






## Enhancing the Sustainability of Concrete Using Recycled Steel Fibers after Fire Exposure

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### ABSTRACT

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*steel fiber, exposure, elevated temperature, residual strength, sustainability*

The deterioration of concrete mechanical properties after firing is a major challenge to the safety and sustainability of concrete structures. This research aims to evaluate the effectiveness of recycled steel fibers extracted from used car tires in improving the residual mechanical properties of concrete after exposure to high temperatures, while also promoting environmental sustainability. Five concrete mixes were prepared at a 1:2:4 ratio, including a reference mix and four fiber-reinforced mixes, and the fibers vary in length. All samples were hydro treated for 28 days and then fired at 600 °C for one hour. Compressive, splitting tensile, and flexural strength tests were conducted before and after firing. The results showed that the reference mix retained only about 29.96% of its compressive strength after firing, while the residual strength increased to approximately 42.29% when using 3 cm fibers. The residual splitting tensile strength also improved from approximately 18.39% in the reference mix to 34.25% in the fiber-reinforced blend of the same length. Flexural strength retention increased from about 39.28% in the reference concrete to approximately 42.16% when reinforced with 3 cm steel fibers. This significant improvement is attributed to the effective role of the fibers in crack sealing and stress transfer following thermal damage. Based on the findings of this paper, the use of recycled steel fiber denotes a real and sustainable solution to enhance concrete fire resistance and decrease the environmental impact of waste.

## 1. INTRODUCTION

High-temperature fires pose a significant hazard to concrete structures. However, there has been little research on the effects of fire on concrete. Therefore, further research is required to investigate the performance of concrete exposed to extreme temperatures [1, 2]. As a result of the very high fire temperature, the strength of the concrete will decrease due to softening or melting of the reinforcing steel and loss of bond between the reinforcing steel and the concrete, thereby reducing the structural capacity of the reinforced concrete structure [3-6]. Concrete constructions are subjected to fire, which results in several physical and chemical reactions, including the thermal degradation of cement paste components and water evaporation. These reactions damage the concrete microstructure and reduce its internal cohesion, adversely affecting the mechanical properties of concrete. In addition, the buildup of vapor pressure in the pores can lead to explosive spalling of concrete, which is one of the most severe types of damage due to fire [7-10]. Utilized car tires constitute an environmental risk due to their accumulation and the emission of toxic chemicals and gases when burned. However, the steel wire content within them can be utilized as a concrete reinforcement when it is subjected to fire [11-14]. Numerous

experimental studies have found that adding suitable fibers, especially steel fibers, to concrete can improve the resistance of concrete structures to cracking caused by high temperatures [15]. The effect of temperature on steel fiber-reinforced concrete was studied by exposing samples to high temperatures ranging from 150 °C to 1200 °C. The results showed an increase in compressive and flexural strength and modulus of elasticity for concrete containing 1% steel fibers [16]. An analysis was conducted to determine the effect of incorporating recycled steel fibers into concrete on its mechanical properties after exposure to high temperatures, as part of the search for concrete materials more resistant to cracking and thermal degradation. The results showed that adding 1% recycled steel fibers significantly reduced the loss of compressive strength in the concrete, improved indirect tensile strength, and enhanced the concrete's resistance to heat-induced cracking. This demonstrates the effectiveness of these fibers for strengthening mechanical performance after fire, as well as supporting sustainability by converting industrial waste into high-value concrete materials [17]. The addition of recycled fibers from end-of-life tires enhances the resistance of high-performance concrete to cracking and fire-induced spalling. The results indicated that polymer fibers at a dosage of 2 kg/m<sup>3</sup> reduce spalling, while steel fibers help maintain the

