

EFFECT OF NATURAL AND SYNTHETIC FIBERS ON THE PROPERTIES OF ORDINARY CONCRETE

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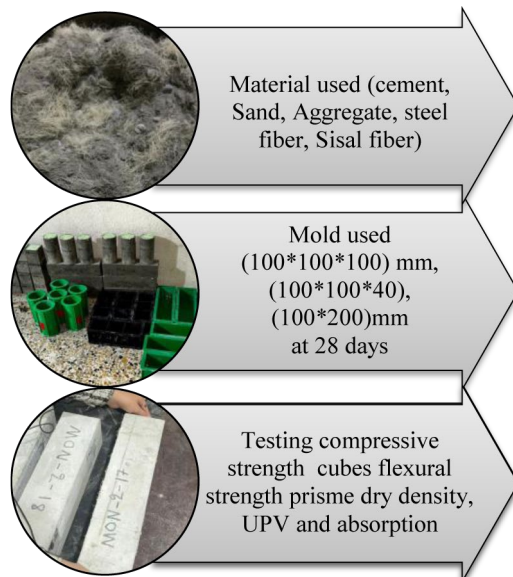
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Graphical abstract



Abstract

This research investigates the effect of natural and synthetic fibers on the properties of ordinary concrete, focusing on sisal fibers as a natural option and hooked-end steel fibers as a synthetic alternative. The study examines the mechanical and physical properties of concrete, including compressive strength, flexural strength, tensile strength, dry density, and water absorption. Fibers were added at varying volume fractions, ranging from 0.25% to 0.75% for sisal fibers and 1% to 1.5% for steel fibers. The experimental results revealed that sisal fibers improved flexural and tensile strengths up to an optimal content of 0.5%, with a slight reduction in compressive strength due to increased voids at higher fiber contents. Steel fibers consistently enhanced compressive strength, flexural strength, and density, with maximum performance observed at 1.5% content. Additionally, sisal fibers increased water absorption due to their hydrophilic nature, while steel fibers reduced it by enhancing matrix cohesion. This study concludes that sisal fibers are suitable for sustainable and lightweight applications, while steel fibers are more appropriate for high-strength concrete in structural applications. The findings provide valuable insights into optimizing fiber-reinforced concrete for various engineering applications.

Keywords: Sisal Fiber, Steel Fiber, Compressive Strength, Flexural Strength, Splitting Strength.

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1.0 INTRODUCTION

This use of natural and synthetic fiber additives in plain concrete has gained a lot of interest to enhance their mechanical property of the material. Increasing strength, durability, and improving their crack and shrinkage resistances come from these incorporated fibers. Natural fibers, jute, hemp, cotton, bamboo, etc., are also renewable and environment-friendly. Therefore, they become a good option for adopting sustainable construction practices. The other end of the scale provides synthetic fibers, such as fiberglass and polypropylene, which offer a lot of mechanical performance but are costlier. Some types of fibers can be added to concrete to improve its durability and physical properties such as cracking induced by plastic shrinkage, drying shrinkage and

thermal gradient on the surface of fresh and mature concrete due to the environmental conditions.

Fibers are incorporated to reduce shrinkage cracking and to enhance the tensile strength, toughness and durability. The effectiveness of the fibers, therefore, depends on the following characteristics of the fibers, their length, diameter, shape, proportion, and distribution within the cement matrix [1]. In general, concrete composition can incorporate four different types of fibers: steel, glass, natural, and synthetic fibers [2]. For both commercial and experimental applications, a wide variety of fiber types in various diameters and forms are available. Steel fibers, fibers from solid waste wastes, and synthetic fibers including polypropylene, glass, carbon, and polyolefins are the fundamental types of fibers. The mechanical consequences of using these fibers separately and in combination have an impact on fiber reinforced concrete (FRC)[3].

