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Evaluation of mechanical properties of concrete containing tire-rubber particles, steel fibers, and polypropylene fiber modified with highly concentrated sulfuric acid

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Abstract

In general, waste materials exist as solid, liquid, or gas. The wastes from the tire industries are classified as solid wastes, and due to their harmful environmental consequences, they cannot be buried in landfills. On the other hand, if waste car tires are buried, a significant area will be occupied without any environmental benefits. Landfills of rubber waste may cause uncontrollable fires, resulting in widespread air pollution. At the same time, due to the possibility of replacing a part of fine-grained or coarse-grained concrete with tire-rubber particles, two main advantages of using economic concrete with special characteristics and positive environmental consequences will be obtained. In this research, we will evaluate the effect of the modification of tire-rubber particles using sulfuric acid solution on improving mechanical characteristics and fresh rubber concrete containing steel and polypropylene fibers. The obtained results indicate that modifying the characteristics of tire rubber particles using highly concentrated sulfuric acid positively improves the properties of concrete.

Keywords: rubberized concrete, tire-rubber particles, compressive strength, flexural strength, sulfuric acid, steel fibers, polypropylene fibers
2020 MSC: 00A06

1 Introduction

Overall, every year, about 1.5 billion car tires are produced worldwide. It is also estimated that for one tire that enters the market, another tire reaches the end of its useful life and becomes waste. Rubbers usually come in natural rubber (NR) and synthetic rubber (SR). The main consumers of the produced tires are the industrial factories producing car tires, which consume about 70% of the produced tires. Used tires and other rubber-based products can be recycled as energy raw materials. Car tires produce more energy than other fuels, such as coal, which equals 36 MJ/kg in tires and 25 MJ/kg in coal. Usually, car and truck tires comprise 75-90% rubber, 15-5% high-resistance steel wire, and 20-5% polymer textiles. Usually, waste tire rubber (WTR) is used as fuel in cement kilns. Generally,

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waste rubber added to concrete is classified by size. Rubber waste requires grinding the rubber and turning it into small sizes. The grinding process is mechanical and is usually done at room temperature or cold. Mechanical grinding at ambient temperature is often used in industries. Much research has been conducted on the effect of using car tire waste on the characteristics and properties of concrete, which showed that adding appropriate amounts of tire-rubber particles can improve durability, which is caused by the increase in the number of closed porosities in the cement paste matrix and the interfacial transition zone (ITZ) between the cement paste and aggregates, and creating a pressure release system due to the freezing and thawing cycles phenomenon [57]. In parallel to protecting the environment and preventing environmental damage from rubber waste landfills, in 2006, the EC [15] banned the landfilling of used car tires and forced tire recycling plants to appropriate methods used to clean steel fibers and separate them from rubber so that the fibers separated from rubber can be melted again [8]. The research on the possibility of using recycled tier steel fiber (RTSF) as reinforcement materials in concrete indicated that the mentioned fibers improve the flexural performance of concrete and can replace factory steel fibers [28, 45, 49]. At the same time, rubberized concrete is always considered one of the most suitable materials for constructing pavements. In the meantime, the appropriate choice of pavement system depends on various factors, including traffic loading, environmental conditions, subgrade conditions, cost, and availability of materials [61]. It should be noted that using flexible pavements is more common due to its lower cost and faster implementation than the rigid concrete pavement system [60]. Because of the lack of joints, this type of pavement system provides a good ride quality for vehicle drivers, and because of sufficient flexibility, control of settlement and movement of the bottom layer is provided. Compared to the flexible type, rigid pavements have advantages such as high flexural strength, lower maintenance cost, and longer service life [60]. According to the report of the American Concrete Pavement Association [2], if rigid concrete pavements are properly designed, their useful life will increase up to 2.5 times compared to the flexible type. At the same time, its maintenance cost is improved by 21%, and its cost/benefit ratio is improved by 21%. In addition, using rubber can improve the strain capacity of concrete pavement and cracking resistance due to the shrinkage of concrete (especially in situations where the subgrade layer supports the shrinkage). At the same time, adding large amounts of tire-rubber particles to concrete will hurt its mechanical properties and durability [13, 19, 31, 62].

The use of fibers to strengthen and reinforce building materials has a long history, and this method has been used for years. For example, in ancient times, horse hair was used to reinforce mortars and bricks. Studies show that using fibers in brittle materials has a long history, dating back at least 3,500 years ago, when straw-reinforced bricks were used to build the 57-meter-tall Aqar-Quf hill near Baghdad. Asbestos fibers have been used as reinforcement in cement products for about 100 years, and cellulose fibers for at least 60 years. At the same time, the available evidence indicates the wide range of use of natural fibers in the construction of clay bricks and concrete. In today's modern world, using different types of fibers, such as glass, natural fibers, and steel, has become common. Different types of steel fibers are made for different applications and uses. The fibers' geometry and mechanical properties differ depending on the production process. The conducted studies show that the mechanical properties of SFRC are influenced by the characteristics of fibers (type, amount, geometry, and distribution in concrete), properties of concrete (strength and maximum nominal size of aggregates), sample size and geometry, loading rate, and the molding method [11, 18]. When added to concrete, steel fibers improve flexural strength, toughness, ductility, and impact strength. At the same time, thin and small fibers (microfibers) tend to sew small cracks, and on the contrary, long and thick fibers (macro fibers) play a significant role in limiting crack propagation by bridging wider cracks [42, 53]. It has also been proven that adding steel fibers positively affects durability and shrinkage cracks [20, 25].

In many studies, concrete reinforced with hybrid steel fibers was tested to achieve better performance by combining the advantages of different types of fibers. For example, Hu [28] investigated the mechanical performance of undulated MSF and RTSF composites and concluded that hybrid mixtures show better overall performance at the same dosages of fibers than concrete mixtures reinforced with one type of fiber. In addition, Younis [69] observed that hybrid mixtures containing undulated MSF and RTSF compounds show higher toughness and flexural strength compared to mixtures reinforced only with MSF. In both studies, undulated MSF was used, so its undulated pattern improved the continuity [30] and the pull-out strength [39]. Compared with hooked-end steel fibers, undulated steel fibers positively affect concrete shrinkage inhibition [41]. At the same time, the low stiffness of rubber is one of its advantages for use as aggregate. In addition, it positively affects some mechanical properties of concrete, such as ductility, energy absorption, toughness, and fracture [10, 24, 33, 58, 65]. This can be attributed to the rubber's ability to deform and fill the internal voids of concrete under load and absorb the deformation energy caused by crack propagation [37]. These characteristics, along with the features of light materials, lead to weight reduction [46], better resistance to fatigue and impact loading [23], sound absorption [59], and thermal and electrical insulation [29]. The economic and environmental benefits of RuC make it suitable for conducting academic and industrial research. Researchers found that when rubber aggregates replace mineral aggregates, a significant drop in compressive strength, flexural strength, and stiffness occurs.

