EASR

Engineering and Applied Science Research

https://www.tci-thaijo.org/index.php/easr/index

Published by the Faculty of Engineering, Khon Kaen University, Thailand

# Flexural performance of reinforced concrete beams used shredded scrap tire rubber and steel fibers

Wadhah M. Tawfeeq*[1)], Taghreed Khaleefa Mohammed Ali[2)], Ahmed W. Al Zand[3)], Malik Al-Ajmi[1)], Maha Al-Shaidi[1)], George Jerinmon[1)] and Fatema Al Saidi[1)]

[1)]Civil Engineering Program, Faculty of Engineering, Sohar University, Sohar, Oman
[2)]Department of Architecture, Faculty of Engineering, Koya University, Koya, Kurdistan, Iraq
[3)]Department of Design, College of Fine Arts, Al-Turath University, Baghdad, Iraq

Received 7 January 2025
Revised 14 July 2025
Accepted 5 August 2025

**Abstract**

This research experimentally investigates the flexural performance of fibrous reinforced concrete beams containing shredded scrap tire rubber (SSTR) as a substitute for gravel. Six reinforced concrete (RC) beams (1500 × 300 × 200 mm) were prepared with varying steel fibers (SF) (0%, 0.5%, 1%, and 1.5%) and SSTR (0%, 5%, 7.5%, and 10%) by volume of concrete. All samples were tested as simply supported beams under 3-point static loads. The RC beam with natural materials (0% SSTR and 0% SF) exhibited a typical crack propagation pattern, while the addition of 1% SF and 5% SSTR caused cracks to cease, resulting in ductile behavior. The optimal percentages were found to be 1% SF and 5% SSTR. The presence of SSTR reduced the compressive strength due to the impermeability of rubber, which helps absorb load energy, though SF additions improved this. Compressive strength reductions for 5%, 7.5%, and 10% SSTR were 15.37%, 11.64%, and 18.08%, respectively, compared to the control mix. However, the compressive strength of concrete containing 1% SF and 5% SSTR increased slightly by about 2.52%. Flexural strength of concrete prisms also decreased with higher SSTR content and varied SF dosages. Compared to the control mix, reductions in flexural strength for 0.5% SF with 5%, 7.5%, and 10% SSTR were 14.29%, 19.05%, and 19.05%, respectively. These reductions are due to the poor bond between SSTR and the cement matrix. The flexural performance of the reinforced concrete beam improved slightly by 1.71% for the B5 beam, which was made with 5% SSTR and 1% SF, accompanied by a slight increase in deflection (2.24%) and beam weight. The design ultimate loads from BS8110 were lower than the experimental values, with ratios of tested failure load to design ultimate load ranging from 1.99 to 2.78, the maximum ratio achieved by the B5 beam.

**Keywords:** Tire waste, Compression strength, Beam, Displacement, Fiber

## 1. Introduction

The amount of tire rubber waste is growing rapidly, especially in developing countries like Oman, where the number of vehicles is skyrocketing. The number of scrap tires increases every year due to factors such as road safety regulations, hot weather, long-distance travel, and the availability of agencies that sell new or re-used tires with an average lifespan of two to three years. Urbanization is expected to increase Oman's production of end-of-life tires to approximately 45,000 tons annually. In Oman, millions of tires are currently stored in two major dump sites, including one in Dhofar Governorate. A tire dump poses a safety hazard because it can ignite, endanger groundwater, and potentially pollute the environment if not properly handled [1]. Among waste tires, only a small percentage is recycled, while the majority is disposed of in landfills, stockpiled, or buried. There is a major problem with this accumulation of non-biodegradable tire waste. Even though most tire rubber waste is used as fuel in industries like thermal power plants, cement kilns, and brick kilns, this practice is environmentally unfriendly and costly. To protect the environment, tire rubber waste has been used in concrete production.

Many researchers studied the effect of the usage of tire waste (TW) in the production of concrete structures. They used TW as coarse and fine aggregates, fillers, and binders in concrete production [2, 3]. Treated TW was used as a replacement for sand in different ratios in concrete mixes [4, 5]. There was an improvement in mechanical properties and deformations [4, 5]. Using TW as sand, or gravel, or sand and gravel together in concrete production led to reduced density, mechanical properties, and a considerable decrease in thermal conductivity [6]; besides that, there were substantial variations in concrete's properties after being exposed to 400 ºC [6]. Different particle sizes of untreated TW that ranged from 2-38 mm were used by Eldin and Senouci [7] as coarse aggregates or fine aggregates in concrete mixes through four ratios (25, 50, 75, and 100) %. They indicated that workability, density, and strength were reduced by increasing the ratio and particle size of TW, and the usage of TW as fine aggregates led to higher concrete strength compared with its use as coarse aggregates. The aggregate of TW could delay the formation and growth of cracks in the micro size of concrete,

*Corresponding author.
Email address: WTawfeeq@su.edu.om
doi: 10.14456/easr.2025.53

and the impact resistance improved by using 50% TW [8]. Concrete's entire deformation was augmented by increasing TW's ratio, and its extreme loading ability was reduced [8]. Two particle sizes of TW 3.35 mm and 0.688 mm were used in the production of lightweight concrete boards [9]. The size of TW particles had a significant effect on the drying shrinkage and absorption ratio of lightweight concrete boards, and its compressive strength was reduced in the case of using two sizes of TW particles [9]. TW was used as aggregates and as cement replacements in concrete specimens [10]. The 5% ratio of TW as aggregate or cement led to a slight decrease in compressive strength without noticeable changes in other properties [10]. Water absorption and abrasion resistance (up to 10% substitution of TW) were better than the normal mix [11]. The water permeability was increased, whereas the modulus of elasticity, flexural strength, and tensile strength were reduced with an increased ratio of TW [10].

A 10 % and 20 % of TW as substitution of sand and hooked steel fibers of two lengths (65 and 35) mm in two volumetric ratios (0.5 and 1) % were used to improve the concrete blocks' properties [12]. Adding steel fiber led to a slight upsurge in absorption and density. Also, there was a significant improvement in toughness, abrasion resistance, and flexural strength by increasing the ratio of steel fiber. In contrast, the steel fiber did not affect the slip resistance [12]. 2% of dual hooked steel fiber of 60 mm length and an aspect ratio of 80 was utilized in concrete production that contained four ratios of TW (10, 20, 30, and 40) as gravel in a mix ratio of 1-1.55-2.53 [13]. There was an improvement in strength via the use of steel fiber, and 10% TW led to a 13%, 18%, and 27% increase in flexural, splitting tensile, and compressive strengths, respectively [13]. The use of less than 10% of TW as sand and 0.75% hooked steel fiber of length 30 mm and aspect ratio 60 in concrete production can lead to sufficient strengths and good impact abrasion resistance [14]. The ratio of 3% of tire rubber as coarse aggregate in the production of concrete of grade M20 could develop slightly higher compressive strength compared with the reference mix without tire rubber [15]. The rubberized concrete that contained TW as coarse aggregates in three ratios (5, 10, and 15) % had lower unit weight and a reduction in workability [16]. Also, there was a reduction in the compressive strength of rubberized concrete, which restricts its structural applications, but it preserves some desirable characteristics [17]. The ratio of TW up to 8% as fine aggregate in concrete production could be used without a considerable reduction in strength [17].

