Impact of elevated temperature on the mechanical properties of cement mortar reinforced with rope waste fibres

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Abstract: The exposure of concrete or cement mortars to fire or other elevated temperatures negatively affects the mechanical properties, and a change may also occur in the pore structures, leading to cracking and spalling. In order to hinder or reduce the negative impact of elevated temperature on cement mortar, as well as to promote reuse of waste in the concrete industry to improve the environment, this study aims to investigate the effect of elevated temperature on the mechanical properties of cement mortar reinforced with rope waste fibres (RWF). The fibres were obtained by cutting a used polymeric rope (0.034 mm in diameter) into small fibres with average lengths of 12 mm. Four mortar mixtures, including one reference mixture (without fibres) and three mixtures containing RWF in proportions of 0.25%, 0.5% and 0.75% (by mortar weight), were cast. After 28 days of curing, the hardened specimens were air dried for at least two weeks, and some specimens were exposed to a controlled temperature of 300 and 600 °C for two hours, while the others were placed at ambient temperature. All specimens were then examined via compressive strength, flexural strength, mass loss, ultrasonic pulse velocity and visual inspection tests. The results indicated that RWF can prevent cracks appearing at 600 °C; however, the RWF had a negative impact on the compressive strength of the mortar under elevated temperatures, despite the flexural strength and UPV properties being improved significantly.

Keywords: Rope waste fibres, cement mortar, elevated temperature, mechanical properties.

1. Introduction
The exposure of concrete or cement mortars to fire or other elevated temperatures negatively affects the mechanical properties, and a change may also occur in the pore structures, leading to cracking and spalling, destroying of the bond between the cement paste and its aggregates, leading to deterioration of the hardened cement paste [1,2].

Factors affecting the strength of cement-based mortars at elevated temperatures can be divided into two groups: environmental factors and material characteristics [3]. Thus, focusing on material-related factors, the search for new mortar combinations to impede the degradation of concrete structures at high temperatures is of great importance [4]. One of the materials that has been combined with concrete or mortar to reduce the negative impact of high temperatures is polymeric fibre, as polymeric fibres have low melting points and can thus reduce internal vapor pressure after melting by creating expansion channels in the concrete, reducing the likelihood of fragmentation (spalling) [5]. Different sources of polymeric materials have been used in the literature to improve concrete (or mortar) performance under high temperatures, including polypropylene fibres [6–10] and polyethylene terephthalate (PET) [11–13].
Cleaner and more effective management of different forms of waste propagation are also of great importance for sustainability in green building, and the use of waste materials is one of the key issues faced by waste administration strategies in most parts of the world [14]. Based on this, in order to hinder or reduce the negative impact of elevated temperature on cement mortar while encouraging the reuse of waste in the concrete industry for environmental reasons, this study features the use of polymeric fibres obtained from chipping rope waste, thus investigating their influence on the mechanical properties of the mortar under high temperatures (up to 600 °C).

2. Materials and methods

The following materials were used in the manufacture of the fresh mortars tested: cement, natural sand, water, superplasticizer, and rope waste fibres (RWF). The cement (Type CEM II/A-L 42.5R) and sand meet Iraqi Standards No. 5 [15] (Table 1) and No. 45 [16] (Table 2), respectively. The superplasticizer, commercially available as Glenium 54, met ASTM C494 Type A and F [17] for use as a workability adjuster for fresh mortars. The RWFs were obtained by cutting polymeric rope fibres (0.34 mm in diameter) into small pieces (12 mm in length) as shown in Figure 1.

| Sieve opening (mm) | Accumulative passing, % | Iraqi specification No.45, zone 3 |
|--------------------|--------------------------|----------------------------------|
| 4.75               | 100                      | 90-100                           |
| 2.36               | 91.6                     | 85-100                           |
| 1.18               | 80.1                     | 75-100                           |
| 0.60               | 70.8                     | 60-79                            |
| 0.3                | 24                       | 12-40                            |
| 0.15               | 7.6                      | 0-10                             |

Figure 1: Rope waste fibres.
Four mortar mixtures were made for this study in which the cement: sand and water: binder ratios were fixed as 1:3, and 0.45 respectively. The superplasticizer was added in a proportion of 1.3% by cement weight for all mortars. The RWF were employed in four percentages: 0%, 0.25%, 0.5% and 0.75% by mortar weight. The details of these mix proportions are shown in Table 3.

