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RESEARCH **Open Access**

Effect of Wollastonite Microfibers and Waste Tire Rubber on Mechanical Properties of Concrete

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Abstract

The main objective of the present research is to investigate the effect of adding wollastonite microfibers and waste tire rubber on the mechanical properties of concrete. For this purpose, two different series of mixtures were considered. Different percentages (5, 10, 15, and 20 percent) of wollastonite microfibers were added to the ordinary concrete and tested in the first series. Then, in the second series, wollastonite microfibers were added to the specimens in the amount of 20% by the weight of cement, and waste tire rubber was replaced with fine aggregate in different percentages (3, 5, 7, and 10 percent by the weight of fine aggregate), and the specimens were tested again. All the specimens were cured at the two ages of 7 and 28 days, and they were tested for the slump, compressive strength, tensile strength, and flexural strength. The results showed that the addition of 20% wollastonite microfibers to the specimens increased the compressive, flexural, and tensile strengths of the concrete at 28 days of age by 16, 87, and 78%, respectively, compared to the control specimen. The outcomes also demonstrated that replacing fine aggregate with tire rubber in samples containing 20% wollastonite microfibers reduces the strength of the samples. The highest reduction is related to the sample containing 20% of waste tire rubber, which has a reduced compressive strength of about 20% compared to the control sample. Furthermore, the results of this research showed that adding wollastonite microfibers to concrete reduces the concrete slump, while the density of the samples increases with the addition of wollastonite. Moreover, the presence of wollastonite microfibers reduces the porosity of concrete, but there is an increase in the number of pores in concrete samples containing waste tire rubber.

Keywords Concrete, Waste tire rubber, Wollastonite microfibers, Compressive strength, Flexural strength

1 Introduction

As the most widely used material in the world, concrete has a significant role in consuming natural resources and producing environmental pollution (Gagg, 2014). Overexploitation of Natural Resources, on the one hand, and the increase in the production of polluting wastes and the problems caused by the management of these wastes, on the other hand, have led researchers to use environmentally friendly and recycled materials in the production of concrete. The use of mineral materials such as pozzolans as natural materials for reducing the amount of cement in concrete could be an important factor in reducing the pollution associated with cement production (Pachideh & Gholhaki, 2020; Qian & Li, 2001; Toufigh

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& Pachideh, 2022). Also, such materials as wollastonite microfibers could be used in concrete as an adhesive material (Mathur et al., 2007). Wollastonite microfibers are a mineral material based on calcium inosilicate that may contain iron and magnesium. CaO and SiO_2 constitute 48.3 wt% and 51.7 wt% of wollastonite microfibers, respectively. In addition to the two materials, other materials may be found in the wollastonite microfibers structure, such as aluminum, iron, magnesium, manganese, potassium, and sodium (Mandel et al., 2018). The use of wollastonite microfibers as an additive or replacing cement in the mortar and concrete has been the focus of the attention of researchers. The results of studies show that adding wollastonite microfibers to concrete has improved the compressive and flexural strengths of specimens by 35% and 42%, respectively (Fazeli et al., 2021). Moreover, replacing cement with wollastonite microfibers in the cementitious mortar could improve the compressive and flexural strengths by 5% and 12%, respectively (Öz & Güneş, 2021).

In addition to mineral materials, the use of recycled and waste materials in producing concrete has increased in recent years. Due to the problems associated with the disposal of waste materials and their adverse effect on the environment, researchers are looking to replace such materials as cement and sand with proper recycled materials to solve the problems mentioned above (Fazeli et al., 2021; Pachideh & Gholhaki, 2021). As a widely applicable waste material, tire rubber has attracted researchers to incorporate it in producing various types of concrete and asphalt (Pachideh et al., 2020). Using waste tire rubber in the production of materials such as concrete while removing the problem of disposal of these materials in the environment and pollutions associated with them also could improve some properties of concrete (Siddika et al., 2019). Such properties enhancement as the increase of resistance against chemical materials, increase of resistance against abrasion, and damping of vibrations due to the elasticity characteristics of waste tire rubber has increased the daily application of waste tire rubber in the construction industry (Mohajerani et al., 2020).

Investigations show that adding waste tire rubber to concrete or replacing materials like sand with this material reduces the early compressive strength of specimens (7 and 28 days) up to 50% compared to the control specimen, and increasing the waste rubber content decreases the compressive strength. Investigations represented that by replacing 10% to 100% of sand with waste tire rubber in concrete, the compressive strength decreases by 25% to 88 (Aslani, 2016). However, the compressive strength results of the specimens cured for 90 days exhibit increased strength compared to the control specimen (Sofi, 2018; Thomas & Gupta, 2016). Furthermore, the presence of waste tire rubber in concrete increases sound absorption and reduces sound transmission at high frequencies compared to the specimens without waste tire rubber. Therefore, this property justifies using this type of concrete at airport runways and freeways (Medina et al., 2016; Ridgley et al., 2018). Besides, some studies have been carried out in order to find a mathematical equation predicting the effect of rubber particles on the mechanical properties of concrete (Li et al., 2014). Moreover, using waste tire rubber increase the ductility of the concrete and reduces the crack width under compression loads (Khaloo et al., 2008).

Investigations showed that many research works have already been done on the use of waste tire rubber in concrete. Nevertheless, there was no investigation on using an appropriate additive to modify some of the properties of waste tire rubber-containing concrete. Thus, the simultaneous use of wollastonite microfibers and waste tire rubber in concrete is investigated in the present research. Since the addition of waste tire rubber to concrete reduces its strength parameters, in this study, wollastonite microfibers were used as a natural pozzolan to improve the properties of concrete containing waste tire rubber to provide a new mixing design to produce green and durable concrete. Fig. 1 shows the flowchart of investigation process in this study.

