



Enhancing the Mechanical Properties of Fiber-Reinforced Concrete with Recycled Crumb Rubber: A Sustainable Approach

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Abstract

The disposal of rubber waste poses a significant environmental challenge, and its reuse in the production of green concrete offers a sustainable solution. This study explores the mechanical behavior of fiber-reinforced concrete incorporating recycled crumb rubber (CR) as a partial aggregate replacement. Three types of fibers-polypropylene (PP), plastic-based macro-synthetic (MS), and steel (ST)-were combined with crumb rubber (CR) in three particle size ranges (0–1 mm, 1–3 mm, and 3–5 mm) to evaluate their impact on the compressive and tensile strength of concrete. PP fibers (12 mm in length) were used at cement weight fractions of 0.2%, 0.4%, 0.7%, 1.0%, and 1.2%. Similarly, MS fibers (40 mm in length) were incorporated at the same fractions (0.2% to 1.2%). ST fibers (30 mm in length) were added at higher dosages of 0.5%, 1.0%, and 1.5% by weight of cement. The results showed that the inclusion of fibers reduced workability, with PP fibers causing the most significant reduction (up to 80%). CR further decreased workability, particularly at higher particle sizes and percentages. In terms of mechanical performance, the compressive and tensile strengths of fiber-reinforced concrete improved by 22–

27% and 22–59%, respectively. However, the addition of CR alone led to reductions in compressive and tensile strengths of up to 60% and 15%, respectively. Notably, the combination of fibers and CR (CRF) enhanced concrete performance, with compressive strength increasing by up to 14% and tensile strength by 35% when using the optimal fiber content and 5% CR. These findings demonstrate that while CR reduces the mechanical strength of concrete, its combination with fibers significantly enhances performance, offering a viable approach to producing more sustainable, high-performance concrete.

Keywords: Crumb rubber, Synthetic fibers, Polypropylene, Steel fiber, Aggregate Replacement, Green Concrete, Mechanical Behavior

1. Introduction

The increasing demand for sustainable and eco-friendly construction materials has driven extensive research into incorporating recycled waste products in civil projects (Roshani et al., 2025). One promising approach is the use of crumb rubber (CR) from discarded tires as partial replacements for natural aggregates. These materials provide significant environmental benefits by reducing landfill waste and promoting recycling. However, their inclusion typically results in reduced compressive and tensile strengths, which can limit their structural applications. To address these challenges, fibers such as steel or synthetic materials have been added to improve the mechanical properties, toughness, and ductility of CR concrete (CRC), making it a more viable solution for green construction. This study aims to explore the combined effects of CR and fibers on the structural behavior of concrete, contributing to the development of more durable and sustainable building materials.

1.1 Crumb Rubber Concrete

CRC incorporates waste tire rubber as a partial replacement for fine aggregates in concrete, offering a sustainable solution to the environmental challenges of tire disposal (A. Ahmed et al., 2024; B. S. Mohammed et al., 2017). On the positive side, CR promotes sustainability by recycling waste rubber and enhances the concrete's flexibility, impact resistance, and durability, making it suitable for non-structural applications like pavements. However, it significantly reduces compressive strength and workability, limiting its use in load-bearing structures (Assaggaf et al., 2022a; Shahjalal et al., 2023a). Despite these drawbacks, with proper mix design and reinforcement, CR can be a valuable addition to concrete in specific contexts where its benefits, such as improved ductility, outweigh the disadvantages. The incorporation of CR in concrete enhances energy absorption and impact resistance by reducing brittleness and dissipating dynamic loads, making it suitable for applications such as road barriers, pavements, and seismic-resistant structures (Aghamohammadi et al., 2024; Assaggaf et al., 2022b). It can also be valuable in protective structures, like blast-resistant walls or sports surfaces, where absorbing and diffusing energy is crucial for performance and safety. Mo et al. (2024) found that smaller CR particle sizes improved concrete workability and brittleness, with the lowest strength occurring around 1.18 mm CR. Although CR weakens interfacial transition zones (ITZs), its crack-arresting capabilities were more effective with smaller particles, leading to enhanced crack propagation resistance (Mo et al.,

2024). Antil et al. (2014) indicated that increasing rubber particle size mitigates the loss of compressive strength (Antil et al., 2014).

In the development of CRC, various additives and admixtures have been utilized to enhance its performance and address challenges such as reduced strength and workability. Here's a comprehensive introduction to the key additives used in CRC:

Silica Fume (SF): A byproduct of silicon metal production, silica fume is a highly reactive pozzolanic material that improves the compressive strength and durability of concrete (Shaaban et al., 2024; Dadashi et al., 2024).

Fly Ash (FA): This industrial byproduct from coal combustion is commonly used as a partial replacement for cement (S. O. Ahmed, 2024; Mo et al., 2024).

Superplasticizers: These chemical admixtures are used to improve the workability of concrete while maintaining its low water-to-cement ratio (Youssf et al., 2016, 2020).

Steel Fibers: The addition of steel fibers can improve the toughness and impact resistance of CRC, addressing the inherent brittleness that can arise from using rubber aggregates (Naaman, 2018; Xu et al., 2023; Wang et al., 2018).

Polypropylene Fibers: These fibers improve the crack resistance and ductility of CRC, enhancing its performance under dynamic loads (Hossain et al., 2023; Zhou et al., 2023).

Magnetized Water: Some studies have explored the use of magnetized water for mixing CRC, which has shown promising results in enhancing workability and mechanical properties by influencing the properties of water at the molecular level (Sawant, 2022; Youssf et al., 2023).

1.2 Fiber-reinforced Concrete

The use of fibers in civil engineering projects has gained widespread attention due to their ability to enhance the mechanical properties of concrete, particularly in improving tensile strength, crack resistance, and durability in various structural applications (Hosseini et al., 2025; Yabaluie Khamesluei et al., 2024). Fiber-reinforced concrete (FRC) is a composite material that integrates short, dispersed fibers into conventional concrete to enhance its mechanical properties (P. Zhang et al., 2023; Zhao et al., 2023).

Fibers used in FRC are classified as either micro or macro based on their diameter, and a variety of materials—including steel, glass, polymers, carbon, and natural fibers—are employed to optimize performance (Beaudoin, 1990; Jamshidi Avanaki et al., 2018). FRC's enhanced toughness under tensile and compressive loads makes it ideal for a wide range of applications, such as precast structures, bridges, tunnels, and high-rise buildings (Beaudoin, 1990). In recent years, the incorporation of waste materials and natural fibers in FRC has gained attention for its potential to improve concrete properties while promoting sustainability (Abdalla et al., 2023; Althoey et al., 2023).