Eldin and Senouci published the first paper on rubberized concrete in the early 1992s [17]. This research aimed to study the effect of using car tire rubber on the mechanical properties of concrete. They found that adding automobile tire-rubber particles to concrete reduces its strength and, as a result, limits its use in structural elements, but it has a positive effect on concrete ductility. Then other researchers also conducted more extensive studies on crumb rubber concrete. In research conducted in 2019 by F.M. Zahid Hossain et al. [70] under the title "Mechanical properties of recycled aggregate concrete containing crumb rubber and polypropylene fiber," the researchers investigated the performance of crumb rubber concrete containing recycled aggregate and polypropylene fibers. Experimentally investigated the characteristics of crumb rubber concrete containing polypropylene fibers. The obtained results indicate that compressive strength, flexural strength, and splitting tensile strength decrease with the increase in tire-rubber particles, but with the increase in fibers, the aforementioned mechanical properties also decrease. In another research conducted in 2020 by Jinxu Mo et al. [43], the effect of rubber powder on mechanical properties and damping capacity of polypropylene fiber reinforced concrete modified with polypropylene fibers (PFRC) was investigated. The result showed that the surface friction between polypropylene fibers, aggregates, and cement paste is the main energy loss factor in the concrete mix. Another research in 2019 by Yang Li et al. [36] entitled "Performance Enhancement of Rubberized Concrete via Surface Modification of Rubber- A Review" was done. This research investigates the methods published regarding modifying rubber aggregates to improve the performance of rubberized concrete and its advantages and disadvantages. The results indicate that the mechanical properties of different rubberized concrete types can be improved using the tire-rubber particles pre-coating method. Another research was conducted in 2020 by Arash Karimipour [32] and colleagues under the title "Mechanical and durability properties of steel fiber-reinforced rubberized concrete." In this research, the effect of steel fibers on mechanical and durability properties of steel fiber-reinforced rubberized concrete, as well as the effect of waste rubber aggregates on compressive strength, splitting tensile strength, ultrasonic pulse speed, shrinkage due to drying, dynamic modulus of elasticity has been studied. The obtained results indicate that by increasing the amount of rubber aggregates, the amount of slump decreases. Especially when the combination of 20% rubber waste and 2% steel fibers is used. At the same time, the splitting tensile strength of concrete decreases due to the use of rubber waste. Another research was conducted in 2018 by Xu et al. [68] under the title "Cyclic stress-strain rate-dependent response of rubberized concrete." In this research, results have been obtained and indicate that rubberized concrete containing steel fibers can be used as an alternative to flexible pavements. At the same time, the mentioned concrete shows a good resistance against chloride penetration. This research investigated the stress-strain response of rubberized concrete under certain cycles and different strain rate levels with moderate and severe seismic performance. As expected, increasing the amount of rubber hurt strength and stiffness. Therefore, by increasing the amount of rubber, recycled concrete materials showed better compressive strength and higher energy accumulation under periodic loading.

Another research was conducted in 2020 by Zhao Wang [66] and colleagues under the title "Tensile stress-strain characteristics of rubberized concrete from flexural tests." In this article, the three-point flexural test is used to describe the fracture behavior of concrete. The results obtained from this research indicate that the fracture energy, energy absorption capacity, and ductility of rubberized concrete are more suitable compared to conventional concrete.

Another research was conducted in 2020 by Emad A. Alwesabi [7] and colleagues under the title "Impact resistance of plain and rubberized concrete containing steel and polypropylene hybrid fiber." In this research, an experimental impact test was performed by dropping a hammer at a low speed (with an impact speed of 2.8 m/s) on fiber-reinforced concrete (FRC) and fiber-reinforced rubberized concrete (FRRuC) samples. Based on the results obtained from this experimental study, the amount of water absorption and voids decreases with the increase in polypropylene fibers (PP) dosages in concrete mixtures containing rubber. This is because polypropylene fibers improve the bond between the components of the cement matrix and the fibers. Another research was conducted in 2021 by Md. Shahjalal [55] and colleagues under the title "Flexural response of fiber reinforced concrete beams with waste tires rubber and recycled aggregate." This research investigates the combined effect of RCA, CR, and polypropylene fibers (PP) on the physical and mechanical properties of fiber-reinforced recycled rubber concrete (FR^3C). In addition, the flexural response of FR^3C beams was investigated. This research indicates that using RCA and CR instead of natural aggregates in structural concrete elements has a positive role in preserving the ecosystem. In another research conducted in 2020 by Cesare Signorini [56] and colleagues under the title "Failure mechanism of silica-coated polypropylene fibers for fiber reinforced concrete (FRC)," the role of curing time has been investigated. The results indicated that 28-day curing had a better effect on silica-coated fibers' energy dissipation capacity than 8-day curing. At the same time, however, they concluded that curing plays an insignificant role in the energy dissipation capability of uncoated FRC because the increase in strength can compensate for the reduction in ductility. In another research conducted in 2021 by Marcin Małek [40] and colleagues under the title "Physical and Mechanical Properties of Polypropylene Fiber-Reinforced Cement–Glass Composite," they investigated the use of recycled polypropylene fiber to improve the tensile strength of cement–glass composite. Reducing the efficiency of glass-cement composites by adding polypropylene fibers, the insignificant effect of waste fibers on the compressive strength of glass-cement composites, and the effect of adding polypropylene fibers on flexural strength have been discussed.

