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Coupled effect of waste tire rubber and steel fibers on the mechanical properties of concrete

Mohsin Adeel Waris[1], Umbreen us Sahar[2], Usman Akmal[2], Nauman Khurram[2], Fahid Aslam[3,*], Dina Fathi[4]

[1]Civil Engineering Department, University of Engineering and Technology, Lahore, Pakistan
[2]Civil Engineering Department, University of Engineering and Technology, Lahore, Pakistan
[3]Department of Civil Engineering, College of Engineering in Al-Kharj, Prince Sattam Bin Abdulaziz University, Al-Kharj 11942, Saudi Arabia
[4]Structural Engineering and Construction Management Department, Faculty of Engineering and Technology, Future University in Egypt, 11845 New Cairo, Egypt

Studies in the literature indicate that while tire crumb rubber can be added to concrete to replace some natural aggregates, steel fibers need to be introduced to overcome the compromise in the mechanical properties of concrete, especially compressive and tensile strength, that would be caused due to the addition of tire crumb rubber exclusively. In the present study, a minimum content of steel fibers has been added to mitigate the negative impact of addition of tire rubber fibers on the mechanical properties of concrete. The tire rubber fibers content was varied from 1% to 3% by volume whereas steel fibers were added from 0.1% to 0.3% by volume only. In this way, the effectiveness of hybridized concrete using tire rubber and steel fibers was evaluated based on its mechanical properties. The results revealed that inclusion of steel fibers overcame the reduction in strength and toughness of concrete to which tire rubber fibers have been added. Concrete with 2% tire rubber fibers and 0.2% steel fibers showed better mechanical performance in terms of compressive strength (10%), split tensile (14.7%), flexural strength (6.6%), and flexural toughness indices ($T^D_{150} = 46\%, f^D_{150} = 45\%$) as compared to the concrete with only 3% tire rubber fibers.

Keywords: *waste tires, fibers, waste management, waste elimination, hybridized concrete, strength of concrete*

1. Introduction

Millions of tires are discarded all over the world each year. A large amount of vehicle waste is produced annually, of which tires pose the greatest hazard to the environment if not disposed of properly. In particular, tires constitute one of the largest sources where mosquito larvae find favorable conditions to develop. So, to ensure that the waste tires are disposed of in an eco-friendly and environmentally sustainable manner, and at the same time put to a productive use, they may be processed and used in construction-based materials. Concrete is a brittle material that exhibits a nonlinear response before cracking. It is often necessary to modify the specific properties of concrete as per the requirements of a particular member [1]. Fiber-reinforced concrete (FRC) is a compound material consisting basically of concrete or mortar, and reinforced with arbitrarily spread short, intermittent, and distinct fine fibers of a distinct geometry [2]. Mostly, fibers used commercially in concrete include glass, rubber, steel, aramid, and other types of synthetic fibers. The efficiency of fiber-reinforced concrete depends on the properties, geometry, and shape of the fibers [3].

Not following environmentally sustainable procedures for disposal of used rubber from tires has become a major ecological problem all over the world. All over the world, millions of tires are disposed of by simply discarding them in the open or burying them, and this poses a very serious environmental risk [4]. An appreciation is given to waste reuse and recycling, instead of its disposal. Considering this perspective, various initiatives are

* E-mail: f.aslam@psau.edu.sa

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being taken worldwide in an attempt to transform waste materials into useful products [5]. One of the possible solutions for using the waste rubber generated by tire-manufacturing processes is to add it in concrete to replace some natural aggregates [4].

Rubberized concrete can be considered an environment-friendly material obtained by recycling used tires to form various rubber crumbs and mixing with concrete by substituting a definite part of the aggregate [6]. Rubber can mend the energy degeneracy, damping factor, ductility, and elastic properties of concrete, which are important factors in earthquake-prone concrete structures [7].

Crumb rubber concrete (CRC) has some known disadvantages in terms of mechanical properties compared with conventional concrete, especially with regard to compressive strength [8]. It was found that the use of CRC as a replacement of 20% of the fine aggregate and 5% of the whole mixture contents showed satisfactory properties for practical use [9]. Steel fiber-reinforced concrete (SFRC) has many excellent properties, such as crack resistance, durability, resistance to bending properties, impact resistance, etc. [10]. Steel fiber concrete mix may increase the cracking resistance and toughness of concrete due to the bridging effect of steel fibers. Flexural strength of concrete was improved and enhanced by adding the strong long steel fibers but the incorporation of small steel fibers may also result in the split cylinder strength of concrete [11].

The addition of crumb rubber gives flexibility to the concrete; however, further increase in flexibility due to the increased strength obtained by the inclusion of steel fibers as a second component played a more leading role in refining this property [8]. An "optimum" rubberized concrete was prepared, comprising of mix parameters, which led to higher workability and higher strength at various levels of rubber content [12]. Studies have also ascertained that adding rubber crumbs improves the elasticity of the concrete; however, the increased flexibility due to the increased strength as a result of the inclusion of steel fibers as a second component played a more significant role in modifying this property [13].

The impact resistance and maximum deflection of rubber specimens were significantly improved. All SFRC mixes showed the highest strength values compared with other samples [14]. The impact index and compressive strength of the concrete samples have shown that rubber crumbs can successfully be used in combination with steel fibers to provide good compressive load characteristics [15].

