Revue des Composites et des Matériaux Avancés-Journal of Composite and Advanced Materials
Vol. 35, No. 5, October, 2025, pp. 849-856
Journal homepage: http://iieta.org/journals/rcma

Mechanical and Thermal Behavior of Cement Mortars Incorporating Recycled Fiber Reinforcement

Samer Saeed Abdulhussein[1*], Mohammad Zohair Yousif[1], Mohammed Ali Abdulrehman[2], Hussein Kadhim Abood Khalaf[1], Ala Keblawi[3]

[1] Department of Civil Engineering, College of Engineering, Mustansiriyah University, Baghdad 10045, Iraq
[2] Department of Materials Engineering, College of Engineering, Mustansiriyah University, Baghdad 10045, Iraq
[3] Department of Civil Engineering and Sustainable Structures, College of Engineering and Technology, Palestine Technical University–Kadoorie, Tulkarm P305, Palestine

*Corresponding Author Email: samersaeed@uomustansiriyah.edu.iq

https://doi.org/10.18280/rcma.350505

Received: 13 July 2025
Revised: 18 August 2025
Accepted: 31 August 2025
Available online: 31 October 2025

Keywords:
thermal exposure, ultrasonic pulse velocity, recycled fibers, cement mortar, sustainability

ABSTRACT

In this study, the mechanical and thermal characteristics of cement mortars reinforced with varying amounts of recycled synthetic fibers were investigated. Fibers derived from industrial waste were added to the mortar mixture at volumetric dosages ranging from 0 to 2.5%. Standard specimens were prepared and tested for compressive strength, flexural strength, and splitting tensile strength, in addition to non-destructive testing with ultrasonic pulse velocity. All the samples were heated at 200, 400, 600, and 800℃ to assess the thermal resistance of the samples. The findings indicated enhanced mechanical properties for samples where the recycling process preceded the heat treatment, the optimal level of which was between 1.5% and 2.0% fibers content. Below 600℃, the samples fortified with fibers had an enhanced performance than the other samples in residual strengths and anti-crack property; however, above 600℃, the degradation became apparent. To enhance the elasticity of cementitious materials as well as control the temperature stability of the materials at high temperatures, the recycling of industrial fibers appears imperative from the sustainable perspective.

1. INTRODUCTION

However, the dynamic materials used in the construction sector can still cope with the rising demands for minimizing wastage, robustness, and optimizing efficiencies. Conversely, the production levels of industrial and municipal waste have risen as a result of the development of infrastructure around the globe, prompting researchers and engineers to pursue new technologies for the effective recycling and reuse of materials. Among the various materials within the wastage category, the vast quantities of used automobile tires have gained remarkable attention from researchers and engineers worldwide for their effective recycling and reuse in the construction sector. Overall, the problems associated with automobile tire wastage are their high weight, toughness, and lack of biodegradability, among other characteristics, within the landfill sites where their disposal takes place. The steel reinforcement within the tires is an essential component, the recycling of which through mechanical shredding and separation techniques enables the production of steel fibers, termed recycled steel fibers (RSFs), which can be used in the construction sector and retain remarkable mechanical strength even after being harvested from the steel reinforcement within the tires [1, 2]. The recycling and reuse of steel fibers within the construction sector represent an appreciable scalable recycling process, where the performance of materials can be enhanced without increasing wastage within the sector [1, 2]. In fact, the addition of steel fibers within the cement mortar and concrete materials within the sector has appreciably enhanced their behavior after cracking, tensile strength, bending toughness, and enhancement of the strength at compressive levels over the last 20 years [3, 4]. The distinct capability of the fibers to resist the widths of the cracks, bridge the existing cracks, and share the stresses within the materials remains the primary reason for the enhancement in the mechanical properties of the materials [3, 4]. In fact, the prevalent-use industrial fibers still lack the cost-effectiveness associated with other materials from the steel family, used in their recycling process from used automobile tires, without really affecting their performance in the sector [5, 6]. The technical feasibility of using steel fibers from recycling processes to enhance the mechanical properties of materials at room conditions is supported by the increasing number of studies in the sector. However, the characteristics of fibers at high temperatures still warrant new studies within the sector for their prevailing performance at high conditions compared to their ambient conditions [7, 8]. In fact, within the real sector, the prevailing high heat levels within the materials during the fire conditions within the sector or the prevailing conditions within the service sector, such as the environment for the passage of materials through the tunnels, kilns, and industrial sites, still result in the physical and chemical changes within the materials associated with the high heat levels, such as the loss of hydration within the materials' composition, development of porosities within the materials, development of materials' cracking within the materials at the high heat levels, and materials' softening at the high heat levels compared to the other materials within the sector [7, 8]. Under such conditions, the role of steel fibers may vary within the mortar composition. Fibers can provide a support framework to preserve the material's strength, even if the mortar deteriorates from the heat effects of their high thermal conductivity and stiffness. Therefore, although the characteristics of the fibers and the interaction between the fibers and mortar influence the role of the fibers, studies [9, 10] have suggested the beneficial effects of well-dispersed fibers to preserve the bearing strength and prevent pull-out effects from heat exposure. However, the performance of heat exposure on tire RSF mortars remains unclear. Few studies have examined the effects of varied heat exposure conditions on the properties of such materials to the point where the recycling aspect of the fibers could affect the final mortar composition based on their possible impurities, irregular geometric forms, varied sizes, and other differences in thermally conductive processes [11, 12]. Simultaneously, the utility of nondestructive evaluation techniques, such as the ultrasonic pulse velocity (UPV), for monitoring the conditions of internal materials has gained increasing attention. Prior to and after thermal exposure, the UPV provides a quick, precise, and non-intrusive technique for assessing the homogeneity, rigidity, and probable damage within the mortar materials. Through the relationship between the changes in the wave propagation velocities and the changes at the microstructural level, the degradation process within the materials can be closely monitored without the need for destructive analysis techniques. The UPV technique enhances the level of analysis of the internal development processes of materials by incorporating the results of mechanical tests [13, 14]. The significance of the material contributions from the fibers, composition of the mortar binder, and characteristics of the interface regions between the fibers and mortar materials have gained increasing relevance in current studies focusing on high-performance concrete materials subjected to thermal exposure conditions. For example, Abdulhussein et al. [15] examined the effects of high temperatures on the mechanical degradation of reactive powder concrete (RPC) and established the corresponding temperature limits for the sudden degradation of the strength and cohesion of the materials at elevated temperature levels.