The rubberized concrete that contained 30% of TW as coarse aggregate had a reduction in unit weight up to 24% [18]. There was an increase in the workability of rubberized concrete due to an increase in the content of TW [18]. The density of concrete decreased in the range of (14-28) % when the sand was substituted by TW in the range of 10-30% [19]. The compressive strength of non-reinforced concrete decreased in ratios (30-63) % by using TW as fine aggregate in ratios (5-20) % [20]. 12.5% of TW as sand in concrete could be the best ratio to get good resistance to carbonation and absorption of water with suitable compressive strength [21]. Utilizing TW in concrete can be useful in getting regular and non-difficult dilation when the load is applied [22]. The 5% of TW as sand in the production of cement mortar led to a change in the failure mode into ductility failure and more resistance to deformation [23]. The 10 % of TW as an aggregate in concrete production led to an increase in the entire creep strain by 61.04%, 78.44%, 81.07%, and 43.94% at ages 7, 30, 90, and 365 days, respectively, compared with the normal concrete without TW [24]. The 1% of steel fiber (SF), 100% of recycled gravel as gravel, and four ratios of TW (4, 8, 12, and 16) % as fine aggregate were used in concrete production [25]. There was less stiffness and strength with more ductility by using SF, TW, and recycled gravel compared with normal concrete [25]. The 0.5% of SF and three ratios of TW (5, 10, and 15) % as fine aggregate were used in concrete production [26]. There was an improvement in the strain capacity and the ductility via the use of TW, and an enhancement in stress by using SF when compared with reinforced concrete [26].

Through the references, the results manifested by the researchers disclosed that the type and ratio of fiber have affected the strength of concrete [27]. The addition of steel fiber into the concrete mix improves the mechanical properties, durability, ductility, stiffness, and serviceability of the structure while decreasing the workability of concrete. Incorporating shredded scrap Tires into the concrete mix decreases the compressive strength, split tensile, and flexural strength. Hence, consider using scrap tire rubber in concrete preparation as an alternative to disposing of this waste to preserve the environment. The speculation of using steel fiber and shredded scrap tire rubber in sync with concrete, with the intuition of getting rid of shortcomings of the use of scrap Tire rubber by using Steel fiber in the concrete mix, is executed in this research.

Also, from previous studies, there is an improvement in the properties of concrete that contains TW and SF together. The beams cast with rubberized concrete containing up to 20% and 80% crumb rubber in their bottom and middle layers could attain about 94.3 to 99% of the load for beams made with plain concrete. This small reduction encouraged the use of crumb rubber in concrete to reduce its harmful environmental effects and save natural sand [28]. With the addition of 1% steel fiber with 35 mm length, the safe content of crumb rubber increased to 35%, resulting in concrete beams with greater flexural capacity, ductility, and toughness for multiple structural applications [29]. Also, there was an improvement in flexural capacity, ductility, and toughness of reinforced concrete beams containing 30% recycled coarse aggregate, 5% crumb rubber, and 0.5% polypropylene fiber [30]. By combining rubber with steel fiber, the residual phase can be greatly reduced [31]. Using recycled tires and fibers in concrete can contribute to sustainable construction and circular economies [32]. Use of eco-friendly building materials and/or recycling technologies has become a trend in the construction industry [33]. Utilizing SSTR in concrete production contributes to lowering the embodied carbon of construction materials. Replacing a portion of natural aggregates with rubber particles reduces the demand for virgin materials, thereby decreasing the carbon footprint associated with extraction and processing. Moreover, diverting tires from incineration prevents the release of harmful emissions. For example, preventing the burning of one ton of waste tires can save the environment from releasing 450 kg of toxic gases and 270 kg of soot [34].

Oman's commitment to a circular economy is evident through initiatives that repurpose waste materials. For instance, Oman Cement Company has partnered with the Oman Environmental Services Holding Company (be'ah) to utilize tire-derived fuel (TDF) in cement production. This collaboration not only provides an alternative energy source but also supports waste reduction goals. Be'ah aims to achieve 60% waste utilization by 2025 and 80% by 2030, reflecting the nation's strategic direction towards sustainable resource management [35].

There is a growing hobby in making use of scrap tires and steel fibers in construction. Numerous studies have shown that incorporating shredded tire rubber and steel fibers in concrete can enhance overall performance, specifically in earthquake-prone regions and packages exposed to dynamic forces like railway sleepers. Rubber waste additionally gives the ability in non-load-bearing packages such as noise barriers. Research findings suggest that concrete overall performance depends heavily on the properties of waste aggregates and fibers, influencing compressive energy. This study aims to investigate how one-of-a-kind quantities of steel fibers and shredded scrap tires can enhance can improve the fresh and hardened properties of reinforced concrete beams and their structural behavior.

Therefore, in this study, the TW and SF are used in concrete production, where, TW is used as a coarse aggregate in ratios (5%, 7.5%, and 10%) to reduce the use of natural resources and save the environment from dumping piles of TW in landfills, and SF is added in volumetric ratios (0.5%, 1%, and 1.5%) to the concrete to improve its properties. This study is being conducted to examine the effects of adding different amounts of steel fiber with different amounts of shredded scrap tires to reinforced concrete beams to improve fresh and hardened concrete performance. To better understand the behavior of reinforced concrete beams with SSTR and SF, six reinforced concrete beams that used shredded scrap tire rubber and steel fibers were cast and tested. Besides that, their fresh and hardened properties were found.

## 2. Investigation works

### *2.1 Work strategy*

The research work is divided into two groups. In the first group, the coarse aggregate was replaced with shredded scrap tire rubber (SSTR) in volume ratios (5%, 7.5%, and 10%) with 0.5% SF in three concrete batches. In batches of the second group of batching, SF is added in volumetric ratios (0.5%, 1%, and 1.5%) along with a 5% replacement of coarse aggregate with SSTR.

### *2.2 Utilized materials*

#### *2.2.1 Fine aggregate*

In this study, an Omani crusher from the region of Sohar / Sallan provided the natural sand-fully washed. Fine aggregate grades are tested by BS 882:1992 [36]. Figure 1 shows the sieve analysis of fine aggregate, which was used in this study following BS EN 993-1:1997 [37]. The water absorption capacity of utilized sand is 2.04% according to BS 812-2:1995 [38] and BS EN 1097-3:1998 [39]. According to BS 882:1992[36], used sand has a clay percentage of under 3% with a rate of 2.005%.

#### *2.2.2 Coarse aggregate*

This study used aggregates crushed at a local crusher (Sallan region, Sohar, Oman). According to BS 882:1992, sieve analyses of coarse aggregate have been conducted [36]. A procedure presented in [37] is applied to determine the grade of used gravel as shown in Figure 2. Water absorption by gravel is experimentally determined to be 1.62% according to [37, 38].

#### *2.2.3 Cement*

Al-Fujairah-OPC Type (I) complies with BS EN 197-1:2000 [40] CEM-1 Class 42.5N (Ordinary Portland Cement Specification). The main chemical components and properties of Portland Cement are shown in Table 1.

#### *2.2.4 Steel Fiber (SF)*

Oman-made SF was used with the following specifications: straight in shape, length of 30 mm, and diameter of 1 mm (see Figure 3). Ultimate tensile strength is 370-500 MPa, yield tensile strength is 235 MPa, and the density is 7840 kg/m$^3$.

#### *2.2.5 Shredded Scrap Tire Rubber (SSTR)*

Disposed scrap tire rubber was shredded in the dimension of 20 mm × 20 mm which was manufactured locally in the concrete laboratory of Sohar University, as shown in Figure 4. Specific gravity and density were equal to 1.05 and 600 kg/m$^3$, respectively.