The maximum deflection and durability of the rubber concrete samples are adequately reported. All rubber SFRC mixes showed the highest stiffness values compared with the other samples in this study. Granulated steel fiber concrete can be used for practical applications that require further investigation [14].

Mechanical properties – i.e., compressive strength, modulus of elasticity, and stress and strain diagrams – showed a potential interaction between steel fibers and crumb rubber to improve these properties of concrete. The results obtained showed an improvement in the compressive strength resultant to increasing the crumb rubber content by up to 15% and a change in the behavior from normal concrete to a tough instead of a brittle material [15]. Waste tire fibers were considered more suitable as additives than waste tire chips because they produced the highest hardness. The ultimate tensile strength of concrete is very important, as it is the property that is responsible for the concrete failure, even under pressure [16]. Steel fiber or crumb rubber-reinforced concrete can be used for practical application, which requires further studies [14].

Many past researches [17–19] reported that addition of waste tire rubber chips significantly increased the toughness, plastic deformation, and impact resistance of concrete – thus making it good for use in crash barriers, pavement structures, and retaining structures. However, almost all researchers have observed loss in strength and stiffness of such a concrete.

Li et al. [20] have studied the use of tire rubber fiber concrete and compared the results with control concrete without rubber and with concrete with rubber chips. Test results show that, while the strength and stiffness of the concrete modified with waste tire fibers were still lower than those without waste tires, they were higher than those with waste tire chips.

Table 1. Physical properties of fine and coarse aggregates

Sr. No.	Aggregate property	Fine aggregates	Coarse aggregates
1	Fineness modulus	2.40	6.48
2	Specific gravity	2.70	2.64
3	Water absorption%	1.00	0.70
4	Bulk density (kg/m^3)	1,650	1,590

Hence, it is clear from the above discussions that tire rubber fibers are more suitable as compared to crumb rubber. Due to inherent problems of relatively low stiffness and strength, as well as early cracking, as a result of lack of proper bonding between rubber and the paste matrix in rubberized concrete, its use is limited to instances not involving structural application. It is well known that the addition of steel fibers can enhance the toughness, strength, and cracking resistance of concrete. Therefore, the problem of lower strength and stiffness of rubber fiber concrete could be overcome by using them in combination with steel fibers. Considering this possible improvement, it was decided to evaluate the mechanical behavior of the said hybrid concrete. The proposed mechanical properties involved compressive strength, split tensile strength, flexural strength, and toughness.

2. Research significance

A review of the literature showed that substantial research work has been carried out to evaluate the performance of steel fiber-reinforced rubber based concrete involving crumb rubber. Limited research work is available on the use of hybrid waste tire rubber fibers and steel fibers in concrete. To contribute to this sparsely addressed aspect in the literature, the current detailed experimental study was carried out to assess the coupled effect of tire rubber fibers and steel fibers on workability and mechanical performance of concrete. The proposed mechanical properties involved measurement of compressive strength, split tensile strength, and flexural strength and toughness of concrete.

3. Experimental details

3.1. Materials

Ordinary Portland type I cement with a specific gravity of 3.15 was used in this research. Natural river sand with fineness modulus of 2.40 was used as fine aggregate. Crushed aggregate from the local source with a maximum aggregate size of 19 mm was used as coarse aggregate. The properties of fineness modulus, saturated surface dry (SSD) specific gravity, moisture content, and bulk density of fine and coarse aggregates are listed in Table 1. High range water reducer Sika ViscoCrete-20 HE superplasticizer was used to enhance the workability of the concrete mixtures.

Tire rubber and steel fibers, as shown in Figure 1, were used in this study to evaluate their coupled effect on mechanical performance of concrete. Tire rubber fibers were obtained from the waste tires. For this purpose, the central portion between the tire steel fibers and protrusions was obtained, and cut into strips of length 25 mm and width 2–3 mm. Commercial straight steel fibers with length of 25 mm, diameter of 0.50 mm, specific gravity of 7.85, and tensile strength of 1,100 MPa were used. Properties of fibers are enlisted in Table 2.

Table 2. Physical properties of fibers

Sr. No	Properties	Tire fibers	Steel fiber
1	Average lengths (mm)	25	25
2	Average diameter (mm)	2.5	0.5
3	Aspect ratios	10	50
4	Tensile strength (MPa)	16.5–21.2*	1,100
5	Density (kg/m^3)	1,140	7,850

*Tensile strength of tire rubber fibers = 16.5–21.2 MPa [21]



(A) (B)

Fig. 1. **(A)** Steel fibers; **(B)** Rubber fibers

Table 3. Concrete mixture details

Mix name	R0S0	R0S0.3	R3S0	R1S0.1	R2S0.1	R3S0.1	R1S0.2	R2S0.2	R3S0.2
Cement (kg/m^3)	541	541	541	541	541	541	541	541	541
Sand (kg/m^3)	541	541	541	541	541	541	541	541	541
Gravel (kg/m^3)	1,082	1,082	1,082	1,082	1,082	1,082	1,082	1,082	1,082
Water (kg/m^3)	194.8	194.8	194.8	194.8	194.8	194.8	194.8	194.8	194.8
Admixture (kg/m^3)	5.41	5.41	5.41	5.41	5.41	5.41	5.41	5.41	5.41
Steel fibers (kg/m^3)	0	23.55	0	7.85	7.85	7.85	15.7	15.7	15.7
Rubber fibers (kg/m^3)	0	0	34.2	11.4	22.8	34.2	11.4	22.8	34.2

