Physical and mechanical behaviour of recycled PET fibre reinforced mortar

Luiz A. Pereira de Oliveira *, João P. Castro-Gomes

C-MADE, Centre of Materials and Building Technologies, University of Beira Interior, Calçada Fonte do Lameiro, 6201-001 Covilhã, Portugal

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A B S T R A C T

This study investigated the utilization of polyethylene terephthalate (PET) bottle fibre recycled as fibre-reinforced renders mortar. The fibres were obtained by simple mechanical cutting from bottles. Investigation was carried out on cement-lime mortar samples. Different volumes of fibres, i.e. 0%, 0.5%, 1.0% and 1.5%, were introduced in dry mortar mixes. Specifically, the mechanical properties as flexure, compressive strengths and mortar toughness were measured. The results indicate that the incorporation of PET fibres significantly improve the flexural strength of mortars with a major improvement in mortar toughness. The maximum volume of PET fibre for a desired workability was 1.5%.

Keywords:
Flexural strength
PET fibres
renders mortar
Toughness

1. Introduction

During the last two decades, the waste plastics have been studied as concrete and mortar components. It has been used as aggregate, as binder replacing cement and as fibre reinforcement [1]. After the polyethylene, the polyethylene terephthalate (PET) forms one of the largest fractions, in the plastic waste stream [2]. Nowadays, the literature report many plastic waste applications on mortar and concrete [3–5], specially the use of recycled PET as mortar and concrete aggregates [6–9] and as mortar and concrete fibre reinforcement [10–13]. The PET fibres additions in cementitious matrix have been an alternative to control of plastic shrinkage cracking. The plastic shrinkage cracks are widely evident in renders. This process aims to reduce energy consumption by preventing the bottles go through all cycles of industrial sides of recycled bottles. This process involves the incorporation of fibres into the matrix.

The experimental study was developed with a typical render mortar mix proportion by volume of 1:1:6, cement, hydrated lime and natural sand. To compare the mortar strength magnitude and stiffness, a typical 1:3 cement mortar composition was taken as reference mortar. Different volumes of fibres, i.e. 0%, 0.5%, 1.0% and 1.5%, were introduced in dry mortars during the mixing. Different volumes of fibres, i.e. 0%, 0.5%, 1.0% and 1.5%, were introduced in dry mortars during the mixing. In this dry mixing process, the fibres were mixed with sand and binders before being placed in the mixer. After weighing, the material is gradually introduced in a container. The fibres are manually entered the container and always on the finer material (binders). The dry mixing is carried out by three steps: Step 1: The container is shaken in the vertical and horizontal direction for about 1 min. Step 2: The mixture is performed with a hand mixer. Step 3: The mixture is performed with a hand mixer.
and horizontal for about 1 min. After the dry mixing, the dry mortar is mixed using the mixer, according EN 196-1 [19]. With the mixer in the operating position first the water was poured into the bowl and the dry mortar is added; then the mixer is immediately started at the low speed during 1 min, followed by an additional 30 s at high speed. The mixer is stopped for 1 min and 30 s. During the first 15 s, all the mortar adhering to the wall and bottom part of the bowl is removed by means of a rubber scraper and placed in the middle of the bowl. Then, the mixing is continued at the high speed for 60 s.

The mixed state was carefully observed, and neither fibre balling nor any abnormalities were observed.

2.1. Materials

A commercial Portland cement type CEM II 32.5 conforming to European Standards EN 197-1 [20] and a hydrated lime were used to produce mortars. The fine aggregate was natural sand having 0/4 mm dimensions, fineness modulus (FM) of 2.97 according to EN 1319 [21] and density of 2450 kg/m³ obtained by EN 1097-3 [22].

The polyethylene terephthalate (PET) fibres, as shown in Fig. 1, were formed by mechanical cutting of lateral sides of PET bottles. The bottle necks and the bottom of the bottles were discarded. The uniformity of fibres is ensured, especially for the dimensions length and width, by fine adjusting executed in a semi-automatic cutting machine. The fibres dimensions were approximately 2 mm width, 0.5 mm thickness and 35 mm length and their aspect ratio is 31. The Eq. (1) was used to determine the fibres aspect ratio taking into account a fibre equivalent diameter.

\[
I = \frac{1 - \frac{1}{2d_s^2} \sqrt{\frac{1}{a^2} + \frac{1}{b^2}}}{2 \times \sqrt{\frac{1}{a^2} + \frac{1}{b^2}}}
\]

(1)

where \(l\) is the fibre length in mm, \(d_s\) is the equivalent diameter, \(A\) is fibre cross section area in mm², \(b\) is the fibre width and \(c\) is the fibre thickness.