Sisal, Jute, Coconut, Cotton, Flax, Hemp and Kenaf Fiber Reinforced Concretes Impact resistance strength and energy absorption of plain concrete considerably enhance with addition of deformed steel fibers and their progression under compression tension and flexure. Plain concrete greatly improves with the inclusion of deformed steel fibers and increasing their amount under compression, tension, and flexure. Regarding the application of steel fibers in concreting, it is evident that hooked steel fibers enhance more impact resistance than crimped, flat-end and twin-cone steel fibers [4]. The manufacture of synthetic fibers is wrong for the environment and it was shown to cause global warming. These fibers are not biodegradable and are very, very expensive. The recycling of these fibers is also complicated. Numerous research analyses indicate that the demand for synthetic fiber substitutes with a lesser environmental impact has revived interest in natural fibers. Natural fibers added extra benefits like low CO₂ emission, low cost, better energy return, good reinforcing effect, and highly available which in turn minimize the management and application of these material other characteristics of natural fibers are biodegradable and nontoxic mechanically preferable than synthetic fiber in terms of strength and durability confirm by various researches [5]. Natural fibers are biodegradable products which do not result to the impacts of toxicity, the mechanical activities of natural fibers have a higher rating on strength and durability when compared with synthetic fibers, Natural fibers like flax, hemp, kenaf, and sisal are increasingly used in composite materials as a renewable alternative to glass. They offer low density, high toughness, and low energy consumption, but their hydrophilic nature can cause adhesion issues with hydrophobic polymer matrices [6], the incorporation of bio fibers reduces cracking, while an appropriate content of natural fibers can enhance both flexural and compressive strengths [7]. Sisal fibers are a promising sustainable material for cementitious materials, but their use can decrease mortar compressive strength. However, fiber-reinforced mortars show retardation of failure, with larger deformations and gradual load drop. Longer sisal fibers are more effective in promoting fracture resistance, despite their negative impact on compressive strength [8], adding 0.5% sisal fibers, 20–50 mm in size, to cement increases its tensile strength and decreases cracking [9]. Natural fibers were mixed with concrete in varying proportions, resulting in increased tensile and compressive strength. Jute and sisal fiber reinforcement improved tensile and compressive strength by 11.6% to 20.2% compared to plain concrete. Bending strength increased with fiber loading up to 1.5%, but cracks at fiber-concrete interface caused a decrease. Impact performance improved with fiber loading up to 2%. Natural fiber reinforced concrete could be commercially used for pavements and flooring [10]. Concrete's compressional qualities were enhanced by adding natural fibers up to 1% of the cement mass, and the quantity of fibers added limits abrupt brittle failures [11].

Fibers can be produced and classified on the basis of the type of material and the form in which it is used. The most frequently used fibers are the steel ones, however macro synthetically fibers have developed tremendously for the last ten years and can actually afford the concrete a nice amount of hardness [12]. Although adding fibers to concrete has several advantages, it is generally recognized that doing so will decrease workability, or stability, mobility, and compatibility

[13]. Concrete's workability, strength, and durability may all be impacted by the air content, which is another significant new feature that fibers may have an impact on. Nevertheless, there aren't many studies in the literature, and the scientific community is still divided about whether fibers have an impact on the air content of concrete. One study [14] indicated that fibers raise the air content of concrete, with the percentage varying depending on the kind and form of the fiber.

This aspect reveals the need to consider certain FRC fresh properties that have implications on workability carefully. Settlement is affected by various elements such as workability which includes among other things water cement ratio, cement content, aggregate type and size, use of admixtures and type of fiber used and its volume.

2.0 METHODOLOGY

Locally available OPC cement was used in this research and was obtained from the locally available Badush factory in Nineveh province Table 1 shows the physical properties, and Table 2 shows the chemical composition according to ASTM C150 [15] and Iraqi Specifications No.5- 1984 [16]. The fine aggregate in all the mixtures used in this study was natural river sand obtained from Kanhash area in Mosul, Iraq. The sand underwent a thorough washing process with multiple water rinses to remove impurities and clay lumps. After that, it was spread and left to air dry until it reached a saturated surface dry state. After that, the sand was sieved to ensure that it passed through a 4.75 mm sieve. The physical properties of the sand, according to ASTM C 33-02 [17] and ASTM C128 [18], the dry bulk density and absorption of this sand were 2.62 and 1.9%, respectively. Natural river gravel with a maximum aggregate size of (12.5) mm was used, with a specific gravity of 2.65 and absorption of 0.81% according to ASTM C127 [19]. Tap water was used to mix the components. Free from oils, organic matter and other potentially harmful components. Sisal is a natural fiber with high modulus of elasticity, unique strength, low price, easy accessibility, recyclability, high durability with low maintenance and low wear. ASTM D3822 [20] is a standard specification for measuring the mechanical properties of individual fibers. This specification can be applied to test the mechanical properties of sisal fibers such as tensile strength and elongation. The density of sisal can be obtained from ASTM D3800 [21]. The dry density of sisal fibers typically ranges from 1.45 to 1.55 g/cm³. The water absorption is high. Volumetric ratios of 0.25%, 0.5% and 0.75% of the mixture volume were added to the normal concrete (MO) mix and the physical properties of sisal fibers are given in Table 3. The steel fibers with hooked ends were used in all types of concrete mix with a length of 35 mm, a diameter of 0.3 mm and a density of 8750 kg/m³. The properties of steel fibers are listed in Table 4. Volumetric ratios of 1%, 1.25% and 1.5% of the mixture volume were added to the normal concrete mix.