**Table 1** The main chemical components and properties of portland cement

| Chemical Components and Properties | Values |
|---|---|
| Lime (CaO) | 60 to 67% |
| Silica ($SiO_2$) | 17 to 25% |
| Alumina ($Al_2O_3$) | 3 to 8% |
| Iron oxide ($Fe_2O_3$) | 0.5 to 6% |
| Magnesia (MgO) | 0.1 to 4% |
| Sulphur trioxide ($SO_3$) | 1 to 3% |
| Soda and/or Potash ($Na_2O$+$K_2O$) | 0.5 to 1.3% |
| Specific Gravity | 3.12 |
| Normal Consistency | 29% |
| Initial Setting time | 65 min |
| Final Setting time | 275 min |
| Fineness | 330 kg/m$^2$ |
| Soundness | 2.5 mm |
| Bulk Density | 830-1650 kg/m$^3$ |

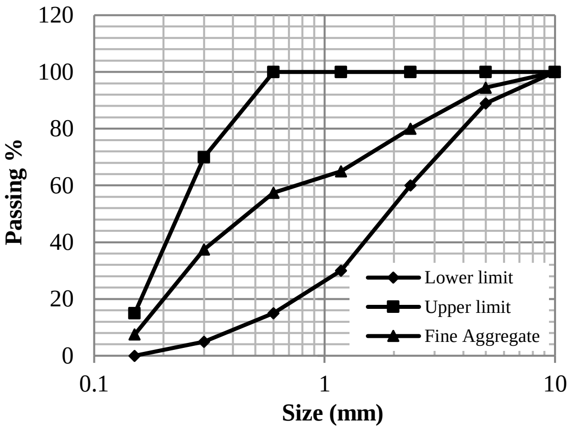



**Figure 1** Grading of fine aggregate

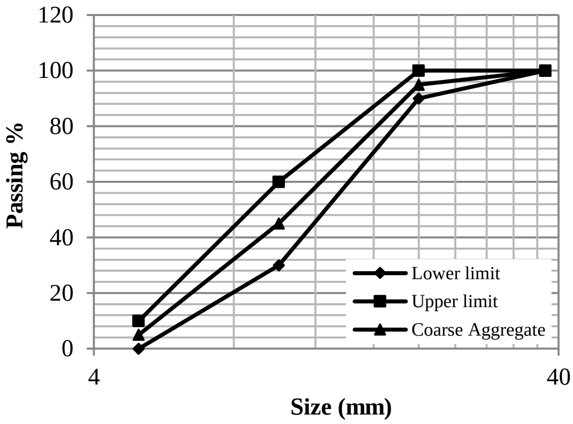



**Figure 2** Grading of coarse aggregate

**Figure 3** Steel fiber

**Figure 4** SSTR

*2.3 Concrete mixture*

Whenever SSTR is used instead of natural gravel with SF, adequate quantities of mortar fraction must be present in the concrete mix to adhere to the fibers and allow them to flow freely, and the cement content must be higher than in conventional mixes, where aggregate shapes and content are important. To replace coarse aggregates with SSTR and adding SF, it is typically possible to mix these proportions as follows: cement quantity is (325 - 560) kg/m$^3$; water-cement ratio is (0.4 - 0.6); the ratio of fine aggregate to total aggregate is (0.5 - 1.0); maximum coarse aggregate size is 20 mm; air content is (6 – 9) % [41]; fiber content is (0.5- 1.5) % by volume of concrete. Given that, the implemented mix ratio is 1:2.0575:2.24 with a water/cement ratio of 0.555. Where the quantity of cement is 400 kg/m$^3$ and the quantity of sand is 823 kg/m$^3$ for all trial mixes. During the stages of mixing and curing, drinking water was utilized. In all trial mixes, the amounts of gravel, SSTR, and SF are changeable as shown in Table 2. The pre-treatment of SSTR involves washing it with water and coating it with cement. SSTR is coated in a 1:1 ratio with grout during mixing as a coating layer for better bonding and mixing of other components of concrete. The cement coating formed a rigid shell around the rubber particles, effectively reducing voids and significantly enhancing the adhesion between the rubber and the cement matrix [42].

The bonding interface among shredded scrap tire rubber and the cementitious matrix plays a pivotal role in determining the mechanical integrity and sturdiness of rubberized concrete. Unlike traditional mineral aggregates, rubber particles are hydrophobic, bendy, and chemically inert, which inherently limits their ability to form a robust interfacial transition zone (ITZ) with the surrounding cement paste. At the microstructural level, rubber debris exhibits poor adhesion to the cementitious matrix due to its smooth, non-polar surfaces and absence of reactive purposeful corporations. These consequences occur in a susceptible ITZ characterized by better porosity and microcracking below load, which negatively influences load transfer and overall mechanical performance. The interface frequently acts as a stress concentrator, initiating early failure in compressive and tensile pressure regimes. Furthermore, the elastic mismatch between the stiff cement matrix and the deformable rubber particles contributes to localized debonding underneath mechanical masses. This debonding is exacerbated with the aid of the shrinkage of the cement paste throughout curing, which introduces additional interfacial strain. To beautify the bonding at this interface, several surface amendment strategies were explored. Treatments which include NaOH washing, silane coupling dealers, and cement paste pre-coating can roughen the rubber surface and introduce polar functional groups, thereby improving mechanical interlock and chemical affinity with the cement matrix. These remedies can appreciably enhance the ITZ density and reduce the porosity, mainly to achieve higher mechanical overall performance and durability [43, 44].

SSTR was replaced by volume and then converted to weight using the specific gravity of the material, as detailed in Table 2. To achieve uniform distribution, steel fibers (SF) were manually sprinkled into the mixing machine after all other concrete ingredients had been thoroughly blended. This method ensured the random orientation of the fibers within the concrete matrix. To facilitate easy removal of the concrete specimens and to prevent leakage or sticking, the internal surfaces of all molds, including those for three cubes, one prism, and one reinforced concrete beam, were coated with a thin layer of oil before casting for each trial mix. Six trial mixes with different replacement percentages for coarse aggregate with SSTR (0%, 5%, 7.5%, and 10%) and added SF (0%, 0.5%, and 1%) were used to cast the specimens in this study, Figure 5 shows the casting of specimens. Once casting was complete, the specimens were allowed to set for 24 ± ½ hours after water was added to the dry ingredients. After demolding, they were immediately submerged in a curing tank maintained at a temperature of 25 ± 5 °C. This curing process continued until the testing date, which was set at more than

28 days to ensure full hydration and proper strength development. For the reinforced concrete beams, additional curing was performed by covering them with wet sacks, maintaining consistent moisture levels. Before any test took place, all specimens were allowed to dry to ensure accurate testing conditions and reliable results.

**Table 2** Trial mixes proportions

| Beam Designation | Cement (kg/m$^3$) | Sand (kg/m$^3$) | Gravel (kg/m$^3$) | Water (kg/m$^3$) | SSTR (kg/m$^3$) | SF (kg/m$^3$) | Replacement (%) |
|---|---|---|---|---|---|---|---|
| B1 | 400 | 823 | 896 | 222 | 0 | 0 | 0% SF and 0% SSTR |
| B2 | 400 | 823 | 851.2 | 222 | 44.8 | 39.2 | 0.5% SF and 5% SSTR |
| B3 | 400 | 823 | 828.8 | 222 | 67.2 | 39.2 | 0.5% SF and 7.5% SSTR |
| B4 | 400 | 823 | 806.4 | 222 | 89.6 | 39.2 | 0.5% SF and 10% SSTR |
| B5 | 400 | 823 | 851.2 | 222 | 44.8 | 78.4 | 1% SF and 5% SSTR |
| B6 | 400 | 823 | 851.2 | 222 | 44.8 | 117.6 | 1.5% SF and 5% SSTR |

**Figure 5** Casting of Specimens

*2.4 Tests of concrete samples*

Whenever SSTR is used instead of natural gravel with SF, adequate quantities of mortar fraction must be present in the concrete mix.