2 Materials and Methods

2.1 Materials

In this research, ordinary Portland cement is used according to EN 197-1 Standard (EN & B.S., 2000). Tables 1 and 2 show the chemical analysis and mechanical properties of the cement, respectively. The values given in the tables are based on the chemical analysis provided by the cement manufacturing plant. The wollastonite microfibers used in this research with diameters ranging from 90 to 150 µm were prepared from mines of Isfahan Province. Table 3 and Fig. 2 show the percentages of different elements in the wollastonite microfibers

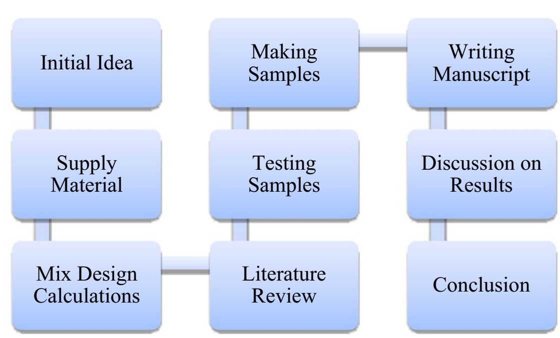

Fig. 1 Investigation process

Table 1 Cement chemical analysis

Chemical composition	SiO_2	Al_2O_3	Fe_2O_3	K_2O	CaO	MgO	SO_3	Na_2O
Percentage	21.7	5	3.8	0.33	63.2	1.85	2.1	0.53

Table 2 Cement Properties

Properties	Value
Initial setting time	140 min
Ultimate setting time	210 min
1-day strength	95 kg/cm^2
2-day strength	170 kg/cm^2
3-day strength	210 kg/cm^2
7-day strength	310 kg/cm^2
28-day strength	440 kg/cm^2

obtained from x-ray fluorescence (XRF) and x-ray diffraction (XRD) tests. As a calcium silicate system is a predominant part of cementitious compounds, the presence of major pozzolanic compounds, such as SiO_2 and CaO, and other compounds useful in pozzolanic activity such as Al_2O_3 in wollastonite chemical composition, can justify the replacement of wollastonite with cement.

Furthermore, in this research, the use was made of waste tire rubber as a partial replacement for sand. The consumed waste tire rubber was prepared from a single source and produced using the peripheral milling process. The properties of used waste tire rubber are

Table 3 Percentages of the constituent elements of wollastonite microfibers obtained from the XRF test

Element	SiO_2	CaO	Al_2O_3	Fe_2O_3	TiO_2	MnO	MgO	Na_2O	K_2O
Percentage	51	48	0.20	0.30	0.06	0.10	0.20	0.10	0.04

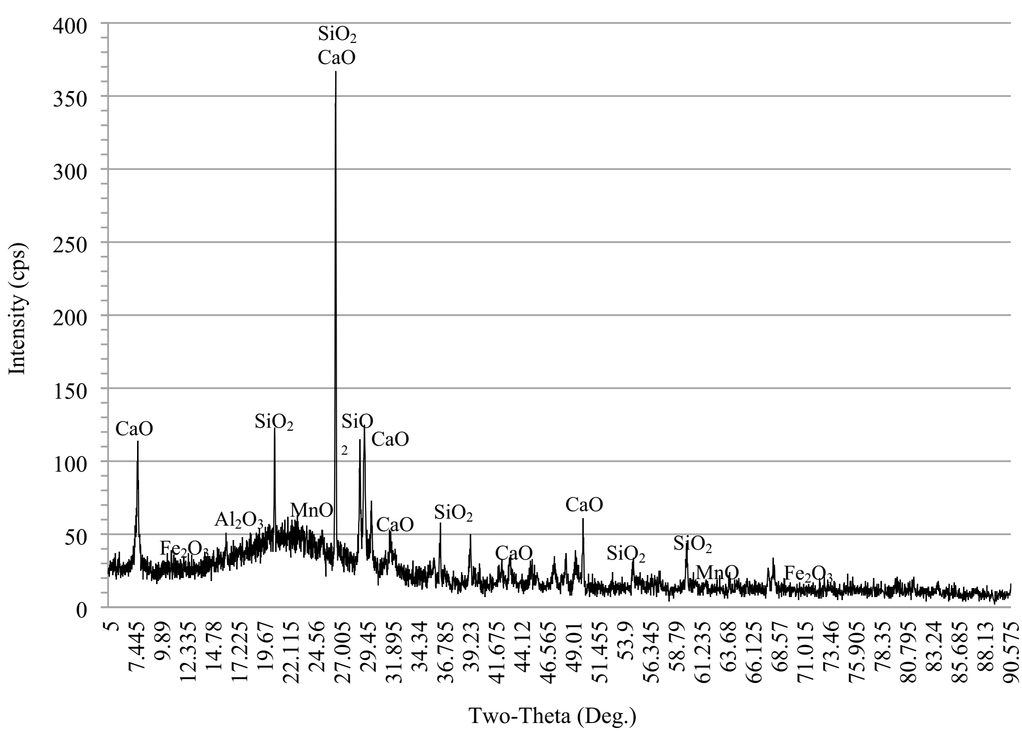

Fig. 2 Diffraction pattern from XRD test

given in Table 4, and its particle size distribution curve is shown in Fig. 3. The values given in Table 4 are based on the chemical analysis provided by the tire and rubber manufacturing company. The used gravel and sand were of the well-graded type according to ASTM C33/C33M Standard (2013). Fig. 3 also depicts the particle size distribution curve of the used gravel and sand aggregates. The used water was of drinking water type and met all the requirements of ASTM C1602/C1602M-12 Standard (2012).

2.2 Methods

In order to investigate the effect of wollastonite microfibers on the strength parameters of the waste tire rubber containing concrete, a mix design was prepared according to ASTM C618-00 (2001) and ACI 211.1-91 Standards (1991). The prepared mix design was divided into two series; the specimens contained wollastonite microfibers, and the specimens contained wollastonite microfibers and waste tire rubber.

In this research, wollastonite microfibers were added to the specimens at 5, 10, 15, and 20 wt% of the cement (W5R0–W20R0) as an additive, and different tests were carried out on them. Subsequently, 20 wt% of the cement wollastonite microfibers, which is the optimal percentage of wollastonite microfibers obtained from the tests, were added to the specimens that contained waste tire rubber, which replaced fine aggregate at 3, 5, 7, and 10 wt% (W20R3–W20R10). In addition, a specimen of ordinary concrete (W0R0) was prepared as the control specimen for comparison purposes. All the specimens were cured at the 7-day and 28-day ages according to ASTM C192/C192M (2013). Table 5 shows the concrete mix design used in this study.