Table 1 physical properties of the OPC *

Tests	Results	Limitations of the ASTM C150	IQS No.5-1984
Initial Setting Time,	61 min	≥ 45 min	≥ 45 min
Final Setting Time,	329 min	≤ 375 min	≤ 600 min
Fineness, (Blaine Test)	287.9 m ² /kg	≥ 260 m ² /kg	≥ 230 m ² /kg
Compressive Strength (MPa) at 3 Days	18.1 Mpa	≥ 12 Mpa	≥ 15 Mpa
at 7 Days	31.1Mpa	≥ 19 Mpa	≥ 23 Mpa

*The test was conducted in the laboratories of Mosul Technical College

Table 2 Chemical properties of used cement (OPC)**

Constituent	Component of used Cement (%)	Limits of IQS : 5/1984
SiO ₂	21.31	----
Al ₂ O ₃	5.89	----
Fe ₂ O ₃	2.67	----
CaO	62.2	----
MgO	3.62	≤ 5%
SO ₃	2.6	≤ 2.8%
Loss of ignition	1.59	≤ 4%
Insoluble residue	0.24	≤ 0.75%
Free CaO	1.74	----
L.S.F.	0.8818	0.66-1.02
C ₃ S	33.37	----
C ₂ S	35.92	----
C ₃ A	11.09	----
C ₄ AF	8.12	----

**The chemical composition was obtained from data sheet of cement factory

Table 3 physical property of sisal fiber

Dry Density	1510kg/m³
length	35mm
Diameter:	0.1 to 0.5 mm
Elongation percentage %	14.80%
Tensile strength	31-221 N/mm ²
Absorption/24 hours	28%

Table 4 Properties of hooked end glued steel fiber

Density	8750km/m³
length	35mm
Diameter:	0.3mm
L/D%	11.67%
Tensile strength	2600 MPA
Type	Hooked end glued

3.0 RESULTS AND DISCUSSION

3.1 Mix properties

After selecting the materials and mixing ratios, the MO mixture was adopted as a reference mixture and volume ratios (0.25%, 0.5% and 0.75%) of natural fibers were added. In this research, sisal fibers were added and volume ratios (1%, 1.25% and 1.5%) of synthetic fibers and steel fibers were used in this research. According to Table 5. After that, the volume of the reference mixture was calculated according to Table 6 for the purpose of calculating the weights fires should be added to the mixture according to Table 7.

Table 5 Mix properties for Ordinary Concrete and No of samples

Mix Number	Cement Kg/m ³	Fine Aggregate Kg/m ³	Coarse Aggregate Kg/m ³	W/C 50%	Natural Fiber% Volume	Steel Fiber% Volume
MO	300	800	1150	150	0	
MON1	300	800	1150	150	0.25%	
MON2	300	800	1150	150	0.5%	
MON3	300	800	1150	150	0.75%	
MOS1	300	800	1150	150		1%
MOS2	300	800	1150	150		1.25%
MOS3	300	800	1150	150		1.5%

Table 6 Calculate Volume of the Ordinary mix

Material	Weight kg	S.P kg/m ³	Volume m ³
Cement (1)	300	3150	0.095
Sand(2.67)	800	2620	0.305
Gravel(3.83)	1150	2650	0.434
Water(0.5)	150	1000	0.15
Volume of Mix			0.985