*2.4.1 Slump test*

Concrete's workability was tested using a cone of 300 mm height, 200 mm base diameter, and 100 mm top diameter, according to BS EN 12350-2 [45]. Each trial mix had a slump value exceeding 100 mm.

*2.4.2 Compressive strength test*

BS EN 12390-3 [46] was followed for the measurement of concrete's compressive strength with a cube size of 150 × 150 × 150 mm. This study was conducted with an ADR-Auto 2000 compression machine with a 2000 kN capacity, and the load rate was 13.5 kN/sec. The recorded concrete compressive strength was averaged from three samples. In Figure 6(a), you can see the specimens inside the testing machine.

*2.4.3 Flexural strength test*

Based on BS EN 12390-5 [47], the flexural strength of a prism with dimensions of 500 mm length by 100 mm width by 100 mm depth was determined using three-point loading. With a load rate of 0.2 kN/sec, a flexural and transverse frame with a capacity of 100 kN was utilized. Figure 6(b) depicts a specimen within the testing apparatus.

(a) Concrete Cube (b) Concrete Prism

**Figure 6** The tested specimens

## 3. Design and test setup of concrete samples

The beam used in this study had a 1500 mm span. The cross-section size was 300 mm in height and 200 mm in width. To prevent concrete crushing, the design moment of the beam must be equal to or less than the design moment of the steel reinforcement [48].

$$A_s \leq \frac{0.156bd^2 f_{cu}}{0.95 f_y\, z} \tag{1}$$

Where the tension reinforcement's area is ($A_s$), the width of the beam is ($b$), the effective depth of the beam is ($d$), the concrete cube's compressive strength is ($f_{cu}$), the lever arm is (z), and the tension reinforcement's yield strength is ($f_y$). The reinforcement used was two steel reinforcement bars of diameter 12 mm having a 460 MPa yield strength, providing 226 mm$^2$ in the tension zone, which was greater than the minimum steel area of the section, which was 78 mm$^2$. Stirrups with a diameter of 10 mm were positioned with a spacing of 100 mm along the entire beam length to prevent any failure due to shear. Two steel reinforcement hanger deformed bars of diameter 10 mm, having a 460 MPa yield strength, were used to hold the stirrups in place. Figure 7 shows the details of the utilized beam.

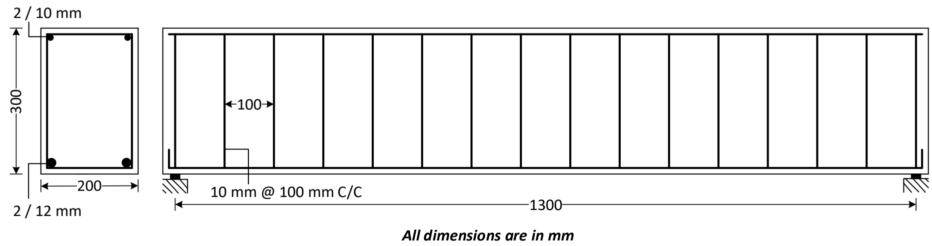



**Figure 7** The utilized beam

All the beams were simply supported during the testing process, and a single point load was applied at the mid-span from the top flange, as depicted in Figure 8. The load was applied by a Pakistani hydraulic pressing machine of 1500 kN, and a Turkish 600 kN load cell was used to take measurements. The load is applied to the beam through a 200 mm square plate. The load was recorded on a computer through the company's data logger and software for this issue. The vertical displacement at the middle of the beam's span was recorded straight from an electronic dial gauge fixed at the top flange of the samples. The experimental program and testing conditions are shown in Table 3.

**Table 3** Experimental program and testing conditions

| Trial Mix No | Beam Designation | RCC Beam Size Length (mm) | RCC Beam Size Width (mm) | RCC Beam Size Depth (mm) | SF % | SSTR % | No. of Cubes Cast 150×150×150 mm | No. of Prism Cast 100×100×500 mm | No. of RCC Beams Cast | Type of Beam | Span Between Supports (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | B1 | 1500 | 200 | 300 | 0 | 0 | 3 | 1 | 1 | SSB | 1300 |
| 2 | B2 | 1500 | 200 | 300 | 0.5 | 5 | 3 | 1 | 1 | SSB | 1300 |
| 3 | B3 | 1500 | 200 | 300 | 0.5 | 7.5 | 3 | 1 | 1 | SSB | 1300 |
| 4 | B4 | 1500 | 200 | 300 | 0.5 | 10 | 3 | 1 | 1 | SSB | 1300 |
| 5 | B5 | 1500 | 200 | 300 | 1 | 5 | 3 | 1 | 1 | SSB | 1300 |
| 6 | B6 | 1500 | 200 | 300 | 1.5 | 5 | 3 | 1 | 1 | SSB | 1300 |

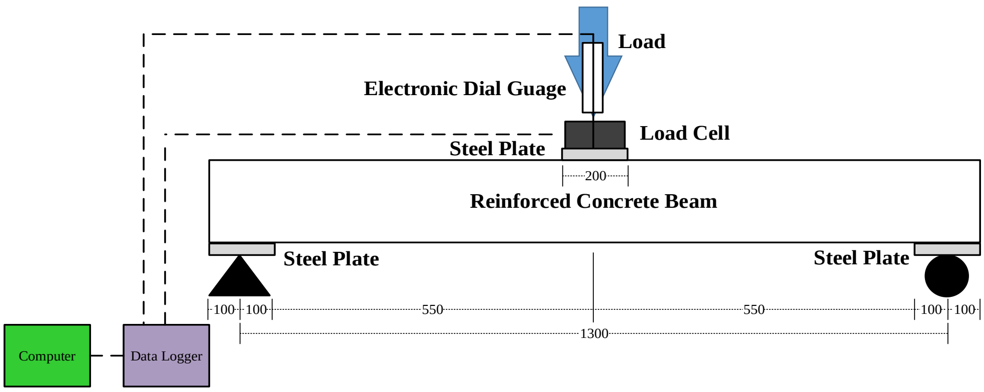



**Figure 8** The test setup of the beam

## 4. Results and discussion

### *4.1 The properties of concrete*

After 28 days, three cubes from each trial mix were measured for their average compressive strength. For each trial mix, three cubes were tested to determine the average compressive strength with a standard deviation of about 0.5. All tests were conducted following standardized procedures to ensure consistency and minimize variability. The results showed no significant differences among the three specimens. Table 4 displays the compressive strength values for every mix. A concrete mix containing 1% SF and 5% SSTR had a maximum compressive strength of 30.56 MPa, while a concrete mix with 0.5% SF and 10% SSTR had a maximum compressive strength of 24.42 MPa. The replacement effect of gravel by a small amount of SSTR has a small effect on the compressive strength of the concrete cube. Also, adding steel fiber to the concrete with SSTR will reduce this effect more, as shown in Table 4 and Figure 9. Variation of SF% from 0.5 to 1.5 with 5% SSTR gave compressive strength varied from 25.21 MPa to 30.56 MPa. Increasing the SF% increases the compressive strength of concrete, as shown in Figure 10. Concrete is more resistant to bending and cracking when it is reinforced with steel fibers. Using steel fibers prevents cracks from becoming large and potentially compromises the integrity of the structure by controlling their width and propagation. Coming within the same line, Shahjalal et al. [49] observed that compressive strength reduced as the proportion of crumb rubber inside the concrete blend improved. In evaluation, incorporating steel fibers advances compressive strength due to their bridging traits. The lowest compressive strength changed into recorded in mixes containing 30% recycled aggregate, 10% crumb rubber, and no fibers, reflecting the very best crumb rubber content. Conversely, the highest compressive strength turned into performed in mixes with 30% recycled aggregate, no crumb rubber, and 0.5% fiber, exceeding the manipulate pattern by 8.1% and 2.5% on 28 and 56 days, respectively.