Researchers have proposed various solutions to improve the durability of concrete exposed to damage caused by the freezing-thawing phenomenon. For example, Richardson [52] suggested using 0.9 kg/m^3 polypropylene fibers for this purpose. Although this value is not very high, it is not as environmentally friendly as rubber waste because it is hydrophobic, has a high energy absorption capability, and can significantly reduce the stresses caused by concrete freezing and improve its durability [48, 67]. In addition, Hua [27] and colleagues believe that the deformation of rubber provides enough space for the expansion of water after freezing and thus prevents the cracking of cement paste. Although rubber improves the resistance of concrete against freezing, there is still no decisive conclusion regarding the size selection of tire rubber particles and their amount. For example, Mohajerani [44] believes that if the amount of rubber in C40 concrete equals 0.6%, better resistance against the freezing-thawing phenomenon will be obtained in concrete. In addition, Osama [1] believes that the resistance of crumb rubber concrete containing 15% rubber against freezing is about 25% higher than conventional concrete. Richardson et al. [51] allocated about 0.6% of the concrete weight to tire rubber particles to prove rubber's ability to control concrete freezing. In another research, Richardson et al. [50] found that using rubber powder smaller than 0.5 mm is suitable for dealing with concrete freezing. Therefore, using small rubber particles and large amounts of incoming air improves this characteristic in concrete. Gonen et al. [21] focused on the effect of different amounts of rubber, with different sizes, on the impact strength of concrete subjected to the freezing-thawing cycles. Other researchers presented their proposed model based on the prediction model of concrete strength according to porosity [9, 16]. Zhu et al. [72] found that the percentage of micro-porosities in the range of 10-100 nm is affected by the amount of rubber and controlled by it. In another study that was conducted, researchers [5] emphasized that the use of fibers in rubberized concrete containing a large volume of rubber (for example, 30% or 60%) improves flexibility and ductility characteristics of rubberized concrete, according to the specifications defined in the design of pavements [14]. In addition, the obtained results [4] indicate that replacing natural aggregate with tire rubber particles increases the permeability of crumb rubber concrete. The advantages of rubberized concrete reinforced with fibers make it a suitable option for constructing flexible concrete pavements. At the same time, more research should be done on the behavior and performance of fiber crumb rubber concrete under conditions of exposure to the freezing-thawing phenomenon. Due to the poor adhesion between cementitious materials and tire-rubber particles [33, 34], the possibility of rapid propagation of hairline cracks increases, and as a result, concrete becomes susceptible to damage. The durability of crumb rubber concrete has not been well studied. Few studies have been done on the durability of the mentioned concrete when faced with the freezing-thawing phenomenon. Most of these researches have focused on the strength of crumb rubber concrete containing tire-rubber particles [47, 50, 51, 54, 64, 71]. For example, regarding the depth of carbonation of concrete, which is one of the factors affecting the durability of concrete, researchers [22] have pointed out that the depth of carbonation of crumb rubber concrete was within the range of concrete production standards. In this situation, low amounts of water-cement ratio have been used. Thomas [63] concluded that the carbonation depth of concrete mixtures containing 2.5% to 12.5% tire-rubber particles is less than or equal to the carbonation depth of the control concrete mixture. In addition, in the conditions of alkali-silica reaction (ASR), one of the most important factors threatening the durability of concrete is that the flexible pieces of rubber absorb the ASR gel and create internal expansion stress in the mortar. Similar results were presented by Afshinnia and Poursaee [3]. Other researchers [71] studied the effect of tire-rubber particles' size on the concrete's strength against the phenomenon of freezing and thawing (with a fixed amount of 30 kg/m^3 of rubber).

Table 1: A summary of the research carried out on the subject of replacing part of the traditional aggregates of concrete mixtures with rubber and the obtained results

Researcher	Year	Results
[26]	2019	By increasing the dosages of tire-rubber particles, the compressive strength, flexural strength, and splitting tensile strength decrease. However, by increasing the dosages of fibers, the aforementioned mechanical characteristics also increase. In the condition of 10% replacement of RCA, the compressive strength increases in the first place, but in the condition of 30% replacement of RCA, it faces a decrease. Compared to the control concrete sample, CR in concrete mixtures decreases compressive strength. This is because while increasing the dosages of fibers, the compressive strength also increases. With increasing dosages of tire-rubber particles (CR), Poisson's ratio also increases, but it decreases with increasing dosages of fibers.

[43]	2020	Adding rubber powder improves the damping capacity of PFRC, reduces the compressive strength of concrete, and increases the strain at the peak point. The degree and dispersion of polypropylene fibers affect concrete density. By increasing the dosages of polypropylene fibers, the strength and toughness of concrete samples improve, and at the same time, the ductility of concrete containing fibers increases. The main energy loss factor is surface friction between polypropylene fibers, aggregates, and cement paste. The dynamic bending stiffness of the cross-section increases with the increase in the dosages of polypropylene fibers. This indicates that polypropylene fibers can effectively prevent the reduction of stiffness.
[36]	2019	The mechanical properties of different types of rubberized concrete can be improved by pre-coating of tire-rubber particles. Hydrophobicity and low elastic modulus of rubber cause weak adhesion and stress concentration between cement matrix and tire-rubber particles. Rubber surfaces' physical/chemical modification methods improve the adhesion between cement paste and rubber. As a result, the mechanical properties and durability of rubberized concrete will be significantly improved. Increasing rubberized concrete's resistance is impossible by washing it with water alone. Therefore, as a cost-effective and environmentally friendly method, washing rubber with water effectively removes many pollutants attached to the rubber. At the same time, it will positively affect the hydrophilicity characteristic of the rubber. Using the pre-coating method of rubber using cement materials such as cement paste, micro silica, etc., increases the elastic modulus and improves the conditions of the interfacial transition zone (ITZ). As a result, we will see significant positive results in improving rubberized concrete's mechanical properties and durability.
[32]	2020	The slump decreases by increasing the amount of rubber aggregates, especially when the combination of 20% rubber waste and 2% steel fibers is used. The splitting tensile strength of concrete decreases due to rubber waste. On the other hand, steel fibers significantly improve that strength. So, in the conditions of using 20% waste rubber in the concrete mix, we will see a 21% decrease in splitting tensile strength. At the same time, adding 2% steel fibers results in a significant improvement. The use of rubber aggregates reduces the compressive strength of concrete. Therefore, it is necessary to use steel fibers to improve this feature. So, the use of 2% steel fibers along with 0%, 5%, 10%, 15%, and 20% rubber improves the 7-day compressive strength of concrete by 27%, 28%, 26%, 26%, and 25%, respectively (compared to the sample without steel fibers, but with similar amounts of rubber). The flexural strength of concrete samples also decreased due to the use of rubber, but the addition of steel fibers compensated for most of the decrease in strength. Steel fibers improve flexural performance, especially when rubber is not used. By adding 2% steel fibers, the flexural strength of the samples is improved up to 35%. Using rubber and steel fibers reduces the speed of the ultrasonic pulse. They will be more effective if used together.
[4]	2018	Adding fibers reduces workability and increases unit weight and air volume. Replacing rubber aggregates in rubberized concrete mixtures significantly reduces the workability and unit weight (caused by the low density of rubber) and increases the amount of air (more than 100%). No signs of degradation or cracking (except surface rust) were observed on the surface of concrete samples exposed to a chloride environment for 150 to 300 days. In addition, there was no evidence of rusting of fibers within the concrete, indicating that the steel reinforcement was not corroded under exposure to wet chloride. Therefore, fibers mixed in concrete will have a positive effect on durability. Using large amounts of rubber aggregate in rubberized concrete causes a gradual decrease in the compressive strength and elastic modulus of concrete. Meanwhile, flexural strength is also affected, but the effect is insignificant due to fibers in the concrete mix. As a result of the hydration of cement materials, a slight increase in the mechanical properties of all concrete mixtures was achieved after 150 and 300 days of exposure to chloride conditions (drying- and soaking). The chloride penetration depth in both conditions (drying-soaking, full saturation) increases with increasing amount of rubber.
[68]	2020	By increasing the amount of rubber, recycled concrete materials showed better compressive strength and higher energy accumulation under cyclic loading. It was also shown that strength and stiffness increased with the increase in strain, from static to severe seismic. By increasing the amount of rubber, the mentioned factors improve less.
[66]	2020	Replacing mineral aggregates with tire-rubber particles reduces the strength (compressive, tensile, and flexural) and elastic modulus. The decrease in tensile and flexural strength will be less than compressive strength. Replacing aggregates with rubber positively affects fracture energy and energy absorption capacity, leading to more flexible behavior after cracking.
[7]	2020	Increasing the dosages of polypropylene fibers (PP) in concrete mixtures containing rubber decreases the amount of water absorption and voids. This is because polypropylene fibers improve the bond between the components of the cement matrix and the fibers. Adding 1% microsteel fibers to concrete does not have much effect on compressive strength. At the same time, adding steel fibers improves the tensile strength and impact of concrete.
[55]	2021	The concrete mixture's short-term and long-term mechanical properties have been improved using polypropylene fibers and crumb rubber (CR) particles. Using RCA and CR instead of natural aggregates in structural concrete elements has a positive role in preserving the ecosystem. The compressive strength decreases by increasing the concrete mixture's crumb rubber (CR) percentage. On the other hand, adding fibers increases the compressive strength due to the bridging characteristic of fibers. The lowest compressive strength was observed in the mixture containing large tire-rubber particles. The compressive strength decreases by increasing the concrete mixture's crumb rubber (CR) percentage.