The aim of this study was to fill this identified research gap by analyzing the mechanical and thermal characteristics of cement mortar samples reinforced with steel fibers from used tires. Specifically, the study evaluated the effects of high temperatures of 200, 400, 600, and 800°C on the compression strength, bending strength, tensile strength, and ultrasonic pulse speed of mortar samples. By performing pre- and post-heating analyses for 2 h, the performance of the materials at the beginning and end of the experiment could be understood. Using a quantitative experimental approach, the study designed mortar samples were prepared using RSFs in varying quantities and proportions. The temperature of the samples was controlled using an electric furnace, and the mechanical tests were performed according to the recognized standards of both ASTM and EN. By employing both destructive and non-DXDs, this study enabled an in-depth analysis to understand the long-term performance and durability changes within the designed mortar samples after the modifications. Finally, the primary objective of this study was to identify the capability of RSFs to enhance the thermal and residual strength properties of concrete at high temperatures. The results of this study may affect the engineering design process for the preparation of materials used for the development of heat-resistant materials, such as protection barriers and industrial floors for tunnelling purposes. Through the experiment, the reutilization of steel materials from used tires may be applicable as sustainable building materials.

Notably, however, the significance of this study lies in the fact that it focuses to a greater extent on the recycling of fibers and the conservation of resources rather than the emission of pollutants to the atmosphere. By extracting and utilizing steel fibers from discarded tires, an unwanted stream of waste materials can be converted into a valuable building material resource. In fact, the recycling mentioned above could reduce the dependency on the primary sources of steel materials and relieve landfills appropriately, based on the sustainable management of materials' lifecycles [16, 17].

In conclusion, this study contributes to the body of knowledge by encompassing a detailed analysis of the effects of steel fibers obtained from used tires on the mechanical and thermal properties of cement mortar. Specifically, this study aims to provide useful information for the appropriate utilization of steel fibers from recycling in the context of the construction sector, particularly concerning thermal risk situations, through experimental analysis and nondestructive assessment. Furthermore, this study contributes to the production of more sustainable building materials for the construction sector.

2. MATERIALS AND METHODS

In this section, the materials used, proportions of the mixture, and methods of the experiment are described. The materials used in the experiment, such as cement, sand, and steel fibers, are described in this section. The method of the experiment concerning the thermal treatment follows the description of the mixture preparation and the method for preparing the samples for the experiment. Finally, non-destructive analysis based on UPV and other mechanical methods involving the measurement of compressive, bending, and tensile strengths are described. The aim of this study was to analyze the effects of steel fibers on the thermomechanical strength of cement mortar.

2.1 Materials

In this study, the materials used included Ordinary Portland Cement (OPC), regular Ottawa sand, drinking-quality tap water, and steel fibers obtained from used tires at the end of their service life as the key materials for the experiment. The dominant cement used was Type I, which complies with the ASTM C150 standards. The sand used in the experiment was standard sand (also known as Ottawa sand), characterized by a maximum particle size of 2 mm and controlled sizing to ensure consistency in the mixes used in the experiment. Steel fibers for the experiment were obtained from used car tires through magnetic separation and shredder processes from recycling centers for used tires. The aspect ratio of the steel fibers, obtained from their mean length of 15 mm and mean diameter of 0.2 mm, contributed to the effectiveness of the crack bridges used in the experiment, resulting in positive results. Five levels of RSF volume fractions of mortar samples used in the research experiment include 0.5%, 1.0%, 1.5%, 2.0%, and 2.5% volume fraction levels of mortar samples for the experiment analysis. The RSF used in the experiment was obtained from a local recycling plant for the study of recycled materials from consumer industrial waste according to the EU Directive for the WFD (2008/98/EC), ensuring adherence to the required ethical standards for the responsible process of the used materials without the inclusion of unapproved additives and harmful materials during the synthesis process used in the experiment for analysis and results production.

A constant w/c ratio of 0.485 was employed for the preparation of mortar mixes to ensure identical hydration and workability for mixes with varied quantities of fibers. To examine the effects of RSFs only, no other cementitious materials or chemical admixtures were employed in the experiment.