1.3 Motivation for Combining Crumb Rubber and Fibers in Concrete

Given the growing importance of utilizing recycled materials to protect the environment, the incorporation of CR in concrete has become a significant focus in the construction industry. However, previous studies have consistently reported that the inclusion of CR tends to reduce the

mechanical properties of concrete. To address this limitation, this study explores the combined effects of CR and fibers, a topic that has received limited attention in earlier research (Shahjalal et al., 2023a; Eisa et al., 2020a). The first phase of the research identifies the optimal fiber percentages based on the test results. In the second phase, the effects of incorporating rubber particles into these fiber-reinforced concretes are examined. Guo et al. (2014) explored the fracture behaviors of a novel steel fiber-reinforced recycled aggregate concrete (RSRAC) incorporating varying amounts of CR under different temperature conditions (Y. Guo et al., 2014). Eisa et al. (2020) found that replacing fine aggregates with 10% CR enhanced ductility and toughness, while incorporating 1% steel fibers further improved the performance of the beams (Eisa et al., 2020a). Shahjalal et al. (2023) reviewed rubberized recycled aggregate concrete (RRAC) and fiber-reinforced RRAC (FRRAC), finding that adding fibers improves toughness and ductility, despite CR and recycled coarse aggregate (RCA) reducing strength. CR and RCA can be used up to 10% and 30% respectively, with fibers bridging cracks to enhance performance. They also proposed equations and machine learning models to predict the mechanical properties of RRAC and FRRAC (Shahjalal et al., 2023a).

1.4 Innovation and Contribution of the Current Research

The innovative aspect of this research lies in its comprehensive investigation of the combined effects of CR and various types of fibers in concrete, which addresses a gap in the existing literature. While past studies have focused primarily on the individual impacts of either CR or fibers, the synergistic potential of combining these two materials has not been fully explored. This study not only identifies the optimal fiber content for enhancing mechanical properties but also examines how the addition of CR can influence the behavior of fiber-reinforced concrete. The findings are expected to offer new insights into the development of more sustainable and resilient concrete mixtures, with the potential to improve both environmental outcomes and mechanical performance in structural applications.

2 Materials and Methods

2.1 Materials

The cement used in this research, as shown in Figure 1, was Portland Type II, with a specific gravity of 3,150 kg/m³ and a specific surface area of 2,900 cm²/g. The physical and chemical properties of the cement are summarized in Table 1. The sand utilized in this study consisted of both crushed and river aggregate materials, with maximum particle diameters of 19 mm and 4.75 mm, respectively, as shown in Figure 1. The sand had an apparent specific gravity of 2420 kg/m³ and a water absorption rate of 1.5%.

Table 1. Physical properties of Portland cement (Type II)

Chemical Parameters	Material Percentage (%)
CaO	63.0
SiO ₂	20.4
Al ₂ O ₃	4.9
Fe ₂ O ₃	3.9
MgO	1.7
SO ₃	2.0

Na ₂ O+K ₂ O	0.9
Loss on ignition (LOI)	1.5
Specific gravity	3.1
Blaine fineness (m ² /kg)	295.0
Average particle size (μm)	26.0

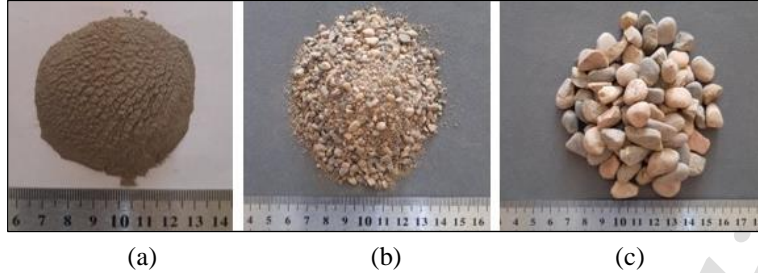


Figure 1. Materials utilized in the present study (a) Cement, (b) Fine aggregates, (c) Coarse aggregate

The grain size distribution of the fine and coarse aggregates used in the concrete was obtained according to ASTM C-637, as shown in Figure 2.

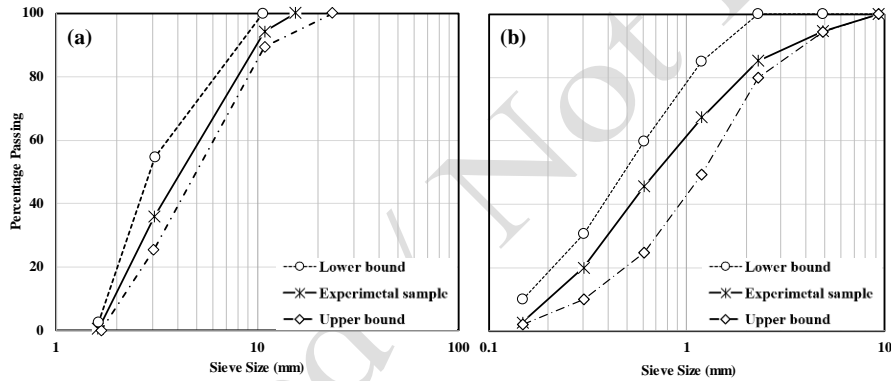
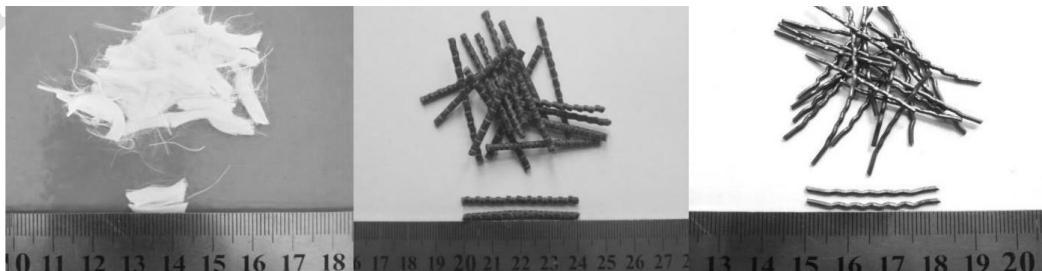


Figure 2. Particle size distribution curves with upper and lower bounds of ASTM c33: (a) Gravel, (b) Sand

Three types of discrete fibers—steel (ST), macro-synthetic (MS), and polypropylene (PP)—were incorporated into the concrete mixtures to investigate their influence on mechanical performance. These fibers were selected due to their distinct mechanical roles and geometric characteristics, which affect crack-bridging capacity and composite interaction mechanisms. The geometric parameters of the fibers, including length, equivalent diameter (or thickness), and aspect ratio, are presented in Table 2 to provide a clear comparison with the particle-size distribution of the river sand and crumb rubber used in this study. Specifically, the selected fibers had lengths of 30 mm (ST), 40 mm (MS), and 12 mm (PP). Their schematic configurations, illustrating surface texture and cross-sectional shape, are shown in Figure 3.