3.2. Mix proportioning

In this study, nine mixes were prepared for better understanding of the coupled effect of tire rubber and steel fibers on mechanical properties of concrete. The control mix was prepared according to ACI 211.1 [22] to achieve a target compressive strength of 45 MPa at 28 days. Each mix is designated as *RxSy*, where *R* represents the tire rubber fibers, *x* is the percentage of tire rubber fibers, *S* represents the steel fibers, and *y* is the percentage of steel fibers. To evaluate the performance of the various mixes against that of plain concrete, the control mix has been prepared without any fiber. Concrete mixtures were prepared with different percentages of tire rubber and steel fibers. The tire rubber fibers were added as 1%, 2%, and 3% by volume of concrete while steel fibers were added as 0.1%, 0.2%, and 0.3% by volume of concrete. For all mixes, the water/cement ratio was fixed at 0.36 and a nominal mix of 1:1:2 was used. Compositions of concrete mixes are presented in Table 3.

In this research, batching is done by weight. The order that was followed in adding the ingredients was: coarse aggregate, fine aggregate, and then binder; after that, the mixer was started to mix the dry ingredients. Then, water was added, and almost after adding half amount of water the admixture (superplasticizer) was mixed in the remaining half water. Now the remaining water that has been mixed with admixture was added to the concrete within 2–3 min. After adding the whole amount of water and admixture, steel fibers and tire rubber fibers were added to the mixer. This whole procedure of mixing was done within 5–6 min. The material after mixing was homogenous in color, non-bleeding, and non-segregated. All the remaining batches were mixed in the same way. At the end of mixing, prepared concrete was poured into the steel molds. After removing from the molds at the age of 1 day, specimens were moist cured using jute bags up to the age of 28 days at ambient conditions.

3.3. Research methodology

The slump test was performed for each batch to verify the uniformity or homogeneity of the concrete during construction as per ASTM C143 [23]. Tests were performed on hardened concrete at the age of 28 days to evaluate mechanical properties, including compressive strength, splitting tensile strength, and flexural strength. The compressive strength test was performed on cylindrical specimens of Φ 150 mm × 300 mm as per the ASTM C39 [24]. Two specimens were prepared for each type of concrete mix to determine the compressive strength. The compressive strength test was performed on 1,000 kN capacity displacement controlled universal testing machine (UTM) at a platen displacement rate of 1 mm/min.

The splitting tensile strength test was performed on cylindrical specimens of Φ 150 mm × 300 mm as per the ASTM C496 [25]. Two specimens were prepared for each type of concrete mix to determine the splitting tensile strength. The same UTM that was employed in compressive strength determination was used at a platen displacement rate of 0.5 mm/min to determine the splitting tensile strength. Split tensile strength was calculated using Eq. (1).

$$f_t = \frac{2P}{\pi DL} \tag{1}$$

where f_t represents the splitting tensile strength (MPa), P the load at failure (N), D the diameter of the specimen (mm), and L the length of the specimen (mm).

Four-point bending tests were performed on tire rubber and steel fiber beams to investigate the effect of the combination of rubber fibers and steel fibers on the bending performance of concrete. Three beams of 100 mm × 100 mm × 350 mm for each type of mixture were prepared for this test. The test was performed using a Shimadzu 1,000 kN UTM. The concrete specimens were loaded to final failure at a constant loading rate. Loads were recorded against first crack and the modulus of rupture (MOR) was calculated. The area under the load-deflection curve corresponding to deflection equal to span divided by 150 (Figure 2A) was calculated to assess the flexural toughness for all types of concrete mixes according to ASTM C1609 [26]. Equivalent flexural strength ($f^D_{e,\,150}$) and equivalent flexural strength ratio ($R^D_{T,\,150}$) were also calculated to evaluate the post-peak behavior as per ASTM C1609 using Eqs (2) and (3), respectively.

$$f^D_{e,150} = \frac{150T^D_{150}}{bd^2} \tag{2}$$

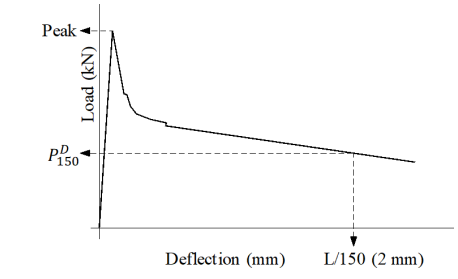
where $f^D_{e,\,150}$ represents equivalent flexural strength (MPa), T^D_{150} the area under load-deflection curve from 0 to L/150, b the width of the specimen (mm), and d the depth of the specimen (mm).

Further,

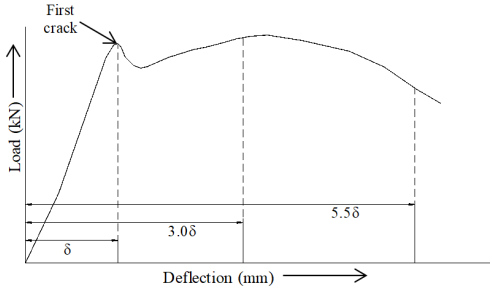
$$R^D_{T,150} = \frac{f^D_{e,150}}{f_1} \times 100\% \tag{3}$$

where $R^D_{T,\,150}$ represents the equivalent flexural strength ratio, $f^D_{e,\,150}$ the equivalent flexural strength (MPa), and f_1 the first peak strength (MPa).