2.2. Physical and mechanical properties

Characterization of the behaviour of the render mortar was performed through measurements of properties of this product in the hardened state. It involved the determination of density, mechanical strength (flexure and compression) and capillary absorption. The mortar density was determined on six 40 x 40 x 160 mm mortars samples at the age of 28 days according to EN 1015-10 [23]. The water absorption coefficient due to capillary action of hardened mortar was determined, according to EN 1015-18 [24], at ages 7, 28 and 63 days. The compressive strength and flexural strength of hardened mortars was performed according to EN 1015-11 [25]. These tests were conducted at ages of 7, 28 and 63 days. The post-cracking fibres performance was evaluated during the bending test by measuring the loads due to deformation increasing. The test was performed on universal testing equipment (model Zwick 1435) with deflection control and the results were used to quantify the mortars toughness.

2.2.1. Toughness determination

In the absence of a specific standard for mortar, the contribution of PET fibres in the mortars toughness was assessed according to the concrete standard ASTM C 1018 [26]. Within concrete materials characterization testing, toughness is a term that provides some indication of the concrete energy absorption capability. Usually, toughness is quantified in terms of the area under a load–deflection response curve. Toughness values are specific to the testing procedure implemented. The ASTM C 1018 test method presents one means of determining the toughness of fibre-reinforced mortar. The test results are analyzed in terms of the area under the load–deflection curve up to specific deflection levels. The toughness results are then normalized by dividing the total area under the curve up to the specified deflection by the area under the curve up to the deflection at first cracking.

ASTM C1018 defines a set of toughness indices in terms of the behaviour that might be expected from a material that exhibits an elastic–plastic, flexural, load–deflection response. The points that limit the areas are defined as multiples of first cracking (\(d\)) deflection, as shown in Fig. 2.

The \(I_5\) index corresponds to the ratio between OAGH area and OAB area, and the point D corresponds to a deflection equivalent to three times the first deflection (\(d\)). The \(I_{10}\) index corresponds to the ratio between OAEF area and OAB area, and the point F is equivalent to a 5.5 x \(d\). Finally, the \(I_{30}\) index corresponds to the ratio between OAGH area and OAB area, and the point H corresponds to the deflection of 15.5 x \(d\). ASTM C 1018 recommends that the end point of the deflection and its index are selected to reflect the level of cracking and deflection required in service.

Obtaining index values of toughness on the order of 5 to \(I_5\), and 10 to \(I_{10}\), and so on, indicates that the composite has perfect elasto-plastic behaviour. Values are dimensionless and provide a reference to the proximity of the material behaviour in relation to an idealized elasto-plastic material. These indices have the advantage of presenting an evaluation of the behaviour of the fibre/matrix (composite).

From the results obtained for the toughness indices \((I_5, I_{10}, I_{20}, I_{30})\) it is possible to determine the relationship of toughness as shown by ASTM C1018, according to Eq. (2).

\[
R_{	ext{res}} = \frac{100}{I_a} \times (I_b - I_a)
\]

(2)

where \(R_{	ext{res}}\) is the residual strength index between the reference indices “\(a\)” and “\(b\)” and \(I_a\) and \(I_b\) is the toughness indices with references “\(a\)” and “\(b\)”.

3. Results and discussion

3.1. Mortar density

The hardened mortars density results, presented in Fig. 3, shows that the fibres addition causes a small decrease in density, such reduction does not exceed 5% even for 1.5% fibre volume. Whereas the density of PET fibre-reinforced mortars are around 1450 kg/m³. It is concluded that the PET fibres incorporation, used in this study, do not significantly change the density of hardened mortar.

3.2. Water absorption by capillarity

The capillary water absorption coefficients for all the dosages are shown in Fig. 4. It can be seen that the capillarity coefficient of mortar without fibre decreases from 7 to 28 days with the increasing of mortar age. At 63 days any significant change was observed in the water absorption coefficient of non-reinforced
mortar. Taking into account the standard deviation results, the same assumption can be applied for 0.5% fibre volume mortar. The highest water absorption coefficients were obtained in mortars with 1.0% fibre volume. The standard deviations of the 0.5% and 1.5% fibres mortars coefficients values leads to conclude that there was no significant difference between these mortars. The addition of fibres modifies the mortar porosity, especially around the fibres-matrix contact zone, reducing the number of capillary pores.

The standard method EN 1015-18 provides that the sample face in contact with water level should be the fractured face of the two segments resulting from the specimen prisms broken, after the bending test. Thus, in the case of mortars with fibres, these faces suffer a fracture pullout that greatly amending the vicinity of these plans. This is the more probable cause of the results variability. In the specific case of capillary absorption tests on samples with fibres would be recommendable a mechanical cutting to remove the damaged region by the fibre pullout occurred during the sample break.

