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On the use of R-PET strips for the reinforcement of cement mortars

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ABSTRACT

We study the alkali resistance and the flexural response of a cement-based mortar reinforced through polyethylene terephthalate (PET) strips obtained through hand cutting of ordinary post-consumer bottles. On considering 1% fiber volume ratio and different strip geometries, we show that the analyzed reinforcing strips owe remarkable alkali resistance and are able to markedly improve the toughness of the base material. Comparisons are established with the outcomes of a recent study on a similar reinforcement technique of a cement–lime mortar.

1. Introduction

Over the last two decades, plastic materials have been widely investigated and experimented as concrete and mortar components, such as, e.g., aggregates, reinforcing fibers and binders. Commercially available construction materials usually include virgin plastic elements, while recycled plastic is receiving growing interest in the scientific community, since researches conducted in recent years have shown that several construction materials incorporating waste plastics combine remarkable thermo-mechanical properties with economic and environmental benefits. Mahdi et al. [1] analyze the mechanical properties of polymer mortars and concretes, proposing different mix-designs that include resins derived from recycled polyethylene terephthalate (R-PET). Concretes and mortars including R-PET aggregates are instead studied in [2–6]. It has been found that the partial replacement of traditional coarse and fine aggregates with R-PET aggregates may lead to significant beneficial effects in terms of weight reduction and post-cracking strength of the material. Concerning the use of R-PET fibers for concrete reinforcement, we refer the reader to [7–12] for an extensive literature review. The R-PET reinforcement of a render mortar through PET strips hand cut from post-consumer bottles is analyzed in a recent work by Pereira de Oliveira and Castro-Gomes [13]. Such a study investigates on the physical properties, the first-crack strength and the toughness of a cement–lime mortar. Different volume fractions of R-PET strips with fixed aspect ratio (ranging from 0% to 1.5%) are added to the mix design, and noticeably increases of the flexural properties of the examined mortar are observed in presence of the R-PET reinforcement. A similar reinforcement technique of a Portland concrete is analyzed in [11], considering both lamellar and 'O' shaped strips (or fibers).

The present work deals with an extension of the study presented in [13] to cement-based mortars. A commercial cement mortar is reinforced through R-PET strips of different lengths and fixed width and thickness, which are obtained through hand cutting of ordinary post-consumer PET bottles. We study the alkali resistance of the examined R-PET strips, and the flexural properties of the mortar reinforced at 1% fiber volume fraction. The remainder of the paper is organized as follows. In Section 2 we describe the employed hand cutting technique of post-consumer PET bottles. Section 3 is devoted to the analysis of the alkali resistance of the analyzed R-PET strips. The preparation of fiber-reinforced mortar specimens is outlined in Section 4, while an extensive analysis of the flexural response of such specimens is presented in Section 5. Here, some comparisons are established between the flexural responses of the cement-based mortar analyzed in this paper, and the cement-lime mortar analyzed in [13]. We draw the main conclusions of the present study and describe future work in Section 6.

2. Hand cutting of PET strips from post-consumer bottles

Following [13], we examine a low-cost reinforcing technique of cementitious mortars, which is based on the insertion of R-PET strips of various length into a commercial mortar. The examined strips are obtained through hand cutting of post-consumer PET bottles with 1.5 l capacity, square cross-section, 0.5 mm thickness,

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and corrugated surface (Fig. 1, top). We begin the hand cutting process by removing the neck and the base of the PET bottles through ordinary scissors. We then longitudinally cut the lateral surface of the bottles obtaining macroscopic R-PET strips with 11 mm width and 200 mm length (Fig. 1, center). In a third and final step, we transversally cut the above macro-strips into a number of smaller strips having 2 mm width and three different lengths: 11.3 mm (hereafter named 'R-PET 1.13' strips, cf. Fig. 1, bottom-left); 22.6 mm ('R-PET 2.26' strips, Fig. 1, bottom-center), and 35 mm ('R-PET 3.50' strips, Fig. 1, bottom-right). It is worth noting that the 'R-PET 3.50' strips coincide with the fibers examined in [13].