The density, slump, compressive strength, flexural strength, tensile strength, and air void ratio tests were performed on the concrete specimens based on ASTM Standards. The workability of fresh concrete was investigated using the slump test according to ASTM C143/C143M-20 Standard (2020). Furthermore, for determining the compressive strength of the specimens, ASTM C39 Standard was considered (ASTM C39/C39M-10, 2010). Also, the compressive strength and flexural strength of the specimens were obtained according to ASTM C496/C496M-11 (2004) and ASTM C78-94 Standards (2002), respectively. The flexural test was the 3-point flexure test, and the size of the specimens was $150 \times 150 \times 750$ mm. Finally, scanning electron microscopes (SEM) were used to study concrete microstructure, and SEM images taken from the samples were analyzed. In all the tests, per each mix design, three specimens were prepared, and the final result is the mean of the three results obtained from three specimens of each mix design. As many research works have been done on the various parameters of the concrete containing waste tire rubber, therefore, in the present study, duplicate experiments have been avoided, and the results of past

Table 4 Waste tire rubber properties

Properties	Values
Density (g/cm^3)	1.16 g/cm^3
Ash (%)	5%
Plastic (%)	10%
Black Carbon (%)	29%
Polymer (%)	50%
Particle size (mm)	0.0–0.7 mm

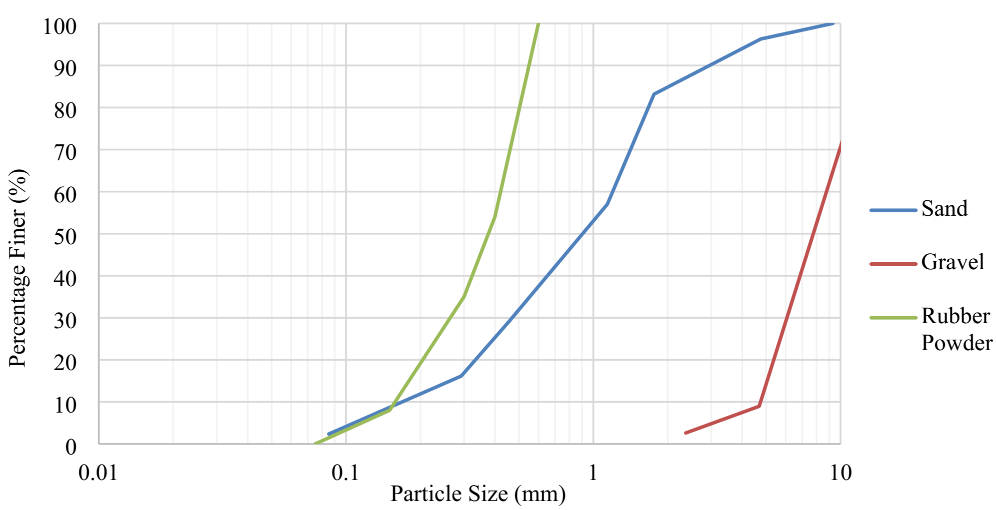

Fig. 3 Particle size distribution curves for waste tire rubber, sand, and gravel

Table 5 Mix design

Mix design	Water/cement ratio	Water (kg)	Cement (kg)	Gravel (kg)	Sand (kg)	Wollastonite microfibers (kg)	Wollastonite %	Waste tire rubber (kg)	Waste tire rubber (%)
W0R0	0.50	192	368	770	1053	0	0	0	0
W5R0	0.50	192	368	770	1053	18.4	5	0	0
W10R0	0.50	192	368	770	1053	36.8	10	0	0
W15R0	0.50	192	368	770	1053	55.20	15	0	0
W20R0	0.50	192	368	770	1053	73.6	20	0	0
W20R3	0.50	192	368	770	1021.41	73.6	20	31.59	3
W20R5	0.50	192	368	770	1000.35	73.6	20	52.65	5
W20R7	0.50	192	368	770	979.29	73.6	20	73.71	7
W20R10	0.50	192	368	770	947.7	73.6	20	105.3	10

research in this field have been used (Aslani et al., 2018; Choudhary et al., 2020; Moustafa & ElGawady, 2015; Rajan et al., 2021).

3 Results and Discussion

3.1 Workability

Fig. 4 shows the slump results of the specimens containing wollastonite microfibers in comparison with those of the control specimen. As seen in Fig. 4, the addition of wollastonite microfibers decreases concrete workability compared to the control specimen, which decreases more with increasing the percentage of wollastonite microfibers. The highest slump reduction is related to the sample containing 20% wollastonite microfibers (W20R0), which caused a 52% reduction in the concrete slump. The main reason for the decrease in concrete workability is the high specific surface area of wollastonite microfibers, which increases the concrete required water, and by increasing the water absorption in concrete containing wollastonite microfibers compared to the control sample (ordinary concrete), the slump of the samples decreases (Soliman & Nehdi, 2012; Zareei et al., 2019). In addition, the needle-shaped structure of wollastonite microfibers increases the entanglement between wollastonite microfibers and cement paste, which reduces the workability of concrete (Khan & Ashraf, 2019).

Moreover, as shown in Fig. 4, replacing sand with different percentages of waste tire rubber in concrete containing 20% wollastonite microfibers increases the workability compared to samples only containing wollastonite microfibers; however, the amount of concrete slump is less than the control sample. Insufficient adhesion between the waste tire rubber and the cement paste makes the soft waste tire rubber particles in the fresh concrete move more easily than the aggregates, increasing the concrete slump compared to the sample without

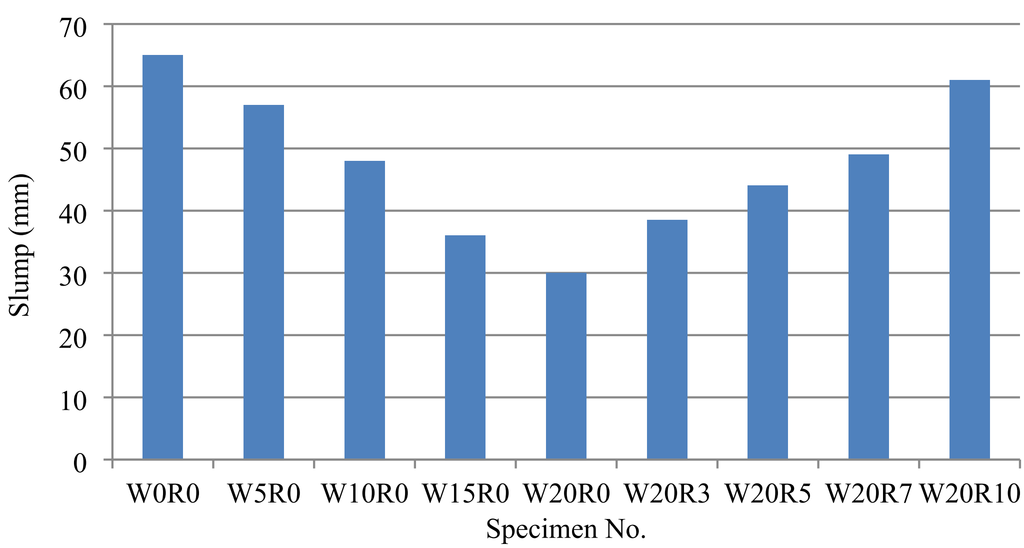

Fig. 4 The slump of the specimens

the waste tire rubber. Furthermore, the lack of adhesion between waste tire rubber and cement paste increases the porosity of concrete, increasing the concrete slump. Moreover, the water absorption of the waste tire rubber is much less than the sand; therefore, the increasing waste tire rubber content increases the slump and workability of the concrete. Other scholars have also reached the same results in their research (Bharathi Murugan & Natarajan, 2015).