Table 7 Calculate weight of % fibers added to ordinary mix

Sisal	Volume of Mix	S.P Sisal	Weight kg
0.25%	0.985	1510	3.717
0.50%	0.985	1510	7.433
0.75%	0.985	1510	11.150
steel	Volume of Mix	S.P steel	Weight kg
1.00%	0.9845	8750	77.287
1.25%	0.9845	8750	96.608
1.50%	0.9845	8750	115.930

3.2 Test And Result

3.2.1 Slump Test

The slump test by using slump cone according to ASTM C143/C143M [22]. Results as shown in Table 8 and Figure 1, sisal fibers gradually reduce slump with increasing percentage

compared to the reference mix by 12%, 16% and 27% depending on the percentage of sisal addition 0.25%, 0.5% and 0.75%, respectively. This is due to their ability to absorb water and enhance internal cohesion within the mixture, which reduces flowability. Steel fibers have a more pronounced effect on reducing slump due to their stiffness and random distribution, which hinders the natural flow of the concrete mix. At percentages of 24%, 35% and 43% depending on the percentage of steel fiber added 1%, 1.25% and 1.5%. In general, the higher the fiber content (natural or steel), the stiffer the mixture becomes, which leads to a significant decrease in workability.

Table 8 Results of Slump Test

Mix Number	Sisal %	Steel Fiber%	Slump Test
MO	0		100
MON1	0.25%		88
MON2	0.5%		84
MON3	0.75%		73
MOS1		1%	76
MOS2		1.25%	65
MOS3		1.5%	57

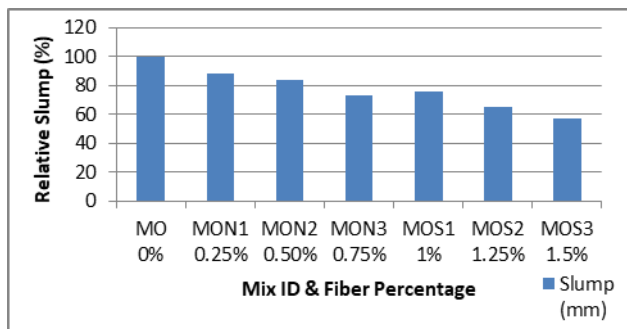


Figure 1 System prototype architecture of FPV

3.2.2 Compressive Strength

Compressive strength was tested with (100*100*100) mm cubes according to ASTM C-39 [23]. Sisal and steel fibers were added to the reference mix of ordinary concrete. From Table 9 and Figure 2, the test results show a slight decrease in the compressive strength value by 1.5% to 4% when adding 0.25% and 0.5% of sisal fibers, while a significant decrease appears when adding 0.75% up to 8.5%. Sisal fibers are natural materials with elastic properties, which may lead to a reduction in the density of concrete and an increase in porosity when added at high concentrations. This explains the significant decrease in strength at ratios greater than 0.5%. As for adding steel fibers, it improves the compressive strength by up to 5% when adding 1.5% of fibers. It enhances the bonding within the mixture, which reduces the possibility of micro cracks and improves the overall performance of concrete.

Table 9 Results of Compressive strength

Mix Number	Sisal %	Steel Fiber%	Compressive strength 28 day
MO	0		31
MON1	0.25%		30.5
MON2	0.5%		29.8
MON3	0.75%		28.32
MOS1		1%	31.6
MOS2		1.25%	32.35
MOS3		1.5%	32.93

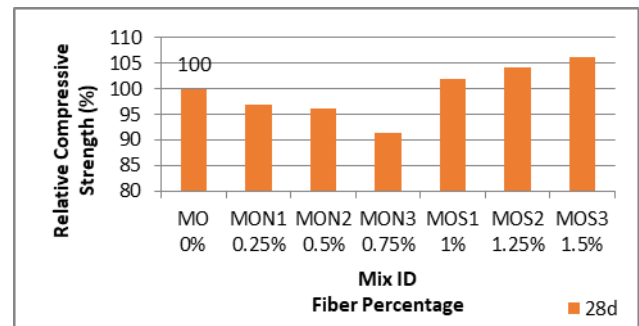


Figure 2 Comparison of Relative % compressive strength

3.2.3 Dry Density Test

The dry density was calculated at the ages of 28 days according to ASTM C642 [24]. It is noted from the table 10 and Figure 3 that the dry density decreases when adding sisal fibers by percentages reaching 2% when adding 0.75% of sisal fibers, since sisal fibers are less dense than traditional concrete components, which leads to a decrease in the overall density of the mixture. While adding steel fibers, the increase in density reaches 5% when adding 1.25%, because steel fibers have a much higher density compared to other components of concrete, which leads to an increase in the total weight of the mixture.