3.3. Compressive strength

The results of compressive strength presented in Table 1 indicates that the fibres incorporation does not significantly change the magnitude of the mortar compressive strength. As expected, the compressive strength of the render mortar without fibres raise around 75% at 28 days. The fibres reinforced mortars were subject to the random nature of the fibre effect and the compressive strength increases of 50% for mixtures with 1.0% and 1.5% fibre volume. From 28 days to 63 days there was not observed significant changes in the compressive strength results that demonstrate a clear influence of fibres. Assuming that strength development is influenced by the sample conditioning, prescribed by EN 1015-11, it is expected that the cement hydration of mortars samples in the laboratory environment (60–70% HR) is slow and the matrix is not significantly strengthen. Fig. 5 shows a typical failure mode of compression test obtained with the mortar samples.

3.4. Flexural strength

Table 2 presents the average values of flexural strength results and their standard deviation values obtained for the reference cement mortar 1:3 and 1:1:6 mortars render. Fig. 6 shows a sample at the beginning of a typical bending test.

The results presented in Table 2 shows that the fibre incorporation in the render mortar increases the flexural strength in the order of 60% up to 100% at 7 days, 30% at 28 days and in the order of 50% at 63 days. There is any relevant effect of fibres on the flexural strength from 7 to 28 days. The strength augmentation is more significant at 63 days, where the mortar strength can attain more than the double of 7 days strength obtained with 1:1:6 mortars without fibre. Fig. 7 illustrates the typical load vs. net mid-span deflection curves from the flexural tests on mortar prisms without reinforcement, where the similarity in the curve slopes shows the same rigidity that is indifferent to the mortars ages. When the fibre content is 0% (plain mortar), the maximum load is at a deflection of 0.17–0.29 mm (deflection at the load point); following this, the load suddenly decreases.

Figs. 8 and 9 show the load vs. net mid-span deflection curves of the PET reinforced mortars. When the contents of PET fibre increase from 0.5% to 1.5%, the flexural behaviour is supposed to increase owing to the fact that a greater amount of fibre exists, which

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**Table 1**

<table>
<thead>
<tr>
<th>Mortar Proportion</th>
<th>Fibre volume (%)</th>
<th>7 days</th>
<th>28 days</th>
<th>63 days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r&lt;sub&gt;c&lt;/sub&gt;</td>
<td>σ&lt;sub&gt;r&lt;/sub&gt;</td>
<td>Average</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>1:3</td>
<td>0</td>
<td>13.72</td>
<td>1.19</td>
<td>16.31</td>
</tr>
<tr>
<td>1:1:6</td>
<td>0</td>
<td>3.27</td>
<td>0.40</td>
<td>5.69</td>
</tr>
<tr>
<td>1:1:6</td>
<td>0.5</td>
<td>5.19</td>
<td>0.49</td>
<td>4.92</td>
</tr>
<tr>
<td>1:1:6</td>
<td>1.0</td>
<td>3.64</td>
<td>0.66</td>
<td>5.44</td>
</tr>
<tr>
<td>1:1:6</td>
<td>1.5</td>
<td>3.84</td>
<td>0.34</td>
<td>5.80</td>
</tr>
</tbody>
</table>

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**Fig. 3.** Density of hardened mortar as function of mortars fibres volume.

**Fig. 4.** Capillarity coefficient as function of the mortars ages.

**Fig. 5.** Typical failure of a mortar after compressive test.
enables a greater capability of resisting the tensile stress, especially at the post-cracking stages. However, in the reality it depends of fibre random distribution in the tensile zone of the test samples. Fig. 8 shows a flexural behaviour very consistent to the precedent supposition as obtained for 28 days mortars ages, but Fig. 9 shows that this is not always valid as is the case between 0.5% and 1.0% fibre. Although in both cases the first cracking strength values are identical, their post-cracking behaviour is different with a better response provided by 0.5% of fibre volume. When the fibre content is increased, cracks form around the same deflection point at which the maximum load was reached for plain mortar; however, since the load is supported with the PET fibre, the load increases. Subsequently, the load repeatedly increases and decreases and the load is 965 N even when the deflection is 5 mm, indicating high toughness for the 1.5% fibre volume.

