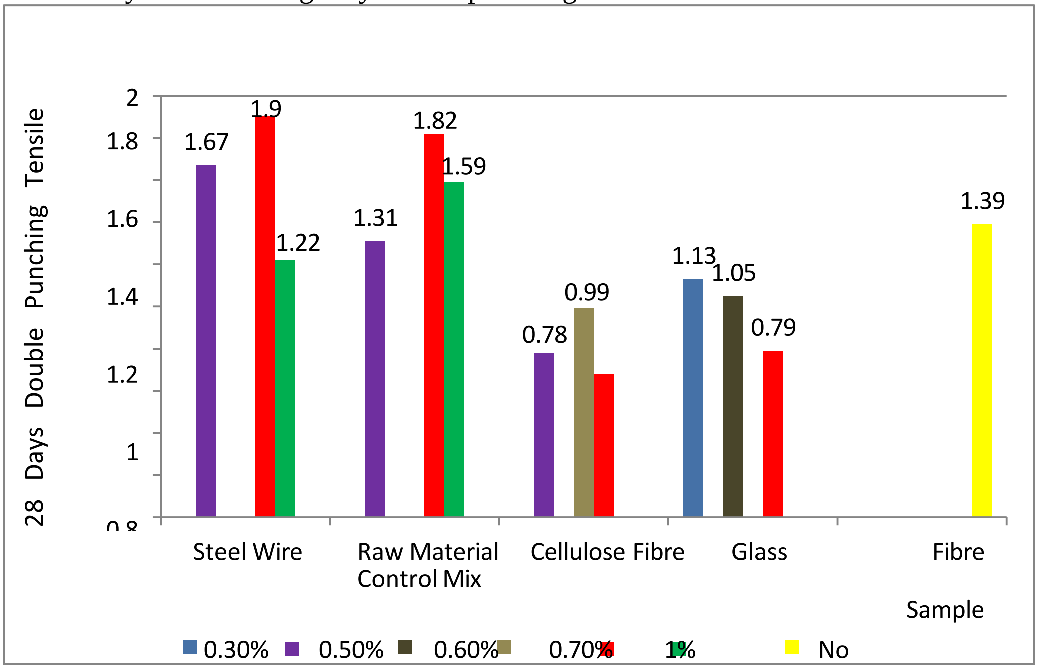
3.1. Double punching test

The 28 and 56 days results of the double punching test by adding different types of reinforcements with different percentages are given below:

3.1.1. 28 days double punching test analysis

Figure 10 shows that the steel wire fibre imparts more strength to the concrete particularly at 1% (1.9 Mpa) of 28 days as compared to other fibres as well as controlled sample.

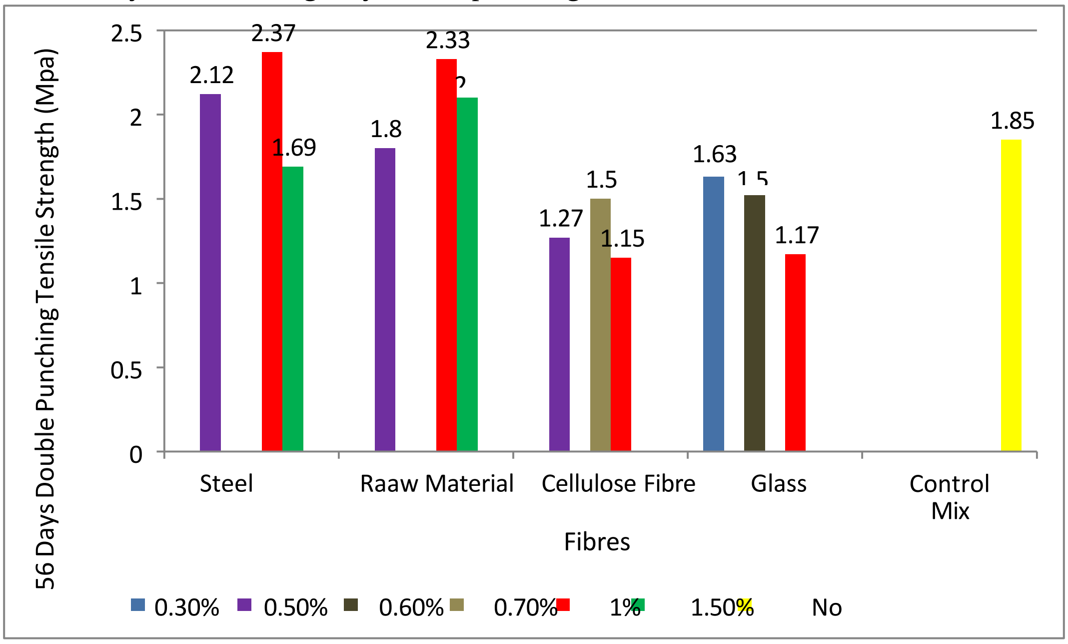
Figure 10: 28 days tensile strength by double punching test



3.1.2. 56 days double punching test analysis

Figure 11 shows that the steel wire fibre imparts more strength to the concrete, particularly at 1% (2.37 Mpa) of 56 days compared to other fibres. Also, the following increased strength at 56 days is of raw material at 1% (2.33 Mpa) compared to the controlled sample.