[38]	2019	As the percentage of waste rubber fibers increases, the strength of concrete decreases at all ages. Geopolymer concrete achieves 95% of its compressive strength in only 7 days. The compressive strength of concrete made with ordinary Portland cement is lower compared to geopolymer concrete. Due to the good cohesion between aggregates and geopolymer paste, geopolymer concrete's tensile strength is higher than that of conventional concrete. Increasing the amount of rubber fibers in geopolymer concrete increases its tensile strength and bending. The maximum flexural strength value was obtained when 30% of the sand was replaced with rubber fibers. In all geopolymer concrete mixtures, the modulus of elasticity has been reduced by increasing the amount of rubber fibers.
[35]	2021	If rubber aggregates are used in concrete, its compressive strength is reduced compared to conventional concrete. The density of crumb rubber concrete is lower compared to conventional concrete. By reducing the size of rubber aggregates, its thermal conductivity is also reduced. Increasing the amount of rubber in concrete mixtures increases the number of voids and cracks. As a result, permeability increases, too. With the increase of rubber aggregates, the compressive strength decreases, but the tensile strength increases.
[12]	2017	The experimental results show that tire rubber particles, as a function of the replacement percentage with natural aggregates, affect the mechanical properties of concrete. In addition to the volume replacement ratio, the type of mineral aggregate also affects the behavior of concrete. A uniaxial compression test was done to evaluate the stress-strain response of cylindrical samples, and it showed that the compressive strength and elastic modulus decreased with the increase in the amount of rubber used. The reduction of elastic stiffness results from the high flexibility and low weight of rubber aggregates compared to mineral aggregates.
[6]	2019	Compared to conventional concrete, increasing the dosages of tire rubber particles from 0% to 20% in rubberized concrete improves all structural ductility factors. Rubberized concrete can be used as an environmentally friendly building material to improve the ductility of reinforced concrete elements. In addition, it is considered a new design strategy to prevent progressive deterioration in concrete structures.

2 Materials and methodology

2.1 Tire-rubber particles

This research used tire-rubber particles with 1-2 mm dimensions. Tire rubber particles are the result of crushing used car tires.

2.2 Modification of tire rubber particles using the sulfuric acid solution

To modify some characteristics of tire rubber particles, it is necessary to act on the characteristics of rubber before conducting mechanical tests and fresh concrete. For this purpose, tire rubber particles were placed in a 95% sulfuric acid solution for 5 minutes, as will be fully explained in the laboratory test program section. NaOH solution was used in the neutralization process.

2.3 Cement

The control mix was prepared based on the ACI Method of Concrete Mix Design and with 28-day compressive strength equal to 40 MPa. The cement materials used include 52.5 MPa type one Portland cement. According to ASTMC150, the specific weight of cement equals 3.15. The chemical characteristics of cement are shown in Table 2.

Table 2: Chemical characteristics of cement used in this research

Item	**Percent (%)**
Sio_2	19.59
Al_2O_3	5.05
Fe_2O_3	3.67
Cao	64.27
MgO	1.63
SO_3	2.75
The total amount of alkali	0.51
Remaining insoluble elements	0.28
Loss on ignition (LOI)	2.13

2.4 Aggregates

Consumed aggregates in this research include natural river sand with a specific gravity of 2.57, a Fineness Modulus (FM) of 3.05, a water absorption rate of 0.8%, and a moisture content of 2%. The maximum size of fine grain used is 4.95 mm. The coarse aggregate used in this research is crushed stone with a specific gravity of 2.65, mass density of 1350 kg/m^3, water absorption rate of 0.2%, and maximum nominal size of 10 mm. The size range of tire rubber particles obtained from used car tires is 1-2 mm, with a specific gravity of 0.73 and negligible water absorption. The granulation curve obtained from fine grain, coarse grain, and tire-rubber particles used in this research is shown in Figure 1.

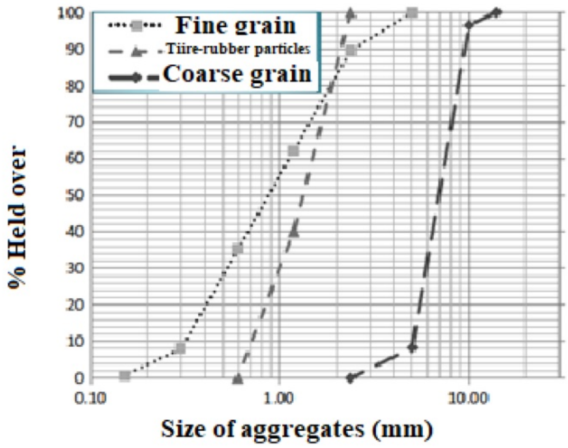

Figure 1: Granulation curve obtained for fine grain, coarse grain, and tire-rubber particles

2.5 Fibers

The combined fibers used in this research include two types of fibers. Type one: Micro steel fibers (with a length of 21mm and aspect ratio of 60) and tensile strength of 2800 MPa. Type two: Polypropylene fibers with a length of 3mm and a tensile strength of 550 MPa. The specific weight values of polypropylene and steel fibers equal 0.91 and 7.85, respectively. The appearance of polypropylene fibers, steel fibers, and tire-rubber particles is shown in Figure 2.