3.2 Concrete Density

Fig. 5 shows the density of the specimens. As shown in Fig. 5, increasing the percentage of wollastonite microfibers in concrete increases the density of the samples compared to the control sample. The highest increase is related to the sample containing 20% wollastonite microfibers (W20R0), which led to a 5.5% increase in density compared to the control sample. Compared to cement, finer particles of wollastonite and its filler effect can reduce the porosity of the concrete matrix, which ultimately improves the density of concrete (Kalla et al., 2013, 2015).

Studies show that adding waste tire rubber to concrete or replacing it with aggregates in concrete reduces the density of concrete due to the lower density of waste tire rubber than natural aggregates (Gupta et al., 2014; Sofi, 2018; Wang et al., 2013; Xue & Shinozuka, 2013). Fig. 5 also shows that concrete density decreases with the increasing replacement percentage of waste tire rubber with sand. However, the presence of wollastonite microfibers in concrete containing waste tire rubber decreases the reduction of concrete density so that in W20R3 and W20R5 mixtures, there are 0.5 to 2.67% increases in density compared to the control sample.

3.3 Air Void Percentage

Investigations show that the presence of waste tire rubber in concrete increases the percentage of air void, which is due to a lack of enough adhesion between cement paste and waste tire rubber, which causes air trapping between waste tire rubber and cement paste and as a result increase porosity of concrete (Grinys et al., 2012). Fig. 6 shows the changes in air void percentage in different specimens.

As can be observed, adding wollastonite microfibers to concrete decreases the air void percentage. The filler effect of wollastonite microfibers fills the concrete pores and subsequently decreases the air void percentage of concrete specimens. Dinh-Cong et. al. (2019) reached similar results. Furthermore, as seen in Fig. 6, the presence of waste tire rubber in concrete increases the air void percentage. Increasing the amount of waste tire rubber increases the air void percentage, so this value exceeds that of the control specimen. Investigating various resources shows that using waste tire rubber in concrete increases the air void percentage of the specimen (Grinys et al., 2021; Mushunje et al., 2018). In other words, by adding 20% wollastonite microfibers, the air void percentage decreases by 0.73%, and by replacing waste tire rubber at 10 wt% of sand, the air void percentage increases by 1.57% compared to the control specimen.