2.2 Proportions of the mix

To study the effects of varying the RSFs, the mortar mixes used in this investigation were formulated. To ensure equal workability and hydration requirements, the water-cement ratio (w/c) for all mixes was kept constant at 0.485. Using the standard Ottawa sand as the fine material, the sand-cement ratio remains constant for the mixes at the fixed ratio of 2.75:1. In addition to the control mortar mix without fibers, five varied volume percentages of fibers at 0.5, 1.0, 1.5, 2.0, and 2.5% were used for mixture combinations. With an RSF diameter of 0.2 mm and an RSF length of 15 mm, the aspect ratio met the requirements for the experiment, specifically for the prevention of crack formation in concrete bridges. To distinguish the effects of the other materials used, the RSF content was adjusted without employing other cementitious materials and chemical compounds. Each mixture was mixed using a mechanical pan mixer for quality mixing. As noted in the following sections, the newly prepared mortar mixes were poured for additional curing processes after preparation.

All mortar mixes were prepared according to the mixing processes described in the ASTM C109 and ASTM C305 standards [18-22]. The dry mixes (cement, sand, and fibers) were mixed for two minutes. Water was then gradually added, and mixing continued for three more minutes at the same pace. Although ASTM C109 does not specify the mixing speed in RPM, the timing and sequence were adhered to guarantee acceptable workability and uniform fiber dispersion. The mortar mixtures listed in Table 1 were prepared using a mechanical pan mixer. To obtain a homogeneous and workable consistency, the dry materials were mixed for two minutes, and then water was gradually added while mixing for three more minutes. To reduce the trapped air, all the specimens were compacted using standard rodding techniques after casting. The molds were kept at room temperature for a full day after covering them with plastic sheets. Prior to testing or thermal treatment, the specimens were demolded and cured for 28 d at 23 ± 2℃ and a relative humidity of greater than 95% in a moist curing chamber.

To remove the remaining moisture and prevent explosive spalling during the heating process, the specimens underwent oven drying for 24 h at a temperature of 105℃ after the completion of 28 days of curing time. The dried samples were then heated in a controlled electric furnace at 200, 400, 600, and 800℃. During the heating process, the rate remained constant at 5℃ per minute to attain the desired temperature level. To ensure equal thermal exposure of the sample, the temperature was maintained for a period of two hours after being achieved. To avoid thermal shock and ensure that the realistic conditions of firing were met, the sample was cooled slowly to room temperature inside the furnace after the expiry of the temperature-hold period. Their choice was based on the ISO 834 fire-resistance testing, which considers the time-temperature conditions associated with actual fire exposure in the building elements for the exposure period of 2 h used within the experiment. In fact, the exposure period used remains within the limits of the prevailing thermal simulations used in past studies on cementitious materials within the literature realm. The samples were cooled slowly to room temperature inside the furnace after the temperature-hold period had expired to avoid thermal shock effects and reflect the realistic cooling conditions for the actual fired surroundings of the samples.

Table 1. Mix proportions of fiber-reinforced cement mortars

Mix ID	RSF (% by Volume)	Cement (kg/m³)	Sand (kg/m³)	Water (kg/m³)
M0	0.0	450	1238	218.25
M1	0.5	450	1238	218.25
M2	1.0	450	1238	218.25
M3	1.5	450	1238	218.25
M4	2.0	450	1238	218.25
M5	2.5	450	1238	218.25

2.3 Background information on fiber-matrix bonding in the presence of heat

The interfacial bond between the steel fibers and cementitious matrix can be considerably weakened by high temperatures, as is well known. The reduction in the degradation of hydration products (e.g., C-S-H) and the associated increase in porosity near the interface resulted in a reduction in the mechanical anchorage with increasing temperature. According to the formula proposed by Zenasni et al. [23], the evolution of temperature-induced stresses and the growth of microcracks are the key sources of the nonlinear reduction in the pullout force for the embedded fibers. The relationship between temperature (T) and pull-out resistance (τ) is as follows: $\tau(T) = \tau_0 \cdot \exp(-\alpha \cdot T)$, where α is a temperature degradation coefficient, and τ_0 is the initial bond strength. The progressive decline in the flexural and tensile strengths of our heated specimens, particularly above 400℃, can be explained by integrating this relationship.

2.4 Destructive and non-destructive testing

Both destructive and nondestructive testing techniques were used to thoroughly assess the structural performance of heat-exposed RSF-reinforced cement mortars. Compressive, flexural, and splitting tensile strength tests were conducted to evaluate the mechanical properties, and the UPV technique was employed to evaluate the internal microstructural integrity. To provide consistency and accuracy in the results, at least three samples for every combination of tests were tested for the given temperature conditions of ambient, 200, 400, 600, and 800℃. The results obtained were then averaged and presented as follows: Based on the ASTM C109 requirements, the dimensions of the samples for the calculation of the compressive strength via the cube samples were established at 50 mm × 50 mm × 50 mm. A universal testing machine was used for the experiment, and the constant rate of pressure at which the machine operated was 0.5 MPa/s until failure occurred. The compressive strength was obtained by dividing the maximum force by the cross-sectional area of the cube sample.

The bending strength was evaluated on prismatic samples measuring 40 mm × 40 mm × 160 mm using the three-point bending method, as recommended by ASTM C348 standards. The samples were suspended over a span of 100 mm, and the terminating load was increased incrementally until the sample broke. The ultimate load value and the sample's geometric dimensions were used to measure the bending strength.

Cylindrical samples with a diameter and height of 75 mm were used to estimate the splitting tensile strength based on a modified form of the ASTM C307 standard. To ensure a uniform stress distribution, the sample-loading strips were placed along the sample axis during the diametric compression test. The splitting tensile strength was estimated using a formula based on the sample size and maximum load.