Figure 11: 56 days tensile strength by double punching test



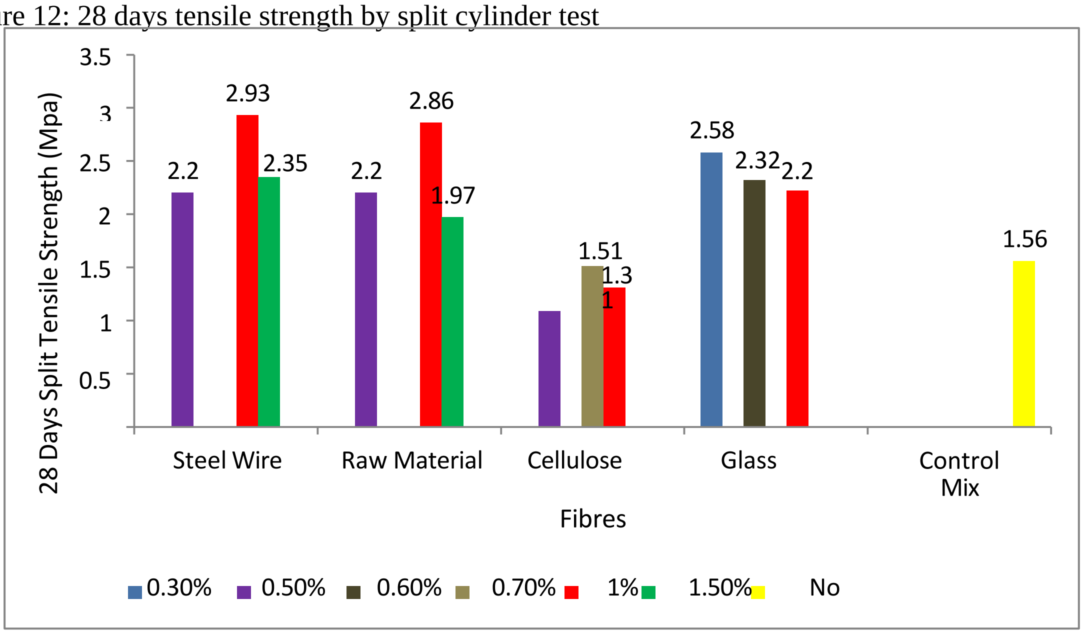
3.2. Split cylinder test

The 28 and 56 days results of the split cylinder test by adding different types of reinforcements with different percentages are given below:

3.2.1. 28 days split cylinder test analysis

Figure 12 shows that steel wire fibre imparts more tensile strength to the concrete, particularly at 1% (2.93 Mpa) in 28 days compared to other fibres. Also, the following increased strength at 28 days is of raw material at 1% (2.86 Mpa) as compared to the controlled sample.

