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EFFECT OF RUBBER AND STEEL FİBERS OBTAINED FROM WASTE TIRES ON MECHANICAL AND PHYSICAL PROPERTIES OF CONCRETE: AN EXPERIMENTAL STUDY

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ABSTRACT

This study investigated the incorporation of rubber particles and steel fibers, derived from end-of-life vehicle tires, into concrete as partial replacements for fine aggregates, with the goal of enhancing sustainability in construction materials. Twelve concrete mixtures containing varying proportions of rubber (5%, 10%, and 15%) and steel fibers (0.4% and 0.8%) were prepared. The mechanical and physical properties of these mixtures were evaluated through compressive and flexural strength tests, ultrasonic pulse velocity measurements, water absorption analyses, and scanning electron microscopy. The results showed that while rubber significantly reduced compressive strength and increased porosity, it improved flexibility at low contents. In contrast, steel fibers increased density and flexural strength, and counteracted the negative effects of rubber by reducing internal voids and inhibiting crack propagation. The combined use of rubber and steel fibers yielded a complementary improvement in both mechanical performance and durability. These findings confirm the technical feasibility of incorporating waste tire materials into concrete and underscore their relevance in sustainable construction practices.

Keywords: Waste tires, Crumb rubber, Waste recycle tire steel fibers, Rubberized steel fiber concrete, Mechanical properties, Sustainability.

1 INTRODUCTION

Nowadays, with the increasing awareness of sustainable development and environmental protection, the recycling and reuse of industrial waste have received significant importance [1–4]. Environmental issues and the limited availability of natural areas are increasing this trend. Trends in the use of industrial waste as a construction material in concrete have increased, especially due to the energy crisis that emerged in 1970 and environmental issues [5]. Especially in the automotive sector, vehicle tires, after completing their lifespan, become waste in large quantities, and the disposal of this waste leads to serious environmental problems. The decomposition of waste tires in nature can take hundreds of years, and during this process, they can cause soil, water, and air pollution. Therefore, in recent years, efforts to recycle waste tires for use in various fields have received momentum [6]. In the process of recycling waste tires, rubber and steel fibers are separated from the tires and can be used in various industrial applications. The use of waste tires does not have a positive effect on the compressive strength of concrete [7,8]. However, it is understood from many studies that waste tire rubbers and steel fibers contribute to the ductile behavior of concrete [9–12].

The use of these materials as aggregates in concrete mixtures provides both environmental benefits and the potential to improve the mechanical and physical properties of concrete. The addition of rubber particles to the concrete mix can increase the crack resistance of the concrete, enhance its impact resistance, and improve its thermal properties [13,14]. Similarly, the addition of steel fibers to concrete can enhance the tensile strength and toughness of the concrete, contributing to the increased durability of structures [15,16].

The use of waste rubber and steel in concrete as a replacement for traditional fine and coarse aggregates has been the subject of extensive research in recent years. The primary goal of these studies is to offer an environmentally sustainable alternative for the millions of discarded tires accumulating worldwide [6,17,18]. Therefore, adopting this approach can reduce the consumption of natural aggregates while significantly mitigating the environmental problems associated with burning or landfilling scrap tires [19].

Waste tire rubber (crumb rubber) has been used as a replacement for fine aggregate at a rate of 0-20%. As a result of the analysis of compressive strength, flexural strength, abrasion resistance, microstructure, and water permeability on concrete samples, it was determined that waste tire rubber could be used as a replacement for fine aggregate up to 7.5% without causing significant strength loss [18].

In the study conducted by Sengül (2016) [20], the use of waste steel fibers recovered from scrap tires and production steel fibers in concrete mixtures was examined. According to the study's results, both waste and production steel fibers were found to negatively affect the workability of concrete. It has been observed that production steel fibers reduce the compressive strength of concrete by approximately 10%, whereas the compressive strengths of mixtures containing waste steel fibers remained at levels similar to the reference mixture. Additionally, it has been determined that the values of flexural strength and splitting tensile strength increase when using waste steel fibers recovered from scrap tires compared to plain concrete. However, no statistically significant difference has been found between the mechanical properties of production steel fibers and waste steel fibers.

The main aim of this study is to experimentally investigate the effects of rubber and steel fibers, recovered from end-of-life vehicle tires using mechanical methods, on the mechanical and physical properties of concrete when used as a fine aggregate substitute in concrete mixtures. In this context, concrete mixtures containing rubber and steel fiber additives in different proportions were prepared, and a comprehensive evaluation was conducted based on parameters such as compressive strength, flexural strength, water absorption rate, unit weight, and ultrasonic pulse velocity (UPV). Additionally, it is aimed to observe the changes in the internal structure of the concrete through scanning electron microscope (SEM) analysis. The study aims to contribute to both the improvement of concrete performance and the re-evaluation of waste tires as construction materials, thereby establishing a scientific foundation for the development of sustainable building technologies.

Toughness and ductility are widely recognized as key parameters in evaluating the post-cracking performance of fiber-reinforced concretes, as they provide valuable insights into energy absorption and deformation capacity [21–24]. While these values are not directly calculated in the present study, their importance is acknowledged, and they are suggested as essential aspects for future investigations.

2 MATERIAL AND METHOD

2.1 Material

The separation of rubber and steel fibers from vehicle tires is a process carried out using mechanical methods. Figure 1 [25], schematically shows the mechanical separation of rubber and steel fibers during the recycling process of waste tires. The process begins with the collection of scrap tires. Then, these tires are broken down into small pieces in machines called tire shredders. During the shredding process, the steel wires and rubber components inside the tires are revealed. The steel wires are separated from the rubber using the magnetic separation method. As a result of this process, steel wire and rubber are obtained separately. Rubber particles are then classified according to their size using methods such as screening or air classification. At this stage, the rubber particles are generally processed to have a particle diameter in the range of 2-4 mm. Steel wires, on the other hand, are converted into finer steel fibers through the heel wire drawing process. These fibers are prepared for use as reinforcement in construction materials such as concrete. The mechanical separation process reduces the environmental impact of waste tires while allowing the recovered rubber and steel fibers to be used in industrial applications.