Figures 9 and 10 show that adding steel fiber increases the weight of a concrete cube, as the density of steel is almost three times the density of concrete. The steel fibers are added at a certain volume to the concrete mix. This additional volume of steel adds to the total volume of the mixture, thereby increasing its overall weight. Also, to achieve the desired mechanical properties, steel fibers need to be evenly distributed throughout the concrete mixture. This means that the fibers are spread out over the entire volume of the concrete, contributing to the overall weight. Replacing coarse aggregate with SSTR reduces the weight of the concrete cube because the specific gravity of SSTR is almost less than half that of the specific gravity of aggregate, therefore, the variation in the weight of the sample is small. When SSTR is incorporated into the concrete mix, we are essentially introducing a lightweight material that displaces some of the heavier components, resulting in a reduction in overall density and weight. Using rubberized concrete can produce a lightweight concrete structure [50].

For the flexural strength of concrete, increasing the percentage of SSTR decreases the flexural strength because SSTR particles are not chemically compatible with the cement matrix in the same way that traditional aggregates are. Increasing the percentage of rubber in the mix can disrupt the bonding between the cement paste and the aggregate particles, resulting in reduced cohesion and overall strength, as shown in Figure 9. Adding steel fiber to the concrete trial mix increases flexural strength because SF acts as a form of reinforcement within the concrete matrix. When properly distributed throughout the mix, these fibers create a three-dimensional network that enhances the material's ability to resist tensile stresses, including those experienced during flexural loading. This reinforcement helps prevent cracking and enhances the overall strength of the concrete, as shown in Figure 10.

The reduction in flexural strength observed when increasing SF content from 1.0% to 1.5% at 5% SSTR may be attributed to several factors. At higher fiber volumes, the risk of poor dispersion and fiber agglomeration increases, leading to uneven stress distribution and the formation of weak zones within the matrix. Additionally, elevated fiber content can significantly reduce workability, making it more difficult to achieve proper compaction and homogeneous mixing. These effects can negatively impact the interfacial bonding between fibers and the cementitious matrix, ultimately diminishing the reinforcing efficiency of the fibers. Similar trends have been reported in previous studies, where excessive fiber content led to a decrease in mechanical performance due to these practical limitations in fresh concrete behavior. Excessively high fiber content leads to fiber clustering, reducing mechanical performance [51].

**Table 4** Results of the tested reinforced concrete beams using SSTR and SF

| Beam No. | Concrete Compressive Strength [MPa] | Concrete Flexural Strength [MPa] | Weight of Concrete Cube [kg] | Ultimate Experimental Load ($P_{EX}$) [kN] | Design Ultimate Load ($P_{DUL}$) [kN] | Steel Yield Stress [MPa] | $P_{EX}$ / $P_{DUL}$ | Deflection of Beam at Ultimate Load [mm] | Exp. Ultimate Moment [kN.m] |
|---|---|---|---|---|---|---|---|---|---|
| B1 | 29.81 | 4.20 | 8.02 | 175 | 63.86 | 460 | 2.74 | 24.8 | 65.63 |
| B2 | 25.21 | 3.60 | 7.76 | 138 | 62.93 | 460 | 2.19 | 25.1 | 51.75 |
| B3 | 26.34 | 3.40 | 8.10 | 142 | 63.25 | 460 | 2.25 | 25.1 | 53.25 |
| B4 | 24.42 | 3.40 | 7.90 | 125 | 62.82 | 460 | 1.99 | 25.1 | 46.88 |
| B5 | 30.56 | 3.8 | 8.20 | 178 | 64.00 | 460 | 2.78 | 24.7 | 66.75 |
| B6 | 28.35 | 3.2 | 8.48 | 175 | 63.50 | 460 | 2.76 | 25.1 | 65.63 |

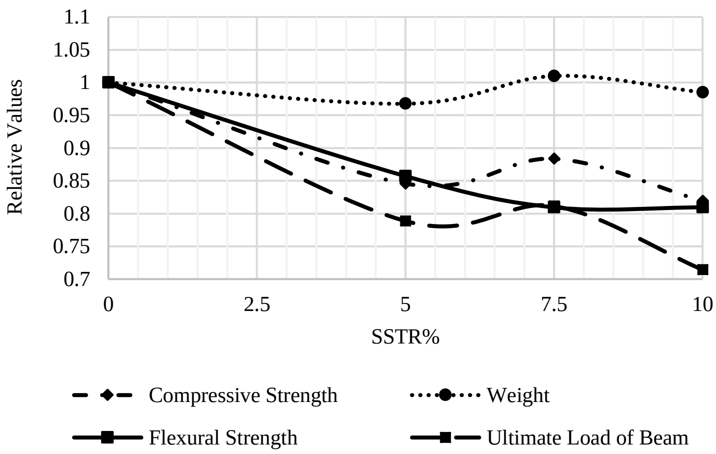



**Figure 9** The effect of various replacement percentages of SSTR on the properties of concrete

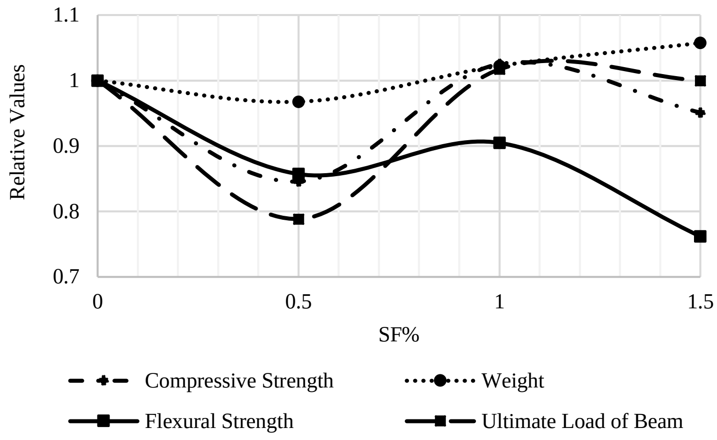



**Figure 10** The effects of varying amounts of SF added to concrete on its properties

*4.2 Flexural behavior*

Six reinforced concrete beams were cast and tested to investigate their flexural behavior. A computer recorded the load value after the load was applied manually over the beam. All beams behave linearly until the first crack appears. As can be seen in Figures 11 and 12, the displacement dramatically increased after that. The cracks' width expanded until complete disappointment occurred. In the region of greatest flexural moment and at the bottom of the beam depth, cracks can be seen. Figure 11 shows the effect of using SSTR in concrete instead of coarse aggregate in different proportions on the behavior of reinforced concrete beams. It is important to note that the data was recorded only up to the maximum load due to limitations in the dial gauge used during the experimental setup. The different amounts of SSTR did not affect the behavior of B2, B3, and B5, as these beams have the same performance. Also, the presence of SF in the concrete mix reduces this effect and makes it useful for users. In general, the use of SSTR will reduce the strengthening of the beam when it is compared to the beam with natural materials (B1), although 0.5% of SF is used. This reduction is because the compressive strength and flexural strength of concrete with different SSTR percentages (5%, 7.5%, and 10%) are less than the compressive strength of a normal concrete beam (B1).