Figure 2: The appearance of polypropylene fibers, steel fibers, and tire-rubber particles

2.6 Concrete superplasticizer

The concrete superplasticizer used in this research is of polycarboxylate type to improve the slump of mixtures containing steel fibers with 0.2% weight of cement. The characteristics of the concrete superplasticizer used are as follows:

- Specific weight, equal to 1.06
- PH value equal to 9.5
- Color: light brown liquid
- Flash point: None

- Chlorine content: None
- Volatile weight: 62%

2.7 Theoretical research models

The following formula is used to determine flexural strength:

$$M_R = \frac{3 * P * L}{2 * b * (d^2)} \tag{2.1}$$

M_R: Flexural strength of a sample

P: Failure force

L: Sample length

B: The average width of the samples

D: Average depth of samples

To reduce the error, it is necessary to perform this test on several samples and declare a number as an average. The formula listed is for failure outside the third middle. If the failure occurs in the third middle, the coefficient of the formula is removed, and the calculations are performed.

$$M_R = \frac{P * L}{b * d^2} \tag{2.2}$$

Bending strength is generally calculated from the following equation:

$$F_b = \frac{M * y}{I} + \frac{P}{by} \tag{2.3}$$

In this regard, the main condition is the occurrence of cracks between the two middle supports. In the above formula, M is the maximum bending moment, y is the distance from the body center to its surface, I is the moment of inertia of the body surface, P is the applied force, and b is the width of the body surface.

By testing compressive and b specimens in the laboratory, a general formula is obtained for any concrete. Still, the following relationship is a good approximation for cases without special requirements in its design.

$$F_r = 7.5\sqrt{F'c} \tag{2.4}$$

F_r: Concrete bending strength and compressive strength.

To extract the results from the bending test, it is necessary to accurately measure the values of the following variables. Depending on the variable type, these measurements may be done before or after the bending test.

σ_f: Bending stress on the external surface and the middle point

ε_f: Bending strain on the external surface

E_f: Flexural / elastic modulus

F: Applied force through the mandrel

L: Distance between supports

b: The width of the sample

d: Thickness (depth) of the sample

D: The maximum deviation of the sample from the perfect horizontal position

m: The slope of the elastic line of the test chart

R: Sample radius

Then, the test piece's flexural modulus, bending stress, and bending strain are calculated with the following relations.

Measurement formula and Quantity

Bending stress for rectangular cross-section

$$\sigma_f = \frac{3FL}{2bd^2} \tag{2.5}$$

Bending stress for circular cross-section

$$\sigma_f = \frac{FL}{\pi r^3} \tag{2.6}$$

Bending strain

$$six\varepsilon_f = \frac{6dD}{L^2} \tag{2.7}$$

Flexural modulus

$$E_f = \frac{L^3 m}{4bd^3} \tag{2.8}$$

3 Laboratory tests plan

3.1 Modification of rubber characteristics using a sulfuric acid solution

In the first stage, before performing the relevant tests, it is necessary to modify the tire-rubber particles using 95% sulfuric acid solution to improve their characteristics and increase their strength. The method of modifying tire-rubber particles using sulfuric acid solution includes the following steps:

1. Immersion of rubber in sulfuric acid 95% for one minute
2. Removing the tire-rubber particles from the sulfuric acid solution and allowing it to continue reacting with air for two minutes
3. Carrying out the neutralization process using NaOH solution and then washing it completely with distilled water at room temperature (neutralization is done until the pH of the water reaches 7)
4. Drying the modified tire-rubber particles for 48 hours in the air and then placing them in a drying machine (oven) at a temperature of 100 degrees Celsius for 24 hours

Therefore, modification of tire-rubber particles with sulfuric acid significantly improves the stiffens of tire-rubber particles. At the same time, it removes the angular surfaces of tire-rubber particles and results in a smoother surface. Meanwhile, using a sulfuric acid solution of 95% to modify tire rubber particles caused a significant increase in porosity and created a smoother rubber surface.

3.2 Concrete mix design

This research prepared a control concrete sample and 11 concrete mixtures with different combinations of fibers according to Table 3.

Table 3: The percentage of fibers used in different concrete mix mixtures

No	Mix ID	Tire-rubber particles	Fiber volume percentage		Total volume
			Polypropylene Fibers	Steel Fibers	
1	PC1	0	0	0	0%
2	PC2	0	0	1%	1%
3	PC3	0	0.1%	0.9%	1%
4	PC4	0	0.175%	0.825%	1%
5	PC5	0	0.25%	0.75%	1%
6	PC6	0	1%	0	1%
7	RuC1	20%	0	0	0%
8	RuC2	20%	0	1%	0%
9	RuC3	20%	0.1%	0.9%	1%
10	RuC4	20%	0.175%	0.825%	1%
11	RuC5	20%	0.25%	0.75%	1%
12	RuC6	20%	1%	0	1%

Concrete samples are prepared in three fiber combinations. (1) Concrete mixture containing polypropylene fibers, (2) Concrete mixture containing steel fibers, and (3) Concrete mixture containing a combination of steel fibers and polypropylene fibers. The amount of volume fraction is also considered 1%. Concrete mixtures are also classified into two main categories. For example, with or without tire rubber particles with a replacement percentage of 20% (by volume) of fine grains.

The mixtures' water-to-cement ratio is considered equal to 0.42. The amount of cement used is 538 kg/m^3. ASTM C143 states that the design slump is 75-100 mm. More details related to the mixing ratio and components of concrete mixtures are mentioned in Table 4.

Table 4: Details of the mixing ratio and components of concrete mixtures

Mix	Superplasticizer (Liter)	Polypropylene Fibers	Steel Fibers	Tire-Rubber Particles	Fine Grain	Mixing Ratio (Unit Weight, kg/m^3)		
						Coarse grain	Cement	Water
PC1	0	0	0	0	905	620	538	242
PC2	1.1	0	78.5	0	905	620	538	242
PC3	1.1	0.92	70.7	0	905	620	538	242
PC4	1.1	1.15	68.7	0	905	620	538	242
PC5	1.1	2.3	58.9	0	905	620	538	242
PC6	1.1	9.2	0	0	905	620	538	242
RuC1	1.1	0	0	51.5	724	620	538	242
RuC2	1.1	0	78.5	51.5	724	620	538	242
RuC3	1.1	0.92	70.7	51.5	724	620	538	242
RuC4	1.1	1.15	68.7	51.5	724	620	538	242
RuC5	1.1	2.3	58.9	51.5	724	620	538	242
RuC6	1.1	9.2	0	51.5	724	620	538	242