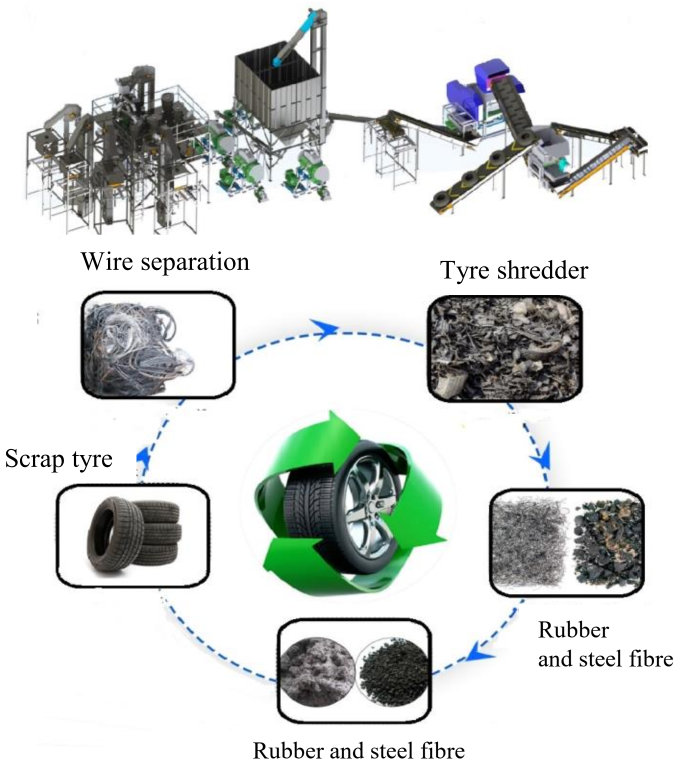

Figure 1. The process of separating rubber and steel fibers from waste tires using mechanical methods [25]

The waste rubber and steel fiber materials used in this experimental study were obtained from the Yakupoğulları Recycling Facility located in the Mardin Organized Industrial Zone [26] (Figure 2). The facility in question produces rubber for areas such as children's playgrounds, walking paths, and artificial turf fields; rubber powder for the production of wheels, shoe soles, vehicle mats, and conveyor belts; and waste steel fibers for use as raw materials in iron and steel factories. This facility contributes substantially to sustainable material production through recycling processes. The diameters of the steel fibers (Figure 3a) separated from heavy vehicle waste tires using mechanical methods were determined through measurements made with an electronic caliper. The analytical results revealed two distinct groups of steel fibers with differing diameters. Due to variations induced by mechanical fragmentation processes, fiber lengths were reported as measurement ranges. The fineness values of the fibers were calculated by the ratio of their lengths to their diameters. Type 1 has a diameter of 0.11 mm and Type 2 has a diameter of 0.29 mm, with Type 1 having a length of 25-55 mm and a fineness of 227-500, while Type 2 has a length of 35-50 mm and a fineness of 120-172 (Table 2). After being separated by mechanical methods, the rubber crumbs (Figure 3b) were sieved and found to have a particle diameter in the range of 2−4 mm (Table 3). These findings provide important data for the characterization of the geometric properties of rubber crumbs and steel fibers obtained from waste tires.

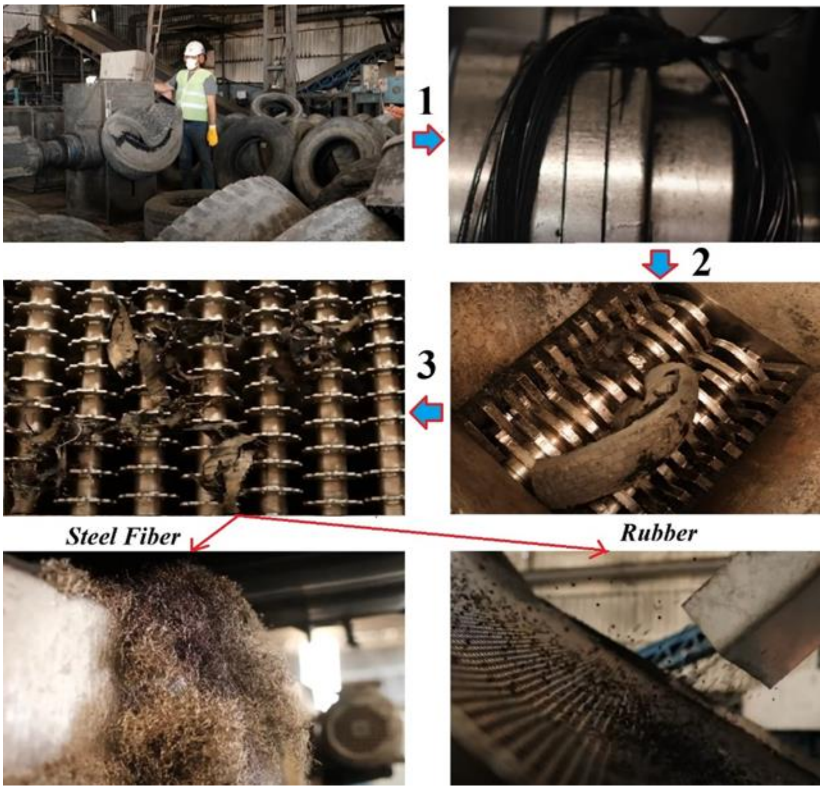

Figure 2. Production process of waste steel fiber and rubber [26]

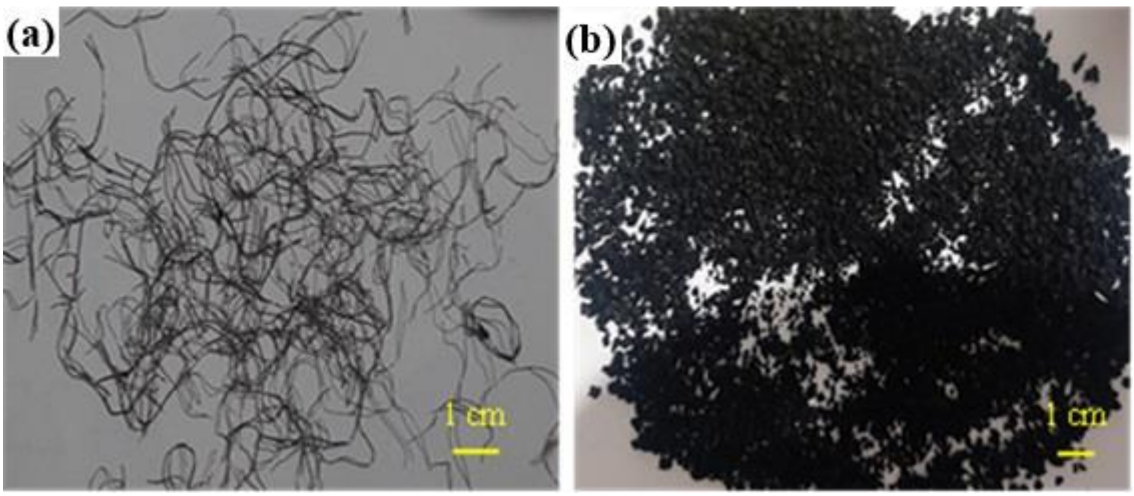

Figure 3. Waste tire rubber and steel fiber utilized in the experimental study.

2.1.1 Cement

In the experimental study, CEM I 42.5 N type Portland cement was utilized. The physical and chemical properties of the cement are offered in Table 1.

2.1.2 Aggregate

Natural aggregates were utilized in three size fractions: 0-4 mm (fine), 4-11.2 mm (medium), and 11.2-22.4 mm (coarse). The measured densities were 2.62 g/cm^3 for fine aggregate (sand), 2.69 g/cm^3 for medium aggregate, and 2.72 g/cm^3 for coarse aggregate. The sieve analysis of the natural aggregate utilized in the experiment is given in Figure 4.