Two more flexural toughness indices *I5* and *I10* are calculated according to ASTM C1018 [27]. For calculation of index *I5*, we calculate the area between 0δ to 3δ (3.0 times the first crack deflection)



(A)



(B)

Fig. 2. Load-deflection curves for flexural toughness indices **(A)** as per ASTM C1609, **(B)** as per ASTM C1018

of the load-deflection curve, and divide this area by the area up to the first crack (δ), as shown in Figure 2B. For calculation of index *I10*, we calculate the area between 0δ and 5.5δ (5.5 times the first crack deflection) of the load-deflection curve, and divide this area by the area up to the first crack (δ). Load-deflection data were automatically calculated by the machine.

4. Results and discussions

4.1. Slump

To evaluate the fresh state behavior of concrete, slump tests were performed according to ASTM C143 [23]. Slump test results for all mixes are represented in Figure 3. The slump of all concretes was between 25 mm and 65 mm. For a steel fiber volumetric content of 0.1%, by increasing the value of tire rubber fiber percentage, the slump decreases by 23%, 30.8%, and 38.5% than control concrete for 1%, 2%, and 3% rubber fiber content, respectively. This decrease is further pronounced for tire rubber and steel fiber concrete mixes when steel fiber volumetric content is increased to 0.2%. The slump values for 0.2% steel fibers are decreased by 30.8%, 53.8%, and 61.5% than control concrete for 1%, 2%, and 3% tire rubber fiber content, respectively. In general, with the addition of tire rubber fibers, percentage slump value decreases. Also, this decrease in workability was more pronounced when steel fibers were added. The reason of this decrease is the increased friction between the fibers and other constituents of the concrete mix, resulting in the mobility barrier of concrete. The decrease in workability is in line with past studies, showing that fibers reduced the workability when their volume fraction (V_f) is increased [28, 29].

4.2. Compressive strength

The compressive strength results of all mixes are presented in Figure 4. For a steel fiber volumetric content of 0.1%, by increasing the value of tire rubber fiber content, compressive strength was decreased by 8.1%, 10.3%, and 12.9% than control concrete for 1%, 2%, and 3% tire rubber fiber content, respectively. Similarly, for a steel fiber volumetric content of 0.2%, by increasing the value of tire rubber fiber content, compressive strength was decreased by 2.4%, 5.3%, and 11% than control concrete for 1%, 2%, and 3% tire rubber fiber content, respectively. Compressive strength for all the mixes was reduced by increasing the tire rubber fiber content.

Comparing the concrete mixes with same tire rubber fibers content, an increase in compressive strength was observed with the increase in steel fiber content. For rubber fiber volumetric content of 1%, 2%, and 3%, by increasing the value of steel fiber content from 0.1% to 0.2%, compressive strength was increased by 6.2%, 5.6%, and 2.2%, respectively. This shows the positive effect of steel fibers on strength and stiffness of concrete mixes with tire rubber fibers. In general, with the addition of tire rubber fiber content, compressive strength values were decreased. However, when steel fiber percentage was increased, compressive strength values showed an improvement. The loss

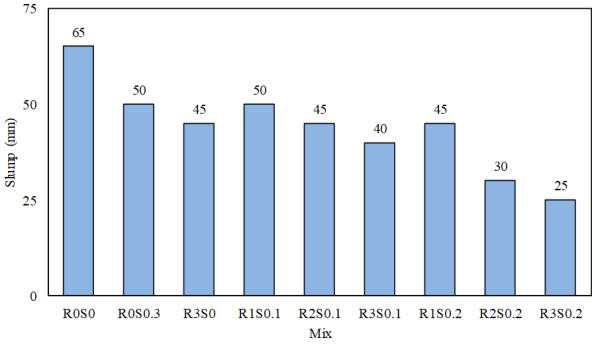


Fig. 3. Slump test results

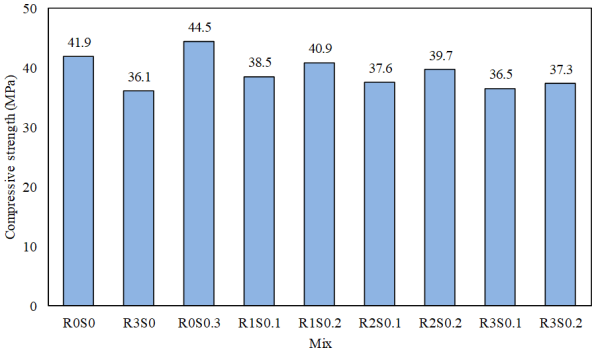


Fig. 4. Compressive strength results

in the compressive strength pursuant to an increase in the percentage of tire rubber fibers is due to the deformability of rubber fibers and a weak interfacial bond between rubber fibers and surrounding concrete. On other hand, when steel fiber was incorporated into the concrete that contained rubber fiber content, it exhibited an increased compressive strength, which is due to the bridging action of the former fiber.Similar results of increased compressive strength pursuant to the addition of steel fibers to rubberized concrete have been reported in the literature [30].