3.2.1 Preparation of samples (mixing, molding, and curing)

In this research, 144 concrete samples were prepared. 12 samples have been prepared for each mixture. 3 cubic samples with dimensions of 100 mm were used to measure mass density (unit weight). At the same time, 6 cylindrical samples with dimensions ($100 \times 200mm$) were prepared. Out of the above 6 cylindrical samples, 3 samples were used to perform compressive strength and modulus of elasticity tests. The remaining 3 cylindrical samples were also used for the splitting tensile strength test. To perform the flexural strength test, 3 beam samples were prepared with dimensions of $100 \times 100 \times 400mm$ (corresponding to the sample's depth, width, and length, respectively). First, fine grain, coarse grain, and tire-rubber particles were mixed for 2 minutes. Then, cement was added to the rotary mixer, and mixing continued for 1.5 minutes. The superplasticizer was mixed with the required water, and 70% of the required water was poured into the rotary mixer, and the mixing continued for 2 minutes. In the next step, the remaining water was poured into the blender, and the mixing continued for 1.5 minutes to obtain a homogeneous mixture. Then, the fibers were poured into the mixture, and the mixing continued for 3-4 minutes until homogenization was complete. The samples were cast into different metal molds. After casting the concrete mixtures into the mold, the samples were covered by nylon for 24 hours at room temperature. In the next step, the samples were removed from the metal molds and placed in the water tank for 28 days for curing. Now, the samples are ready for testing.

3.3 Test method

3.3.1 Slump test

A slump test was performed on prepared samples according to ASTM C143. Slump value was measured by determining the difference in vertical distance between the center of the upper surface of the concrete mixture and the upper part of the inverted mold. 3 samples of 28-day hardened concrete were used to test density, compressive strength, splitting tensile strength, and flexural strength. The result is the average of 3 samples. The density test was also performed according to ASTM C642 on cubic samples with a length of 100 mm. The compressive strength test was also performed on cylindrical samples based on ASTM C39 using a hydraulic machine with a capacity of 100 kN. In this research, a constant axial load of 0.3 MPa/s was applied to the concrete sample to break the sample. The static elastic modulus was also measured according to ASTM C469. Splitting tensile strength test was also performed based on ASTM C496 on cylindrical samples. For this purpose, a load of 0.9 MPa/min was applied to the sample until the sample failed. The flexural strength test was also performed on the beams using a machine with a capacity of 100 kN. At the same time, axial displacement was applied to the samples at a constant rate of 0.1 mm/min under the conditions suggested by ASTM C78.

Slump values for all samples are shown in Figure 3. Adding 1% of fibers, especially composite fibers (a combination of steel and polypropylene), to concrete mixtures reduced the slump. In general, the slump type of all mixtures can be considered a real slump type with high workability classification due to adding superplasticizer to concrete to improve its workability. Due to large amounts of polypropylene fibers, mixtures PC6, RuC3, RuC4, RuC5, and RuC6 have moderate workability. The result obtained from this slump test indicates that the workability decreases with the increase in polypropylene fiber dosages. In replacing steel fibers with polypropylene fibers, with ratios of 0.1%, 0.175%, 0.25%, and 1%, the slump decreased by 25%, 29.17%, 29.17%, and 41.67%, respectively. The significant decrease in the workability of concrete mixtures caused by the addition of polypropylene fibers and steel causes the formation of a network structure in the mixture. This prevents surface bleeding and separation of aggregates. Due to regular distribution (spreading) and large dosages of fibers (especially fibers with small diameters) in concrete, the mixture's viscosity increases while its slump decreases.

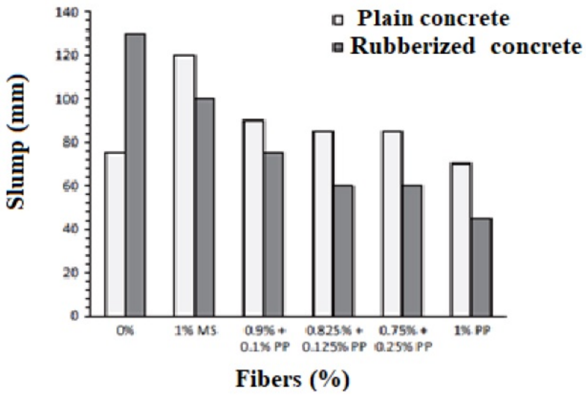

Figure 3: Slump values for all mixtures

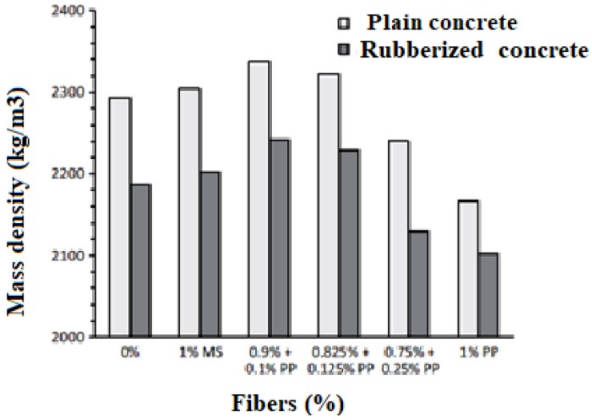

Figure 4: Mass density values for all mixtures

3.3.2 Properties of hardened concrete

The experimental results of the properties of hardened concrete are summarized in Table 5.

3.3.3 Mass density

The mass density of plain concrete without fibers is 2293.3 kg/m^3. The addition of steel fibers significantly affects the mass density of concrete. Therefore, the PC3 and PC4 concrete mixtures, which contain combined fibers, have more density than the PC2 mixture containing steel fibers. The reason is that when steel fibers replace a small percentage of Polypropylene fibers (0.1% and 0.175%), large amounts of steel fibers remain in the mixture. Therefore, adding polypropylene fibers to the concrete mixture improves the bond between the stone grains and the cement paste. In this case, the amount of mixed air decreases, consequently increasing the density of concrete samples. The density values of PC2, PC3, and PC4 mixtures were obtained by 2304.3, 2337.7, and 2322.7 kg/m^3, respectively. By adding

Table 5: Results of mechanical properties of hardened concrete

Mix	Flexural strength (Mpa)	Splitting tensile strength (Mpa)	Modulus of elasticity (Gpa)	Compressive strength (Mpa)	Mass density (kg/m^3)
PC1	5.11	3.52	36.65	38.45	2293.33
PC2	6.41	3.82	35.99	37.39	2304.33
PC3	6.13	5.09	42.02	48.36	2337.80
PC4	6.04	4.57	38.62	41.82	2322.73
PC5	5.58	3.85	34.82	35.56	2240.33
PC6	3.60	2.39	26.24	24.66	2166.37
RuC1	3.34	2.60	22.98	21.45	2187.43
RuC2	5.54	2.79	21.95	20.53	2202.83
RuC3	5.55	3.72	33.73	33.94	2242.00
RuC4	5.14	2.95	26.41	24.83	2229.47
RuC5	4.74	2.77	24.79	23.18	2129.63
RuC6	3.42	2.25	22.33	20.86	2102.83

1%, 0.9%, and 0.825% steel fibers and 0%, 0.1%, and 0.175% Polypropylene fibers, concrete density values increased by 0.5%, 1.9%, and 1.3%, respectively.