Figure 12 shows the effect of using different percentages of steel fiber (0.5%, 1.0%, and 1.5%) with a constant 5% of SSTR, on the flexural behavior of reinforced cement concrete beams (B2, B5, and B6). The behavior of these beams was compared with the beam having 0% SSTR and 0% SF (B1). Adding more steel fiber will improve the strengthening of beams. The existing 5% SSTR reduces this increment. The difference in performance between B5 and B6 is due to the difference in compressive strength of the trial concrete mix. In general, there was a good improvement in the behavior of beams when SF was added. In concrete, SF serves as a crack arrestor. Flexural loads usually cause cracks to form along the tensile zone of the concrete beam. The steel fibers aid in regulating and limiting the depth and spread of these fissures. This indicates that even if cracks do develop, they are smaller and less harmful to the beam's structural integrity. For the beam to continue to function properly and carry its load, effective cracking control is essential.

Figure 13 illustrates the failure modes of the tested reinforced concrete beams beyond the yield point of the steel reinforcement, specifically to investigate the failure mode of the beams. Reinforcement bars and flexural bending of the beam reach the maximum stress in the region below the load position. The maximum flexural moment was concentrated in the middle of the beam, which was the primary cause of the failure mode. For all beams, the main crack starts at the mid-span of the beam at the early load stage and then starts to propagate. The crack became wider, and new cracks developed in the tension zone of the beam. By increasing the load, the displacement at the mid-span of the beam increased. For all the tested beams, the failure mode was a flexural failure. The inclusion of SSTR and SF together results in a synergistic enhancement, promoting a more ductile and gradual failure mode. This combination improves crack distribution and toughness when compared to conventional concrete beams. In the tension zone, the steel reinforcement may reach its yield point, where it starts to undergo plastic deformation. This plastic deformation allows the steel to continue carrying the increasing tensile forces while maintaining its strength and resisting further elongation.

Based on BS8110 [52], the design ultimate load ($P_{DUL}$) was compared with the ultimate load of the test, which is shown in Table 4. The values of the load ($P_{DUL}$) presented in Table 4 are defined as design values. These design values are calculated by applying a partial safety factor for materials, $\gamma_m$ is equal to 1.5, following standard design practice. The incorporation of this factor ensures that the calculated flexural capacity reflects a conservative and safe estimation of structural performance under ultimate limit state conditions, see Equations (2-6). The comparison with BS8110, as there is no standard accounting for the design moment of reinforced concrete beams with SSTR and SF. BS8110 considers the effect of SSTR and SF implicitly inside the design cube compressive strength of concrete. The compressive strength of concrete plays a good role in the position of the neutral axis.

Because the steel reached yield before the concrete collapsed, the beams were constructed with reinforcement. The experimental ultimate load was nearly 2 to 2.8 times greater than the design value. The codes generally underpredict the beams' design moment capacities with waste tire rubber, recycled aggregate, and fiber [30]. Additionally, the beams had SF and SSTR, whereas the design values only considered the effect of SF and SSTR through the design cube compressive strength. When the SF% went up, the experimental ultimate moment went up. When the SSTR% went up, the experimental ultimate moment went down.

In the design of most reinforced concrete structures, it is standard practice to begin with design calculations based on the ultimate limit state. For this reason, the analysis in this study first focuses on the simplified rectangular stress block, which is used for ultimate limit state design. This rectangular stress block, illustrated in Figure 14, will be used instead of the more complex rectangular-parabolic stress block. The simplified version helps streamline calculations and makes it easier to develop design equations.

From Figure 14, it is evident that the stress block doesn't extend to the neutral axis but instead has a depth of $0.9X$, where $X$ is the depth to the neutral axis. As a result, the centroid of the stress block lies at $S/2 = 0.45X$ from the top edge of the section. This closely matches the centroid location of the more precise rectangular-parabolic stress block. Moreover, the total areas under both stress blocks are approximately equal. Therefore, the moment of resistance calculated using either stress block will be very similar, and equations 2 to 5 were used to calculate the design Moment (M).

For the equilibrium of the compressive and tensile forces on the section

$$F_{cc}=F_{st} \tag{2}$$

$$0.45 \times f_{cu} \times b \times S = 0.95 \times f_y \times A_s \tag{3}$$

Where $f_{cu}$ is the design cube compressive strength of concrete, reflecting the inclusion of the material partial safety factor, $\gamma_m$, which is taken as 1.5 following standard design practice.

$$M= F_{st} \times z \tag{4}$$

$$M = 0.95 \times f_y \times A_s \times (d- \frac{S}{2}) \tag{5}$$

To calculate the design ultimate load ($P_{DUL}$) for a simply supported beam subjected to a point load at midspan, Equation 6 was used.

$$P_{DUL} = \frac{4M}{L} \tag{6}$$

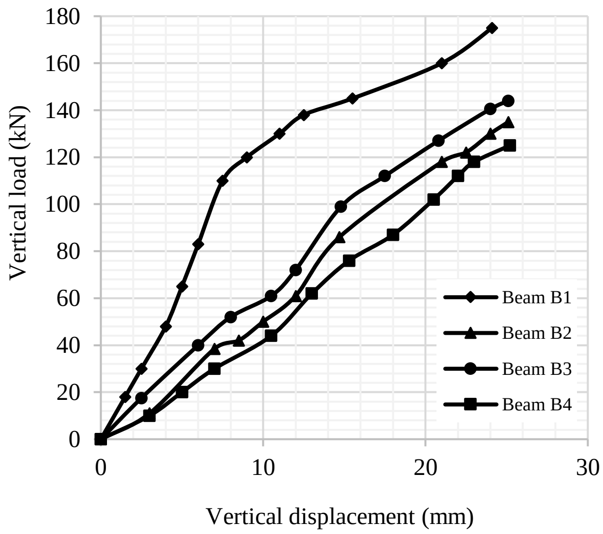



**Figure 11** Beam load-displacement at mid-span for various SSTR%

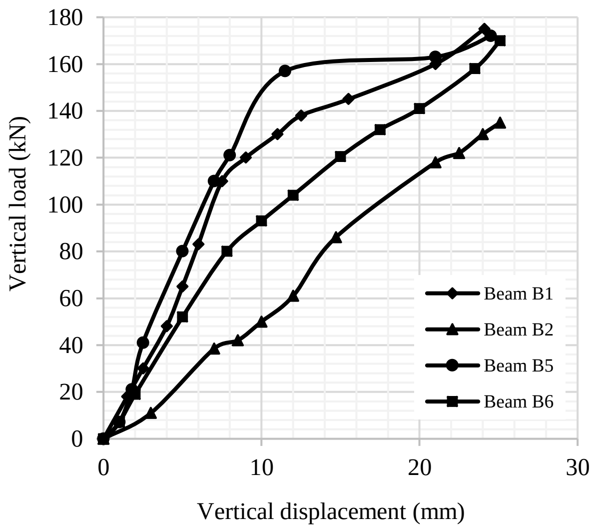
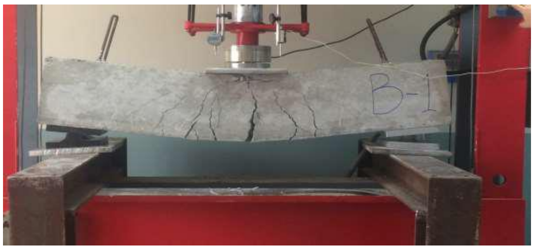
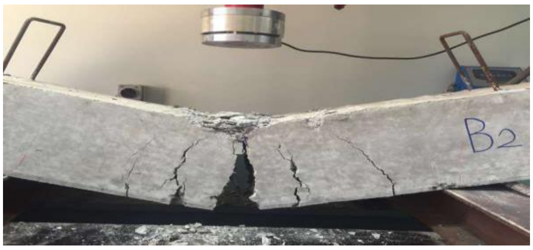