attachment of the spalled concrete to the heated surface, protecting the main steel reinforcement and providing safe and sustainable solutions to mitigate fire-induced damage [18]. Adding used tire steel fibers at a volume of 0.4% and 0.8% improved the performance of concrete when exposed to high temperatures (400 – 800 °C) and reduced the loss of compressive strength compared to ordinary concrete [19]. Using thin strips of soft drink cans as a reinforcing element in concrete resulted in a significant improvement in its impact resistance. The findings revealed that the samples with 1.5 percent fibers and a length of 9 cm had a decrease in surface scaling, back face spalling, and radial crack length relative to those samples without such mineral fibers, and this proves to be an advantage of this waste solid in improving structural integrity over high-speed impacts [20]. Also, numerous studies have shown that the bond behavior between concrete and reinforcing steel is significantly influenced by several factors, most notably the surface properties of the reinforcing steel, the water-cement ratio, the type of cement and aggregates, the use of admixtures, the age and curing stage of the concrete, relative humidity, and exposure to environmental conditions and high temperatures [21-25]. This research focuses on studying the residual mechanical properties of steel fiber-reinforced concrete after exposure to high temperatures and assessing its compressive, tensile, and flexural strength after firing. Furthermore, it also aims to reduce the scientific gap resulting from the low number of studies on the use of recycled steel fibers in concrete, highlighting the promotion of environmental sustainability through material reuse, improved service life, and reduced need for building maintenance or replacement.

## 2. EXPERIMENTAL PROGRAM

### 2.1 Material

To produce suitable concrete mixes to evaluate their performance after being subjected to fire, the cement used in this study is produced by the local Almas Cement Factory in northern Iraq. It is ordinary Portland cement (OPC) from an aluminum block, conforming to ASTM type 1, and it conforms to the Iraqi specification IQS No. 5 of 1984. The sand used in the concrete mixes is natural within the standard Iraqi specification. The aggregate used is washed and clean, which complies with the requirements of the Iraqi specification. Steel fibers were mechanically extracted from old, used tires. The rubber in the surroundings was peeled off, and the fibers were pulled out and cut to different lengths. The fibers were added at a rate of 1% of the total concrete volume, excluding the reference mix. The maximum tensile and maximum yield strengths of these fibers, based on the load-displacement curve in Figure 1, are around 1840.67 and 1560.51 MPa, respectively.

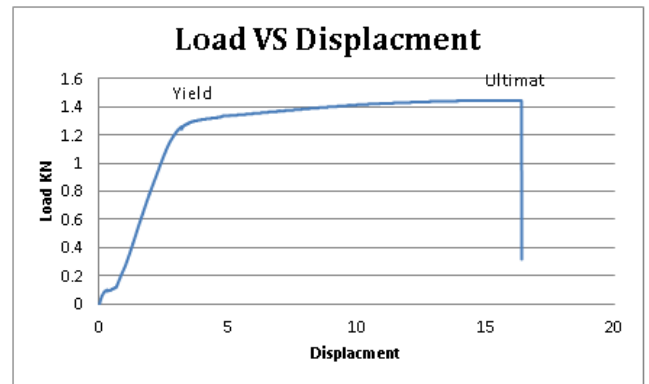


Figure 1. Load and displacement curve

### 2.2 Mix proportions

Five concrete mixtures were made with a ratio of 1:2:4 (cement: sand: coarse aggregate), which is a normal ratio used in experimental research because the ratio gives a balance between strength, density, and workability [26]. The first is a reference mix (R) without fibers, and the other 4 mixes included steel fibers at 1% of total concrete volume. Only the fiber lengths were varied (1, 2, 3, and 4 cm), as shown in Figure 2, to study their effect on the concrete's heat resistance and mechanical loss after fire exposure. The coarse aggregate and sand were first mixed dry for one minute, after which cement was added; the mixture was further mixed to guarantee the homogeneity of the dry ingredients. Next, the fibers were gradually and sparingly incorporated to prevent clumping before water was added gradually while mixing for 2 minutes until a homogeneous concrete mix with suitable workability for pouring was obtained. This will result in even distribution of the fibers, which will assist in better bending resistance and energy absorption following heat exposure [27]. Three specimens were prepared for each mix in each mechanical test (n = 3 for each state), for both before and after fire exposure, and the average values of the three specimens were used for each condition. Table 1 revealed the values of the concrete mixes.