The mass density of all concrete mixtures was decreased by replacing the fine-grained volume (1-2 mm) with tire-rubber particles. The decrease in the mass density of concrete mixtures containing 20% tire-rubber particles was about 4.2%. PC6 and RUC6 mixtures (containing 1% Polypropylene fibers) have the lowest mass density among all concrete mixtures. Therefore, replacing the fine grains with the tire rubber particles reduced the mass density value.

3.3.4 Compressive strength

Figure 5 shows the 28-day compressive strength of all concrete mixtures. Experimental compressive strength values obtained for different concrete mixtures are listed in Table 5.

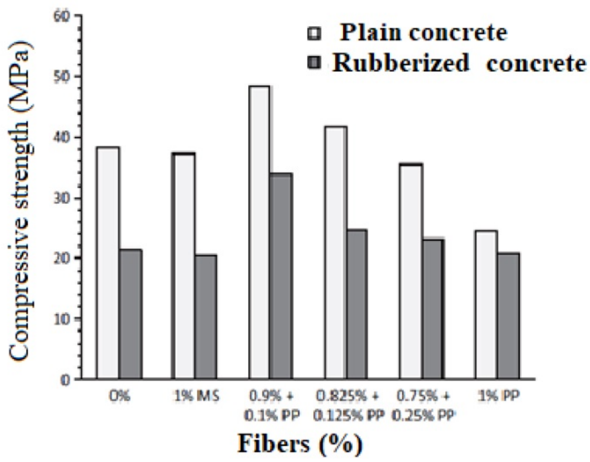

Figure 5: The effect of different dosages of fibers on the compressive strength of concrete mixtures

The results indicate that the compressive strength is slightly reduced when only steel fibers are used. The compressive strength of the control mixture (PC1) is equal to 38.5 MPa. Meanwhile, the compressive strength of the PC2 mixture (containing 1% steel fibers) is 37.4 MPa. By adding 0.5%, 0.75%, 1%, and 1.25% steel fibers to concrete, compressive strength has decreased by 5.5%, 10%, 10.1%, and 11.9%, respectively. The compressive strength of the PC4 mixture (0.175% PP +0.825% MS), with an increase of 8.8%, is equal to 41.8 MPa. As shown in Figure 6, the use of low dosages of polypropylene fibers (< 0.255%) and high amounts of steel fibers (> 0.75%) significantly improves compressive strength. The compressive strength of sample PC5 (0.25% PP +0.75% MS) and sample PC6 (1% PP) were obtained as 35.6 and 24.7 MPa, respectively. The value of compressive strength has also decreased by 7.5% and 35.9% compared to plain concrete. As shown in Table 4, the PC6 mixture has the lowest compressive strength among all concrete mixtures because the dispersion of polypropylene fibers in the concrete mixture reduces the properties of concrete. Replacing 20% fine grain (natural sand) with tire-rubber particles in concrete mixtures has caused a 38.9% decrease in compressive strength in all rubber mixtures (RuC).

3.3.5 Elastic modulus

The results obtained from the elastic modulus test of plain concrete and HFRC samples containing and without tire rubber particles are shown in Figure 6.

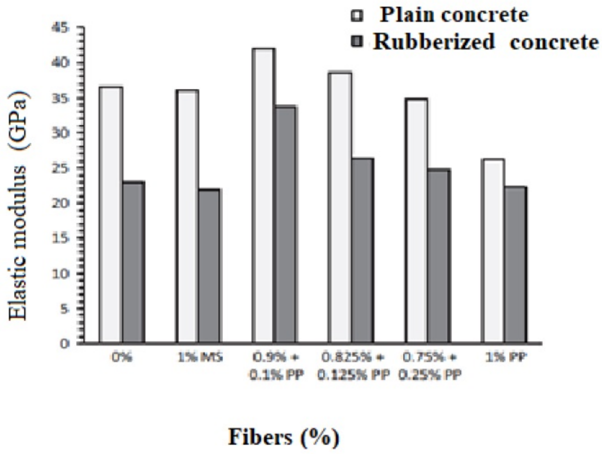

Figure 6: Results of elastic modulus for concrete mixtures

The results obtained from elastic modulus are similar to compressive strength. Using steel fibers in plain concrete mixtures causes a slight decrease in elastic modulus. The elastic modulus of the control mixture (PC1) is equal to 36.7 GPa. Meanwhile, this value equals 36 GPa in the PC2 mixture containing 1% steel fibers. Therefore, there is about a 1.8% decrease in elastic modulus.

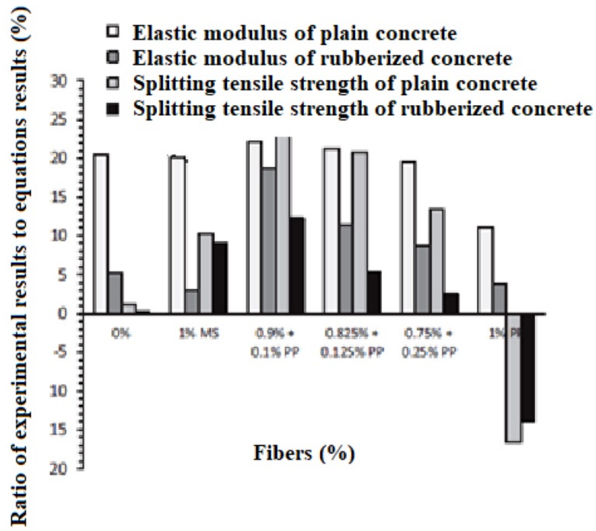

Figure 7: The ratio of experimental results to equations results - for prediction according to ACI318-14 codes

As you can see in the above figure, the relative difference between the obtained experimental results and the equation of the ACI code, which is presented as $4600\sqrt{f_c'}$ to predict the value of the elastic modulus, is mentioned. Also, a comparison has been made with the splitting tensile strength related to the compressive strength of concrete, with the equation of $0.65\sqrt{f_c'}$. The experimental results of elastic modulus and splitting tensile strength, in all concrete mixtures, except the mixtures reinforced with polypropylene fibers, have been higher compared to the calculated values obtained from the relevant equations. This increase was about 22%. Meanwhile, this value was equal to 11% in mixtures reinforced with polypropylene fibers. Adding fibers to concrete mixtures simultaneously has positive and negative effects on the properties of concrete (especially on splitting tensile strength). Therefore, equations must be prepared to cover the effect of fibers on concrete.