4.3. Split cylinder strength

The split tensile strength of all mixes is represented in Figure 5. Concrete mix R3S0, in which 3% tire rubber fibers were added, showed 4.2% less split cylinder strength than control concrete. However, concrete mix R0S0.3, in which only 0.3% steel fibers were added, showed a 5.6% increase in split cylinder strength in comparison with control concrete. It was observed that split tensile strengths of mixes R2S0.1 and R3S0.1 are decreased in comparison with mix R1S0.1 by 7.7% and 11.5%, respectively. Also, split tensile strengths of mixes R2S0.2 and R3S0.2 are decreased in comparison with mix R1S0.2 by 3.7% and 11.1%, respectively. In coupled tire rubber and steel fiber concrete mixes, for a given steel fiber content, split tensile strength decreased corresponding to an increase in the tire rubber fiber content.

For tire rubber fiber volumetric content of 1%, 2%, and 3%, by increasing the value of steel fiber percentage from 0.1% to 0.2%, split tensile strengths were increased by 3.8%, 8.3%, and 4.3%, respectively. Hybrid fiber concrete mix R1S0.2 showed a relatively better performance with respect to split tensile strength among coupled tire rubber and steel fiber concrete mixes. In general, with an increase in the tire rubber fiber percentage, split tensile strength values were decreased. However, when steel fiber percentage was increased, split tensile strength values were improved. The reduction in the split tensile strength corresponding to an increase in the percentage of tire rubber fibers is due to lower stiffness and a weak interfacial bond between rubber fibers and surrounding concrete. Using steel fibers has a positive effect on the splitting tensile strength. Concrete is a brittle material and cannot withstand tensile force, and the initiation of cracks within concrete is still controlled by the quality of the cement matrix. However, after crack initiation, the fiber bridging effect played an important role in controlling the crack growth. Therefore, steel fibers improved the splitting tensile strength and controlled crack propagation effectively. The results obtained in the present research, indicating an increase in tensile strength in rubberized concrete resultant to the addition of steel fibers, are in line with the findings reported in the literature, which showed that the tensile strength reduced pursuant to increasing the content of rubber in concrete and increased for each dosage when steel fibers are introduced in the concrete [31, 32].

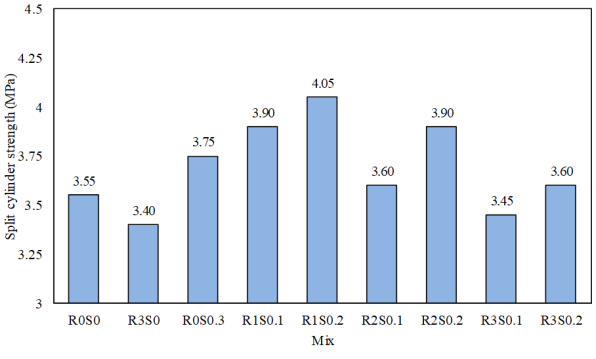


Fig. 5. Split cylinder strength

4.4. MOR and flexural toughness

4.4.1. Load-deflection response

Load-deflection diagrams under flexural loading for all concrete mixes are shown in Figure 6. Controlled samples (R0S0) and concrete samples containing 3% tire rubber fibers only (R3S0) showed brittle behavior, whereas all other concrete samples showed significant post-peak behavior. It was also observed that for a given amount of tire rubber fibers, peak load was increased when steel fiber content was increased from 0.1% to 0.2%. This increase in peak load is contributed by the steel fiber bridging effect.

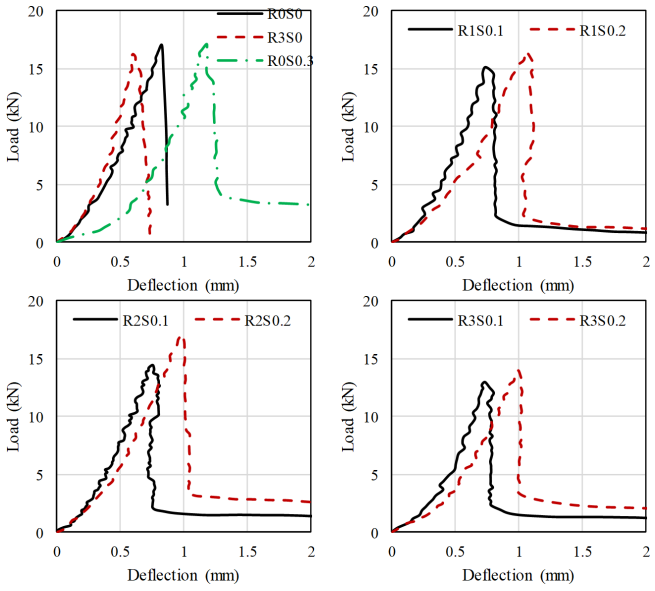


Fig. 6. Load-deflection curves **(A)** Control and mono fibers; **(B)** 1% rubber, 0.1% and 0.2% steel fibers; **(C)** 2% rubber, 0.1% and 0.2% steel fibers; **(D)** 3% rubber, 0.1% and 0.2% steel fibers