Figure 2. Steel fiber

Table 1. Details of concrete mixes

Mixes	Steel Fiber Content (%)	Steel Fiber Length (cm)	Cement (Kg/mex)	Fine Aggregate (Kg/mex)	Coarse Aggregate (Kg/mex)	W/C Ratio	Exposure Temp. ( °C)	Curing Period (Day)
R	—	—	39	78	156	0.45	600	28
1	1	1	39	78	156	0.45	600	28
2	1	2	39	78	156	0.45	600	28
3	1	3	39	78	156	0.45	600	28
4	1	4	39	78	156	0.45	600	28

### 2.3 Preparing concrete specimens

Cylindrical specimens (300 mm × 150 mm) were prepared for compressive strength testing according to ASTM C09 [28], while other cylindrical specimens (200 mm × 100 mm) were used for tensile strength testing according to C496/C496M [29]. Prism specimens (400 mm × 100 mm × 100 mm) were also prepared for flexural strength testing according to the ASTM standard [30]. The concrete was poured into standard steel molds and thoroughly compacted using a laboratory vibrator to ensure the removal of air voids. The specimens were left in the molds for 24 hours, after which the molds were removed, and the specimens were transferred to hydro-curing tanks for 28 days.

### 2.4 Burning furnace and thermal program



Figure 3. Burning furnace

The concrete models were placed in an electric furnace equipped with a digital temperature control system (as shown in Figure 3) and then exposed to high temperatures to replicate the conditions of a fire. This type of furnace provides for an even heat distribution throughout the heating chamber and thus provides a uniform thermal condition for all of the specimens that are being tested [31]. The concrete samples were heated inside the furnace, where the temperature gradually rose to 600 °C at a rate of 10 °C per minute. Once that temperature was reached, it was maintained for a period of one hour to ensure there was enough heat penetration into the specimens and for them to reach a semi-thermally stable state, which is a common method of conducting concrete tests that have been exposed to fire [32]. At the end of the heating period, the kiln was turned off and allowed to cool until it

reached room temperature to minimize thermal shock and prevent further cracking that could affect the results of subsequent mechanical tests [31].

## 3. RESULTS AND DISCUSSION

### 3.1 Compressive strength

The results of the compressive strength test, as shown in Table 2 and Figure 4, showed a significant decrease in the strength of all concrete mixes when exposed to a temperature of 600 °C for one hour as a result of thermal deterioration in the microstructure of the concrete [33]. Steel fiber-reinforced concrete mixes made from car tires exhibited a notable improvement in residual strength after firing, as shown in Table 3, with residual strength percentages ranging from 29.96% to 42.29%, depending on the fiber length, with the best performance observed at 3 cm. Adding steel fibers enhances the residual strength of concrete after exposure to high temperatures, as it helps to bond thermal cracks and reduce their propagation rate within the concrete matrix, thus improving mechanical performance after firing compared to unreinforced concrete [34, 35]. Hence, this experiment validates that recycled steel fibers can make a significant contribution to the residual strength of the concrete after firing as opposed to a traditional mix, highlighting the significance of the choice of the most appropriate fiber length and proportion in the context of thermal performance and regulation of the internal homogeneity of the mixture.

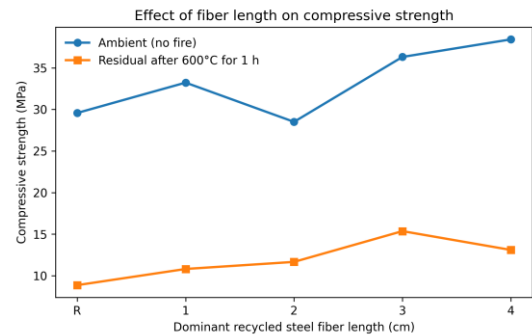


Figure 4. Effect of fiber length on compressive strength (before and after fire)

Table 2. Mechanical properties before and after fire

Mixes	Length of Added Fiber	Splitting Without Fire (MPa)	Splitting Residual (600 °C) (MPa)	Compression Without Fire (MPa)	Compression Residual (600 °C) (MPa)	Flexure Without Fire (MPa)	Flexure Residual (600 °C) (MPa)
R	—	3.64	0.67	29.58	8.86	6.39	2.51
1	1 cm	3.84	0.90	33.23	10.81	5.57	2.15
2	2 cm	4.50	1.51	28.51	11.66	6.29	2.46
3	3 cm	4.76	1.63	36.32	15.36	6.12	2.58
4	4 cm	4.10	1.26	38.43	13.10	5.85	2.01