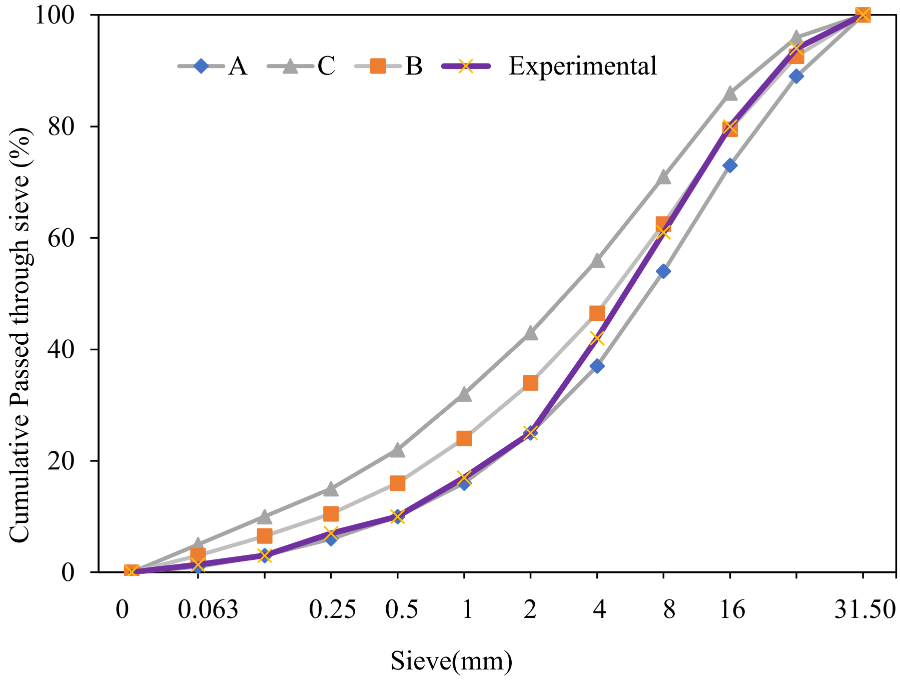

Figure 4. Aggregate gradation.

2.1.3 Waste Tire Product

The diameters of steel fibers extracted from heavy-vehicle waste tires via mechanical processing were measured using an electronic caliper. The results revealed two distinct groups of fibers with different diameters. Due to differences in length caused by mechanical breakage, fiber lengths are presented as a range. The aspect ratio (length-to-diameter ratio) was calculated to determine fiber fineness. Table 2 summarizes the physical properties of the steel fibers. As a result of sieve analysis of rubber crumbs obtained from waste tires after mechanical shredding, it has been determined that they have a diameter range of 2−4 mm. The physical properties of the rubber are offered in Table 3.

Table 1. The properties of cement

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	LOI*	Blaine (m^2/kg)	Specific gravity (g/cm^3)
21.12	4.62	3.80	62.94	2.73	2.20	0.02	0.35	2.22	338	3.10

LOI = Loss on ignition*

Table 2. Characteristics of steel fiber [6]

Steel fiber	Diameter (mm)	Length (mm)	Slenderness	Weight ratio
Type I	0.11	25-55	227-500	61%
Type II	0.29	35-50	120-172	39%

Table 3. The properties of rubber

Diameter range	Fineness module	Specific gravity (g/cm^3)
2-4 mm	2.17	0.95

2.1.4 Superplasticizer

Superplasticizer The Chryso Delta Superplasticizer additive contributed to concrete strength by reducing the water/cement ratio. The dosage was set at 6 kg/m^3 of concrete.

The weight ratio given in Table 2 is provided as the percentage by weight of the waste steel fibers in the mixture, as the fibers are a blend of different sizes and diameters. The weight ratio is the percentage distribution by weight of the components that make up a mixture relative to the total weight of the mixture. It is a proportion used in designing the mixture, not a calculated property of the components. The fineness modulus (Table 3) is a calculated parameter that expresses the average particle size of the rubber granules used in the study as a numerical value, replacing the aggregate.

2.2 Method

The experiments were conducted in the Structural Laboratory of Siirt University using testing instruments and equipment calibrated by TÜRKAK (Figure 5).

To improve the mechanical properties of concrete and contribute to the recycling of waste tires, which are an environmental issue and prohibited from storage by the European Union [27,28], fine aggregate in concrete mixtures has been partially replaced with rubber crumbs and steel fibers. In this context, rubber crumbs were used as a partial replacement for fine aggregate in volumes of 5%, 10%, and 15% (the acceptable replacement rate is up to 25% [29]), and steel fibers were used in volumes of 0.4% and 0.8% (the optimum steel fiber replacement rate is 0.56% − 0.64% [16]). These substitution ratios aim to both enhance the performance of concrete and evaluate waste tires by adopting a sustainable approach. The concrete mix design values and details are presented in Table 5. This study demonstrates that the use of environmentally friendly materials in concrete technology is possible and that waste management and building materials performance can be optimized to obtain them.

In the process of preparing the concrete mix, first, coarse aggregates, sand, and cement were placed into the mixer. These materials were mixed homogeneously in the mixer for three minutes before adding the superplasticizer and water. Then, water and superplasticizer were added, followed by steel fibers and rubber, and the mixer was run for an additional two minutes. As a result of this process, a homogeneous fresh concrete was obtained, particularly with the steel fibers evenly distributed.

Mechanical Analysis Concrete mixtures produced in accordance with the TS EN 206-1 [30] standard was poured into cylindrical molds sized 150 × 300 mm and beam molds sized 150 × 150 × 600 mm (Figure 6). The samples were removed from the molds after 24 h and cured for 28 days under conditions of 20 ± 5 °C temperature and 97 ± 2% humidity. This process provided standard curing conditions for the development of the mechanical properties of the concrete. Based on the experimental results, 12 different designs were prepared, and the average of the results obtained from analyses conducted on 3 samples for each design was taken.

The compressive strength tests of cylindrical concrete specimens with dimensions of 150 × 300 mm were carried out in accordance with the requirements of both the TS EN 12390-3 and the ASTM C39/C39M, ensuring the reliability and international comparability of the results.

The flexural strength test was performed on a 3-point bending test setup. The flexural strength test was performed on the beam specimens using the device in accordance with, TS EN 12390–5[31], ASTM C 78 [32] , and the flexural strength was calculated using the following equation (1):

$$\sigma_f = \frac{3 \times (F \times l)}{2 \times (b \times h^2)} \tag{1}$$

where σ_f is the flexural strength (MPa), F is the failure load (N), l is the span length (mm), b is the specimen width (mm), and h is the specimen height (mm).

2.2.1 Ultrasonic Experiment

Ultrasonic tests were conducted using the Proceq brand ultrasonic pulse velocity (UPV) measurement device (Pundit Lab) in accordance with the EN 12504-4 [33], ASTM C 597-02 [26], and ISO 1920-7:2004 standards to determine the sound transmission velocities. The ultrasonic tests, on the other hand, were conducted according to ASTM C597-02 [34], and the average value of three readings was calculated.