Table 10 Results of dry density

Mix Number	Sisal %	Steel Fiber%	Dry Density 28Day
MO	0		2441
MON1	0.25%		2438
MON2	0.5%		2433
MON3	0.75%		2397
MOS1		1%	2510
MOS2		1.25%	2539
MOS3		1.5%	2553

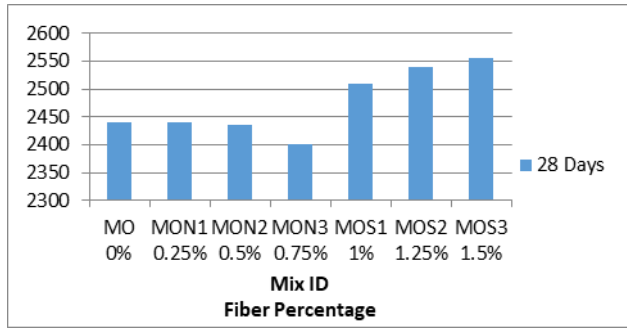


Figure 3 Comparison of Relative % Dry Density with Reference MO mix

3.2.4 Water Absorption

The water absorption test of concrete was carried out according to ASTM C642-13 [24]. The results as shown in Table 11 and Figure 4 show an increase in the water absorption value upon adding sisal due to its absorption of water and causing an increase in voids, reaching 15% at the age of 28 days when adding 0.75% of sisal fibers. When adding steel fibers, a decrease was observed at 1.5% by 9% compared to the reference mixture value.

Table 11 Results of Water Absorption

Mix Number	Sisal %	Steel Fiber%	Water Absorption 28Day
MO	0		4.5%
MON1	0.25%		4.75%
MON2	0.5%		4.95%
MON3	0.75%		5.2%
MOS1		1%	4.35%
MOS2		1.25%	4.25%
MOS3		1.5%	4.1%

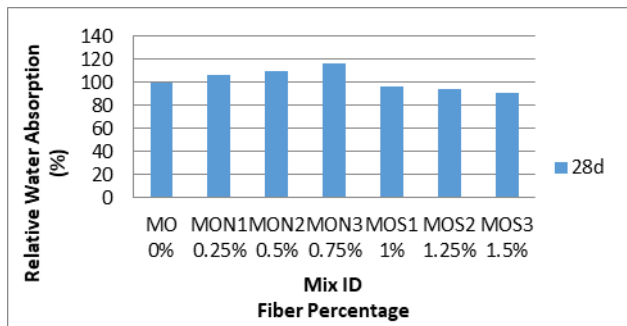


Figure 4 Comparison of Relative % Water Absorption with Reference MO mix

3.2.5 Flexural Strength

Using a sample of (100*100*400) mm prism, the test was conducted according to ASTM C78/C78M specifications [25]. We conclude from Table 12 and Figure 5 that adding sisal fibers at a ratio of 0.75% gives an increase of up to 22% in flexural

strength compared to the reference mixture, while it reaches 50% when adding steel fibers at a ratio of 1.25%. This is due to the fact that the fibers act as bridges connecting the sides of small cracks, preventing them from expanding to become large cracks. Thus, increasing the flexibility of the material and enabling it to withstand greater tensile and bending stresses. Figure 6 shows that when examining the flexural strength of concrete without fibers, failure occurred with clear separation of the prism. More than one fracture was observed in the middle third, indicating a typical brittle failure of concrete, where the material does not provide any additional resistance after reaching the maximum bending limit. When sisal fibers were added, the failure type changed to become less permeable, as the crack width did not exceed 1-2 mm. This behavior shows that sisal fibers improve internal bonding and reduce the effect of cracks by transferring stress through the fibers, which increases the ability to bear loads after the onset of cracking. When steel fibers were added, failure was represented by the appearance of small hairline cracks instead of large cracks or complete separation. This indicates that steel fibers are very effective in improving the flexural strength and reducing the brittleness of concrete, as they work to distribute stress better within the material, which hinders the formation of large cracks.