Table 3. Residual strength after fire

Mixes	Length of Added Fiber	Splitting Tensile Residual (%)	Compression Strength Residual (%)	Flexural Strength Residual (%)
R	—	18.39	29.96	39.28
1	1 cm	23.40	32.53	38.60
2	2 cm	33.56	40.90	39.11
3	3 cm	34.25	42.29	42.16
4	4 cm	30.74	34.09	34.36

### 3.2 Split tensile strength

Exposing concrete to high temperatures for at least one hour leads to a significant decrease in splitting tensile strength due to loss of bonding between the components of the cement paste [36]. Based on the findings in Table 2 and Figure 5, the reference mix showed a splitting tensile strength of 3.64 MPa before firing, which then decreased to 0.67 MPa after firing, resulting in a residual tensile strength of approximately 18.39%, as shown in Table 3. This reflects the brittle and weak behavior of the concrete when exposed to fire. In contrast, mixes reinforced with steel fibers showed a significant improvement in residual splitting tensile strength after firing. The mix containing 1 cm fibers recorded strength of 3.84 MPa before firing and 0.90 MPa after, achieving a residual strength of approximately 23.40%. This percentage increased to approximately 33.56% for the mix with 2 cm fibers, where the tensile strength decreased from 4.50 MPa to 1.51 MPa after firing. The mixture containing 3 cm fibers exhibited a splitting tensile strength of 4.76 MPa before burning, which decreased to 1.63 MPa after burning, achieving the highest residual strength of approximately 34.25. The mixture containing 4 cm fibers recorded strength of 4.10 MPa before burning and 1.26 MPa after, with a residual strength of approximately 30.74%. This improvement in the residual tensile performance of fiber-reinforced concrete is attributed to the effective role of steel fibers in cracks sealing, transferring tensile stresses, and delaying brittle failure even after fire [37]. The outcomes indicate that fiber length (3 cm) achieves the best balance between stress transfer efficiency and distribution quality within the concrete mix.

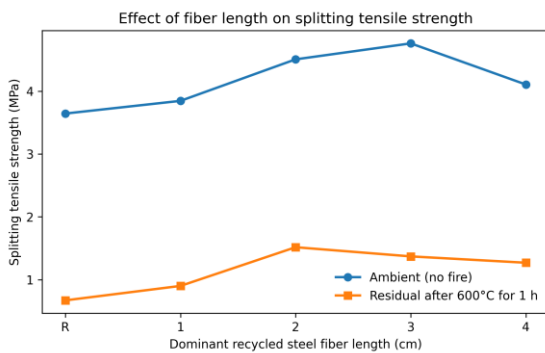


Figure 5. Effect of fiber length on splitting tensile strength (before and after fire)

### 3.3 Flexural strength

The flexural strength of the basic mixture (R) was 6.39 MPa before fire exposure, but it decreased to 2.51 MPa after firing, as shown in Table 2 and Figure 6, indicating a residual strength of approximately 33.28%. This decrease is attributed to the deterioration of the cement paste and the loss of bond between the concrete components due to thermal decomposition [16]. In contrast, the steel fiber-reinforced mixtures exhibited better performance after heat treatment. The flexural strength of the 1 cm fiber-reinforced mixture was approximately 5.57 MPa before firing and decreased to 2.15 MPa after firing, while the 2 cm fiber-reinforced mixture recorded strength of 6.29 MPa before firing and 2.46 MPa after. The 3 cm fiber-reinforced mixture achieved the highest performance, with a flexural strength of 6.12 MPa before firing and a decrease to 2.58 MPa

after firing, resulting in the highest residual flexural strength of approximately 42.16%. Meanwhile, the flexural strength of the 4 cm fiber-reinforced mixture decreased from 5.85 MPa to 2.01 MPa after firing. The improvement in the residual flexural strength of steel fiber-reinforced mixes is attributed to the fibers' ability to bridge cracks and limit their propagation, as well as to improve the transfer of flexural stresses after the cement paste has been damaged by fire [38]. Furthermore, an optimal fiber length, such as 3 cm, leads to more uniform distribution within the mix and greater efficiency after heat exposure, while increased length may result in poor homogeneity and reduced effectiveness [39]. These findings are consistent with previous studies that confirmed that steel fibers clearly contribute to improving the residual flexural strength of concrete exposed to high temperatures [40, 41]. Figures A1-A8 in the appendix show the graphical results, including compressive, tensile, and flexural behavior.