(a) (b) (c)
 Figure 3. Different fibers used in the present study (a) polypropylene, (b) macro-synthetic (c) steel

Table 2. Physical and chemical properties of fibers

Fiber	Steel (ST)	Macro Synthetic (MS)	Polypropylene (PP)
Shape	Hooked	smooth	smooth
Length (mm)	30	40	12
Diameter (mm)	0.785	0.91	0.091
Aspect ratio (L/D)	38.2	43.95	131.9
Color	Grey metallic	Black	Transparent
Melting point (°C)	-	160	160
Evaporation point (°C)	-	450	-
Modulus of elasticity (GPa)	-	6.5	7.2
Tensile strength (MPa)	1220	580	550

CR in three size ranges (0-1 mm, 1-3 mm, and 3-5 mm) was used as a partial replacement for fine aggregates in the concrete. The particle size distribution and gradation of CR are shown in Figures 4 and 5, respectively. The physical and chemical properties of CR are provided in Table 3.

Table 3. Physical and chemical properties of CR aggregate

Properties	Material Percentage
Physical situation	Solid
Unite weight (gr/cm ³)	1.05 ± 0.05
Color	Black
Elastic Modulus (MPa)	1.82
Tensile Strength (MPa)	19.8

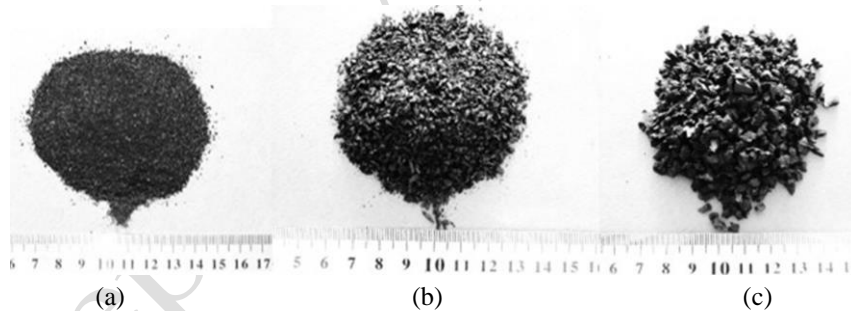


Figure 4. Size distributions of CR used in the present study (a) 0-1mm, (b) 1-3mm, (c) 3-5mm

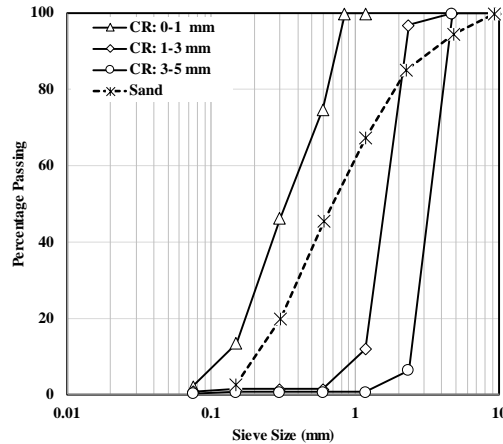


Fig. 5. Particle size distribution of sand and CR aggregates with different sizes

2.2 Concrete Mixing and Preparation Plans

2.2.1 Control Concrete (CC)

The control concrete mix was prepared without the addition of any fibers or CR. This served as a baseline to evaluate the impact of additives on the concrete's mechanical properties.

2.2.2 Optimization of Additives (Fibers and CR)

The objective of this phase was to determine the optimal percentages of each additive (fibers and CR). To achieve this, different concrete mix designs were tested. First, concrete without any fibers or CR was prepared as a control. Then, various percentages of PP and MS fibers (0.2%, 0.4%, 0.7%, 1.0%, and 1.2%) and ST (0.5%, 1.0%, and 1.5%) were introduced into the concrete. Subsequently, CR of different sizes (0-1 mm, 1-3 mm, and 3-5 mm) was added in varying proportions (5%, 10%, 15%, and 20%) as a partial replacement for fine aggregate.

2.2.3 Hybrid Concrete (Fiber-CR Concrete)

After identifying the optimal values of both fibers and CR, they were combined to produce hybrid concrete. The water-to-cement ratio (w/c) for all mix designs was maintained at 0.5. This constant W/C ratio of 0.5 was chosen to ensure a balanced consistency that facilitates the workability of the concrete while maintaining sufficient strength. The process began with the pre-moistening of dry aggregates (both fine and coarse) by adding part of the mixing water. This pre-moistening step lasted for approximately 30 minutes. Once the aggregates were properly moistened, cement was added to the mixture. The remaining water, along with the additives (CR and fibers), was then added and mixed using a mechanical mixer for approximately 1.5 minutes to achieve a homogeneous mix. The concrete mixture was cast into molds of various shapes (cubic, cylindrical, and rectangular). The specimens were left in a controlled environment at a constant temperature of 24°C for 24 hours to allow the cement to fully hydrate. After 24 hours, the samples were removed from the molds and cured under saturated conditions for 7, 14, and 28 days. After each curing period, the samples were dried with a towel, weighed, and their dimensions were recorded. Following this, the samples underwent mechanical testing, including compressive strength, and tensile strength. The mixing schemes used in this research are presented in Table 4.