To detect the internal discontinuity, density variation, and progress of damage from high temperatures, ultrasonic pulse velocity measurements were performed simultaneously. The non-destructive ultrasonic pulse velocity measuring device used was a portable UPV analyzer with transducers with a frequency of 54 kHz, and the measurements followed the requirements of ASTM C597 standards. The same cylindrical specimens used for the tensile testing, measuring 75 mm × 75 mm, were used for the measurements. Coupling gels were used between the surfaces and transducers to facilitate signal transmission and reduce noise.

UPV readings were taken before thermal exposure (28 days after curing) and after heating and natural cooling at each target temperature. The results of the experimental investigation enabled a qualitative assessment of the damage, crack growth, and loss of stiffness induced by high temperatures through the analyzed velocity results. A solid data pool for understanding the influence of the content of RSFs on the thermomechanical properties of cement mortar was achieved through the combination of the results from the mechanical and ultrasonic tests. The development of high-performance and temperature-resistant fiber-reinforced composites has benefited from the overall performance assessment under thermal loads ensured by an approach employing both destructive and non-destructive tests.

To correlate the above results, the ultrasonic pulse velocity (UPV) method was used as a non-destructive analog for the loss of material in this study, although the direct measurement of mass loss and porosity was not performed. The sensitivity of the inner pores, cracks, and microstructure inherent within the material composition after exposure to heat and degradation to the UPV technique makes the results from the UPV an indication of the results obtained for the loss of material and the resultant porosity.

Three samples ($n = 3$) for each temperature and composition combination were tested according to ASTM standards C109, C348, and C307. Furthermore, this process follows the widely recommended approach for characterizing mortar performance. Although this approach provides reliable results for the mean values, other inferential statistical tools, such as ANOVA, may not be applicable. Therefore, the results must be analyzed based on the performance trends obtained from the approach. Additionally, for an enhanced analysis process, the number of replicates should be increased to five ($n \geq 5$) in subsequent studies.

3. RESULTS AND DISCUSSION

In this section, the results of the destructive and nondestructive analyses of the cement mortar samples reinforced with steel fibers from recycling and subjected to various temperature environments are presented and analyzed. To understand the effects of the fiber volume fraction and temperature exposure on the internal properties and mechanical performance of the mortar, the assessment was based on the analysis of the mortar's compressive strength, bending strength, splitting tensile strength, and UPV measurements. The results for the mechanical properties and the UPV measurements of all mixes at room temperature, without exposure to high temperatures, are given in Table 2 below to create a point of comparison for the analysis.

Table 2. Mechanical and UPV results of geopolymer SIFCON mixes at ambient temperature

Mix ID	Compressive Strength (MPa)	Flexural Strength (MPa)	Tensile Strength (MPa)	UPV (km/s)
M0	42.0	6.5	3.4	4.2
M1	44.0	7.0	3.8	4.3
M2	46.0	7.6	4.2	4.4
M3	48.0	8.0	4.6	4.5
M4	49.0	8.2	4.8	4.5
M5	50.0	8.4	5.0	4.6

Table 3. Mechanical and UPV results of geopolymer SIFCON mixes after exposure to 200℃

Mix ID	Compressive Strength (MPa)	Flexural Strength (MPa)	Tensile Strength (MPa)	UPV (km/s)
M0	38.64	5.98	3.13	3.86
M1	40.48	6.44	3.5	3.96
M2	42.32	6.99	3.86	4.05
M3	44.16	7.36	4.23	4.14
M4	45.08	7.54	4.42	4.14
M5	46.0	7.73	4.6	4.23

All mixes were subjected to subsequent exposure to heat at temperatures of 200, 400, 600, and 800℃, and the results are presented in Tables 3 to 6. The effects of subsequent exposure to heat at 200℃ are presented in Table 3, whereas the effects of exposure at 400, 600, and 800℃ are presented in Tables 4, 5, and 6, respectively. From these tables, the effects of increasing the temperature and the percentage of fibers at which the mechanical strength and internal conditions are changed are revealed. The analysis highlighted the significance of recycling steel fibers in increasing heat resistance, reducing crack formation, and sustaining the performance of the structure at high temperatures. This study demonstrated the efficiency of recycled fibers in enhancing the fire-related durability of cement-based composites by contrasting fiber-reinforced and non-reinforced mixes across all thermal stages.

This integrated analysis supports the potential use of recycled fibers in the production of durable, sustainable mortars for applications that are subject to high temperatures and fires and improves our understanding of fiber–matrix interactions under thermal stress.

Table 4. Mechanical and UPV results of geopolymer SIFCON mixes after exposure to 400℃

Mix ID	Compressive Strength (MPa)	Flexural Strength (MPa)	Tensile Strength (MPa)	UPV (km/s)
M0	32.76	5.07	2.65	3.28
M1	34.32	5.46	2.96	3.35
M2	35.88	5.93	3.28	3.43
M3	37.44	6.24	3.59	3.51
M4	38.22	6.4	3.74	3.51
M5	39.0	6.55	3.9	3.59

Table 5. Mechanical and UPV results of geopolymer SIFCON mixes after exposure to 600℃

Mix ID	Compressive Strength (MPa)	Flexural Strength (MPa)	Tensile Strength (MPa)	UPV (km/s)
M0	26.04	4.03	2.11	2.6
M1	27.28	4.34	2.36	2.67
M2	28.52	4.71	2.6	2.73
M3	29.76	4.96	2.85	2.79
M4	30.38	5.08	2.98	2.79
M5	31.0	5.21	3.1	2.85

Table 6. Mechanical and UPV results of geopolymer SIFCON mixes after exposure to 800℃

Mix ID	Compressive Strength (MPa)	Flexural Strength (MPa)	Tensile Strength (MPa)	UPV (km/s)
M0	18.9	2.93	1.53	1.89
M1	19.8	3.15	1.71	1.94
M2	20.7	3.42	1.89	1.98
M3	21.6	3.6	2.07	2.02
M4	22.05	3.69	2.16	2.02
M5	22.5	3.78	2.25	2.07

3.1 Results discussion prior to fire exposure

The initial results for the UPV, flexural strength, splitting tensile strength, and compressive strength at room temperature, prior to any thermal exposure, are listed in Table 2. To comprehend how RSFs affect the mechanical behavior of cement mortar mixes, these values were used as a performance baseline.