**Figure 12** Beam load-displacement at mid-span for various SF%

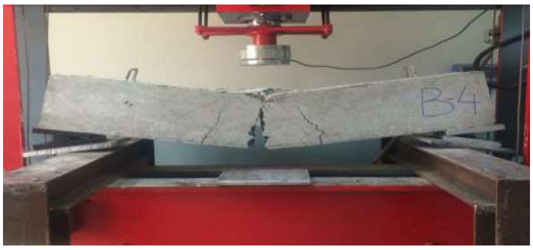



(a) B1



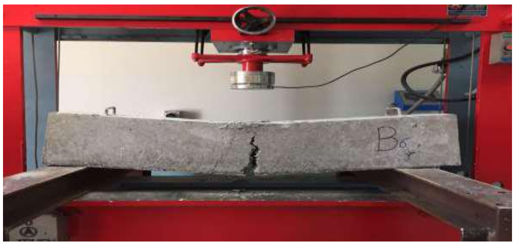

(b) B2

(c) B3




(d) B4

(e) B5



(f) B6

**Figure 13** The failure mode of the tested reinforced concrete samples

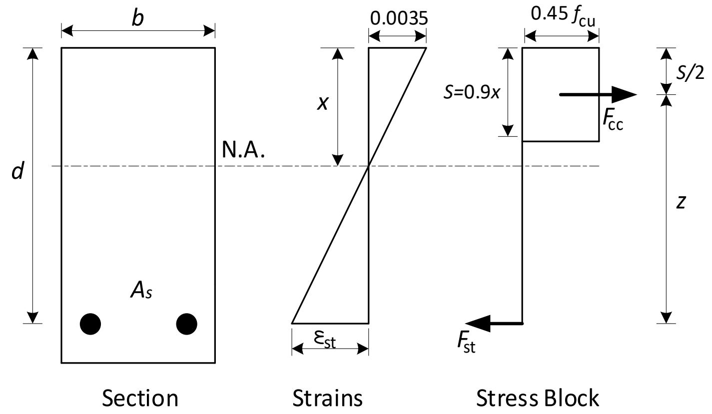



**Figure 14** Simplified rectangular stress block [48].

## 5. Conclusions

In this study, six beams were cast and tested under three bending points, and the failure load was compared against the design value calculated according to BS 8110 [52]. Material tests were conducted to measure the mechanical properties of concrete. The conclusions of the study can be summarized as follows:

1. The reinforced concrete beam with natural materials (0% SSTR and 0% SF) has shown a typical crack propagation pattern. However, due to the addition of 1% steel fibers and the use of 5% scrap tires in concrete, cracks ceased, which resulted in ductile behavior.
2. The optimum percentage of SF and SSTR to be used was found to be 1% Steel Fiber and 5% Sheared Scrap Rubber Tire.
3. The presence of SSTR reduces the compressive strength of concrete due to the impermeability of rubber, which helps more in absorbing the energy of the load, and to improve the compressive strength of concrete, the SF was added. The compressive strength decreased by using SSTR, and the reduction ratios were 15.37%, 11.64%, and 18.08% for 5%, 7.5%, and 10% of SSRT, respectively, compared with the control mix. The compressive strength of concrete cubes with 1% SF and 5% SSTR increased slightly by about 2.52 % compared with concrete with 0% SSTR and 0% SF.
4. The flexural strength of concrete prisms decreased by increasing the SSTR% increased by 0.5% of SF. Compared with the control mix, the reductions in flexural strength were 14.29%, 19.05%, and 19.05% for mixes containing 5%, 7.5, and 10% of SSTR and 0.5% SF, respectively. These reductions were 9.52 and 23.81 for the second series of mixes made by using 5% SSTR

and SF 1% and 1.5 %, respectively. The least decrease in flexural strength was shown when 1% of SF and 5% of SSTR were used. The presence of SSTR in concrete has a significant effect on the flexural strength of concrete because of the regular shape of SSTR, the weak interlock between SSTR and aggregates, and the low bond between SSTR and cement paste, although the SF was added, which is reflected by the reduction in concrete flexural strength

5. The flexural performance of the reinforced concrete beam improved slightly by 1.71% for the (B5) beam made by using 5% SSTR and 1% SF. The deflection of B5 increased slightly, indicating some ductile behavior when utilizing SSTR and SF. Also, there was a slight increase in the weight of B5 by 2.24% compared with the control beam.
6. The ratios of the tested failure load to the design load of BS8110 ranged from 1.99 - 2.78. The maximum ratio was for B5, which contained 5% SSTR and 1% SF.
7. Combined, SSTR and SF create a synergistic effect that leads to a more gradual and ductile failure mode, characterized by better crack distribution and improved toughness compared to conventional concrete beams. All tested reinforced concrete beams with SSTR and SF exhibited a flexural failure mode.

## 6. Acknowledgments

Research conducted in this study was supported by the Research Council of Oman (TRC) under grant no. FURAP/SU/15/006. The authors might want to thank Sohar University for their help during the venture's execution. We want to thank the civil engineering laboratory technician for her assistance.

## 7. References

[1] Oman Daily Observer. Be’ah seeks ways to recycle waste tyres [Internet]. 2017 [cited 2025 Jan 3]. Available from: https://www.omanobserver.om/article/90397/Main/beah-seeks-ways-to-recycle-waste-tyres.
[2] Hernandez-Olivares F, Barluenga G, Bollati M, Witoszek B. Static and dynamic behaviour of recycled tyre rubber-filled concrete. Cem Concr Res. 2002;32(10):1587-96.
[3] Ahmad J, Zhou Z, Majdi A, Alqurashi M, Deifalla AF. Overview of concrete performance made with waste rubber tires: a step toward sustainable concrete. Materials. 2022;15(16):5518.
[4] Venkatesan G, Saravanakumar M, Kapgate BP, Rajkumar K. Laboratory studies on strength behavior of concrete added with tire derived products. Mater Today: Proc. 2020;33:2665-70.
[5] Martínez-Barrera G, del Coz-Díaz JJ, Álvarez-Rabanal FP, Gayarre FL, Martínez-López M, Cruz-Olivares J. Waste tire rubber particles modified by gamma radiation and their use as modifiers of concrete. Case Stud Constr Mater. 2020;12:e00321.
[6] Záleská M, Pavlík Z, Čítek D, Jankovský O, Pavlíková M. Eco-friendly concrete with scrap-tyre-rubber-based aggregate–properties and thermal stability. Constr Build Mater. 2019;225:709-22.
[7] Eldin NN, Senouci AB. Measurement and prediction of the strength of rubberized concrete. Cem Concr Compos. 1994;16(4):287-98.
[8] Reda Taha MM, El-Dieb AS, Abd El-Wahab MA, Abdel-Hameed ME. Mechanical, fracture, and microstructural investigations of rubber concrete. J Mater Civ Eng. 2008;20(10):640-9.
[9] Sukontasukkul P, Tiamlom K. Expansion under water and drying shrinkage of rubberized concrete mixed with crumb rubber with different size. Constr Build Mater. 2012;29:520-6.
[10] Chaikaew C, Sukontasukkul P, Chaisakulkiet U, Sata V, Chindaprasirt P. Properties of concrete pedestrian blocks containing crumb rubber from recycle waste tyres reinforced with steel fibres. Case Stud Constr Mater. 2019;11:e00304.
[11] Vikhyath, Kumar MSR. Experimental investigation of waste rubber and steel fiber reinforced cement concrete. Int J Eng Res Adv Technol. 2018;4(9):25-36.
[12] Sreeshma PK, Varghese S. Effect of combination of steel fiber and crumb rubber on the properties of concrete. Int J Innov Res Adv Eng. 2016;3(8):58-63.
[13] Ganjian E, Khorami M, Maghsoudi AA. Scrap-tyre-rubber replacement for aggregate and filler in concrete. Constr Build Mater. 2009;23(5):1828-36.
[14] Panda KC, Parhi PS, Jena T. Scrap-tyre-rubber replacement for aggregate in cement concrete: experimental study. Int J Earth Sci Eng. 2012;5(6):1692-701.
[15] Dumne SM. An experimental study on performance of recycled tyre rubber-filled concrete. Int J Eng Res Technol. 2013;2(12):766-72.
[16] Eldhose C, Soosan TG. Studies on scrap tyre added concrete for rigid pavements. Int J Eng Res. 2014;3(12):777-9.
[17] Kotresh KM, Belachew MG. Study on waste tyre rubber as concrete aggregates. Int J Sci Eng Technol. 2014;3(4):433-6.
[18] Asutkar P, Shinde SB, Patel R. Study on the behavior of rubber aggregates concrete beams using analytical approach. Eng Sci Technol Int J. 2017;20(1):151-9.
[19] Gerges NN, Issa CA, Fawaz SA. Rubber concrete: mechanical and dynamical properties. Case Stud Constr Mater. 2018;9:e00184.
[20] Thomas BS, Gupta RC. Long term behavior of cement concrete containing discarded tire rubber. J Clean Prod. 2015;102:78-87.
[21] Senin MS, Shahidan S, Abdullah SR, Guntor NA, Leman AS. A review on the suitability of rubberized concrete for concrete bridge decks. IOP Conf Ser: Mater Sci Eng. 2017;271:012074.
[22] Moustafa A, ElGawady MA. Strain rate effect on properties of rubberized concrete confined with glass fiber-reinforced polymers. J Compos Constr. 2016;20(5):04016014.
[23] Onuaguluchi O. Effects of surface pre-coating and silica fume on crumb rubber-cement matrix interface and cement mortar properties. J Clean Prod. 2015;104:339-45.
[24] Adamu M, Mohammed BS, Liew MS. Effect of crumb rubber and nano silica on the creep and drying shrinkage of roller compacted concrete pavement. Int J Geomate. 2018;15(47):58-65.
[25] Xie JH, Guo YC, Liu LS, Xie ZH. Compressive and flexural behaviours of a new steel-fibre-reinforced recycled aggregate concrete with crumb rubber. Constr Build Mater. 2015;79:263-72.
[26] Noaman AT, Abu Bakar BH, Akil HM. Experimental investigation on compression toughness of rubberized steel fiber concrete. Constr Build Mater. 2016;115:163-70.