2.2.2 Water Absorption

Water absorption was measured on 28-day cured specimens following oven-drying at 105°C for 24 h to constant mass. Then, the samples were placed in a water-filled tank and left for 24 hours to determine the saturated dry surface weight. The water absorption of the concrete samples was measured according to equation (2) in accordance with the TS 3624 [35] standard.

$$Water\ absorption\ (\%) = \frac{W_s - W_d}{W_d} \tag{2}$$

$W_s = water - saturated\ weight\ (kg)$

$W_d = dry\ weight (kg)$

2.2.3 Scanning Electron Microscope (SEM) Analysis

Prior to SEM imaging, sample surfaces were sputter-coated with gold (Au) to ensure conductivity. The specimens were then placed in the SEM chamber for examination. Microstructural characterization was performed using a Hitachi SU3500 scanning electron microscope to analyze surface morphology.

Figure 5. The Siirt University Building Materials Laboratory, Where Experimental Studies Are Conducted

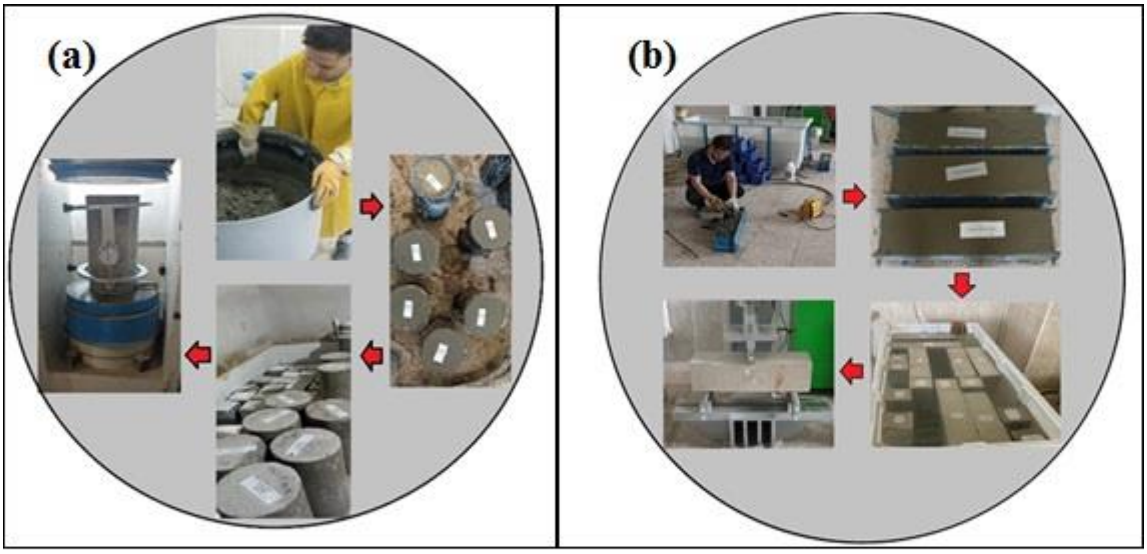

Figure 6. Processes for compressive strength (a) and flexural (b) tests

Table 4. Concrete mix codes (%)

Materials	Mix ID											
	PL	K5C0	K10C0	K15C0	K5C4	K10C4	K15C4	K5C8	K10C8	K15C8	K0C4	K0C8
Rubber	0	5	10	15	5	10	15	5	10	15	0	0
Steel Fiber	0	0	0	0	0.4	0.4	0.4	0.8	0.8	0.8	0.4	0.8

Table 5. 1 m^3 concrete mix ratios (kg)

Mix ID	Cement	Corse Aggregate	Fine Aggregate			Water	Chemical additive
			Sand	Rubber	Steel Fiber		
PL	350	1026.33	813.75	0	0	175	6.0
K5C0	350	1026.33	773.06	13.51	0	175	6.0
K10C0	350	1026.33	732.37	27.02	0	175	6.0
K15C0	350	1026.33	691.69	40.53	0	175	6.0
K5C4	350	1026.33	762.58	13.51	28.36	175	6.0
K10C4	350	1026.33	721.89	27.02	28.36	175	6.0
K15C4	350	1026.33	681.21	40.53	28.36	175	6.0
K5C8	350	1026.33	752.10	13.51	56.72	175	6.0
K10C8	350	1026.33	711.41	27.02	56.72	175	6.0
K15C8	350	1026.33	670.73	40.53	56.72	175	6.0
K0C4	350	1026.33	803.27	0	28.36	175	6.0
K0C8	350	1026.33	792.79	0	56.72	175	6.0

3 RESULTS AND DISCUSSION

3.1 Water Absorption

The water absorption rate of concrete is a critical parameter in terms of durability and service life [36]. According to Figure 7, the measured water absorption rate for the reference concrete sample (PL) was determined to be 4.44%. In the rubber-modified concrete samples (K5C0, K10C0, K15C0), the water absorption rates were measured as 4.48%, 4.80%, and 5.45%, respectively. These results indicate that the rubber additive enhances the water absorption rate of the concrete [13]. The formation of voids within the concrete matrix by rubber has been considered the primary reason for this enhance in water absorption rate [18].

In concrete samples with steel fiber additives (K0C4, K0C8), the water absorption rates were measured as 2.60% and 2.33%, respectively. The results demonstrate that incorporating steel fibers reduces concrete's water absorption while enhancing its tensile strength. The fibers act as crack-arresting components, restricting crack propagation and promoting a denser microstructure. This situation causes water to penetrate less into the concrete and reduces the water absorption rate [37]. However, in cases where steel fibers are not evenly distributed, voids can form within the concrete, which can increase the water absorption rate [38]. The combined use of rubber and steel fibers in concrete has been effective in reducing the voids caused by rubber and has ensured that the water absorption rate remains below the PL value. This situation can be explained by the steel fibers filling the voids created by the rubber within the concrete matrix, resulting in a denser and more homogeneous structure. To reduce the water absorption rate of rubber-modified concrete, the use of steel fibers, which facilitate better compatibility of rubber with the concrete matrix, provides a significant advantage in improving the physical and mechanical properties of the concrete. This approach can be considered an effective strategy, especially for enhancing the durability and water permeability performance of rubber-modified concrete.