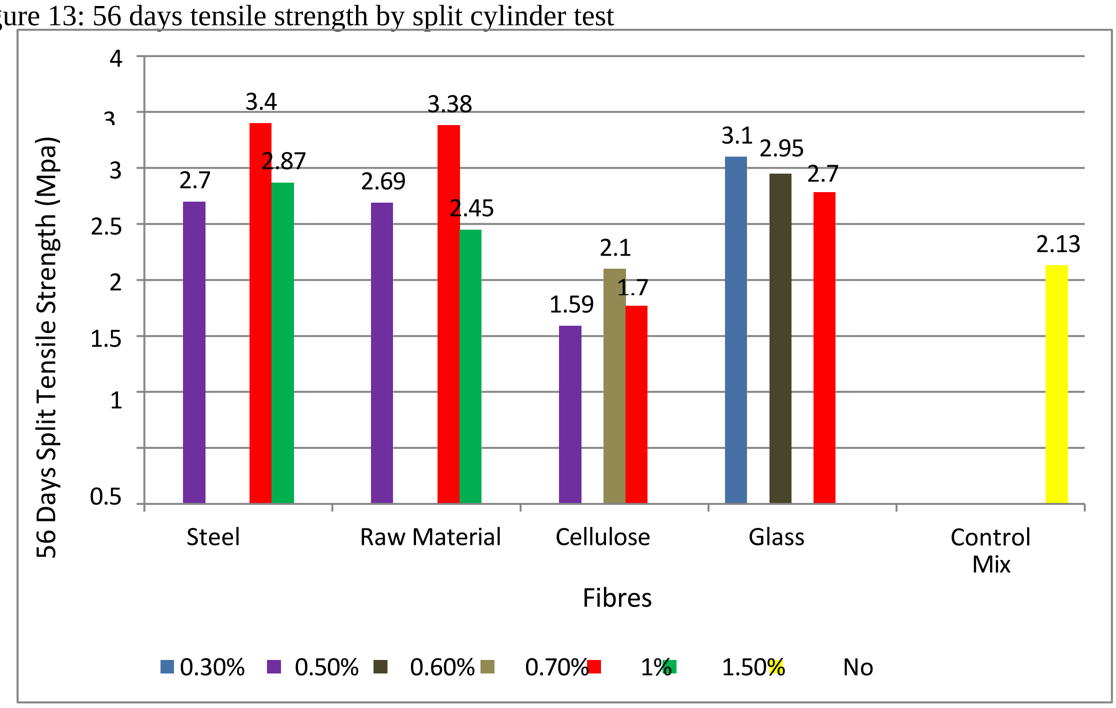
Figure 12: 28 days tensile strength by split cylinder test



3.2.2. 56 days split cylinder test analysis

Figure 13 shows that Steel wire fibre imparts more tensile strength to the concrete, particularly at 1% (3.4 Mpa) of 56 days compared to other fibres. Also, the following increased strength at 56 days is of raw material at 1% (3.38Mpa) as compared to the controlled sample.

Figure 13: 56 days tensile strength by split cylinder test



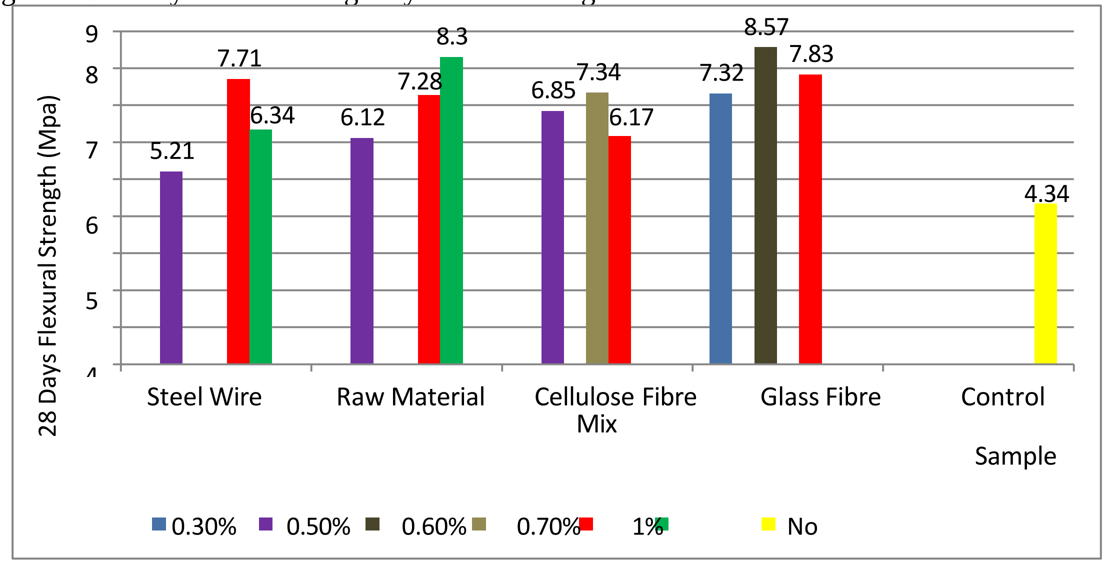
3.3. Flexural strength test analysis

The 28 and 56 days results of the Flexural Strength test by adding different types of reinforcements with different percentages are given below:

3.3.1. 28 days flexural strength test results

Figure 14 shows that the glass fibre imparts more flexural strength to the concrete particularly at 0.60% (8.57 Mpa) of 28 days as compared to other fibres. Also, the following increased strength at 28 days is of raw material at 1.50% (8.3 Mpa) as compared to the controlled sample.