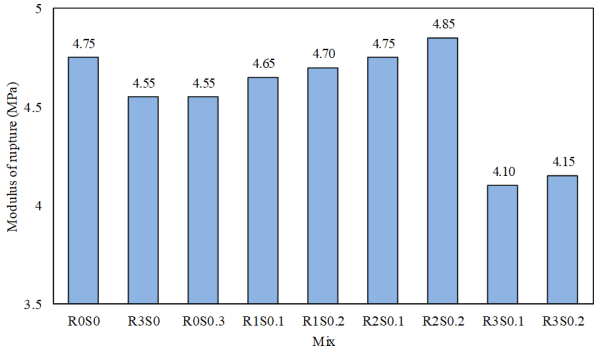


Fig. 7. MOR results. MOR, modulus of rupture

4.4.2. Flexural strength

The results of flexural strength (MOR) for all concretes are shown in Figure 7. For tire rubber fiber volumetric content of 1%, 2%, and 3%, by increasing the value of steel fiber percentage from 0.1% to 0.2%, flexural strengths were increased by 1.1%, 2.1%, and 1.2%, respectively. Hybrid fiber concrete mix R2S0.2 showed a relatively better performance with respect to flexural strength among coupled tire rubber and steel fiber concrete mixes. The increase in flexural strength could be explained by the fiber bridging effect of steel fibers. In the beginning, the load varies linearly with the deflection until the first crack appears; and then, the pattern of its subsequent variation becomes delinked from the course of deflection, and the cause of this estrangement is the decrease in the stiffness of concrete. Now the plain concrete cannot take any more load and after a short adjustment, the fibers' bridging action works as reinforcement to take the flexural tensile stress, and specimens continue taking the load without brittle failure.

4.4.3. Flexural toughness

The flexural toughness (T^D_{150}) of all the concrete mixes is calculated according to ASTM C1609 [26] and results are presented in Figure 8. It is observed that flexural toughness of control concrete (R0S0) and concrete mix containing only 3% tire rubber fibers (R3S0) are similar as they showed brittle failure. Concrete mix R2S0.1 showed the maximum flexural toughness increase of 84.2% than control concrete. Concrete mixes with the higher tire rubber fiber content of 3% showed lesser toughness due to the increased amount of rubber fibers.

Equivalent residual strength (f^D_{150}) and equivalent flexural strength ratio ($R^D_{T,\,150}$) of all the concrete mixes was also calculated according to ASTM C1609 [26] using Eqs (2) and (3), respectively, and the results are shown in Figures 9

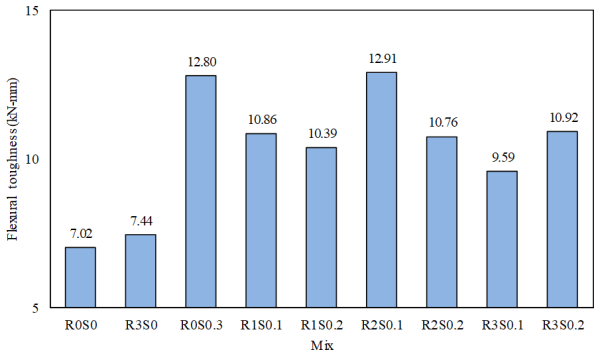


Fig. 8. Flexural toughness results (T^D_{150})

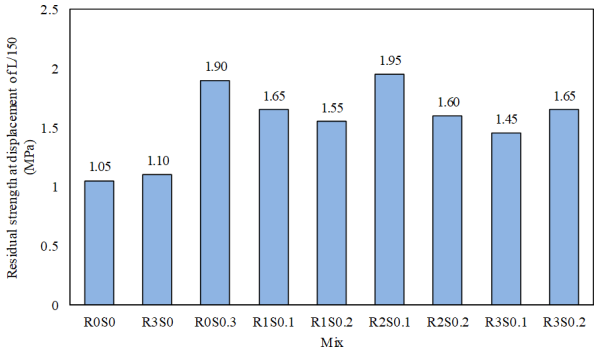


Fig. 9. Residual strength (f^D_{150})

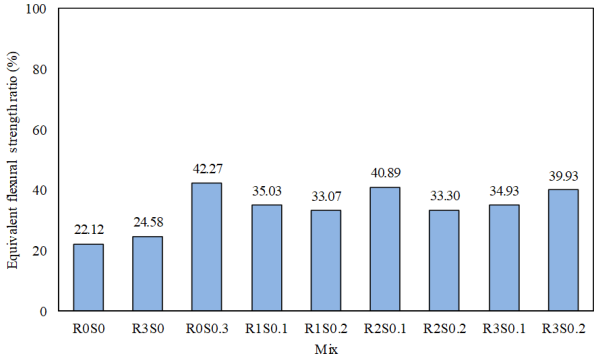


Fig. 10. Equivalent flexural strength ratio $R^D_{T,\,150}$

and 10. For coupled rubber and steel fiber concrete specimens, both indices increased for 0.1% steel fiber addition up to 2% tire rubber fiber addition. For concrete mixes with a high content of tire rubber fibers, both toughness indices were decreased. A similar trend was observed for 0.2% steel fiber content.