Table 2

<table>
<thead>
<tr>
<th>Mortar</th>
<th>Fibre volume (%)</th>
<th>7 days</th>
<th>28 days</th>
<th>63 days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Standard deviation</td>
<td>Average</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>σf – Flexural strength (N/mm²)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1:3</td>
<td>0</td>
<td>1.89</td>
<td>0.06</td>
<td>2.55</td>
</tr>
<tr>
<td>1:1:6</td>
<td>0.5</td>
<td>1.63</td>
<td>0.03</td>
<td>1.03</td>
</tr>
<tr>
<td>1:1:6</td>
<td>1.0</td>
<td>1.31</td>
<td>0.08</td>
<td>1.23</td>
</tr>
<tr>
<td>1:1:6</td>
<td>1.5</td>
<td>1.56</td>
<td>0.14</td>
<td>1.37</td>
</tr>
</tbody>
</table>

The fibres volume of 1.5% that gives the best renders mortar performance was the maximum volume possible to be incorporated in fresh mortar consistent with desired mortar workability.

3.5. Toughness test

Toughness indices $I_5$, $I_{10}$, $I_{30}$, residual strength factors $R_{5,10}$, $R_{10,30}$ and first crack strength were obtained according to ASTM C1018 standard. The results of the toughness parameters for 0.5%, 1.0% and 1.5% of PET fibre volume on render mortars are reported in Table 3.

As expected, the fibres had no influence on the toughness of the mortars up to the first crack, since they do not affect both the ultimate strength and the elasticity modulus. On the other hand, the toughness indices could not be measured in non-reinforced mortars since as shown in Fig. 7 they failed in a fragile way as soon as the first crack appeared.
Fig. 10 illustrates the effect of fibre volume on the flexural toughness indices of mortars. It is observed an increase of the toughness indices with the fibre volume. However, the effect of the age on the toughness of the PET fibre-reinforced mortars is more evident from 7 to 63 days, as can be seen in the figure.

Taking into account the results of residual strength factors shown in Table 3, it is concluded that the critical fibre volume is approximately 1.0% at the ages of 7 and 63 days. The critical volume corresponds to residual strength factors close to 100, which features elasto-plastic behaviour.

The residual strength factor values obtained for mortar with 1.5% fibre lead, in all ages, to an optimum of fibres amount that gives to the mortar a reinforced character with large energy absorption, especially at the ages of 7 and 63 days. Fig. 11 shows the residual strength factors of fibres reinforced mortar at different ages, where it is observed that the residual strength increases as function of fibre volume. At 28 days the residual strength factors decreases slightly for 1.0% fibre volume and more sharply to the case of 1.5%. Such behaviour is consistent with the results obtained for the flexural strength presented in Table 2. It is also possible that the samples conditioning method already mentioned in Section 3.3 could disturb the results, nevertheless the values are close to 100 that confirm the efficiency of PET fibres.

These results are indicative of good performance of fibre obtained by recycling of PET bottles and endorse the importance of further studies that may provide a performance comparison with other synthetic available fibres.

4. Conclusion

The detailed results obtained in this study lead to the following primary conclusions:

- The density of hardened mortar is not significantly altered by incorporation of PET fibres in the volumes and sizes here studied.
- The water capillary absorption determination prescribed by EN 1015-11 does not fit perfectly to the case of mortars with fibres such as those studied in this work, considering that the pullout of the fibres during the test undermines the structure adjacent to samples fracture faces;
- The PET fibres incorporation does not significantly change the magnitude of the mortar compressive strength.
- The PET fibre incorporation in the render reference mortar (1:1:6) increases the bending strength about 100% at 7 days, 30% at 28 days and the order of 50% at 63 days. The volume of PET fibre of 1.5% is the optimum volume for the best performance of the mortar.

The residual strength factors values obtained for 1.5% fibre reinforced mortar leads, in all ages, to an optimum fibres amount that

<table>
<thead>
<tr>
<th>Mortar proportion</th>
<th>Fibre volume (%)</th>
<th>7 days</th>
<th>28 days</th>
<th>63 days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$I_5$</td>
<td>$I_{10}$</td>
<td>$I_{30}$</td>
</tr>
<tr>
<td>1:01:06</td>
<td>0.5</td>
<td>4.7</td>
<td>8.9</td>
<td>21.3</td>
</tr>
<tr>
<td>1:01:06</td>
<td>1.0</td>
<td>5.2</td>
<td>10.3</td>
<td>28.8</td>
</tr>
<tr>
<td>1:01:06</td>
<td>1.5</td>
<td>5.7</td>
<td>12.5</td>
<td>38.2</td>
</tr>
</tbody>
</table>

Fig. 10. Flexural toughness indices of PET reinforced mortars at 7, 28 and 63 days.

Fig. 11. Effect of age on residual strength factors of PET fibre-reinforced mortars.
gives to the mortar a reinforced character with large energy absorption, especially at the ages of 7 and 63 days. These findings are indicative of good performance of the fibres and enable in part the recycling of PET packaging.

References