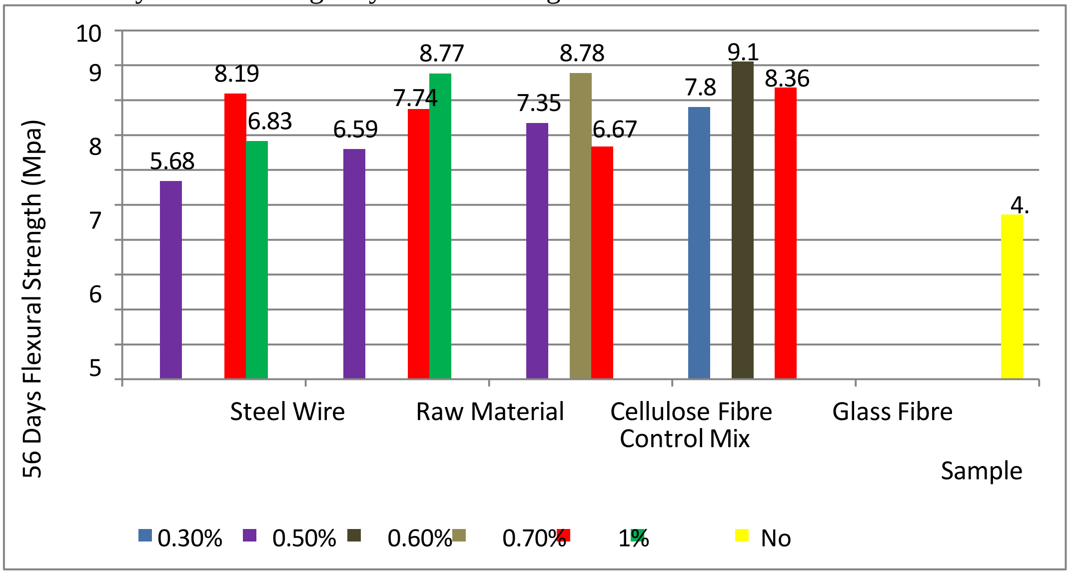
Figure 14: 28 days tensile strength by flexural strength test



3.3.2. 56 days flexural strength test results

The Figure 15 shows that the glass fibre imparts more flexural strength to the concrete, particularly at 0.60% (9.1 Mpa) of 28 days as compared to other fibres. Also, the following increased strength at 28 days is of raw material at 1.50% (8.77 Mpa) as compared to the controlled sample.

Figure 15: 56 days tensile strength by flexural strength test



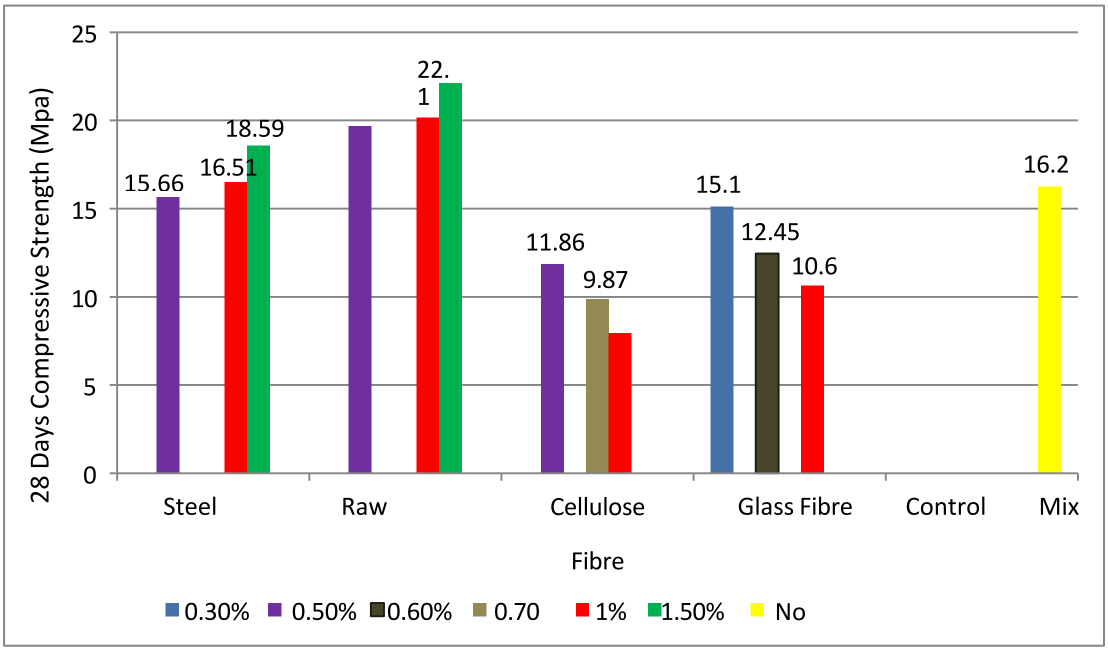
3.4. Compression test analysis

The 28 and 56 days results of the compression test by adding different types of reinforcements with different percentages are given below:

3.4.1. 28 days compression test results

The 28 days results of the compression test are given below in the Figure-16.