Table 12 Flexural strength Result

Mix Number	Sisal %	Steel Fiber%	Flexural strength 28Day
MO	0		3.9
MON1	0.25%		4.15
MON2	0.5%		4.43
MON3	0.75%		4.76
MOS1		1%	5.15
MOS2		1.25%	5.53
MOS3		1.5%	5.87

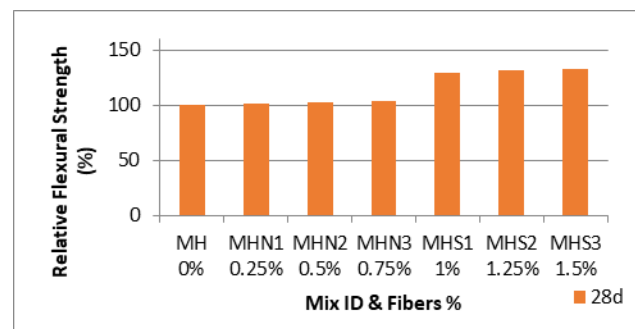


Figure 5 Comparison of Relative % Flexural Strength with Reference MO mix

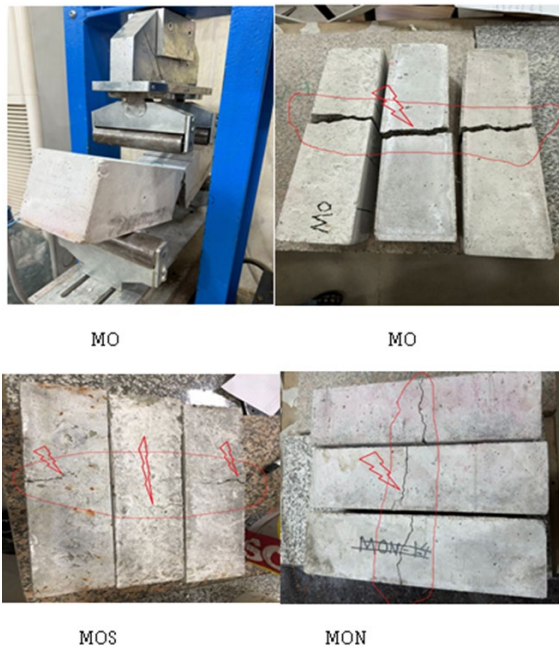


Figure 6 Shape of Failure in reference mix MO, MON and MOS

3.2.6 Ultra- Sonic

Using a prism (100*100*400) mm, the ultrasonic test of the sample was conducted according to ASTM C597 [26]. It was observed that the addition of sisal fibers reduced the speed of ultrasonic waves with increasing fibers compared to the reference mixture. This indicates a slight increase in voids or uneven distribution in the concrete due to the addition of fibers. A slight increase was also observed when adding steel fibers compared to the reference mixture, indicating an improvement in internal bonding and a decrease in porosity. In general, the higher the density and compressive strength, the higher the speed of wave transmission through the concrete. Table 13 shows the results, and Figure 7 shows the effect when adding varying percentages of fibers.

Flexural strength was tested on prisms (100×100×400 mm) according to ASTM C78/C78M [25], and the results from Table 12 and Figures 5–6 demonstrate the significant effect of fiber reinforcement on both strength and failure mode. The reference mix (MO) exhibited brittle failure, with sudden crack formation, clear separation, and multiple fractures in the mid-span, reflecting the low tensile and flexural resistance of ordinary concrete. When sisal fibers were incorporated (MON), flexural strength increased by up to 22% at 0.75% fiber content, and the failure mode changed to narrower (1–2 mm), more distributed cracks, indicating enhanced internal bonding and improved load-carrying capacity after cracking. In contrast, steel fiber concrete (MOS) achieved the highest improvement, with strength gains reaching nearly 50% at 1.25% fiber addition, while failure was characterized by fine hairline cracks and delayed crack propagation without sudden collapse. This confirms the superior efficiency of steel fibers in reducing brittleness, distributing stresses more effectively, and enhancing ductility.