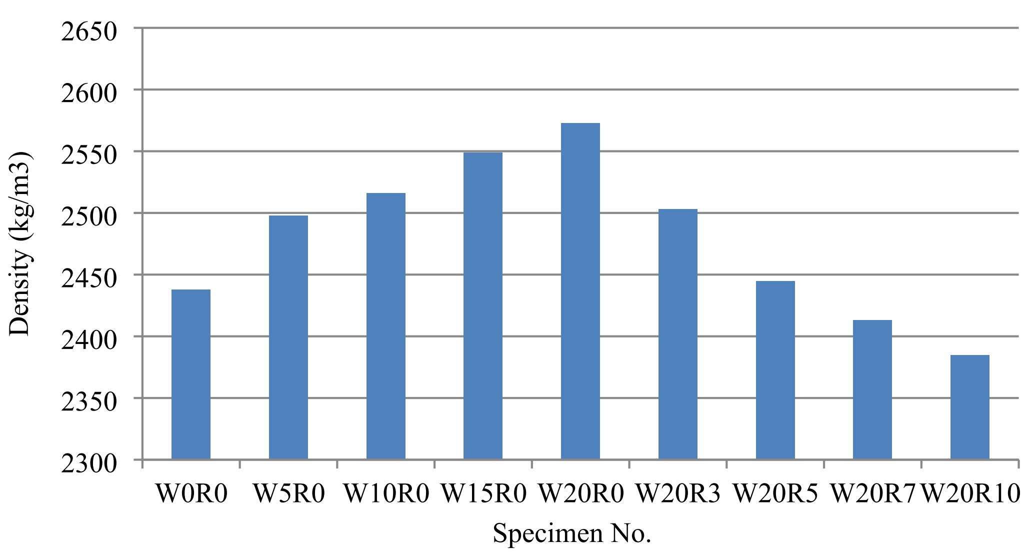

Fig. 5 The density of the specimens

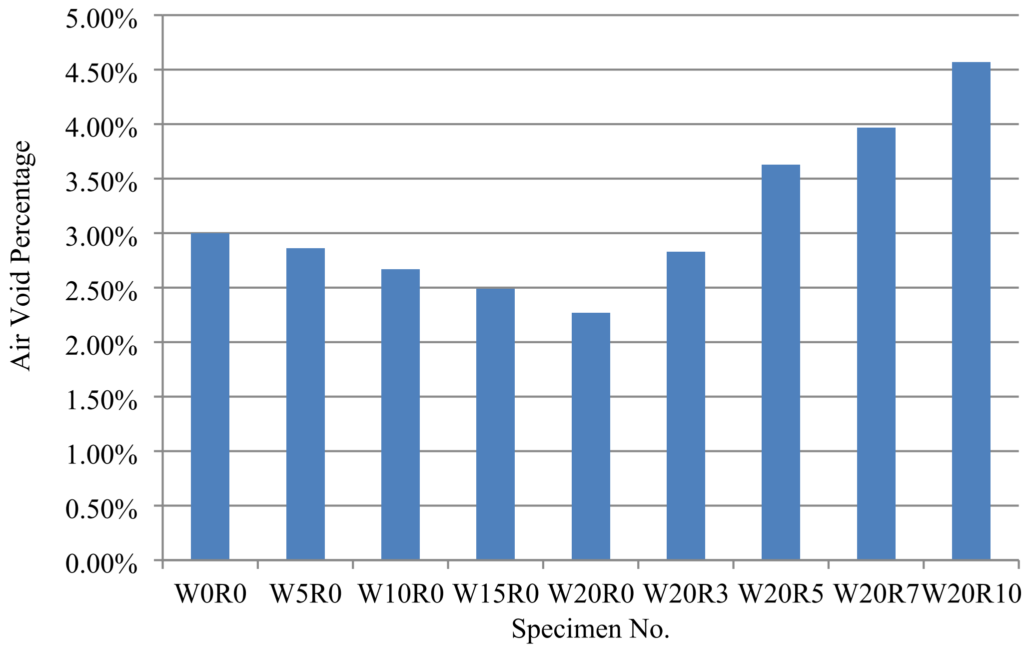

Fig. 6 Changes in the air void percentage in specimens

3.4 Compressive Strength

Fig. 7 shows the compressive strength of the specimens at the two ages of 7 and 28 days. As is seen, adding wollastonite microfibers to the specimens has increased their compressive strength. The reason for this is the filler effect of wollastonite microfibers, meaning that the wollastonite microfibers fill the pores in the specimen and enhance the solidity of specimens. Besides, wollastonite microfibers, in reaction with water, act like cement. Completing the hydration process increases adhesion between

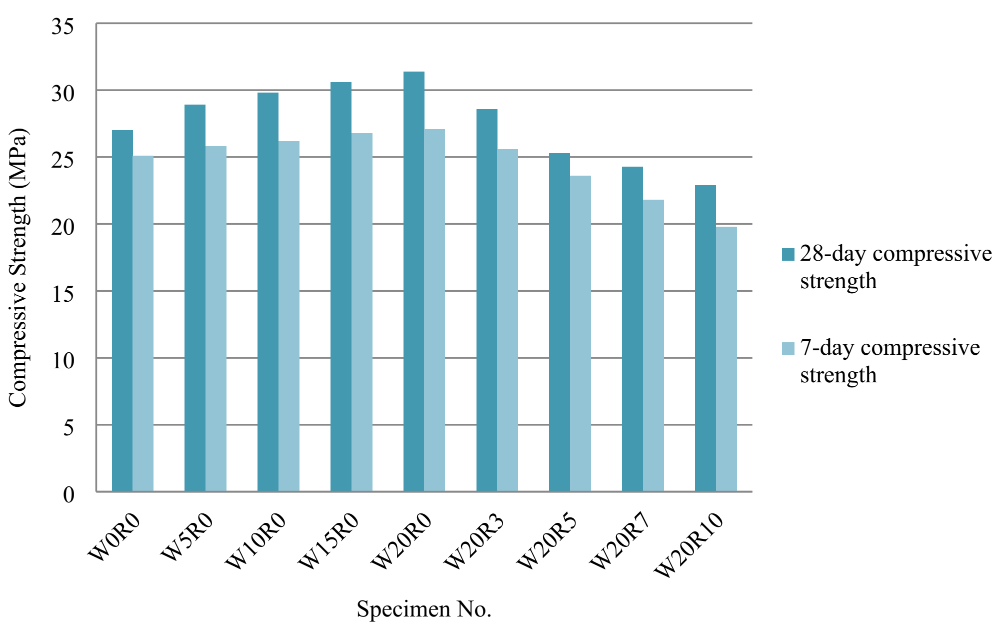

Fig. 7 Compressive strength of the 7-day and 28-day specimens

the particles and, as a result, increases the strength of the specimens. Studies show that replacing wollastonite microfibers with cement reduces the compressive strength due to reducing the amount of calcium silicates hydrates (CSH) gel produced by cement hydration (Low & Beaudoin, 1993; Wahab et al., 2017; Zareei et al., 2019). Nevertheless, in the current research, wollastonite microfibers have not replaced cement but are used as an additive, which has increased compressive strength. Previous studies also indicate that adding wollastonite microfibers to concrete increases the short-term and long-term compressive strength of samples by 10 to 65% compared to the control sample (Khan & Ashraf, 2019; Soliman & Nehdi, 2012). These results show that in projects where concrete needs to gain the desired strength in a short period of time, such as when the molds need to be removed in a short time due to specific limitations, wollastonite can be used to achieve the required strength.

Replacing waste tire rubber with fine concrete aggregates reduces the compressive strength of concrete. The lower stiffness of waste tire rubber particles compared to the replaced aggregates makes them deform immediately under the applied loads and form cracks inside the concrete microstructure, and as a result, they fail at a lower compressive load than the control specimen (Gupta et al., 2014; Sofi, 2018). Also, as stated before, compared to the conventional aggregates in concrete, there is a fragile bond between waste tire rubber and cement paste, resulting in a non-uniform distribution of stress in concrete and stress concentration at some points of concrete which could cause the failure of the particles under lower compressive loads. Furthermore, the hydrophobicity and the lower density of waste tire rubber than sand make rubber particles move towards the top of the concrete mix during the vibration of fresh concrete and create a non-homogeneous concrete mix causing the non-uniform stress distribution in concrete. On the other hand, as stated on the air void percentage test, the presence of waste tire rubber increases the air void amount in concrete, which reduces the compressive strength of concrete (Onuaguluchi & Panesar, 2014; Yung et al., 2013). On the other hand, the presence of wollastonite microfibers in concrete containing waste tire rubber has decreased the reduction amount of compressive strength. As in the W20R3 mixture, a 6% increase in compressive strength was observed compared to the control sample, which may be due to the filler effect and bridging effect of wollastonite microfibers in the concrete matrix.

As seen in Fig. 7, with the increase of the age of the specimen, strength also increases, which is due to the completion of cement and wollastonite microfibers hydration leading to the increase of the compressive strength. Considering the 28-day results of the concrete, the addition of waste tire rubber reduces the concrete strength compared to the concrete containing wollastonite microfibers. In other words, by adding 20% wollastonite microfibers, the 28-day strength increases by 16% compared to the control specimen. Furthermore, replacing 10% of sand with waste tire rubber decreases the 28-day compressive strength by about 15% compared to the control specimen.