Table 4. Concrete mixing design

Mixing Concrete	Cement (kg/m ³)	Water (kg/m ³)	Gravel (kg/m ³)	Sand (kg/m ³)	Fiber (%)			Fiber (kg/m ³)	CR (%)			CR (kg/m ³)	Workability (mm)
					PP	MS	S		0-1 (mm)	1-3 (mm)	3-5 (mm)		
CC	350	175	476	1341	0	0	0	0	0	0	0	0	5
CR-105	350	175	476	1275	0	0	0	0	5	0	0	23.4	14
CR_110	350	175	476	1208	0	0	0	0	10	0	0	46.1	20
CR-115	350	175	476	1141	0	0	0	0	15	0	0	69.1	17
CR-120	350	175	476	1074	0	0	0	0	20	0	0	92.2	9
CR-205	350	175	476	1275	0	0	0	0	0	5	0	26.4	17
CR-210	350	175	476	1208	0	0	0	0	0	10	0	52.8	16
CR-215	350	175	476	1147	0	0	0	0	0	15	0	79.1	12
CR-220	350	175	476	1073	0	0	0	0	0	20	0	105.5	15
CR-305	350	175	476	1275	0	0	0	0	0	0	5	28.1	16
CR-310	350	175	476	1208	0	0	0	0	0	0	10	56.3	15

CR-315	350	175	476	1140	0	0	0	0	0	0	15	84.5	17
CR-320	350	175	476	1070	0	0	0	0	0	0	20	112.6	20
PP-0.2	350	175	476	1313	0.2	0	0	0.7	0	0	0	0	11
PP_0.4	350	175	476	1311	0.4	0	0	1.4	0	0	0	0	12
PP-0.7	350	175	476	1308	0.7	0	0	2.45	0	0	0	0	10
PP-1.0	350	175	476	1305	1	0	0	3.5	0	0	0	0	8
PP-1.2	350	175	476	1303	1.2	0	0	4.2	0	0	0	0	4
MS-0.2	350	175	476	1313	0	0.2	0	0.7	0	0	0	0	14
MS_0.4	350	175	476	1311	0	0.4	0	1.4	0	0	0	0	14
MS-0.7	350	175	476	1308	0	0.7	0	2.45	0	0	0	0	12
MS-1.0	350	175	476	1305	0	1	0	3.5	0	0	0	0	12
MS-1.2	350	175	476	1303	0	1	0	4.2	0	0	0	0	12
ST-0.5	350	175	476	1301	0	0	0.5	39.3	0	0	0	0	13
ST-1.0	350	175	476	1290	0	0	1	79	0	0	0	0	11
ST-1.5	350	175	476	1275	0	0	1.5	118	0	0	0	0	10
PP-1-CR-105-305	350	175	476	1311	0.4	0	0	1.4		5*		23.4	14-16
MS_1_CR_105-305	350	175	476	1305	0	1	0	3.5		5*		23.4	13-15
ST-1-CR-105-305	350	175	476	1290	0	0	1	79		5*		23.4	14-16

CC: Control Concrete, CR: Crumb Rubber, PP: Polypropylene Fiber, MS: Macro-Synthetics Fiber, S: Steel Fiber

* Three different tests were done with different CR size containing 0-1mm, 1-3mm and 3-5mm (In all these tests, CR percentage were 5%).

2.3 Laboratory Test

2.3.1 Fresh Concrete Test

Hydraulic-Cement Concrete), is commonly used to measure the rheological properties of fresh concrete, particularly workability and consistency. This test helps to determine the amount of water required in the mix to ensure that the concrete maintains its fluidity without causing segregation or bleeding. The concrete was cast into a slump cone, which has a top diameter of 100 mm, a bottom diameter of 200 mm, and a height of 300 mm. The fresh concrete was poured into the cone mold in three layers, each with a height of approximately 100 mm, or one-third of the total cone height. Each layer was compacted by tamping it with a rod 25 times, following the guidelines of ASTM C143. After the third layer was compacted, the cone was carefully lifted after about 10 seconds. The reduction in the height of the concrete sample compared to the original cone height was recorded as the slump value, indicating the workability of the fresh concrete mix used in this research.

2.3.2 Hardened Concrete Tests

Three tests were performed to evaluate the mechanical properties of hardened concrete: compressive strength and splitting tensile strength (Brazilian tensile test). The loading rate during testing was controlled between 0.2 to 0.3 MPa per second until specimen failure. Tests were conducted after 7, 14, and 28 days of curing.

2.3.2.1 Compressive Strength Test

The compressive strength test was conducted in accordance with ASTM C39. Compressive strength was measured using cubic samples with dimensions of 150 mm x 150 mm x 150 mm. The compressive strength f_c was calculated using the following equation:

$$f_c = \frac{P}{A} \quad (1)$$

where f_c is the compressive strength of the concrete, P is the maximum force applied to the sample before failure, and A is the cross-sectional area of the concrete sample.

2.3.2.2 Brazilian Tensile Strength Test

The splitting tensile strength test, performed according to ASTM C496, was used to measure the tensile strength of the concrete. Tensile strength was determined using cylindrical samples with a diameter of 150 mm and a height of 300 mm. Each sample was compacted in three layers, each receiving 25 blows. The tensile strength (σ_t) was calculated using the following equation:

$$\sigma_t = \frac{2P}{\pi DL} \quad (2)$$

where σ_t is the tensile strength, P is the maximum load applied to the sample before failure, D is the diameter, and L is the length of the cylindrical sample.

3 Results and discussion

3.1 Fresh concrete test

Concrete samples containing various percentages of CR were subjected to a slump test to assess workability, and the results are presented in Figure 6.

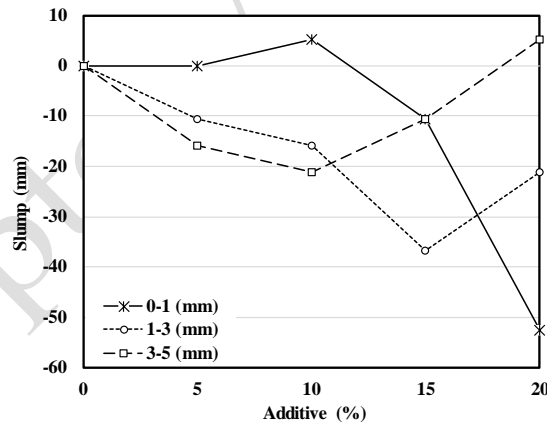


Figure 6. CR effects on concrete workability

The results presented in Figure 6 demonstrate that the inclusion of CR has a profound effect on the workability of concrete, with the particle size and content of CR influencing the slump behavior significantly. For concrete mixes incorporating smaller CR particles (less than 1 mm), the initial increase in slump by 5% as CR content increased from 0 to 10% suggests an improvement in workability. This can be attributed to the smaller rubber particles acting as micro-fillers, improving the lubrication effect within the mix, and promoting easier flow of the concrete. However, once the CR content exceeds 10%, the slump experiences a sharp decline of 55%, indicating that excess fine rubber particles may hinder the mix's fluidity. This drop in workability

is likely due to the high surface area of finer CR particles, which demand more water and increase internal friction, leading to reduced mobility of the concrete matrix.