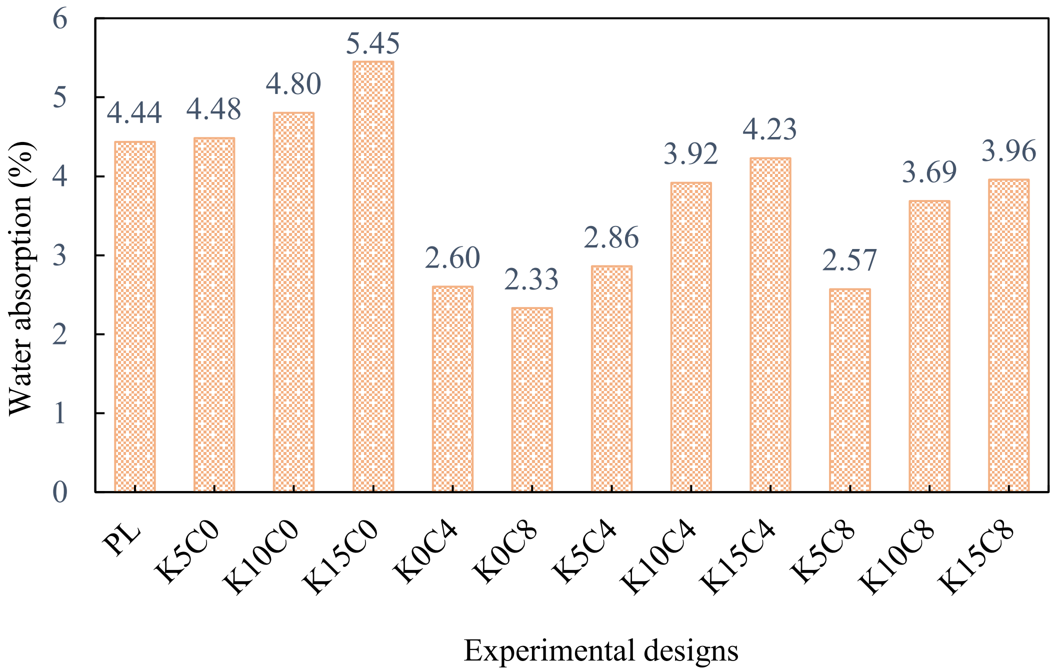

Figure 7. Water absorption

3.2 Unit Volume Weight

The density of a substance is defined as the mass per unit volume. All samples were measured by dividing their masses by the mold dimensions (150 mm × 300 mm) after curing at room temperature for 28 days. As the rubber fiber ratio increased, it was observed that the unit volume weight decreased. According to Figure 8, the density of the PL mixture was 2371.08 kg/m^3, while in the K15C0 mixture, this value decreased to 2289.55 kg/m^3. This situation indicates that rubber fibers reduce the density of the material [13,39]. On the other hand, the addition of steel fibers has increased the unit volume weight. For example, in the K0C8 mixture, the density was measured as 2406.84 kg/m^3. It has been determined that steel fibers increase the density of the material. It is a finding noted by Harshavardhan and Bala Murugan that the density of concrete increases with the addition of aggregates or reinforcement fibers with higher specific gravity [40].

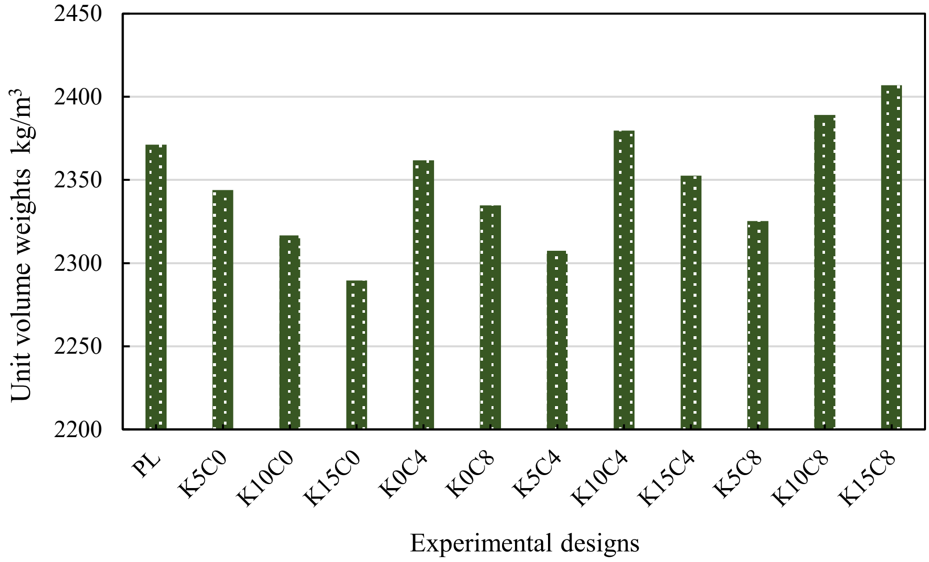

Figure 8. Unit volume weights

3.3 Ultrasonic Pulse Velocity

UPV is an important parameter that provides information about the internal structure, density, and homogeneity of concrete. UPV values depend on factors such as voids, cracks, and density in the internal structure of the concrete. UPV values are used to evaluate the quality of concrete. Table 6 shows the UPV values of the concrete samples and the concrete quality classification based on the BIS 13311-92-Part-I [41] standard according to these values. As long as the UPV values are in the range of 3660 m/s to 4580 m/s, the samples can be categorized as being in good condition, which means they are free from large voids or cracks that could affect the structural reliability of the concrete [42]. Figure 9 presents a schematic simulation illustrating the bridging effect of rubber aggregates and steel fibers. Observations indicate that crumb rubber particles inhibit the propagation of micro-cracks within the cement matrix, while their elastic properties enhance energy absorption [43]. Especially at high crack propagation levels, steel fibers effectively bridged the cracks, and this effect continued until the moment of fracture. The SEM observations presented in Figure 10 clearly reveal the effect of the material's characteristics on the void structure, and these findings are consistent with the results of UPV analysis and water absorption analysis. It has been determined that the addition of rubber crumbs, in particular, causes the formation of voids and microcracks within the material. However, it has been observed that the use of steel fibers plays an important role in reducing these cracks and improving the mechanical properties of the material. These results highlight the effectiveness of steel fibers in optimizing the performance of composite materials and reveal that they are an important parameter to consider in material design. This finding is also supported by Rambo et al. (2014) [44], who examined the effect of fiber hybridization on the fracture behavior of concrete. In the study, it was demonstrated that the combination of rubber aggregate and steel fibers improved the energy absorption by increasing the crack resistance of the concrete, thereby enhancing the toughness of the concrete. These findings demonstrate that incorporating both rubber aggregates and steel fibers in concrete can substantially improve its mechanical performance [45].