Table 2: Chemical composition of cement.

| Oxides   | Content, % | Iraqi specifications No. 5/ 1984 |
|----------|------------|----------------------------------|
| CaO      | 62.1       | ----                             |
| SiO₂     | 22.1       | ----                             |
| Al₂O₃    | 4.2        | ----                             |
| Fe₂O₃    | 3.9        | ----                             |
| MgO      | 3.3        | < 5%                             |
| SO₃      | 1.9        | < 2.5%                           |
| Free lime| 0.7        | ----                             |
| L.O.I.   | 3.1        | < 4 %                            |
| L.S.F.   | 0.86       | 0.66-1.02                        |
| Insoluble residue | 1.1       | < 1.5 %                          |

Table 3: Mix proportion details by cement weight.

| Mix designation | Cement | Sand | Water/cement | Fibres (%) | Superplasticizer |
|-----------------|--------|------|--------------|------------|------------------|
| 0RWF            | 1      | 3    | 0.45         | 0          | 0.013            |
| 0.25RWF         | 1      | 3    | 0.45         | 0.25       | 0.013            |
| 0.5RWF          | 1      | 3    | 0.45         | 0.5        | 0.013            |
| 0.75RWF         | 1      | 3    | 0.45         | 0.75       | 0.013            |
* By weight of mortar.

A planetary mixer was used to mix the fresh mortars using following procedure:

- Dry materials were added to the mixer and mixed for 0.5 minutes at a slow speed (140 rpm).
- The mixer was stopped, and the mixing water (with superplasticizer) was added to the dry materials; the mixer was then operated at a slow speed for 1 minute.
- The mixer was stopped, and the speed was increased to medium (285 rpm) and the mixer was operated for 1 minute.
- In the cases with fibres, the mixer was stopped, and the speed returned to slow; then the mixer was run for 2.5 minutes with the fibres added during the first 0.5 minutes of this period as the mixer was in operation.

After the mixing was completed, the fresh mortar was poured into standard moulds and compacted using an electric vibrator. After about 24 hours, the moulds were removed, and the samples were immersed in a water tank for 27 days. The hardened specimens were then removed and dried at room temperature for at least two weeks to remove excess moisture. Samples were then divided into three groups. A portion of samples was placed in the oven and exposed to 300 °C and another was subjected to temperatures of 600 °C (for 2 hours per exposure); the final group remained at 25 °C. The programme of exposure to elevated temperatures is presented in Figure 2.

![Figure 2: Exposure of mortar specimens to elevated temperatures.](image)

For the purpose of monitoring the effect of RWF on the various properties of the hardened mortar under the influence of elevated temperatures, compressive strength, flexural strength, mass loss, ultrasonic pulse velocity (UPV), and visual inspection tests were carried out. The results were compared with those for specimens not exposed to elevated temperatures. An average of three readings (each reading from each specimen) was adopted for each test.

As standard, 100×100×100 mm cubes are used for compressive strength tests, while the flexural strength tests were executed using 40×40×160 mm prisms and calculated according to equation 1 [18].

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F = \frac{1.5PL}{b^3}
\]

where \(F\) is the flexural strength (MPa), \(P\) is the ultimate load (N), \(L\) is the distance between supports (mm), and \(b\) is the cross-section dimension of the prism.

The mass loss after exposure to elevated temperature was determined using equation 2. The UPV test was measured per ASTM C597 [19], using 100 mm cubes.
Mass loss = \frac{W_2 - W_1}{W_1} \times 100 \tag{2}

where \(W_1\) is the mass of specimen (g) before exposure to elevated temperature and \(W_2\) is the mass of specimen (g) after exposure.

3. Results and discussions

3.1 Visual inspection

In visual inspection, any sign of deterioration in the specimens, such as the presence of cracks and spalling or colour changes, were observed. In general, all of the reference and fibre-containing specimens preserved their shapes without fragmenting, even at 600 °C. Some macro cracks were noticed on specimens without fibres exposed to 600 °C, as shown in Figure 3-a. For fibre-containing mixtures, some brown lines, channels, or spots appeared at the location of the fibres on the sample surface and on the sides of the fibres (see Figure 3-b), indicating melting and possible burning of the fibres due to direct exposure to heat. However, limited or no macro cracks were observable.

![Specimens after exposure to elevated temperature: (a) without fibres, and (b) with RWF fibres.](image)

3.2 Compressive strength results

The compressive strength results for the mortar mixtures are presented in Figure 4. The presence of RWF enhanced the compressive strength at ambient temperature by 13 to 30%, with the maximum enhancement (30%) compared to the fibre-free mixture being recorded by the 0.25RWF mix. The ability of the fibres to arrest cracks at the micro and macro levels in the concrete [20] as well as to reduce the formation of cracks [21] is likely to have generated this improvement. These results are promising in terms of the reinforcing of mortar or concrete, especially when compared with other recycled polymeric fibres as used in the literature [22,23], which reduced the compressive strength of concrete.

At 300 °C, the compressive strengths of 0RWF and 0.5RWF mixtures were increased by 16% and 5% respectively in comparison to the corresponding values at ambient temperature. This strength growth can be attributed to the increase in Van der Walls force as a result of water evaporating [24,25], in addition to the further hydration that caused by the formation of heated steam [26]. However, the 0.25RWF mixture reduced the compressive strength by 7%, while the 0.75RWF mixture presented comparable values to those observed at room temperature.