In contrast, when coarser CR particles (greater than 1 mm in diameter) were used, the initial slump reduction was about 20% at 10% CR content. This suggests that larger rubber particles disrupt the matrix more significantly compared to finer ones, likely due to their lower surface area-to-volume ratio, leading to less effective particle packing and a stiffer mix. However, as the CR content was increased beyond 10%, the slump values showed a slight upward trend, contrary to the behavior observed with smaller CR particles. This could be explained by the fact that larger CR particles might create more voids within the concrete matrix, reducing particle-to-particle contact and, consequently, internal friction. As a result, the mix becomes slightly more workable, even though it remains less fluid than the control mix. Notably, the use of 20% coarser CR particles resulted in higher slump values compared to both the control mix and the concrete containing finer CR particles. This phenomenon suggests that, while the finer CR particles tend to increase water demand and reduce workability, coarser particles might act as aggregate substitutes, allowing for a more open structure and increased ease of flow. However, the improvement in workability with larger CR content must be balanced with the potential compromise in mechanical properties, as discussed in later sections.

The results presented in Figure 7 highlight the substantial impact that different types of fibers have on concrete workability. Consistent with prior studies (Khan et al., 2023; Özen et al., 2024; Tiwari & Singh, 2024; B. Zhang et al., 2022), the inclusion of fibers leads to a significant reduction in slump, primarily due to the increased internal friction and reduced fluidity caused by the fibers' presence within the concrete matrix (Odeyemi et al., 2023). Among the fibers tested, PP fibers had the most pronounced effect on workability, resulting in a drastic 80% reduction in slump. This considerable reduction can be attributed to the relatively high surface area of PP fibers, which tends to absorb more water and create more friction within the mix. The PP fibers' flexibility and tendency to clump together further reduce the free movement of concrete particles, leading to a stiff, less workable mix.

In contrast, MS fibers exhibited the least impact on workability, with only a 35% reduction in slump. MS fibers, being more rigid and having a smaller surface area compared to PP fibers, are less likely to entangle or clump, which allows the concrete matrix to retain a higher level of workability. This makes MS fibers a more favorable choice in applications where the retention of workability is crucial while still benefiting from the mechanical advantages that fiber reinforcement provides.

The incorporation of ST fibers also caused a notable reduction in workability, with a 47% decrease in slump. While less severe than the effect of PP fibers, the decrease in workability with ST fibers is still significant and can be linked to the high stiffness and relatively large size of the steel fibers. The rigid, elongated nature of ST fibers tends to create blockages in the flow of concrete, reducing its ability to compact and move freely, which negatively affects workability.

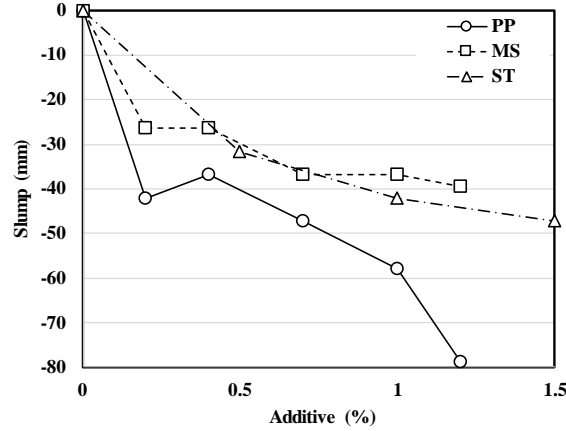


Figure 7. Effect of fibers on concrete workability

3.2 Hardened Concrete Test

3.2.1 Compressive Strength

The effects of different fibers on the compressive strength of concrete at various curing times (7, 14, and 28 days) provide valuable insights into the behavior of fiber-reinforced concrete. As presented in Figure 8a, the incorporation of PP fibers had a significant impact on compressive strength, particularly at 28 days of curing. When the percentage of PP fibers was increased from 0.2% to 0.4%, a notable 27% increase in compressive strength was observed compared to the control concrete. This improvement is likely due to the fibers' ability to bridge microcracks, enhancing the integrity and cohesion of the concrete matrix, which contributes to improved load-bearing capacity.

However, when the fiber content was further increased beyond 0.4%, up to 1.2%, the compressive strength exhibited a decreasing trend. At the highest fiber content of 1.2%, the strength returned to levels similar to the control mix. This reduction in strength at higher fiber dosages can be attributed to fiber clustering and the creation of voids within the concrete matrix. Excessive fibers tend to disrupt the homogeneity of the mix, leading to poor compaction and increased porosity, which negatively affects compressive strength.

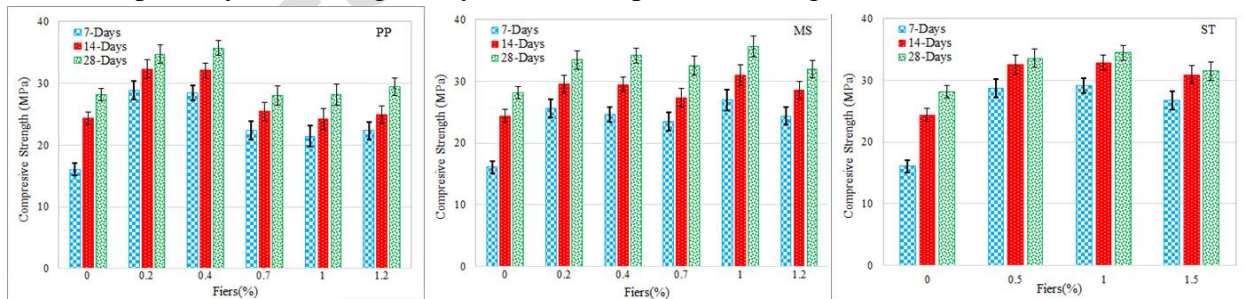


Figure 8. Effects of fibers on compressive strength

Interestingly, the influence of PP fibers on compressive strength was more pronounced during the early stages of curing, particularly at 7 and 14 days. At these early curing times, the presence of fibers may play a more critical role in controlling the propagation of cracks, helping the concrete gain strength more rapidly compared to the control. This suggests that PP fibers may

be particularly beneficial in applications requiring early strength development. However, as the concrete continues to cure and hydration progresses, the positive effect of fibers diminishes, especially at higher dosages, likely due to the aforementioned issues of fiber-matrix interaction and compaction.

In the case of MS fibers (Figure 8b), a distinct pattern emerged compared to PP fibers. When the MS fiber content was increased from 0.2% to 1%, compressive strength improved significantly, showing a 26% rise relative to the control concrete. However, with further increments in fiber content to 1.2%, the compressive strength began to decline, reducing by approximately 12% and reaching a value 14% lower than the strength observed at the 1% fiber content level. This suggests that 1% MS fiber provides optimal reinforcement, while higher contents cause issues similar to those seen with PP fibers, likely due to poor dispersion and fiber clustering.