3. Alkali resistance of R-PET strips

We measure the alkali resistance of the R-PET strips described in the previous section according to the procedure given in [8], which consists of measuring the tensile strength of the strips before and after their immersion in an alkaline solution at 60 °C for 120 h (5 days). The attack solution contains 10 g of sodium hydroxide and 1 dm^3 of distilled water. By averaging tension test results over a set of six 0.5 mm × 20 mm × 200 mm strips, which were suitably bone shaped at the extremities (six tests before alkali attack and six tests after alkali attack), we found that the tensile strength of the analyzed PET after alkali attack was 87% of that before attack. In [8] such a *strength ratio* s_r was found equal to 99% for monofilaments extruded from recycled PET material, while for polypropylene (PP) and for polyvinyl alcohol (PVA) extruded monofilaments s_r was found equal to 86% and 56%, respectively. It can be argued that PET material simply excised from ordinary post-consumer bottles owes a considerable alkali resistance, which is aligned with that observed in the PP monofilaments analyzed in [8].

4. Preparation of mortar specimens

As we already noticed, the recent study by Pereira de Olivera and Castro-Gomes [13] deals with the R-PET reinforcement of a cement-lime mortar, which features 1:1:6 volume proportions of cement, hydrated lime and natural sand, respectively, and flexural strength of about 1 MPa, in absence of reinforcement.

In order to study the effects of the same reinforcement on a high performance, cement-based mortar, we examine in this study a cement mortar kindly provided by Caparol Italiana GmbH & Co. KG of Vermezzo (Milan, Italy), an internationally renowned company producing concrete protection and repair products (www.caparol.it). The examined mortar has the commercial name 'Disbocret Unitech R4' and is resistant to aggressive environmental agents, such as salts and carbonation, crazing and cracking. The manufacturer recommends its use for restoring missing parts of concrete elements with thickness variable from 1 to 5 cm.

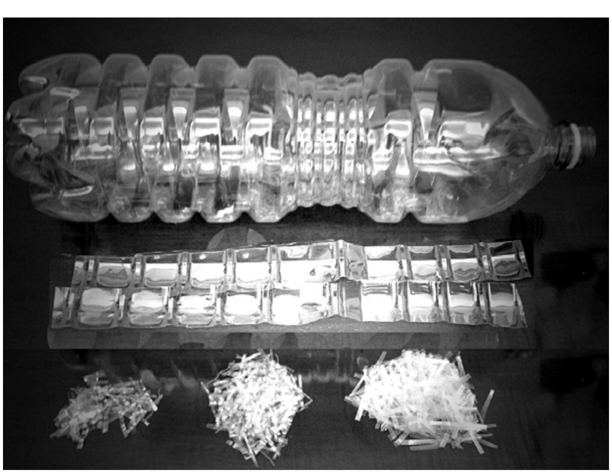

Fig. 1. Hand cutting of R-PET strips from post-consumer bottles. Top: exemplary of the examined bottles; center: macro-strips obtained through longitudinal cutting of the bottle; bottom final 'R-PET 1.13 (left), 'R-PET 2.26' (center) and 'R-PET 3.50' (right) strips.

We prepared prismatic mortar specimens to be subjected to bending tests (cf. the next section), and reinforced several of them with 'R-PET 1.13, 'R-PET 2.26', and 'R-PET 3.50' strips at 1% volume content. The procedure that we adopted for mixing the reinforcing strips with the base mortar included the following steps. First, we separately weighted R-PET strips and dry mortar. We then introduced the target quantities of such components into a container and we hand mixed the resulting composite, in order to uniformly distribute R-PET strips into the mortar matrix. Next, we added water to the mixture (180 cc of water for each kg of mortar) and we mechanically shacked the composite according to manufacturer's directions (the whole preparation process was performed in collaboration with Caparol's technical staff). The hydrated mixture was cast into 40 mm × 40 mm × 160 mm molds. Each specimen was conserved at room temperature for 24 h, and then demolded and cured in water at 23 °C up to testing. Throughout the paper, we name 'UNR' the plain Disbocret Unitech R4 mortar. We instead use the shorthand notations 'R-PET 1.13', 'R-PET 2.26', and 'R-PET 3.50' to denote the Disbocret Unitech R4 mortar reinforced with the corresponding R-PET strips at 1% strip volume fraction. Finally, we denote the cement-lime unreinforced mortar analyzed in [13] by 'UNR-CLM', and the same mortar reinforced with R-PET 3.50' strips at 1 % volume content by 'R-PET-CLM'.