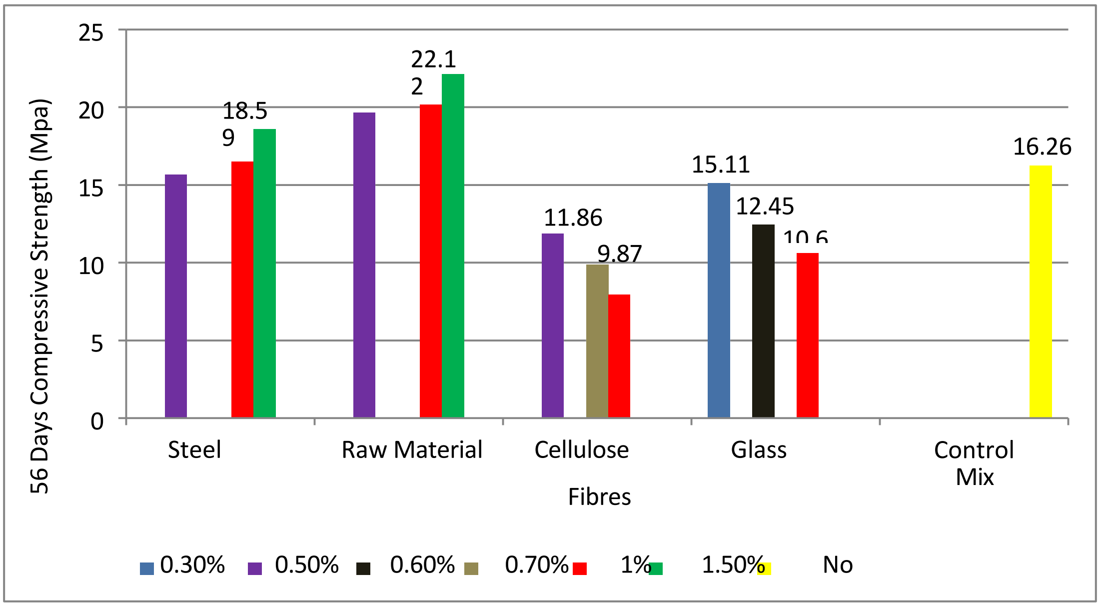
Figure 16: 28 days compressive strength



3.4.2. 56 days compression test results analysis

The 56 days results of the Compression test are given below in Figure-17.

Figure 17: 56 days compressive strength



3.5. Discussions

The study's main findings based on the applied methodology and experimental setup are explained below.

- The results of the experiments indicate that adding 1% of steel fibre (wire) results in maximum double punching strength. We saw a 28% boost in strength. Additionally, we observed that adding more than 1% reinforcement decreases the same strength. In contrast, glass and cellulose fibre reduce the Double Punching Tensile Strength by up to 36.7% and 38%, respectively, as compared to the control mix sample.
- The experimental result indicates that adding 1% of steel fibre results in the greatest split cylinder tensile strength. We observed a 60% boost in strength. Additionally, we observed that adding more than 1% reinforcement decreases the same strength. Conversely, cellulose fibre reduces the split cylinder tensile strength by up to 25.5% when compared to the control mix sample.
- The experimental result indicates that adding 1% of steel fibre (wire) results in the greatest flexural strength. We observed a 93% improvement in strength. Additionally, adding more than 0.6% reinforcement results in a drop in the same strength. No fibre hurts flexural strength.
- The impact of fibre reinforcing on compressive strength was examined using the compression test. The reinforcing of raw materials or steel wire did not negatively impact compressive strength. Conversely, glass and cellulose fibre have negative effects, reducing their compressive strengths by 33.5% and 49.5%, respectively.

4. Conclusion

According to experimental results, steel wire is the best reinforcement for split cylinder and double punching tests, working well up to a 1% reinforcement level. However, going beyond this limit might have negative effects. Glass fibre, on the other hand, works best in flexural testing and may be used with reinforcement levels as high as 0.6%, beyond which performance may suffer. Furthermore, raw materials perform best in compression testing, allowing for up to 1.5% reinforcement without sacrificing structural integrity. Crucially, every fibre utilised in these tests is safe for the environment, guaranteeing sustainable material selections.

Declaration of conflict of interest

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