ST fibers (Figure 8c) followed a similar trend, with compressive strength improvements up to 1% fiber content, showing a 22% increase over the control. However, beyond this level, further increases in ST fiber content led to a gradual reduction in strength (A. A. Mohammed et al., 2025). Even at the highest fiber content, the compressive strength remained 12% higher than the control concrete, but 9% lower than the maximum strength achieved with 1% ST fibers. The optimal range for compressive strength improvement thus appeared to be around 1% for both MS and ST fibers.

Overall, fiber addition enhanced the early-stage compressive strength (7-day strength) regardless of the type or content of fibers. However, as curing time progressed, the rate of strength gains in fiber-reinforced concrete slowed in comparison to control concrete. Between 7 and 14 days, the compressive strength increased by approximately 12%, 15%, and 13% for PP, MS, and ST fibers, respectively. Between 7 and 28 days, this increase was approximately 25%, 31%, and 18%, respectively. These results indicate that FRC accelerates initial strength development, which could be advantageous for projects requiring quicker form removal and reduced curing times. However, at later curing stages, the strength gains become less pronounced, highlighting the importance of fiber dosage and mix design in optimizing long-term performance.

The variation in optimal fiber content across different types can be attributed to several factors, including the fibers' physical properties, bonding mechanisms with the concrete matrix, and their effects on the overall concrete microstructure. PP fibers, with their excellent tensile strength and flexibility, may enhance early-age strength more effectively at lower dosages, leading to significant improvements in compressive strength. However, excessive PP fiber content can lead to poor dispersion and increased viscosity, ultimately hindering the matrix's cohesive strength. Conversely, MS fibers, which are designed to improve toughness and crack resistance, may require slightly higher dosages to achieve optimal performance due to their different bonding characteristics with the concrete. ST fibers, while effective in providing high tensile strength and durability, may also lead to clustering and reduced workability if added in excess, thus impacting the overall strength of the concrete. Therefore, the specific physical characteristics and interaction mechanisms of each fiber type dictate their respective optimal contents, underscoring the importance of tailored mix designs for maximizing concrete performance.

3.2.1.1 Effects of CR on Concrete Strength

To investigate the effect of CR on the mechanical behavior of the mixtures, three CR size ranges (0-1 mm, 1-3 mm, and 3-5 mm) were used as partial replacements for fine aggregates at varying percentages (0%, 5%, 10%, and 20%). The concrete samples were subjected to compressive strength tests at different curing times (7, 14, and 28 days), and the results are illustrated in Figure 9.

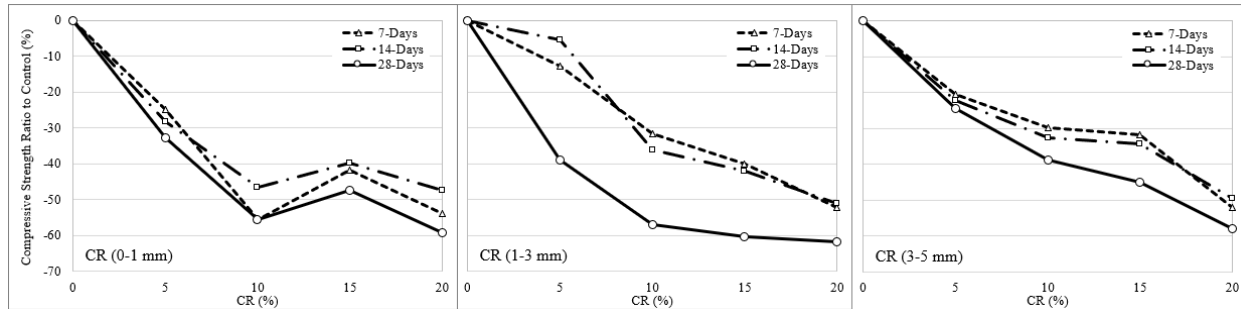


Figure 9. CR effects on compressive strength of concrete

As shown in Figure 9, the addition of CR, regardless of its content, caused a reduction in the compressive strength of concrete, consistent with findings from other researchers (Dahish, 2023; Issa & Salem, 2013; Liu et al., 2022). Across all CR sizes, the compressive strength decreased as curing progressed. This reduction was most pronounced in the 1-3 mm CR size, where the strength decreased by approximately 20%. The decrease in strength can be attributed to the lower stiffness and weaker bonding properties of rubber particles compared to natural aggregates. As the rubber particles replace a portion of the aggregates, they introduce more voids and irregularities in the concrete matrix, which compromise the overall load-bearing capacity. Notably, the compressive strength reduction was more severe as the curing period extended, indicating that the weaker bonding of CR particles persists over time and does not significantly improve with longer curing.

At a fixed CR percentage (e.g., 10%), increasing the CR particle size from 0-1 mm to 3-5 mm led to a significant improvement in compressive strength, an increase of about 50%. This trend suggests that larger CR particles help mitigate the reduction in strength caused by the presence of CR in concrete. This suggests that both the size and content of CR play critical roles in determining the extent of strength reduction, emphasizing the need to carefully balance CR use in mixed designs to mitigate its negative effects on concrete's compressive strength.

Based on the compressive strength results for CR-concrete, the optimal CR content that caused the least reduction in strength was found to be 5%. This percentage was selected for further study in the subsequent phases of the research.

3.2.1.2 Effects of CRF on Concrete Compressive Strength

The optimal percentages of each fiber-PP, MS, and ST-along with 5% of CR, were used to produce crumb rubber fiber-reinforced concrete. The results are shown in Figure 10.

As depicted in Figure 10, the combined presence of rubber fibers and CR resulted in improved concrete performance. Specifically, CR and ST fibers contributed to an increase in compressive strength at 28 days of curing. Increasing the size of the rubber particles in the CRF

concrete led to a compressive strength improvement of about 15%. This increase is likely due to better interlocking and fastening of larger rubber particles compared to finer ones. The positive interaction between CR and ST fibers suggests that fibers can mitigate some of the detrimental effects of CR on concrete strength. Specifically, the larger rubber particles in the CRF concrete improved the mechanical interlocking within the matrix, resulting in a 15% increase in compressive strength compared to finer rubber particles. This improvement can be attributed to the larger rubber particles providing better integration with the concrete matrix, distributing stresses more evenly and reducing the concentration of weak points. Additionally, ST fibers help to bridge micro-cracks and reinforce the matrix, contributing to the increased strength. The results highlight that, despite the general tendency of CR to reduce strength, optimizing the size of rubber particles and incorporating fibers can offset these negative effects, leading to a more durable and higher-performing concrete mix.