3.3.6 Flexural strength

The results of the flexural strength test on 28-day concrete samples are shown in Figure 8. The flexural strength of plain concrete without tire-rubber particles equals 5.11 MPa. At the same time, the flexural strength values of CP2, CP3, CP4, CP5, and CP6 samples without tire-rubber particles were 6.41, 6.13, 6.04, 5.58, and 3.60 MPa, respectively. In general, the amount of flexural strength increases with the increase of steel fibers. The increase in flexural strength in samples containing 1%, 0.9%, 0.825%, and 0.75% steel fibers is 25.27%, 19.86%, 18.09%, and 9.18%, respectively. The CP2 concrete mix containing 1% steel fibers had the highest flexural strength value. The lowest flexural strength is 3.6 MPa, corresponding to a CP6 concrete mix containing 1% polypropylene fibers. Therefore, the results indicate that adding steel fibers to concrete mixtures increases flexural strength (see Figure 8).

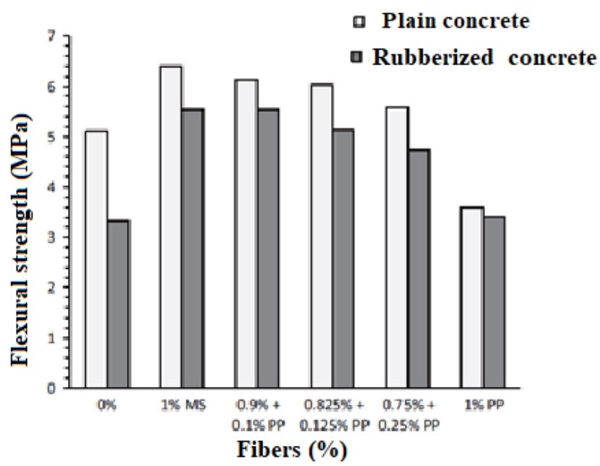

Figure 8: The effects of fibers, dosages of tire-rubber particles on flexural strength of mixtures

As you can see in the above figure, replacing polypropylene fibers with steel fibers has a negative effect on the flexural strength of reinforced concrete. The increase in flexural strength of the samples due to the addition of steel fibers is caused by the high modulus of elasticity and tensile strength of the mentioned fibers. Polypropylene fibers are shorter than steel fibers, and their tensile strength and elastic modulus are lower. Therefore, the role of polypropylene fibers is their ability to bridge and prevent the occurrence of microcracks, and they do not have much effect on flexural strength.

Adding tire-rubber particles to the amount of 20% (replaced with fine grains) to concrete mixtures caused a decrease in the flexural strength of the samples. In this research, the reduction in flexural strength was about 34.73%. This strength is reduced because of the weak connection between tire rubber particles and cement paste or aggregates. This increases the stress concentration around tire rubber particles. As a result, the expansion of cracks is done more quickly. The negative effect of tire-rubber particles on the flexural strength of reinforced concrete is less compared to plain concrete because, in fiber-reinforced concrete, fibers play an important role in cracking resistance due to the presence of tire-rubber particles.

4 Conclusion

4.1 The effect of using the sulfuric acid solution on modifying the characteristics of tire-rubber particles

In general, before using tire-rubber particles in the rubberized concrete mixture, the process of modifying the characteristics of the rubber was done, and the following results were obtained:

1. Tire-rubber particles modified with sulfuric acid solution showed higher adhesion than unmodified samples.
2. Modification of tire rubber particles with sulfuric acid significantly improves the stiffness of tire rubber particles. At the same time, it removes the angular surfaces of tire-rubber particles and results in a smoother surface.
3. The modification method of tire rubber particles with sulfuric acid solution positively affects the behavior of rubber aggregates in the concrete mixture. Meanwhile, it improves the workability of the mixture.
4. Using sulfuric acid solution to modify tire-rubber particles caused a significant increase in porosity and a smoother rubber surface.

4.2 Mechanical tests and fresh concrete

The experimental results obtained in this research are as follows:

1. The results obtained from tests on fresh concrete show that mixtures containing Rubberized concrete (RUC), compared to plain concrete mixtures, have a lower slump due to the need for more mortar. Adding fibers to conventional concrete has a negative effect on its slump value. Increasing the dosages of polypropylene fibers decreases the slump of fresh concrete due to the need for more mortar.
2. In the condition of not using fibers, and adding 20% tire-rubber particles to the concrete mixture, the mass density decreased by about 4.9%. At the same time, with the addition of fibers, the mass density of the mixtures also increased. In the combined use of 0.1% polypropylene fibers and 0.9% of steel fibers, mass density was increased by 1.93%.
3. The compressive strength test results indicate that by replacing 20% of fine grains with tire-rubber particles, the compressive strength of plain concrete samples has been reduced by about 44.21%. Adding fibers to mixtures reinforced with RuC rubber improved the compressive strength. Therefore, combining steel and polypropylene fibers with a ratio of 0.1PP+0.9MS and tire rubber particles, the highest compressive strength (33.94 MPa) was obtained in all rubber concrete mixtures.
4. The results obtained from the modulus of elasticity test are similar to the compressive strength results. By adding fibers to concrete mixtures, the modulus of elasticity increased, and when fine grains were replaced with tire-rubber particles, the modulus of elasticity decreased.
5. By replacing fine grains with tire-rubber particles, splitting tensile strength decreased. Adding fibers with appropriate amounts improved the splitting tensile strength of RuC mixtures. Therefore, splitting tensile strength was higher than plain concrete in combining steel and polypropylene fibers with a ratio of 0.1PP+0.9MS, along with tire-rubber particles.
6. In the conditions of 20% replacement of fine grains with tire rubber particles, the flexural strength of the samples decreased. At the same time, the addition of steel fibers improved the flexural strength.
7. Adding fibers to the plain concrete mixture improved its mechanical properties. The highest splitting tensile strength and compressive strength obtained are related to the concrete samples that were made from a combination of polypropylene and steel fibers with a ratio of 0.1 PP + 0.9 MS. The maximum values were equal to 5.09 MPa and 48.02 MPa, respectively. The highest value of flexural strength (6.41 MPa) was obtained in the concrete mixture containing 1% steel fibers.
8. The most optimal combination of polypropylene and steel fibers is 0.1PP+0.9MS, which has a positive effect on the mechanical properties of both plain and rubber concrete mixtures.
9. Replacing fine grains with tire-rubber particles in all samples had a negative effect on their overall performance and mechanical properties.

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