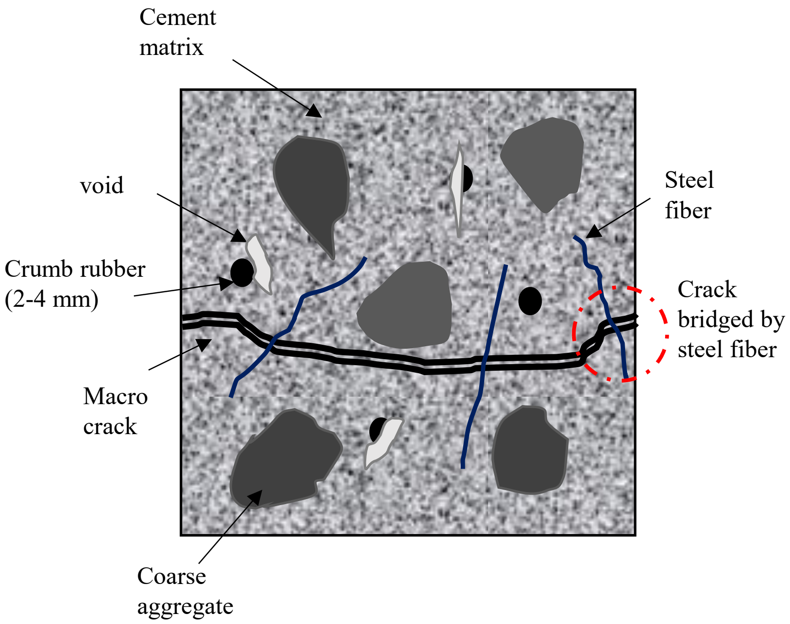

Figure 9. The effect of rubber and steel fibers on crack characterization in a concrete matrix [44]

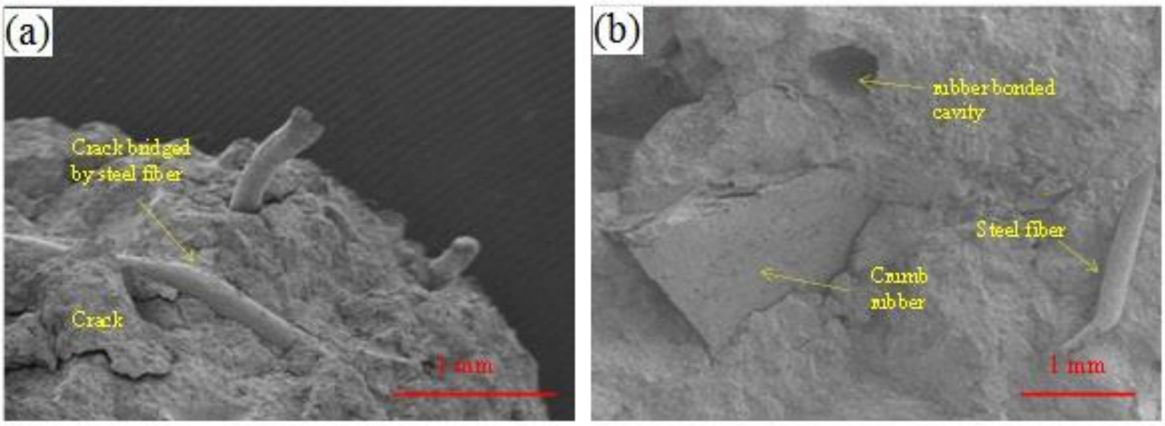

Figure 10. SEM image of the behavior of steel fibers (a) and rubber (b) in a concrete matrix

According to Table 6, the reference PL concrete without rubber and steel fibers has the highest UPV value (4667 m/s) and is of excellent quality class. This indicates that the concrete has a dense and homogeneous structure [46,47]. However, as the rubber content increases, the UPV values decrease [29]. This indicates that rubber reduces the density of concrete and creates voids in the internal structure [48]. However, even with a rubber content of up to 15%, the concrete still remains in a good quality class. Increasing the crumb rubber content to a limit of 25% keeps the alters in the mechanical properties of the rubberized concrete mix within an acceptable range [29]. The addition of steel fibers has maintained UPV values and improved the quality of the concrete [6,45]. Especially the mixtures containing only steel fibers (K0C4 and K0C8) have placed in the excellent quality class.

Table 6. Ultrasonic pulse velocity (UPV) and concrete quality classification.

Mix ID	UPV (m/s)	Concrete quality classification according to the BIS 13311-92-Part-I standard [33].	
		UPV (m/s)	Concrete quality classification
PL	4667	> 4500	Excellent
K5C0	4542	3500-4500	Good
K10C0	4340	3000-3500	Medium
K15C0	3832	< 3000	Doubtful
K5C4	4550		
K10C4	3910		
K15C4	3670		
K5C8	4515		
K10C8	4163		
K15C8	4050		
K0C4	4641[8]		
K0C8	4588[8]		

3.4 Mechanical Properties

The mechanical analysis results of the concrete were obtained in accordance with TS EN 206-1. The results are presented in Table 7.

According to Table 7, the measured compressive strength value for PL has been determined to be 53.22 MPa. In the rubber-modified concrete samples (K5C0, K10C0, K15C0), the compressive strength values were reduced by 16%, 23%, and 41%, respectively. These results indicate that the rubber additive significantly reduces the compressive strength of concrete [49]. The voids created by rubber within the concrete matrix and the weak bond between the aggregate and the cement matrix can be considered the main reasons for this decrease in compressive strength [50]. In concrete samples with steel fiber additives (K0C4, K0C8), the compressive strength values were reduced by 29% and 18%, respectively. In the literature, different results have been reported regarding the effect of steel fiber addition on the compressive strength of concrete. Some studies have reported that the addition of steel fibers causes an increase in compressive strength [51–53], while other studies have stated that steel fibers have no significant effect on compressive strength [15,54]. However, some researchers have suggested that it would be beneficial to conduct more studies on steel fiber-reinforced concrete to achieve more definitive results [55,56].

Steel fibers play an important role in controlling crack formation in concrete. When concrete begins to crack under load, steel fibers prevent the propagation of these cracks, thereby increasing the strength of the concrete. This is particularly a critical factor for flexural strength [57]. Steel fibers increase the energy dissipation capacity of concrete. This makes the concrete more durable under sudden loads or impact and improves its flexural strength [12,16]. The flexural strength of the PL mix was measured at 6.76 MPa. The designs K0C4 and K0C8, which include steel fiber addition, improved the flexural strength by 5.3% and 16.4% respectively compared to PL. However, when rubber was added to the concrete mix, it was observed that more voids and pores formed within the concrete structure. Rubber particles do not fully bond with the concrete matrix, resulting in a decrease in the density of the concrete and an increase in its porosity. This situation negatively affects the flexural strength of the concrete [58,59]. In rubber-added concretes, the K5C0 mixture improved the flexural strength by 16.6% compared to PL, while the K10C0 and K15C0 mixtures decreased it by 13.5% and 23.8%, respectively. These results indicate that rubber increases the flexibility of concrete, but significantly reduces its strength at high ratios. The addition of steel fibers partially compensates for the negative effect of rubber on flexural strength. Especially the K5C8 and K10C8 mixtures with high steel fiber content significantly increase the flexural strength, thereby balancing this negative effect.

Although experimental compressive and flexural strength results were obtained for the 12 different mix designs given in Table 7, the 3D surface graphs in Figure 11 were generated on a 16-point grid. This approach was adopted not to add supplementary data or predictions, but to provide a smoother and more continuous graphical representation of the experimental results. By using this arrangement, the trends between the measured points were visualized more clearly, thereby facilitating a better interpretation of the effects of the WS and WR variables on the mechanical performance.