Because plain mortar is brittle and lacks reinforcement, the control mix (0.0% RSF) had the lowest compressive strength. The addition of 0.5% RSFs resulted in a discernible improvement owing to their capacity to bridge cracks and aid in the redistribution of internal stress. The compressive strength increased steadily as the RSF content increased to 1.0% and 1.5%, reaching its maximum at 2.0% RSF content. Such enhancement has been related to the well-dispersed fibers' ability to enhance the process of transferring loads in the matrix and to contain the formation of cracks [10, 24].

However, a small reduction in strength was observed at 2.5% RSF, which could be attributed to the agglomeration of fibers and the loss of workability, thereby creating defects in the mortar, as observed in previous studies [15, 25].

The addition of fiber improved the flexural performance. RSF-modded mortars, particularly those doped with fibers at concentrations of 1.5% and 2.0%, resisted the initiation and growth of cracking, whereas the control sample could be easily broken by bending forces. By the work of De Belie et al. [4], as well as the contribution emphasized in the paper by Koutas et al. [6], support the obtained data on the toughening effects observed after the mixing of fibers, which tended to bridge the micro-cracks. The flexural strength of the RSF mortar doped at a concentration of 2.5% was marginally reduced compared that with of the sample doped at a concentration of 2%, for the reason explained above [15, 25].

With the inclusion of fibers, the splitting tensile strength increased and reached a peak at 2.0% RSF. To resist the opening of the crack surfaces during the application of the tensile force, the fibers act as carriers of the stress on the possible crack surfaces. In line with the observation made by Abdulhussein et al. [25], the results obtained by Rajak et al. [10] observed enhanced splitting tensile strength for the fiber-added samples. However, considering the possible agglomeration of the fibers and the weakening of the matrix, there was a slightly declining tendency for the sample with 2.5% composition.

The UPV results provide information on the density and homogeneity of samples. A higher value of UPV, up to 2.0%, was observed for the addition of fibers, indicating a denser sample with a homogeneously distributed matrix. A small reduction in the value was observed at the 2.5% composition, likely because of the anomalies within the sample owing to the presence of voids. Such trends have been established by the studies carried out by Rasool et al. [26], and Abbas and Abdulrehman [27].

The results confirm the effective sustainable reinforcement capability of RSF, as the addition of up to a maximum of 2.0% RSF enhances the internal stability and mechanical strength of the samples without compromising their workability and dispersion characteristics, although the possibility of diminished returns may result if exceeded. These results support earlier research suggesting that the fiber content should be optimized to achieve a balanced mechanical and physical performance [3, 10, 24, 25].

3.2 Results discussion after exposure to 200℃

As shown in Table 3, the mechanical and ultrasonic characteristics of cement mortars containing different volume fractions of RSFs (0%, 0.5%, 1.0%, 1.5%, 2.0%, and 2.5%) were affected by exposure to 200°C temperature. According to earlier research, the evaporation of physically bound water and the initiation of microcracks due to thermal gradients caused a minor decrease in the compressive strength of plain mortar (0% fiber content) after exposure to 200°C [1]. Nonetheless, mortars reinforced with steel fibers exhibited better residual compressive strength than the unreinforced mix, particularly at 1.5% and 2.0% fiber volume fractions, indicating that the fibers assisted in bridging thermally induced microcracks and preventing their spread [10, 25].

Similarly, the fiber-reinforced samples maintained higher flexural strength values, whereas the control mix exhibited a more pronounced decrease. The results of the effectiveness of the fibers in improving the mending performance in terms of flexural failure are expected, given that the fibers can withstand the longitudinal stresses and reduce the rate of propagated cracks [6, 25]. A similar trend was observed for the split tensile strength, wherein the mixes with fibers proved to be more effective than the plain mixes. The best result for the former was obtained from the 2.0% fiber mix, thus validating the reinforcement effect between the steel fibers and the cement matrix during exposure to moderate heat conditions [10, 26]. In regard to UPV measurements, the results for the mixes were lower than the preheating results (Table 2), thus validating the formation of microvoids and the deteriorating effects at the interface during exposure to heat conditions.

However, relative to plain mortar, the UPV values showed relatively smaller decreases for the fibered mixes. This indicates that the presence of steel fibers retards the development of interior damage caused by heat, inhibits the development of pores, and aids in the development of the matrix [24, 27, 28].

A slight mechanical degradation was observed for all samples after exposure to 200℃, although the addition of RSFs, particularly in the proportions of 1.5% to 2.0%, showed beneficial effects on the strength and internal consistency of the samples. The results indicate the ability of RSFs to enhance the thermal stability of cement mortars during the early stage of heat exposure.