3.5 Flexural Strength

Fig. 8 shows the flexural strength of the specimens at the 7-day and 28-day ages. As is seen, the flexural strength of the specimens increases with the increase of the wollastonite microfibers amount compared to that of the control specimen, which is due to the filler effect and adhesion of wollastonite microfibers in the presence of water. The specimen containing 20% wollastonite microfibers has the highest flexural strength value. Other researchers have achieved similar results (Kalla et al., 2015; Low & Beaudoin, 1992; Zareei et al., 2019). These studies demonstrated that the addition of 10 to 15% wollastonite microfibers to concrete increases the flexural strength of the specimens compared to the control sample. A reason for increasing the flexural strength of concrete containing wollastonite is the wollastonite microfibers filler effect, which reduces the number of pores in the concrete matrix. Furthermore, the fibrous nature and high elastic modulus of wollastonite microfibers prevent the propagation of cracks (Wahab et al., 2017). Replacing waste tire rubber with fine aggregates reduces the flexural strength of concrete, decreasing more with increasing waste tire rubber percentage. The weak bond between the waste tire rubber particles and the concrete matrix forms microcracks close to the waste tire rubber particles under a lower load, causing the concrete to have a lower strength against flexural load (Dinh-Cong et al., 2019; Sofi, 2018). On the other hand, the addition of 20% wollastonite microfibers to samples containing waste tire rubber decreased the flexural strength reduction due to the filler effect and bridging effect of wollastonite microfibers of the specimens. As can be seen, in W20R3 and W20R5 samples, an increase of 48 and 17% in 28-day flexural strength compared to the control sample, respectively. Despite reducing flexural strength, concrete containing waste tire rubber experienced more deformation before failure, which is due to the high ductility of tire rubber compared to concrete aggregates making concrete more ductile.

In the 28-day specimens, the flexural strength increased due to the completion of the hydration process in cement and the completion of the chemical reaction of wollastonite microfibers, which increased the flexural strength of the specimens with time. Moreover,

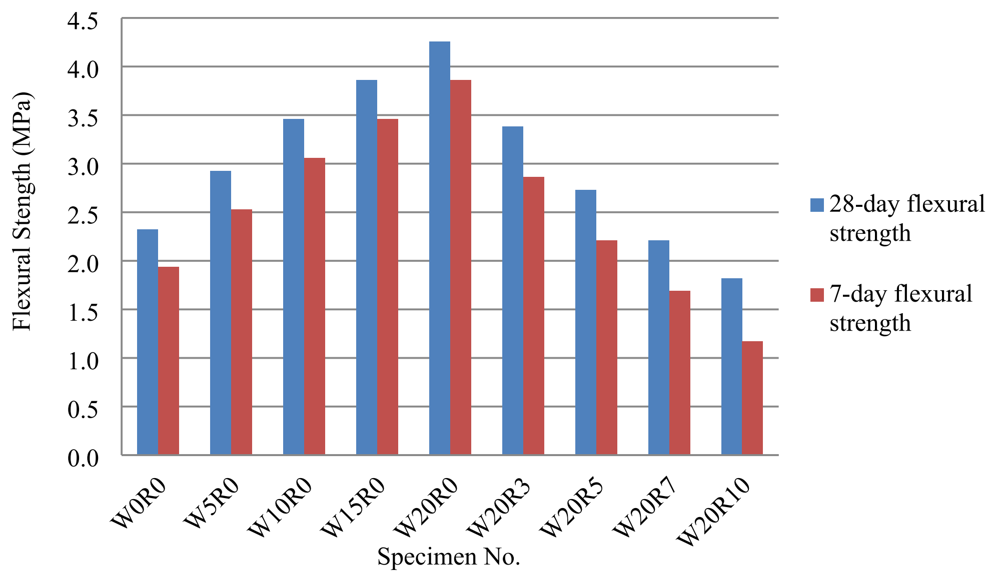

Fig. 8 Flexural strength of the 7-day and 28-day specimens

the addition of waste tire rubber to the concrete containing wollastonite microfibers reduces the 28-day flexural strength of the specimens. In other words, by adding 20% wollastonite microfibers, the 28-day flexural strength increases by about 87% compared to the control specimen. Furthermore, replacing 10% of sand with waste tire rubber allowed the 28-day flexural strength to decrease by about 22% compared to the control specimen.

3.6 Tensile Strength

Fig. 9 shows the tensile strength of the specimens at the 7-day and 28-day ages. As can be seen, wollastonite microfibers have increased the tensile strength of the samples due to the filler effect of wollastonite microfibers and producing additional adhesion between the aggregates because of pozzolanic reactions. Specimen W20R0 has exhibited the highest strength, equal to

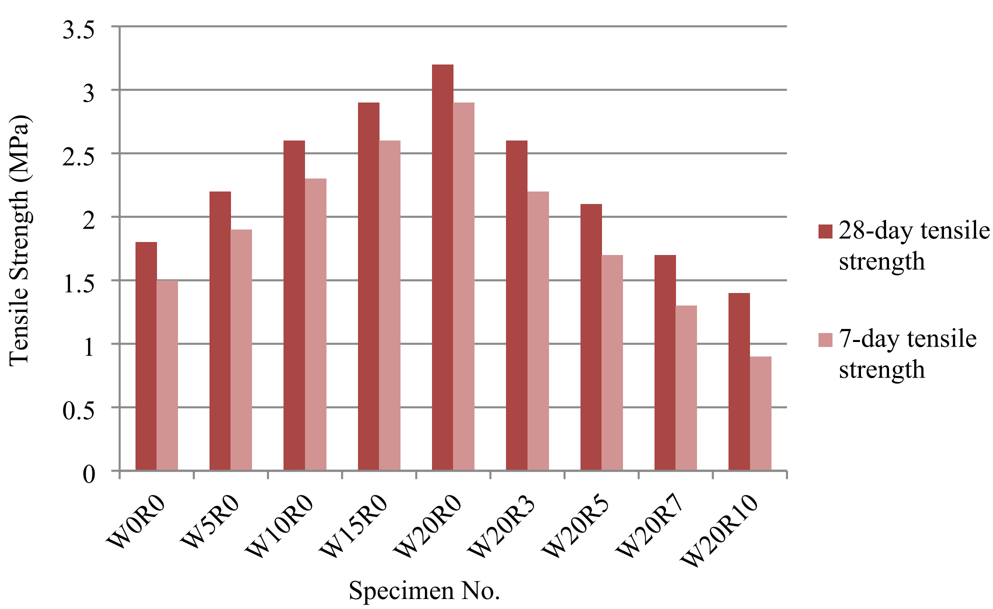

Fig. 9 Tensile strength values of the 7-day and 28-day specimens

3.2 MPa. Previous research has yielded similar results. Wahab et al. concluded that the filler effect and the bridging effect of wollastonite microfibers increase the tensile strength of concrete containing wollastonite microfibers compared to the control specimen (Wahab et al., 2017).