Overall, the ranking of performance and failure resistance can be expressed as MOS > MON > MO, where both natural and metallic fibers enhanced post-cracking energy

absorption and ductility compared to plain concrete, consistent with findings from previous studies [5]–[10].

Table 13 ultra-sonic Result

Mix Number	Sisal %	Steel Fiber%	Ultra-Sonic 28Day
MO	0		4.411
MON1	0.25%		4.393
MON2	0.5%		4.380
MON3	0.75%		4.361
MOS1		1%	4.455
MOS2		1.25%	4.472
MOS3		1.5%	4.494

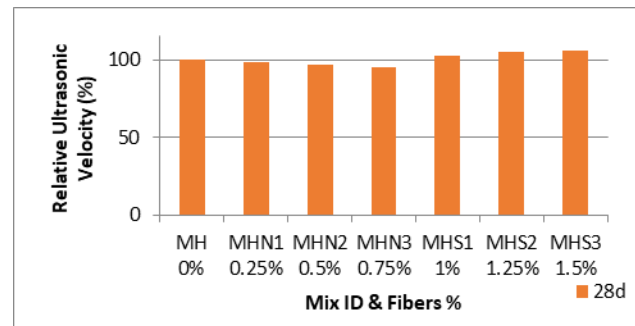


Figure 7 Comparisons of Relative % Ultra-Sonic with Reference MO mix

3.2.7 Splitting Tensile Strength

Using a cylinder (100*200) mm, the splitting tensile strength test was conducted according to ASTM C496/C496M [27] specifications. An increase was observed at 28 days, the increase was 12.5% compared to its value in the reference mixture. The addition of sisal improves the splitting tensile strength. The addition of steel fibers significantly improves the splitting tensile strength, as the fibers act as internal reinforcements that reduce the development of cracks. The percentage of increase at 28 days was 30%. Table 14 shows the results, and Figure 8 shows the effect when adding different percentages of fibers.

Table 14 splitting tensile strength Result

Mix Number	Sisal %	Steel Fiber%	splitting strength 28Day
MO	0		3.85
MON1	0.25%		3.95
MON2	0.5%		4.13
MON3	0.75%		4.33
MOS1		1%	4.42
MOS2		1.25%	4.63
MOS3		1.5%	4.94

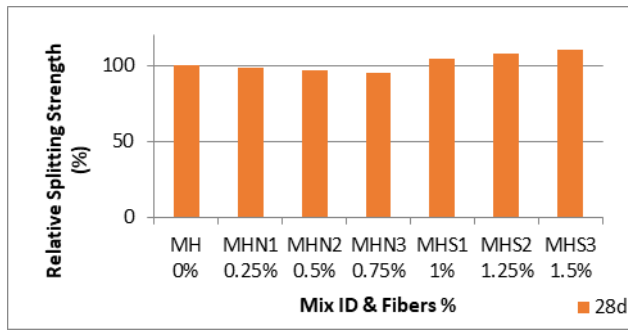


Figure 8 Comparison of Relative % Splitting Strength with Reference MO mix

3.2.8 Cylinder Compressive Strength

Using a cylinder (100*200) mm, the cylindrical compressive strength test was conducted according to ASTM C39/C39M [23] specification. The optimal improvement was observed when adding sisal fibers at a rate of 0.5% at the age of 28 days, the increase was 10.5% over its value in the reference mixture, while a decrease was observed at % 0.75 by an amount due to the increase in voids in the concrete as a result of adding sisal fibers. This means that increasing the sisal percentage by more than 50% gives negative results. When adding steel fibers, the increase at the age of 28 days reached 13% compared to the reference mixture. Adding steel fibers significantly improved the compressive strength, the fibers act reduce the development of cracks. Table 15 shows the results, and Figure 9 shows the effect when adding different percentages of fibers.