5. Flexural response of mortars reinforced through R-PET strips

We investigate on the flexural behavior of the mortars under examination through Third Point Loading (TPL) tests. As in [13], we perform TPL tests on 40 × 40 × 160 mm specimens and measure average values of the first-crack strength, toughness indices and residual strength factors defined by ASTM C1018 [14] for the 'UNR', 'R-PET 1.13', 'R-PET 2.26', and 'R-PET 3.50' mixtures, over a sample of four specimens for each material. Illustrative load–deflection curves at 7 and 28 days of curing are shown in Figs. 2 and 3, respectively (two exemplary curves for each material). The following sections illustrate the outcomes of the present experimental analysis, establishing comparisons with analogous results presented in [13]. The present analysis was carried out in collaboration between the Structural Engineering Laboratory of the University of Salerno and the Geoconsult Laboratory of Manocalzati (Avellino, Italy).

5.1. First-crack strength

The first-crack strength f_{lf} was defined according to [14], in correspondence with the first peak of the load–deflection response.

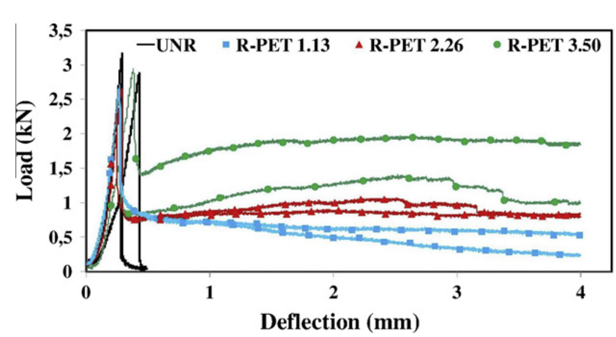

Fig. 2. Load–deflection curves of tested mortars at 7 days.

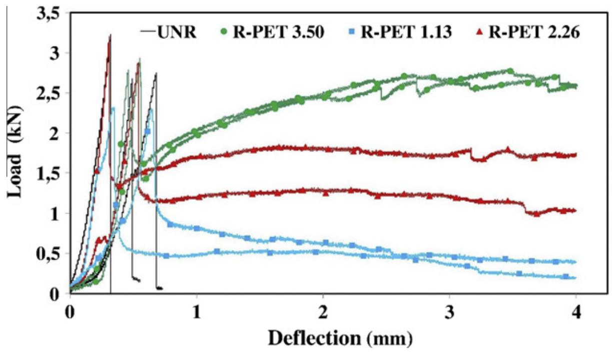

Fig. 3. Load–deflection curves of tested mortars at 28 days.

Tables 1 and 2 show the average values and the standard deviations of the results we obtained for UNR, R-PET 1.13, R-PET 2.26 and R-PET 3.50 at 7 and 28 days, respectively, together with the comparison values given in [13] for UNR-CLM and R-PET-CLM. In such tables, FRR denotes the Fiber Reinforcement Ratio defined as follows.

$$\mathrm{FRR} = \frac{f_{lf} - f_{lf}^0}{f_{lf}^0} \tag{1}$$

where f_{lf} is the first-crack strength of the current R-PET reinforced mortar, and f_{lf}^0 is the corresponding value of the base material (no R-PET reinforcement). The results in Tables 1 and 2 highlight negative FRRs (i.e., decreases in the first-crack strength due to the addition of R-PET strips to the mix design), for all the fiber reinforced mortars analyzed in the present work (R-PET 1.13, R-PET 2.26 and R-PET 3.50). An opposite trend was observed in [13], where instead remarkable increases of f_{lf} were recorded in presence of R-PET 3.50 strips, especially at 7 days. Nevertheless, referring to the present results, it is worth observing that the reduction of f_{lf} significantly decreases as the length of the reinforcing strips increases. In particular, the first-crack strength of the R-PET 3.50 mortar essentially coincides with that of the base mortar after 28 curing days (cf. Table 2). It is worth noting that the cement-based mortar analyzed in the present study exhibits $f_{lf} = 2.88$ MPa at 28 days in absence of R-PET reinforcement (UNR case), while the UNR-CLM mortar analyzed in [13] features $f_{lf} = 1.03$ MPa after the same curing period. Passing from 7 to 28 curing days, it can be observed that the first-crack strength increases in R-PET 2.26 and R-PET 3.50, and slightly decreases in R-PET 1.13 (cf. Tables 1 and 2).