Toughness indices *I5* and *I10* are calculated according to ASTM C1018 [27]. The toughness index

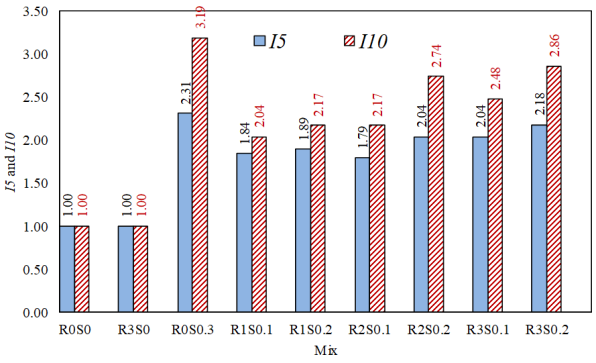


Fig. 11. Results of the I5 and I10 toughness indices

Table 4. Toughness indices *I5* and *I10*

Mix	*I5*	*I10*	*I10/I5*
R0S0	1.00	1.00	1.00
R3S0	1.00	1.00	1.00
R0S0.3	2.31	3.19	1.38
R1S0.1	1.84	2.04	1.11
R1S0.2	1.89	2.17	1.15
R2S0.1	1.79	2.17	1.21
R2S0.2	2.04	2.74	1.34
R3S0.1	2.04	2.48	1.22
R3S0.2	2.18	2.86	1.31

for concrete mixes R0S0 and R3S0 are equal to 1 because their beam specimens failed immediately after the first crack. Toughness indices *I5* and *I10* are tabulated in Table 4 and graphically presented in Figure 11. For a given tire rubber fiber content, index *I5* is increased when steel fiber content is increased from 0.1% to 0.2%. A similar trend was observed for toughness index *I10*. The ratio of *I10/I5* is also calculated, and is given in Table 4. It is a good indicator of the plastic behavior of a concrete specimen. The value of *I10/I5* being equal to 2 indicates perfect plastic behavior for a specimen [33]. None of the mixes showed perfect plastic behavior. Hybrid fiber concrete mix R2S0.2 showed a relatively better performance with respect to flexural toughness indices among coupled tire rubber and steel fibers concrete mixes. The toughness indices for fiber concretes vary greatly depending on the position of the crack, the type of fiber, the aspect ratio, the volume fraction of the fiber, and the distribution of fibers.

5. Conclusions

In this study, the workability and mechanical performance of hybrid rubber and steel reinforced concrete was assessed. For this purpose, nine concrete mixes were prepared. Tire rubber fibers were used at three volume fractions (1%, 2%, and 3%) and steel fibers were also added to the concrete mixes at three volume contents (0.1%, 0.2%, and 0.3%). Subsequently, the slump, compressive strength, splitting tensile strength, and flexural strength of specimens were measured. According to the experimental results, the following conclusions could be drawn:

- Workability was reduced for all hybrid tire rubber and steel fiber-reinforced mixes in comparison with the control mix due to the heightened friction offered by the increased fiber content.
- The compressive strength is improved by the addition of steel fibers as compared to concrete containing only tire rubber fibers. Furthermore, increase in tire rubber fiber content resulted in reduced compressive strength owing to the poor bond between tire rubber fibers and surrounding concrete.
- The split cylinder strength and MOR for concrete mix with 2% tire rubber fibers and 0.2% steel fibers are enhanced by 9.8% and 2.1%, respectively, than control concrete. This increase in due to the bridging action of steel fibers.
- Flexural toughness indices exhibited better results for hybrid mix with 2% tire fibers and 0.1% steel fibers primarily due to the crack-bridging action of steel fibers. However, the increased tire rubber fiber content resulted in reduced flexural toughness indices mainly due to lower stiffness and the poor bond between tire rubber fibers and surrounding concrete.

Addition of steel fibers has improved the strength and stiffness of concrete mixes as compared to the concrete to which only tire rubber fibers have been added. Hence, based on the results of this study, it could be recommended that waste tire rubber fibers could be used in concrete up to 2% with the addition of steel fibers up to 0.2%. Further, the utilization of waste tires in concrete will reduce the burden on the environment.

References

[1] Yu Y, Zhu H. Influence of rubber size on properties of crumb rubber mortars. Materials (Basel). 2016; 9(7):527. https://doi.org/10.3390/ma9070527

[2] Behbahani H, Nematollahi B. Steel fiber reinforced concrete: a review International Conference on Structural Engineering, Construction and Management, Kandy, Srilanka, 2011.

[3] Lawyer JS, Zampini D, Shah SP. Microfiber and macrofiber hybrid fiber-reinforced concrete. J Mater Civ Eng. 2005;17(5):595–604. https://doi.org/10.1061/(asce)0899-1561(2005)17:5(595)

[4] Thomas BS, Gupta RC, Panicker VJ. Recycling of waste tire rubber as aggregate in concrete: durability-related performance. J Clean Prod. 2016; 112:504–13. https://doi.org/10.1016/j.jclepro.2015.08.046

[5] Baricevic A, Bjegovic D, Skazlic M. Hybrid fiber–reinforced concrete with unsorted recycled-tire steel fibers. J Mater Civ Eng. 2017; 29(6):06017005. https://doi.org/10.1061/(asce)mt.1943-5533.0001906

[6] Bakar BA, Noaman AT, Akil HM. Cumulative effect of crumb rubber and steel fiber on the flexural toughness of concrete. Eng Technol Appl Sci Res. 2017; 7:1345–52. https://doi.org/10.48084/etasr.854

[7] Youssf O, ElGawady MA, Mills JE. Experimental investigation of crumb rubber concrete columns under seismic loading. Eng Struct. 2015;79; https://doi.org/10.1016/j.istruc.2015.02.005

[8] Abaza OA, Hussein ZS. Flexural behavior of steel fiber-reinforced rubberized concrete. J Mater Civ Eng. 2016;28(1):04015076. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001334

[9] Liu H, Wang X, Jiao Y, Sha T. Experimental investigation of the mechanical and durability properties of crumb rubber concrete. Materials. 2016; 9(3):172. https://doi.org/10.3390/ma9030172

[10] Liu R, Lui Y. Steel fiber reinforced concrete and its application performance. Int J Multidiscip Res Dev. 2016;3(6):341–3.