Table 15 Results of Compressive Strength

Mix Number	Sisal %	Steel Fiber%	Compressive Strength 28Day
MO	0		22.23
MON1	0.25%		23.13
MON2	0.5%		24.35
MON3	0.75%		23.91
MOS1		1%	24.15
MOS2		1.25%	24.61
MOS3		1.5%	25.2

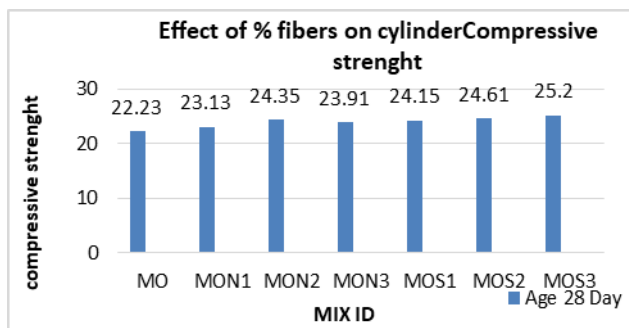


Figure 9 Effect of fibers on cylinder compressive strength

3.2.9 Modules of Elasticity

Using a cylinder (100*200) mm, the static modulus of elasticity test was conducted according to ASTM C469/C469M [28]. An

improvement was observed when adding sisal fibers by 0.5% at the age of 28 days, while a decrease of 0.75% was observed. The increase in voids in the concrete was due to the addition of sisal fibers. This means that increasing the percentage of sisal by more than 50% gives negative results. When adding steel fibers, an improvement of 6% occurred at the age of 28 compared to the reference mixture. Table 16 shows the results, and Figure 10 shows the effect when adding different percentages of fiber

Table 16 modulus of elasticity results

Mix Number	Sisal %	Steel Fiber%	Modules of Elasticity 28Day
MO	0		22.159
MON1	0.25%		22.604
MON2	0.5%		23.192
MON3	0.75%		22.981
MOS1		1%	23.097
MOS2		1.25%	23.320
MOS3		1.5%	23.564

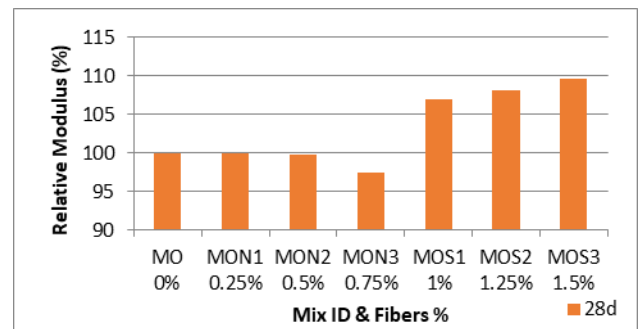


Figure 10 Comparison of Relative % Modules of Elasticity with Reference MO mix

4.0 RESULTS AND DISCUSSION

The experimental results of this study provide valuable insights into the behavior of fiber-reinforced concrete:

- 1- Workability: Sisal fibers reduced slump values due to their water absorption properties, while steel fibers further reduced workability by obstructing flow.
- 2- Compressive Strength: Sisal fibers decreased compressive strength at higher volumes, while steel fibers improved it by up to 13% at 1.5% fiber content.
- 3- Flexural Strength: Significant improvements in flexural strength were observed with both fiber types. Sisal fibers increased flexural strength by 22% at 0.75%, while steel fibers showed a 50% increase at 1.25%.
- 4- Water Absorption: The hydrophilic nature of sisal fibers increased water absorption, while steel fibers reduced absorption by enhancing matrix cohesion.
- 5- Dry Density: Adding sisal fibers reduced the density of concrete, whereas steel fibers increased it due to their higher density.
- 6- Splitting Tensile Strength: Both fiber types improved splitting tensile strength, with steel fibers showing greater enhancement.

These results confirm the complementary benefits of using natural and synthetic fibers in concrete, providing a balanced approach to improving both sustainability and mechanical performance.

5.0 CONCLUSION

- 1- Natural Fibers (Sisal Fibers): They have good flexibility, light weight, biodegradable and are used for temporary or environmental projects. They are also environmentally friendly and are used in low-cost applications. Their effect on concrete properties can be summarized as follows: Sisal fibers are effective for improving tensile and flexural strengths but should not exceed 0.5% to avoid negative effects on compressive strength.
- 2- Synthetic fibers (Steel Fibers): Properties that give high resistance to tension and bending. Improves the durability of concrete and reduces cracks resulting from shrinkage. Used in fiber-reinforced concrete applications used in industrial floors, tunnels, and bridges. Its features include enhancing the resistance of concrete to heavy loads and increasing the service life of concrete. Their effect on concrete properties can be summarized as follows: Steel fibers are ideal for high-strength applications, with optimal performance at 1.5% content.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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