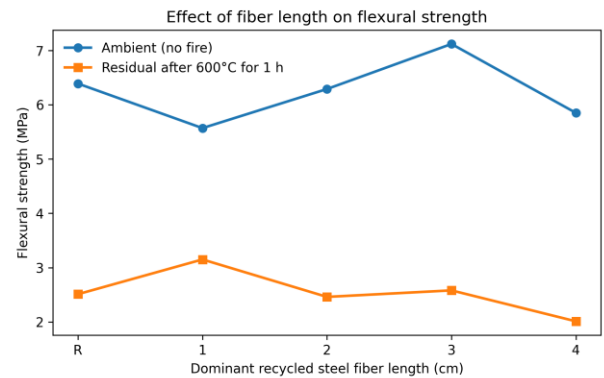


Figure 6. Effect of fiber length on flexural strength (before and after fire)

## 4. ENVIRONMENTAL DIMENSIONS AND SUSTAINABILITY

The idea of research helps achieve the principle of environmental sustainability in the building segment by appraising the remaining structural performance of fire-damaged reinforced concrete, allowing the restoration of concrete elements rather than demolition, reducing the consumption of natural resources, and decreasing carbon production associated with building material production.

## 5. CONCLUSIONS

According to the experimental results of this manuscript, the following conclusions can be drawn:

- The reference concrete showed a sharp decrease in mechanical properties after exposure at 600 °C for 1 hour, with compressive, splitting tensile, and flexural strength decreasing significantly. This is attributed to the deterioration of the cement paste, the loss of associated water, and the formation of micro-cracks resulting from thermal decomposition.
- The addition of steel fibers contributed to improving the mechanical properties of concrete before firing, especially the tensile strength and flexural strength, as a result of the role of the fibers

in bonding cracks, improving ductility, and transferring stresses.

- After exposure to fire, the steel fiber-reinforced mixes showed higher residual resistance compared to the reference mix in all tests, confirming the effectiveness of the fibers in reducing the deterioration of the mechanical properties of thermally damaged concrete.
- It was found that the length of the fibers was a clear factor affecting performance after fire, as the 3 cm fiber-reinforced mix achieved the best balance between distribution within the mix and crack bonding efficiency, and recorded the highest residual resistance in compression, tensile, and flexural tests compared to the other lengths studied.
- It was observed that increasing the fiber length beyond the optimal length led to a relative decrease in residual performance. This is attributed to poor homogeneity within the mixture and the possibility of fiber clumping, which reduces its efficiency after exposure to high temperatures.
- The results of this research confirm that the use of steel fibers extracted from used car tires not only contributes to improving the fire resistance of concrete but also represents a sustainable and environmentally friendly solution through waste recycling and reducing the associated environmental impact.
- Based on the above, recycled steel fiber reinforced concrete, with optimal fiber length, can be adopted as a promising option for improving the performance of concrete elements exposed to fire hazards in future engineering applications.
- The results of this study are limited to exposure to a temperature of 600°C for one hour, and cannot be generalized to all other fire cases, which may vary in temperature or duration of exposure.
- The results indicate that the steel fiber may help crack sealing and stress transmission, based on the interpretation of mechanical test data, without direct visual evidence.

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## APPENDIX

This appendix includes the following images (A1-A8).

A1-A2: Samples of prisms before and after the bending test, illustrating the effect of fibers on crack propagation

A3-A4: Prisms during bending testing, showing the specimen's loading and behavior under loads.

A5-A6: Cylinders before and after exposure to 600 °C for one hour, illustrating the thermal effects on concrete.

A7: Cylinders sample during compression test.

A8: Cylinders sample during tensile test.



**Figure A1.** Samples of prisms after bending test after fire



**Figure A2.** Sample of prisms after bending test after fire



**Figure A3.** Samples of prisms during bending test after fire



**Figure A4.** Sample of prisms during bending test after fire



**Figure A5.** Concrete samples before fire



**Figure A6.** Concrete samples after fire



**Figure A7.** Cylinder sample during compression test



**Figure A8.** Cylinder sample during tensile test