At 600 °C, the reference mixture showed a reduction in compressive strength of about 29%. This reduction can be attributed to the formation of micro-cracks, which change the morphology, and a reduction in calcium hydroxide content as a result of loss of crystal water [27]. However, the residual strength of the reference mixture (compared to its initial value at ambient temperature) remained

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higher than for the RWF mixtures. Furthermore, residual strength decreased as the RWF content increased in the mixes.

![Figure 4: Compressive strength results of mortar mixtures exposed to elevated temperature.](image)

### 3.3 Flexural strength results

Figure 5 shows the results for flexural strength of the mortar mixtures. At ambient temperature, the control mixture had higher flexural strength than mixtures containing fibres. This can be attributed to the low tensile strength and modulus of elasticity of the RWF. However, at elevated temperatures, a significant improvement was shown in RWF mixtures. Compared to the corresponding values at room temperature, the 0.25RWF, 0.5RWF and 0.75RWF mixtures had residual strengths of 81%, 100%, and 76% at 300 °C compared to 54% residual strength for the control mixture. No strength losses were recorded at 0.5% addition of RWF. At 600 °C, the flexural strength values were also improved for 0.25RWF and 0.5RWF mixtures, with strength losses of 95%, 78%, 89% and 96% for 0RWF, 0.25RWF, 0.5RWF and 0.75RWF mixes, respectively. The 0.25RWF mix thus showed the best performance. The channels created as a result of melting of the RWF fibres, which reduces internal vapor pressure (and subsequent micro-cracks) may be assumed to cause this improvement in residual flexural strength.

![Figure 5: Flexural strength results of mortar mixtures exposed to elevated temperature.](image)
3.4 Mass loss results
The mass loss results at 300 °C and 600 °C are illustrated in Figure 6. The reference mixture (0RWF) showed mass losses of 7.1% and 9.7% at 300 °C and 600 °C, respectively. The mass losses of RWF mixes were 7.4%, 8.2%, and 6.1% at 300 °C and 8.9%, 11.1%, and 8.6% at 600 °C for the 0.25RWF, 0.5RWF, and 0.75RWF mixes, respectively. The losses increased as the temperature increased, which is expected behaviour. It is obvious from the results that the RWF has no significant effect on mass loss values on exposure to elevated temperature. The difference in mass at ambient temperature was also less than 2%. This mass loss is most likely caused by evaporation of capillary, interlayer, and adsorbed water [28].

3.5 UPV results
The UPV test is usually used for the evaluation of concrete quality, being sensitive to any deterioration in concrete such as internal cracking [29]. Figure 7 displays the UPV results for the mortar mixtures. At room temperature, the addition of RWF gave similar or slightly higher velocity values than in the without-fibres mixture. At 300 °C, the loss in UPV in fibres-reinforced mixtures was higher than for the control mixture, possibly as a result of melting the RWF creating voids that decrease the transmitted wave velocity through the concrete. This behaviour is supported by the fact that the UPV decreases as the porosity of the medium increases [30]. However, this was inverted at 600 °C, where the velocity losses in the presence of RWF were lower than in the control specimens. The velocity values were 1,321, 2,127, 1,490, and 1,430 m/s for 0RWF, 0.25RWF, 0.5RWF, and 0.75RWF mixes respectively. The smallest losses were given by the 0.25RWF mixture, at about 50% of its original value at ambient temperature compared to 69% for the control mixture. This enhancement in UPV for RWF mixtures at 600 °C can be considered an indication of the lack of micro-cracks within the matrix as a result of reduced internal vapor pressure from the melting of RWF fibres. These findings are supported by the flexural strength results noted above this study.
4. Conclusions
1. Using RWF for mortar reinforcement can reduce or prevent macro cracks at high temperatures (600 °C); in the absence of such fibres, multiple macro cracks were observed.
2. The existence of RWF enhances the compressive strength of mortar at ambient temperatures by 13 to 30%. Higher enhancement was recorded at 0.25RWF. In contrast, at elevated temperatures, the fibre-free specimens showed higher residual strength than RWF mixtures in comparison to their values at room temperature.
3. The inclusion of RWF fibres improved the residual flexural strength at elevated temperatures. Better performance was given by 0.5RWF at 300 °C and by 0.25RWF at 600 °C.
4. The presence of RWF had no significant effect on mass loss after exposure to high temperatures up to 600 °C.
5. The UPV losses of RWF mixtures at 300 °C were greater than for the control mixture. However, at 600 °C the velocity losses for the reference mixture were lower than for the RWF mixtures.
6. The positive role of RWF is more pronounced with regard to flexural strength and UPV tests than compressive strength.

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