Table 7. Mechanical results (28-day)

Mix ID	Compressive strength	σ*	Flexural strength	σ
	MPa		MPa	
PL	53.22	1.32	6.76	0.10
K5C0	45.94	3.36	7.88	0.15
K10C0	43.27	2.29	5.85	0.12
K15C0	37.86	3.28	5.15	0.12
K5C4	40.43	1.98	7.40	0.15
K10C4	34.66	1.93	6.53	0.10
K15C4	33.18	1.61	6.47	0.10
K5C8	38.42	2.00	7.98	0.32
K10C8	36.01	2.68	7.75	0.20
K15C8	34.92	1.97	5.94	0.19
K0C4	41.17[8]	1.86	7.12[8]	0.16
K0C8	44.96[8]	2.59	7.87[8]	0.32

σ* =Standard deviation

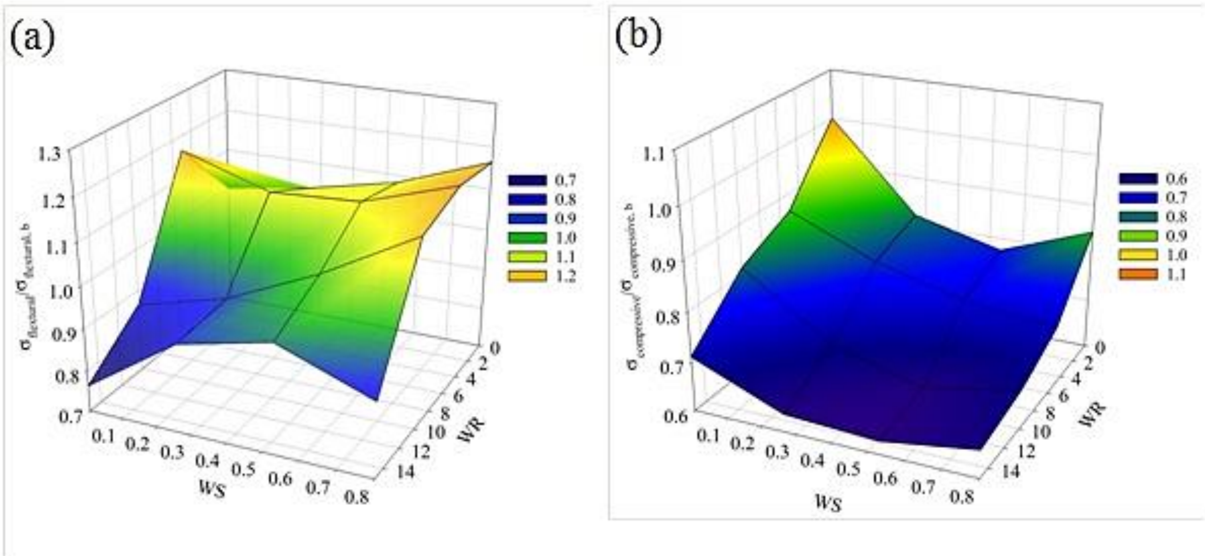

***Figure 11.** According to concrete mixtures, (a) Flexural strength; (b) Effect on compressive strength, (WS: steel fiber; WR: rubber).*

3.5 UPV-Compressive Strength Relationship

According to Figure 12, there is a general positive correlation between UPV and compressive strength [60]. As the UPV value increases, the compressive strength also tends to increase. However, this relationship is not exactly linear, and deviations are observed in some cases. PL has the highest correlation between UPV and compressive strength with R^2= 0.97. Rubber concretes, on the other hand, are the designs with the weakest correlation. Rubber reduces the density of concrete, lowers its elastic modulus, and increases crack formation [29,45].

These factors directly affect the relationship between UPV and compressive strength, causing the correlation to weaken. Rubber and steel fiber combinations perform better, especially as the steel fiber ratio increases. This shows that steel fibers compensate for the negative effects of rubber. The presence of steel fibers plays an important role in maintaining the relationship between UPV and compressive strength, especially in concrete where rubber is used as a substitute. Therefore, combinations of rubber and steel fibers should be carefully balanced to optimize the performance of concrete.