[27] Tawfeeq WM, Ali TKM, Al-Kumzari Y, Al-Hosni M, Al-Fazari K, Al-Bedwawi M, et al. Flexural performance of reinforced concrete beams made by using recycled block aggregates and fibers. Innov Infrastruct Solut. 2021;6:38.
[28] Sharaky IA, Seleem MH, Elamary AS. Minimizing the crumb rubber effects on the flexural behaviour of the layered RC beams cast using rubberized concrete with or without recycled tire steel fibers. Constr Build Mater. 2023;400:132503.
[29] Ismail MK, Hassan AAA. An experimental study on flexural behaviour of large-scale concrete beams incorporating crumb rubber and steel fibres. Eng Struct. 2017;145:97-108.
[30] Shahjalal M, Islam K, Rahman J, Ahmed KS, Karim MR, Billah AHMM. Flexural response of fiber reinforced concrete beams with waste tires rubber and recycled aggregate. J Clean Prod. 2021;278:123842.
[31] Xu J, Chang F, Bai J, Liu C. Statistical analysis on the fracture behavior of rubberized steel fiber reinforced recycled aggregate concrete based on acoustic emission. J Mater Res Technol. 2023;24:8997-9014.
[32] Islam MMU, Li J, Roychand R, Saberian M, Chen F. A comprehensive review on the application of renewable waste tire rubbers and fibers in sustainable concrete. J Clean Prod. 2022;374:133998.
[33] Jirawattanasomkul T, Minakawa H, Likitlersuang S, Ueda T, Dai JG, Wuttiwannasak N, et al. Use of water hyacinth waste to produce fibre-reinforced polymer composites for concrete confinement: mechanical performance and environmental assessment. J Clean Prod. 2021;292:126041.
[34] Shufrin I, Pasternak E, Dyskin A. Environmentally friendly smart construction—review of recent developments and opportunities. Appl Sci. 2023;13(23):12891.
[35] Oman Daily Observer. Be’ah to supply scrap tyres to Oman cement in waste to energy deal [Internet]. 2020 [cited 2025 Jan 3]. Available from: https://www.omanobserver.om/article/16838/Business/beah-to-supply-scrap-tyres-to-oman-cement-in-waste-to-energy-deal.
[36] British Standards Institution. BS 882:1992. Specification for aggregates from natural sources for concrete. London: British Standards Institution; 1992.
[37] British Standards Institution. BS EN993-1:1997. Tests for geometrical properties of aggregates. Part 1: Determination of particle size distribution — sieving method. London: British Standards Institution; 1997.
[38] British Standards Institution. BS 812–2:1995. Testing aggregates. Part 2. Methods of determination of density. London: British Standards Institution; 1995.
[39] British Standards Institution. BS EN1097-3:1998. Tests for mechanical and physical properties of aggregates. Part 3: Determination of loose bulk density and voids. London: British Standards Institution; 1998.
[40] British Standards Institution. BS EN197-1:2000. Cement–Part 1: Composition, specifications and conformity criteria for common cements. London: British Standards Institution; 2000.
[41] Neville AM, Brooks JJ. Concrete technology. 2nd ed. Harlow: Prentice Hall; 2010.
[42] Kashani A, Ngo TD, Hemachandra P, Hajimohammadi A. Effects of surface treatments of recycled tyre crumb on cement-rubber bonding in concrete composite foam. Constr Build Mater. 2018;171:467-73.
[43] Khaloo AR, Dehestani M, Rahmatabadi P. Mechanical properties of concrete containing a high volume of tire–rubber particles. Waste Manag. 2008;28(12):2472-82.
[44] Min K, Pei X, Li H, Cao Z, Yang Z, Hao D, et al. Optimization of cohesive parameters in the interfacial transition zone of rubberized concrete based on the response surface method. Polymers. 2024;16(11):1579.
[45] British Standards Institution. BS EN12350-2:2009. Testing fresh concrete. Part 2: Slump-test. London: British Standards Institution; 2009.
[46] British Standards Institution. BS EN12390-3:2002. Testing hardened concrete-Part 3: Compressive strength of test specimens. London: British Standards Institution; 2002.
[47] British Standards Institution. BS EN12390-5:2019. Testing hardened concrete-Part 5: Flexural strength of test specimens. London: British Standards Institution; 2019.
[48] Mosley WH, Bungey JH. Reinforced concrete design. 4th ed. London: Macmillan; 1999.
[49] Shahjalal M, Islam MA, Prantik RA, Ahmed KS. Mechanical characterization of concrete containing crumb rubber and recycled brick aggregate. AIP Conf Proc. 2021;2441:030012.
[50] Islam MMU, Li J, Wu YF, Roychand R, Saberian M. Design and strength optimization method for the production of structural lightweight concrete: an experimental investigation for the complete replacement of conventional coarse aggregates by waste rubber particles. Resour Conserv Recycl. 2022;184:106390.
[51] Song PS, Hwang S. Mechanical properties of high-strength steel fiber-reinforced concrete. Constr Build Mater. 2004;18(9):669-73.
[52] British Standards Institution. BS8110-1:1997. Structural use of concrete-Part 1: Code of practice for design and construction. London: British Standards Institution; 1997.