[11] Akcay B, Tasdemir MA. Mechanical behaviour and fibre dispersion of hybrid steel fibre reinforced self-compacting concrete. Constr Build Mater. 2012;28(1):287–93. https://doi.org/10.1016/j.conbuildmat.2011.08.044

[12] Raffoul S, Garcia R, Pilakoutas K, Guadagnini M, Medina NF. Optimisation of rubberised concrete with high rubber content: an experimental investigation. Constr Build Mater. 2016;124:391–404. https://doi.org/10.1016/j.conbuildmat.2016.07.054

[13] Thomas BS, Gupta RC, Panicker VJ. Experimental and modelling studies on high strength concrete containing waste tire rubber. Sustain Cities Soc. 2015;19:68–73. https://doi.org/10.1016/j.scs.2015.07.013

[14] Bakar BHA, Noaman AT, Akil HM. Cumulative effect of crumb rubber and steel fiber on the flexural toughness of concrete. Eng Technol Appl Sci Res. 2017;7(1):1345–52.

[15] Noaman AT, Bakar BHA, Akil HM. Experimental investigation on compression toughness of rubberized steel fibre concrete. Constr Build Mater. 2016;115:163–70. https://doi.org/10.1016/j.conbuildmat.2016.04.022

[16] Nitin. Analysis and testing of waste tire fiber modified concrete. Int J Sci Res. 2017;6(2):96–101.

[17] Khatib ZK, Bayomy FM. Rubberized portland cement concrete. J Mater Civ Eng. 1999;11(3):206–13. https://doi.org/10.1061/(ASCE)0899-1561(1999)11:3(206)

[18] Eldin NN, Senouci AB. Rubber-tire particles as concrete aggregate. J Mater Civ Eng. 1993;5(4):478–96. https://doi.org/10.1061/(ASCE)0899-1561(1993)5:4(478)

[19] Topçu IB. The properties of rubberized concretes. Cem Concr Res. 1995;25(2):304–10. https://doi.org/10.1016/0008-8846(95)00014-3

[20] Li G, Garrick G, Eggers J, Abadie C, Stubblefield MA, Pang SS. Waste tire fiber modified concrete. Compos Part B Eng. 2004;35(4):305–12. https://doi.org/10.1016/j.compositesb.2004.01.002

[21] Bijarimi M, Zulkafli H, Beg MD. Mechanical properties of industrial tyre rubber compounds. J Appl Sci. 2010;10:1345–8. https://doi.org/10.3923/jas.2010.1345.1348

[22] ACI Committee 211. Recommended practice for selecting proportions for normal and heavyweight concrete. Detroit: The Institute; 1977., 1991.

[23] ASTM Committee 143. Standard test method for slump of hydraulic-cement concrete. West Conshohocken, PA: ASTM International; 2015.

[24] ASTM Committee 39. Standard test method for compressive strength of cylindrical concrete specimens.West Conshohocken, PA: ASTM International; 2021.

[25] ACI Committee 496. Standard test method for splitting tensile strength of cylindrical concrete specimens. West Conshohocken, PA: ASTM International; 2017.

[26] ACI Committee 1609. Standard test method for flexural performance of fiber-reinforced concrete (using beam with third-point loading). West Conshohocken, PA: ASTM International; 2019.

[27] ACI Committee 1018. Standard test method for flexural toughness and first crack strength of fiber-reinforced concrete (using beam with third-point loading). West Conshohocken, PA: ASTM International; 1997.

[28] Yazıcı S, İnan G, Tabak V. Effect of aspect ratio and volume fraction of steel fiber on the mechanical properties of SFRC. Constr Build Mater. 2007;21(6):1250–3. https://doi.org/10.1016/j.conbuildmat.2006.05.025

[29] Iqbal S, Ali I, Room S, Khan SA, Ali A. Enhanced mechanical properties of fiber reinforced concrete using closed steel fibers. Mater Struct. 2019;52(3):56. https://doi.org/10.1617/s11527-019-1357-6

[30] Topçu IB, Canbaz M. Effect of different fibers on the mechanical properties of concrete containing fly ash. Constr Build Mater. 2007;21(7):1486–91. https://doi.org/10.1016/j.conbuildmat.2006.06.026

[31] Noaman AT, Bakar BHA, Akil HM, Alani AH. Fracture characteristics of plain and steel fibre reinforced rubberized concrete. Constr Build. Mater. 2017;152:414–23. https://doi.org/10.1016/j.conbuildmat.2017.06.127

[32] Fu C, Ye H, Wang K, Zhu K, He C. Evolution of mechanical properties of steel fiber-reinforced rubberized concrete (FR-RC). Compos Part B Eng. 2019;160:158–66. https://doi.org/10.1016/j.compositesb.2018.10.045

[33] Ramakrishnan V, Wu GY, Hosalli G. Flexural behavior and toughness of fiber reinforced concretes. Transp Res Rec. 1989;1226:69–77.

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