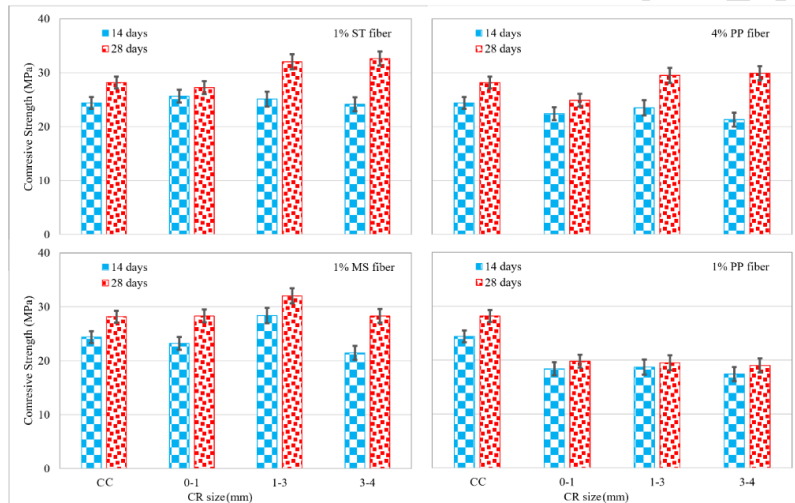


Figure 10. CRF effect on compressive strength of concrete

In the case of CRF-PP, an increase in rubber particle size led to a compressive strength rise of around 6%. However, for smaller CR sizes (0-1 mm), the compressive strength decreased. The results indicate that, at a constant crumb rubber content of 1%, increasing the PP fiber dosage from 0.4% to 1.0% leads to a significant reduction in compressive strength, reaching approximately 33%. This behavior suggests that, in contrast to the ST and MS fibers—which exhibited improved or more stable performance at higher dosages—the PP fibers demonstrate an optimum content around 0.4%. For CRF-MS, the compressive strength increased by approximately 13% as the rubber particle size grew from 0-1 mm to 1-3 mm. However, further increasing the rubber particle size from 1-3 mm to 3-5 mm did not lead to any significant change in compressive strength compared to conventional concrete.

3.2.2 Tensile Strength

To assess the effects of fibers on the tensile strength of concrete, samples containing various percentages of fibers were subjected to the indirect (Brazilian) tensile strength test. The results are illustrated in Figure 11.

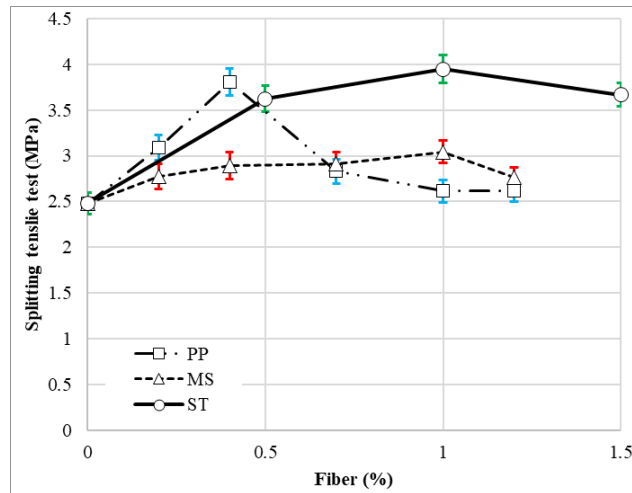


Figure 11. Effects of fibers on splitting tensile strength

The results presented in Figure 11 demonstrate a clear enhancement in the tensile strength of concrete with the incorporation of various fiber types. The maximum tensile strengths observed—53% for PP, 22% for MS, and 59% for ST fibers—highlight the significant role of fiber type in influencing this property. Notably, the optimal fiber content for achieving maximum tensile strength varied among the fibers, with 0.4% being ideal for PP fibers and 1% for both MS and ST fibers. This difference can be attributed to the varying mechanisms by which each fiber type interacts with the concrete matrix.

PP fibers, with their lightweight and high tensile strength characteristics, effectively reinforce the concrete and improve its ductility, which explains their optimal performance at a lower dosage. In contrast, the higher optimal content for ST and MS fibers indicates that these fibers require a greater presence to effectively bridge cracks and improve tensile performance. The enhanced tensile strength achieved with ST fibers, in particular, underscores their superior ability to arrest crack propagation due to their high modulus of elasticity and bonding capacity with the concrete matrix.

The results presented in Figure 12 indicate that the inclusion of rubber particles significantly affects the tensile strength of concrete, with both the percentage and size of the rubber particles playing crucial roles in determining performance. As the rubber particle content increased, there was a notable variation in tensile strength, reflecting the complex interactions between the rubber particles and the concrete matrix. The data reveal that at lower percentages of rubber particles, there is a moderate enhancement in tensile strength; however, as the rubber content increases beyond an optimal level, a decline in tensile strength is observed. This decline can be attributed to the inherent characteristics of rubber, which, while providing flexibility and improving ductility, can also lead to reduced load-bearing capacity when present in excess.

Moreover, the size of the rubber particles also contributed to the tensile strength outcomes. Larger rubber particles generally enhanced the tensile strength more effectively than smaller particles, likely due to their ability to create a more robust interlocking structure within the concrete matrix. The larger particles can better accommodate the stress distribution and contribute to crack

bridging, thereby enhancing overall tensile performance. This trend aligns with findings from previous studies that highlight the importance of particle size in rubberized concrete applications.

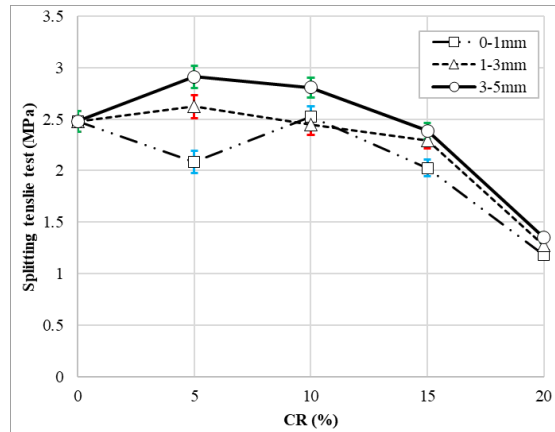


Figure 12. Effects of CR on splitting tensile strength

As depicted in Figure 12, the presence of recycled CR up to a certain percentage resulted in increased tensile strength of concrete. This increase depended on the particle size of the CR. The maximum tensile strength was observed in samples with rubber particle sizes of 1-3 mm and 3-5 mm, both at a CR content of 5%. In contrast, for rubber particles sized 0-1 mm, the maximum tensile strength occurred at a CR content of 1%. Compared to the control concrete, the maximum tensile strength of concrete containing CR particles with sizes of 0-1 mm, 1-3 mm, and 3-5 mm was approximately 1%, 5%, and 17%, respectively. This indicates that larger CR particles led to greater increases in tensile strength, possibly due to the improved interlocking of the coarser CR aggregates along the fracture lines, enhancing resistance to tension.