Moreover, the concrete tensile strength decreases by replacing fine aggregates with waste tire rubber, and this reduction in strength increases by increasing the amount of the waste tire rubber. Previous studies have shown that replacing 7.5% of fine aggregates with waste tire rubber reduces concrete strength by up to 44%, mainly due to insufficient adhesion between waste tire rubber and cement paste, which at the beginning of loading, microcracks appear in the boundary between the particles of waste tire rubber and cement. Studying the microstructure of concrete containing waste tire rubber indicates that rubber particles, by reducing the density of concrete and also establishing weak bonding in the concrete matrix, cause interfacial cracks in the concrete, which eventually form uneven stress distribution patterns in the concrete matrix (Mohajerani et al., 2020). This phenomenon could lead to the non-uniform distribution of stresses in the concrete and stress concentration, and consequently, concrete fails at a lower tensile load (Sofi, 2018; Thomas et al., 2014). Besides, waste tire rubber particles act as separators and prevent the complete adhesion of the aggregates with the concrete matrix. Whereas, the present study reveals that by adding 20% wollastonite microfibers to specimens containing waste tire rubber, the reduction of the tensile strength decreases so that the tensile strength of the sample containing 3% waste tire rubber and 20% wollastonite microfibers increased by 44% compared to the control specimen. Since tensile strength is one of the important characteristics of concrete and the use of waste tire rubber causes a sharp drop in the tensile strength, therefore improving the tensile strength of concrete containing waste tire rubber can be invaluable and essential. Consequently, the present study shows that the use of wollastonite in concrete containing tire rubber can improve its tensile strength. Furthermore, as can be seen in Fig. 9, by increasing the age of specimens, their strength increases compared to that of the 7-day age, which reveals the completion of the hydration process in cement and completion of wollastonite microfibers pozzolanic reactions, which leads to the increase of tensile strength of the specimens with time (Dinh-Cong et al., 2019). In other words, by adding 20% wollastonite microfibers, the 28-day tensile strength increases by about 77% compared to that of the control specimen. Furthermore, replacing 10% of sand with waste tire rubber decreases the 28-day tensile strength by about 22% compared to the control specimen.

3.7 Investigating the Microstructure of Specimens

In order to investigate the microstructure of the specimens in this research, the Scanning Electronic Microscope (SEM) was used. For this purpose, electronic images were taken from the control specimen, the wollastonite microfibers-containing specimen, and the specimen that contained both waste tire rubber and wollastonite microfibers. Fig. 10 shows the SEM images of the concrete specimens.

Fig. 10a clearly shows the pores of the control concrete. These pores affect the durability and strength of concrete. The presence of these pores can cause the propagation of microcracks in concrete, which ultimately reduces the strength of concrete. Moreover, these pores can have a destructive effect on concrete durability parameters by increasing the permeability of concrete (Prakash et al., 2022). As displayed in Fig. 10b, adding wollastonite microfibers reduced the pores due to the filler effect of wollastonite microfibers, and the density of concrete increased. Khan and Ashraf (2019) and Kalla et. al. (2015) achieved similar results by examining concrete microstructure containing wollastonite microfibers. Finally, as illustrated in Fig. 10c, the replacement of fine aggregates with waste tire rubber increases the number of pores; however, it can be noticed how wollastonite microfibers have filled the pores.

4 Conclusion

This research paper was an attempt to investigate the use of wollastonite microfibers and waste tire rubber in making concrete. As cement production increases the amount of greenhouse gases and causes further global warming, the use of natural additives like wollastonite microfibers could be regarded as a solution. Furthermore, the production of waste by-products in various industries leads to environmental pollution, becoming a global dilemma. In many countries of the world, the issue of recycling and reusing wastes is on their agenda. Therefore, the present research evaluated the use of this waste material in concrete by replacing sand with different percentages of waste tire rubber. As many researchers have proved, waste tire rubber reduces concrete strength; therefore, this research uses wollastonite microfibers as a pozzolanic additive to compensate for this reduction in strength. In the current study, two concrete mix designs were assessed.

The first mix design included the specimens containing different percentages of wollastonite microfibers tested at the 7-day and 28-day ages. The second mix design contained 20% wollastonite microfibers, and fine aggregates were replaced with different percentages of waste tire rubber. Waste tire rubber replaced sand in these concrete mix designs by 3, 5, 7, and 10 wt%. The compressive