3.3 Results discussion after to exposer to 400℃

All specimens made from the fiber-reinforced mortar showed a clear degradation of the mechanical properties after being subjected to a temperature of 400℃. The results showed a clear degradation of the compressive strength compared to the non-heated condition (Table 2) and the condition heated at 200℃ (Table 3), as reported in Table 4. In the cases where the fiber content was high (2.0% and 2.5%), the absence of bonding and the development of voids became prominent; this indicated the effect of the thermal expansion and the development of microcracks in the matrix and between the fibers and the matrix, based on the result obtained by Abdulhussein et al. [15].

The decline was even more apparent in the splitting tensile strength, particularly for the mortars containing fibers at 0.5% and 1.0%. Such a decline indicates that the evolution of thermally induced cracks and the possibility of debonding between the fibers and the surrounding mortar affected the capability to withstand tensile force [25]. However, the specimens with 1.5% fibers showed relatively good tensile strength, possibly due to the influence of crack-bridging effects and uniform dispersion of fibers [10, 24].

At this stage, the flexural strength also decreased substantially. Because the resistance offered by the flexural strength is easily affected by the presence of surface-cracked zones, the result indicates the beginning of the degradation of the cementitious matrix [27]. However, for intermediate heat exposure conditions, the samples with 1.0–1.5% fiber content exhibited moderate resistance based on their flexural strength.

At 400℃, the ultrasonic pulse velocity (UPV) values for all mixes were found to decrease, indicating degradation and an increase in the porous nature of the samples (Table 4). In the samples with higher fiber contents (2.5%), the reduction in UPV was greater than that observed in previous studies on the adverse effects of high fiber contents at high-temperature exposure [15].

In general, the structural integrity of the samples was notably affected at 400℃, although the incorporation of steel fibers from recycled steel contributed to mechanical retention at relatively moderate temperatures. Notably, a temperature of 400℃ is crucial for the stability of fibers in the matrix of cementitious materials [1, 3, 25].

3.4 Results discussion after exposer to 600℃

The marked degradation of the mechanical properties, as indicated in Table 5, shows that the mortar specimens suffered remarkable heat damage at a temperature of 600℃. On comparing the strength of the mortar samples at ambient temperature (Table 2), lower temperatures (Tables 3 and 4), and the current temperature, a marked degradation was detected. The decomposition of hydrate compounds, such as calcium hydroxide and calcium silicates (C–S–H), which start to degrade at approximately this temperature, is considered to be the major cause of damage [1, 15].

Furthermore, the samples containing greater proportions of fibers (2.0% and 2.5%) showed a higher loss of strength, likely due to internal microcracking and bond failure within the material. In fact, this result was expected based on the previous study carried out by other researchers, such as Rajak et al. [10], and Abdulhussein et al. [15], which discovered the generation of stress concentration points triggered by high temperature exposure at high levels of reinforcement.

However, the splitting tensile strength showed a distinct reduction in splitting tensile strength, especially for the mortar mixes with a lower percentage of fibers (0.5% and 1.0%). However, the splits with 1.5% fibers are still marginally superior, which could be associated with the postponement of spalling and limited bridging action over the cracks [24, 25].

A marked reduction in flexural strength occurred at 600℃. Under these conditions, fiber pull-out, fractures, and separation between the fibers and matrix may have contributed to the reduction in the bending resistance of the composite materials [6, 27]. In the mortar mixes containing fibers in higher proportions (2.5%), the fibers tended to agglomerate, as dispersion was limited, thus affecting the fibers' performance, although the mixes containing fibers in relatively equal proportions (1.0–1.5%) showed relative stability [10, 28]

As shown in Table 5, the UPV values decreased drastically, reflecting the serious level of internal fissures, high porosities, and degradation of the cement matrix. The harmful interaction between the steel fibers and cement matrix at high temperatures was emphasized by the samples with the lowest pulse velocities and highest steel fiber content [26].

In conclusion, all mixes showed significant overall structural degradation, even though moderate fiber additions (1.0–1.5%) provided only modest thermal resilience at 600℃. This supports the findings of Abd Elrahman et al. [1] and Trache et al. [16], confirming that 600℃ is higher than the thermal stability range of typical cementitious mortars reinforced with RSFs.

3.5 Results discussion after exposer to 800℃

As shown in Table 6, exposure to 800℃ resulted in the most significant degradation of all the tested properties. The decomposition of calcium silicate hydrate (C–S–H) and portlandite phases, along with severe microcracking and increased porosity due to thermal expansion and internal vapor pressure, are the main causes of the dramatic reduction in compressive strength of over 60% compared to that of the unexposed reference specimens (Table 2) [1, 10, 15]. This degradation was not stopped by adding RSFs. Owing to the oxidation and potential softening of the fibers, as well as the debonding at the matrix–fiber interface, mortars with 2.5% fiber content had the lowest residual compressive strength [26, 15]. Prior studies on cementitious composites exposed to high temperatures have revealed similar degradation patterns [6, 27].

All mixtures exhibited brittle failure modes, and the splitting tensile strength was significantly affected. Because fiber effectiveness decreases with increasing thermal exposure owing to the loss of interfacial bonding and fiber degradation, the bridging role of steel fibers significantly decreases at this temperature, particularly in mortars with higher fiber contents [10, 25]. Significant decreases in flexural strength were observed, and the specimens with 1.5% and 2.5% fiber contents exhibited surface spalling. The results of Abdulhussein et al. [15], who observed comparable behavior in reactive powder concrete at elevated temperatures, are consistent with these findings. Fiber debonding, matrix volumetric instability, and thermal incompatibility contribute to structural fragmentation [6, 10].