After determining the optimal fiber percentage and the 5% CR content, Brazilian tensile strength tests were conducted. Figure 13 presents the corresponding results, including the tensile strength of the control concrete (CC), the fiber-reinforced concrete without crumb rubber (CF), and the fiber-reinforced concrete containing various crumb rubber sizes (i.e. 0-1, 1-3, and 3-5 mm).

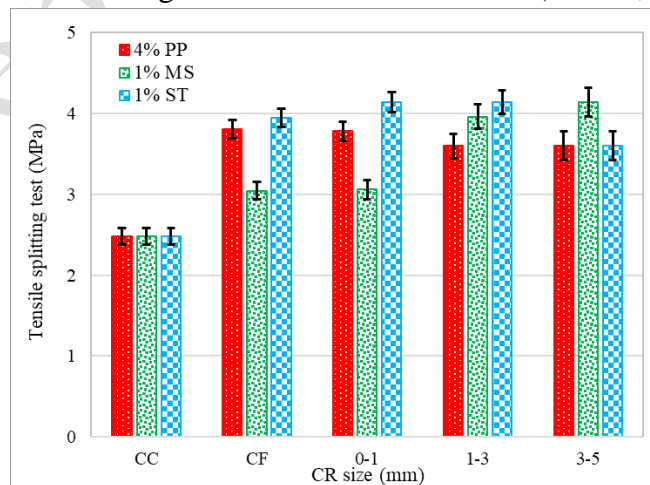


Figure 13. CRF effect on splitting tensile strength

As shown in Figure 13, the incorporation of fibers at their optimal percentages led to a significant improvement in the tensile strength of concrete compared to the control mix. This enhancement can be attributed to the role fibers play in bridging cracks and distributing tensile stresses more uniformly across the concrete matrix. Fibers act as reinforcement, preventing the propagation of microcracks under tensile loading, which helps to delay the failure of the concrete.

Each fiber type (PP, MS, and ST) contributes differently to this performance, with the optimal fiber percentages creating an effective balance between enhancing tensile strength and maintaining concrete workability. For instance, at the optimal percentage, PP fibers improve tensile strength by enhancing the flexibility of the concrete, while MS fibers provide ductility without significantly compromising strength. ST fibers, being more rigid, excel in providing structural integrity and crack resistance under tensile stress.

The improvement in tensile strength with fibers is particularly noticeable because concrete is inherently weak in tension. Without reinforcement, cracks can develop and propagate quickly when subjected to tensile loads. By adding fibers at the optimal percentages, the fibers intercept the cracks, reducing their width and mitigating the extent of damage, which leads to a considerable increase in tensile capacity.

Overall, the improvement in tensile strength with fibers indicates that their use at appropriate levels provides a valuable solution to addressing the tensile weakness of concrete, making it a more resilient material for structural applications. This reinforces the importance of selecting the right fiber type and quantity to achieve desired performance outcomes in concrete structures. Moreover, combining the optimal fiber percentages with rubber particles showed that tensile strength was strongly dependent on the size of the CR particles. For CRF(ST) concrete, increasing the particle size up to 3 mm led to a 5% increase in tensile strength. However, further increasing the rubber particle size from 3 mm to 5 mm caused a reduction in tensile strength by about 8%.

For CRF(MS) concrete, an increase in the size of CR particles from 1 mm to 5 mm resulted in a significant 36% increase in tensile strength. On the other hand, CRF(PP) exhibited a reverse trend; increasing the CR particle size from 1 mm to 5 mm caused a 5% reduction in tensile strength.

4 Conclusions

This study investigated the effects of fibers (PP, MS, ST) and recycled rubber particles (CR) on the fresh and hardened properties of concrete, focusing on workability, compressive strength, and tensile strength. Additionally, the simultaneous presence of both fibers and CR (CRF) in concrete was examined. Based on the experimental results, the following conclusions can be drawn:

1. The incorporation of CR affected concrete workability depending on its particle size and content. Low CR contents ($\leq 10\%$) slightly improved workability (up to $\sim 5\%$), particularly for smaller particles, while higher contents led to a reduction in slump. Larger CR particles showed a modest improvement in workability ($\sim 7\%$) compared to the control mix. The addition of fibers significantly reduced workability, with PP fibers causing the greatest decrease ($\sim 80\%$), followed by ST ($\sim 45\%$) and MS fibers ($\sim 40\%$). The reduction is mainly attributed to fiber interference with mix flow and increased internal friction, especially for PP fibers due to their length and high surface area.

2. The incorporation of fibers significantly enhanced the compressive strength of concrete, with optimal contents of 0.4% for PP and 1% for both MS and ST. Compared with the control mix, compressive strength increased by approximately 27%, 26%, and 22% for PP-, MS-, and ST-reinforced concretes, respectively. In contrast, the use of CR as partial aggregate replacement resulted in a considerable reduction in compressive strength (up to 60%), regardless of CR size or content. However, the combination of fibers and CR (CRF concrete) noticeably improved compressive strength compared to CR-only mixtures, with increases of about 5% for PP-CR and 14% for MS-CR and ST-CR, indicating a synergistic effect.

3. Fibers enhanced the tensile strength of concrete, with optimal contents of 0.4% for PP and 1% for MS and ST. ST fibers provided the highest improvement (up to 59%), while MS fibers showed the lowest (~22%), confirming the strong influence of fiber type. The inclusion of CR further affected tensile behavior, with larger CR particles (3–5 mm) producing the greatest increase (~15%), whereas smaller particles (0–1 mm) resulted in marginal gains (~2%). In CRF concrete, tensile strength increased notably for MS-CR and ST-CR mixtures (up to 35% and 5%, respectively), while PP-CR mixtures showed a slight reduction (up to 4%) at larger CR sizes, highlighting the importance of fiber-CR interaction.

4. The study demonstrates that while CR negatively affects the compressive strength of concrete, it can improve tensile strength, particularly when combined with fibers. The addition of fibers, especially MS and ST, not only enhances the compressive and tensile strength of concrete but also mitigates the negative effects of CR on strength. These findings provide valuable insights for designing sustainable concrete mixtures incorporating recycled materials and fibers for improved performance.

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