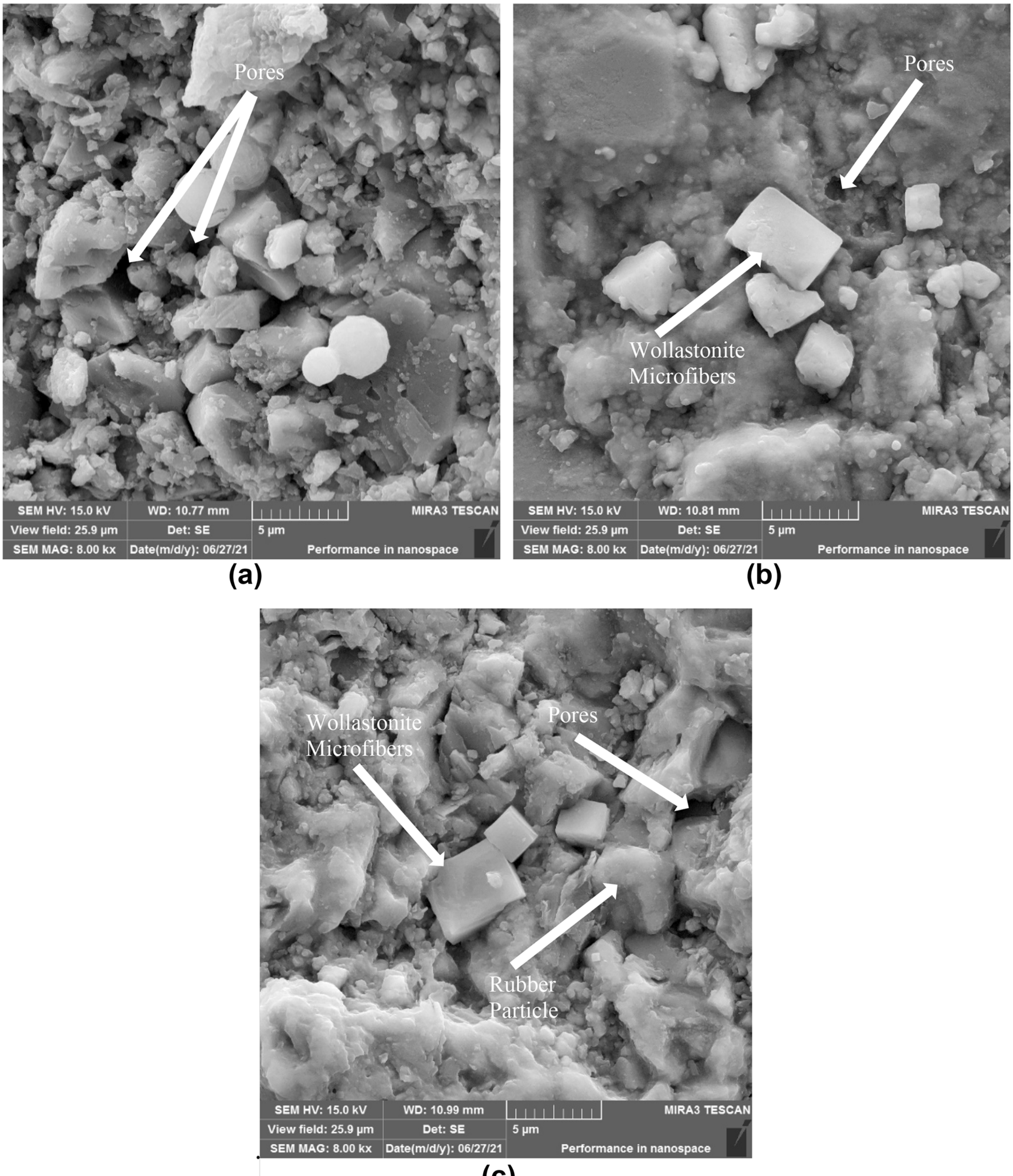

Fig. 10 SEM images of the concrete specimens: **a** control specimen, **b** wollastonite microfibers containing specimen, **c** wollastonite microfibers and waste tire rubber containing specimen

strength, tensile strength, flexural strength, air void percentage, slump, and density tests were performed on all specimens. The obtained results from this research are as follows:

1. The addition of wollastonite microfibers reduces the concrete slump compared to the control specimen. The highest reduction belonged to the specimen that contained 20% wollastonite microfibers,

which reduced the concrete slump by about 54%. This reduction of the slump has a direct effect on the concrete workability and can improve the concrete integrity and prevent concrete segregation during placing concrete.

2. The specimens containing wollastonite microfibers and waste tire rubber demonstrate less workability than the control specimen; but, higher slumps than those specimens which contain only wollastonite microfibers. In the W20R10 specimen, replacing 10% of sand with waste tire rubber increases the concrete slump by 50% compared to the W20R0 specimen.
3. The presence of wollastonite microfibers in concrete increases the density of the specimens compared to the control specimen, in which the addition of 20% wollastonite microfibers increases the density of concrete by about 5.5%. Furthermore, the simultaneous use of waste tire rubber and wollastonite microfibers decreases the density of the specimens compared to the specimens containing only wollastonite microfibers, and they display a lower density than the control specimen. Therefore, adding 20% wollastonite microfibers and replacing 10% of sand with waste tire rubber causes about a 2.2% reduction in concrete density.
4. Wollastonite microfibers reduce the air void percentage of concrete compared to the control specimen. Moreover, the presence of waste tire rubber and wollastonite microfibers in concrete increases the air void percentage in the specimens compared to the specimens containing only wollastonite microfibers; they also show a higher air void percentage than the control specimen. The highest decrease in concrete air void percentage is related to the W20R0 specimen, which by adding 20% wollastonite microfibers to concrete, causes a 23% decrease in the concrete air void compared to the control sample.
5. The addition of wollastonite microfibers to the specimens increases the 7-day compressive strength, in which adding 20% wollastonite microfibers increases the 7-day compressive strength of concrete by about 8%. This increase in strength is because adding wollastonite decreases the porosity of concrete and increases its density, so the strength of the concrete increases.
6. The addition of waste tire rubber to the specimens containing wollastonite microfibers decreases the 7-day compressive strength. By replacing 10% sand with waste tire rubber, the 7-day compressive strength decreases by about 21% compared to the control specimen.
7. In the 28-day specimens, it could be seen that an increase in the percentage of wollastonite microfibers increases the compressive strength. Moreover, by increasing the age of specimens, their strength also increases due to the completion of such reactions as hydration in concrete adhesives like cement and wollastonite microfibers. By adding 20% wollastonite microfibers, the 28-day compressive strength increases by about 16% compared to the control specimen. Furthermore, replacing 10% sand with waste tire rubber decreases the 28-day compressive strength by about 15% compared to the control specimen. Moreover, Adding wollastonite microfibers to the specimens at the 7-day and 28-day ages increases their flexural strength. Adding waste tire rubber reduces the concrete flexural strength compared to the specimen containing wollastonite microfibers. By adding 20% wollastonite microfibers, the 28-day flexural strength increases by about 78% compared to the control specimen. Moreover, replacing 10% sand with waste tire rubber decreases the 28-day flexural strength by about 22% compared to the control specimen.
8. The tensile strength of the specimens at the 7-day and 28-day ages increases by adding wollastonite microfibers to the specimens. Nevertheless, adding waste tire rubber reduces the tensile strength of concrete. By adding 20% wollastonite microfibers, the 28-day tensile strength increases by about 77% compared to the control specimen. Furthermore, by replacing 10% sand with waste tire rubber, the 28-day tensile strength decreases by about 22% compared to the control specimen.
9. Analyzing the microstructure of the specimens using the SEM method shows that the addition of wollastonite microfibers to the ordinary concrete and the concrete containing waste tire rubber increases the concrete cohesion and filling of the pores due to filler effect microfibers; however, the presence of waste tire rubber increases concrete porosity. The needle-like shape particles of wollastonite microfibers enhance the entanglement between cement paste and wollastonite microfibers, increasing the integrity and strength of the concrete.

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Author contributions
SL: writing the manuscript, experimental works, analyzing data, reviewing, editing. AJ: experimental works, reviewing, editing. PB: writing the manuscript, analyzing data, reviewing, and editing. MH: reviewing, editing, supervisor. MG: analyzing data, reviewing. This work was carried out in collaboration with all the authors. All authors read and approved the final manuscript.

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Declarations

Competing interests
The authors declare that they have no competing interests.

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