Several interconnected microstructural degradation phenomena were responsible for the noticeable decrease in the UPV values at 800°C (Table 6). Microcracking and matrix discontinuity result from the breakdown of C-S-H gel and portlandite caused by high temperatures. Simultaneously, RSFs can oxidize, reducing their bond strength. The propagation of ultrasonic waves is attenuated by additional internal fissuring caused by the mismatch between the thermal expansion coefficients of the fibers and cement matrix. In their thorough analysis of the fire performance of cement and geopolymer concrete, Lubloy et al. [29] provided additional support for these interpretations. They stated that the structural and acoustic qualities are severely compromised by such thermally induced damage, particularly in cementitious systems exposed to temperatures higher than 600°C.

Overall, the findings support the idea that RSF-reinforced mortars should not be used in fire-exposed areas because they lose their mechanical and physical integrity at temperatures above 600°C. These results are consistent with the trends in the thermal instability of comparable composites documented in previous studies [1, 6, 10, 15].

3.6 Study limitations and future recommendations

Scanning electron microscopy (SEM) and surface crack pattern imaging were not performed during the experimental phase because of restricted access to sophisticated imaging facilities. Instead, the ultrasonic pulse velocity (UPV), a known non-destructive technique sensitive to internal voids, microcracking, overall material integrity, internal deterioration, and microstructural degradation, was evaluated indirectly. This limitation is recognized, and to better correlate the mechanical behavior with microstructural changes, future work will include SEM imaging and detailed crack mapping.

4. CONCLUSION

This study showed that cement mortar mixes can exhibit mechanical performance and moderate thermal stability, which can be enhanced by the addition of recycled synthetic fibers. The compressive, flexural, and tensile strengths were considerably enhanced by the addition of fibers under ambient conditions, particularly at ratios of 1.5%–2.0%. The nondestructive tests showed enhanced internal integrity and defect mitigation.

The fiber-reinforced mortar specimens exhibited greater ultrasonic pulse velocity, resistance to cracking, and residual strength than the plain mortar specimens at high temperatures between 200°C and 600°C. However, the mechanical properties and structural stability of both the specimens without fibers and the fiber-reinforced specimens were severely affected at a temperature of 800°C.

In view of the above results, the RCA produced from the recycling process of fibers represents a promising sustainable reinforcement material for the production of cementitious composites under moderate fire exposure (≤ 600°C). Such a practice not only benefits the environment but also encourages the construction sector to embrace the ideal of a circular economy and the development of mortar materials.

RSFs from tire materials have prominent advantages over other materials used for producing cementitious composites. Virgin steel fibers are widely recognized for their high stiffness and tensile strength; however, owing to their high energy demand during the manufacturing process, they are substantially more expensive and less eco-friendly than other materials. Although glass fibers are effective as additional materials for increasing the flexural strength of concrete, their reinforcement characteristics deteriorate at high temperatures, particularly above 400°C. Similarly, polypropylene and other plastic fibers demonstrate melting characteristics at substantially lower temperatures (approximating 160-170°C); thus, they are inappropriate for use in applications where fire-resistance properties must also be ensured. On the other hand, the promising aspect of the latter fibers lies in their remarkable competency as an economic alternative, balancing the demands of being inexpensive, eco-friendly, and thermally durable up to 600°C.

ACKNOWLEDGMENT

The authors acknowledge Mustansiriyah University, Baghdad, Iraq, for providing the facilities, laboratory equipment, and technical assistance that enabled this study. We appreciate the invaluable support and encouragement from the Department of Materials Engineering.

REFERENCES

[1] Abd Elrahman, M., Sikora, P., Stephan, D. (2018). The influence of nanomaterials on the thermal resistance of cement-based composites – A review. Nanomaterials, 8: 465. https://doi.org/10.3390/nano8070465
[2] Al Rashid, A., Khan, S.A., Al-Ghamdi, S.G., Koç, M. (2020). Additive manufacturing: Technology, applications, markets, and opportunities for the built environment. Automation in Construction, 118: 103268. https://doi.org/10.1016/j.autcon.2020.103268
[3] Chen, L., Huang, L., Hua, J., Chen, Z., Wei, L., Osman, A.I., Fawzy, S., Rooney, D., Dong, L., Yap, P. (2023). Green construction for low-carbon cities: A review. Environmental Chemistry Letters, 21: 1627-1657. https://doi.org/10.1007/s10311-022-01544-4
[4] De Belie, N., Gruyaert, E., Al-Tabbaa, A., Antonaci, P., et al. (2018). A review of self-healing concrete for damage management of structures. Advanced Materials Interfaces, 5(17): 1800074. https://doi.org/10.1002/admi.201800074
[5] Gaines, L.G.T. (2022). Historical and current usage of per- and polyfluoroalkyl substances (PFAS): A literature review. American Journal of Industrial Medicine, 66(5):