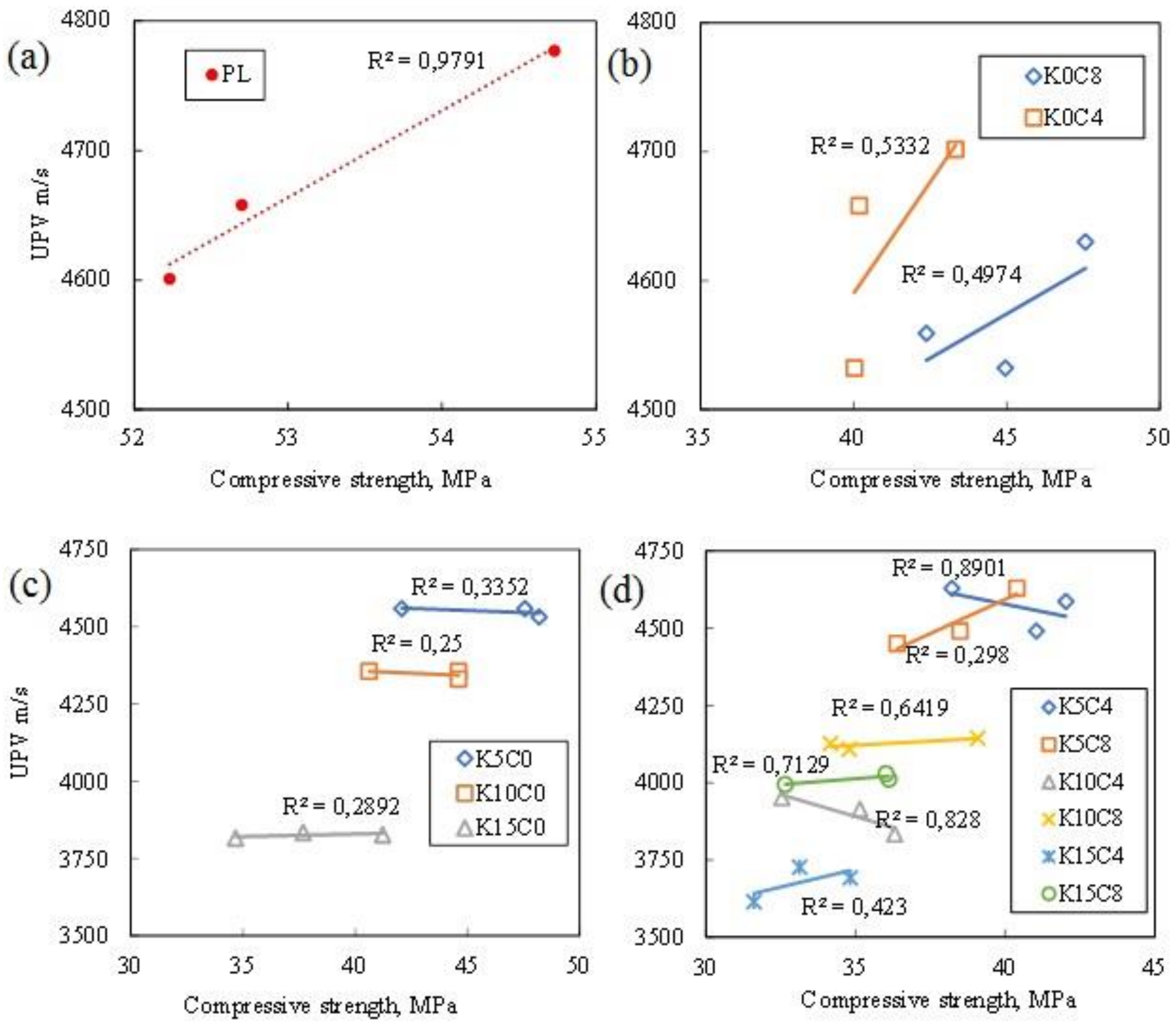

Figure 12. (a) Observation (PL) (b) steel fiber (c) rubber (d) the relationship between UPV-compressive strength of samples using steel fiber and rubber together

Researchers have conducted various experimental studies to evaluate the performance of concrete reinforced with recycled materials. Gül and Naseer (2019) [61] prepared concrete mixtures containing recycled rubber and steel fibers and conducted compression and flexural tests. In their studies, it was found that the addition of rubber reduces the compressive strength of concrete, while steel fibers increase its flexural strength. However, unit weight, ultrasonic UPV, water absorption, and (SEM analyzes were not evaluated in this study. Rahim et al. (2024) [62] conducted a study on the use of rubber and steel fibers in concrete and found that steel fibers significantly contribute to crack resistance. Additionally, it has been observed that the combined use of rubber and steel fiber yields acceptable optimal results that contribute to sustainability. However, the fact that waste tire steel fiber was used in the current study while industrial steel fiber was used in the previous study constitutes a significant difference. In the current study, SEM analyzes were performed. Fu et al. (2018)[63] investigated the effects of rubber and steel fiber on concrete performance. The studies concluded that using rubber alone reduces compressive strength, while adding steel fibers increases tensile strength, and using both materials together improves ductile behavior. While industrial steel fiber and waste tire rubber were used in the example study, the fact that UPV experiments and SEM analyzes were conducted in the current study constitutes a methodological difference. Liu and colleagues (2020) [64] investigated the effect of adding steel fibers to rubberized concrete. It has been observed that the addition of rubber causes a decrease in compressive and tensile strength, while steel fibers increase bending and tensile strength and positively contribute to crack resistance. In the current study, the use of UPV analysis and waste tire steel fibers differs from the previous study, as the previous study used steel fibers with standard properties. Gao et al. (2022) [65]investigated the effect of recycled rubber particles and steel fibers on the compressive toughness of concrete. It has been found that using rubber alone reduces compressive strength, while adding steel fibers partially compensates for this decrease. In the case study, industrial-type steel fibers were used, and SEM and UPV tests were not performed. Luo et al. (2020) [66]added steel fibers to improve the mechanical properties and freeze-thaw resistance of rubber-modified concrete. It has been determined that steel fibers contribute particularly to bending strength and toughness, and that bending strength is more prominent than compressive strength in cold weather conditions. In the current study, rubber granules and waste tire steel are used, while in the reference study, rubber powder and standard steel fibers were used. Additionally, an UPV test was performed in the current study. Finally, Yan et al. (2024) [67] experimentally investigated the effect of rubber particles obtained from waste tires and recycled spiral steel fibers on the mechanical properties and toughness of concrete. It has been found that the use of waste tires causes a loss in mechanical properties, but both materials positively contribute to the toughness properties, and the spiral fibers increase the bending and compressive strength. While the example study used spiral steel fibers, the current study used waste tire steel and rubber; additionally, UPV and SEM analyzes were performed. The use of waste materials, especially waste tires, in concrete mixtures stands out as a more environmentally friendly practice. In literature reviews, the complete data on the comprehensive experiments included in the current study, which combine both rubber and steel fiber-reinforced concrete derived from waste vehicle tires, is not available in one place. In conclusion, the fact that all the steel fibers and rubber used are derived from waste tires, the number and scope of the experiments conducted, and the concrete contents differ from many similar studies in the literature, making an independent contribution to the field.

4 CONCLUSIONS AND RECOMENDATION

This study experimentally investigated the influence of waste tire-derived rubber aggregates and steel fibers on the mechanical and physical properties of concrete. The results demonstrate that incorporating these recycled materials offers substantial technical benefits while simultaneously addressing environmental concerns. The key findings can be summarized as follows:

The measured compressive strength for the reference concrete (PL) was 53.22 MPa, while in the rubber-modified concretes with 5%, 10%, and 15% rubber, this value decreased by 16%, 23%, and 41%, respectively. This decrease is due to the voids created by rubber within the concrete matrix and the weak bond between the aggregate and the cement matrix. The contribution of rubber to mechanical properties improved the flexural strength of the K5C0 sample by 16.6%. However, as the rubber content increased, it decreased by 13.5% and 23.8% for K10C0 and K15C0, respectively.

The designs K0C4 and K0C8, which include steel fiber addition, improved the flexural strength by 5.3% and 16.4% respectively compared to PL. This shows that steel fibers increase the tensile strength of concrete, limiting the expansion of cracks.

The combined use of rubber and steel fibers has been considered an effective strategy for improving the mechanical properties of concrete. Especially the K5C8 and K10C8 mixtures have significantly increased the flexural strength, balancing the negative effects of rubber.

The measured unit weight of PL is 2371.08 kg/m^3, while in rubber concrete K15C0, this value has been reduced to 2289.55 kg/m^3, a decrease of 3%. This decrease is due to the low density of rubber and the voids it creates within the concrete matrix. It shows that rubber can be utilized in the production of lightweight concrete. On the other hand, it increased the unit volume weight by 1.5% in K0C8 with steel fibers. This situation can be explained by the high density of the steel fibers and their ability to make the concrete matrix more compact.

The water absorption rate for PL was 4.44%, while it increased to 5.45% in rubber concrete K15C0. In steel fiber-reinforced K0C8, the water absorption rate has decreased to 2.33%. This situation indicates that the steel fibers increase the density of the concrete, causing less water to penetrate within the concrete.

UPV values have decreased as the rubber content increased. However, the 0.4% and 0.8% steel fiber replacements have maintained the UPV values and improved the quality of the concrete. This shows that steel fibers maintain the internal structural integrity of concrete and serve as an effective additive against void formation.

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

Artificial Intelligence (AI) Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence (AI) tools. All content, including text, data analysis, and figures, was solely generated by the authors.

Contributions of the Authors

First Author contributed to experimental work, investigation, data analysis, interpretation, and writing. Second Author contributed to study design, visualization, interpretation, and writing.

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