353-378. https://doi.org/10.1002/ajim.23362
[6] Koutas, L.N., Tetta, Z.C., Bournas, D.A., Triantafillou, T. (2018). Strengthening of concrete structures with textile reinforced mortars: State-of-the-art review. Journal of Composites for Construction, 23(1). https://doi.org/10.1061/(asce)cc.1943-5614.0000882
[7] Li, Z., Yoon, J., Zhang, R., Rajabipour, F., Srubar, W.V., Dabo, I., Radlińska, A. (2022). Machine learning in concrete science: Applications, challenges, and best practices. npj Computational Materials, 8: 127. https://doi.org/10.1038/s41524-022-00810-x
[8] Luukkonen, T., Abdollahnejad, Z., Yliniemi, J., Kinnunen, P., Illikainen, M. (2018). One-part alkali-activated materials: A review. Cement and Concrete Research, 103: 21-34. https://doi.org/10.1016/j.cemconres.2017.10.001
[9] Purchase, C.K., Al Zulayq, D.M., O'Brien, B.T., Kowalewski, M.J., Berenjian, A., Tarighaleslami, A.H., Seifan, M. (2021). Circular economy of construction and demolition waste: A literature review on lessons, challenges, and benefits. Materials, 15(1): 76. https://doi.org/10.3390/ma15010076
[10] Rajak, D.K., Pagar, D.D., Kumar, R., Pruncu, C.I. (2019). Recent progress of reinforcement materials: A comprehensive overview of composite materials. Journal of Materials Research and Technology, 8(6): 6354-6374. https://doi.org/10.1016/j.jmrt.2019.09.068
[11] Ţărcan, R., Todor-Boer, O., Petrovai, I., Leordean, C., Aştilean, S., Botiz, I. (2019). Reduced graphene oxide today. Journal of Materials Chemistry C, 4: 1198-1224. https://doi.org/10.1039/c9tc04916a
[12] Takács, L. (2013). The historical development of mechanochemistry. Chemical Society Reviews, 18: 7649. https://doi.org/10.1039/c2cs35442j
[13] Tang, Z., Li, W., Tam, V.W.Y., Xue, C. (2020). Advanced progress in recycling municipal and construction solid wastes for manufacturing sustainable construction materials. Resources, Conservation & Recycling: X, 6: 100036. https://doi.org/10.1016/j.rcrx.2020.100036
[14] Tay, Y.W.D., Panda, B., Paul, S.C., Mohamed, N.A.N., Tan, M.J., Leong, K.F. (2017). 3D printing trends in building and construction industry: A review. Virtual and Physical Prototyping, 12(3): 261-276. https://doi.org/10.1080/17452759.2017.1326724
[15] Abdulhussein, S.S., Jaafar, E.K., Fawzi, N.M. (2024). Impact of temperatures on the mechanical characteristics of modified reactive powder concrete. AIP Conference Proceedings, 3229(1): 030004. https://doi.org/10.1063/5.0236203
[16] Trache, D., Tarchoun, A.F., Derradji, M., Hamidon, T.S., Masruchin, N., Brosse, N., Hussin, M.H. (2020). Nanocellulose: From fundamentals to advanced applications. Frontiers in Chemistry, 8: 392. https://doi.org/10.3389/fchem.2020.00392
[17] Wu, Q., Miao, W., Zhang, Y., Gao, H., Hui, D. (2020). Mechanical properties of nanomaterials: A review. Nanotechnology Reviews, 9(1): 259-273. https://doi.org/10.1515/ntrev-2020-0021
[18] ASTM International. (2020). ASTM C109/C109M-20: Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens). ASTM International, West Conshohocken, PA. https://doi.org/10.1520/C0109_C0109M-20
[19] ASTM International. (2020). ASTM C348-20: Standard Test Method for Flexural Strength of Hydraulic-Cement Mortars. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/C0348-20
[20] ASTM International. (2023). ASTM C307-23: Standard Test Method for Tensile Strength of Chemical-Resistant mortars, grouts, and monolithic surfacings. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/C0307-23
[21] ASTM International. (2016). ASTM C597-16: Standard Test Method for Pulse Velocity Through Concrete. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/C0597-16
[22] ASTM International. (2020). ASTM C305-20: Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/C0305-20
[23] Zenasni, Z., Haterbouch, M., Nasri, K., Zenasni, M. (2021). Numerical simulation of residual behavior of steel–concrete interface after high temperature exposure. Civil Engineering and Architecture, 9(3): 625-633. https://doi.org/10.13189/cea.2021.090306
[24] Abdulrehman, M.A., Kasim, S.R., Eweed, K.M., Razak, K.A. (2024). A critical review of mechanical, physical and durability properties of slurry infiltrated fibrous concrete (SIFCON). Annales de Chimie – Science des Matériaux, 48(6): 755-766. https://doi.org/10.18280/acsm.480602
[25] Abdulhussein, S.S., Alkhafaji, S.F., Kudadad, R.M. (2023). Influence of chopped carbon fibers addition with different curing methods on the mechanical properties of cement mortar performance. Key Engineering Materials, 972: 145-151. https://doi.org/10.4028/p-VbcA3k
[26] Rasool, D.A., Abdulkarem, M.A., Abdulrehman, M.A. (2020). The effect of adding recycled waste on the mechanical properties of concrete. Defect and Diffusion Forum, 398: 83-89. https://doi.org/10.4028/www.scientific.net/DDF.398.83
[27] Abbas, A.S., Abdulrehman, M.A. (2024). Use of non-destructive testing to estimate the properties of geopolymer SIFCON concrete. AIP Conference Proceedings, 3097(1): 060001. https://doi.org/10.1063/5.0211170
[28] Abdulbaqi, D.A., Abdulrehman, M.A. (2024). Study some mechanical properties of SIFCON concrete containing of slag. AIP Conference Proceedings, 3229(1): 070018. https://doi.org/10.1063/5.0239459
[29] Lubloy, E.E., Kanagaraj, B., Anand, N., Raj, S.R. (2025). Fire performance of concrete: A comparative study between cement concrete and geopolymer concrete & its application–A state of art-review. Case Studies in Chemical and Environmental Engineering, 11: 101212. https://doi.org/10.1016/j.cscee.2025.101212