5.2. Toughness indices and residual strength factors

According to ASTM C1018 [14,13], the toughness of each mortar specimen is measured through the area under the corresponding load–deflection curve, which is obviously related to the energy absorption capacity of the material. Let $\delta, \bar{\delta}$, and $A(\delta)$ denote the current deflection, the value of δ in correspondence to the first-crack load, and the area under the load–deflection curve up to δ, respectively. We introduce the following *toughness indices*:

$$I_5 = \frac{A(\delta_5 = 3\bar{\delta})}{A(\bar{\delta})}, \quad I_{10} = \frac{A(\delta_{10} = 5.5\bar{\delta})}{A(\bar{\delta})},$$
$$I_{20} = \frac{A(\delta_{20} = 10.5\bar{\delta})}{A(\bar{\delta})}, \quad I_{30} = \frac{A(\delta_{30} = 5.5\bar{\delta})}{A(\bar{\delta})} \tag{2}$$

and the *residual strength factors*

$$R_{a,b} = \frac{100}{b-a} \times (I_b - I_a) \tag{3}$$

The latter are related to the load-carrying capacity of the material after crack onset. Referring to the deflection range (δ_a, δ_b) and assuming linear force–deflection response up to $\bar{\delta}$, it can be easily verified that a perfectly plastic post-crack behavior corresponds to $R_{a,b} = 100$ (cf. also [13]). Tables 3 and 4 show the average values of the above toughness indices and residual strength factors determined for R-PET 1.13, R-PET 2.26 and R-PET 3.50 after 7 and 28 days of curing, respectively, together with the values of analogous quantities provided in [13] for R-PET-CLM. Since the load–deflection curves determined in the present work typically terminate at $\delta < 15.5\bar{\delta}$ (varying from one material to another), we replace the quantities I_{30} and $R_{10,30}$ analyzed in [13] with I_{20} and $R_{10,20}$, respectively, for R-PET 1.13, R-PET 2.26 and R-PET 3.50. Toughness indices and residual strength factors could not be computed for the UNR mortar, due to the brittle behavior of such a material, which features a sudden drop to zero of the load after crack onset (cf. Figs. 2 and 3). As seen in Table 4 and Fig. 3, the present R-PET 3.50 mortar exhibits residual strength factors greater than 100 in the post-crack regime at 28 days ($R_{5,10} = 135.22, R_{10,20} = 150.80$) differently from R-PET-CLM, which instead features $R_{5,10} = 86.3$, and $R_{10,30} = 87.5$. Higher mechanical performances of the cement-lime mortar analyzed in [13] were observed in presence of R-PET 3.50 strips at 1.5 % volume content. Comparing Tables 4 and 3, one realizes that the residual strength factors

Table 1
First-crack strengths at 7 days.

Material id	Avg. (MPa)	St. dev. (N/mm^2)	FRR (%)
UNR	2.93	0.22	0
R-PET 1.13	2.47	0.36	−15.6
R-PET 2.26	2.53	0.17	−13.7
R-PET 3.50	2.76	0.16	−5.7
UNR-CLM	0.80	0.05	0
R-PET-CLM	1.56	0.14	+95.0

Table 2
First-crack strengths at 28 days.

Material id	Avg. (MPa)	St. dev. (N/mm^2)	FRR (%)
UNR	2.88	0.30	0
R-PET 1.13	2.31	0.01	−19.79
R-PET 2.26	2.83	0.39	−1.73
R-PET 3.50	2.86	0.10	−0.69
UNR-CLM	1.03	0.02	0
R-PET-CLM	1.23	0.04	+19.41

Table 3
Average flexural toughness indices and residual strength factors at 7 days.

Material id	I_5	I_{10}	I_{20} (I_{30})	$R_{5,10}$	$R_{10,20}$ ($R_{10,30}$)
R-PET 1.13	2.09	3.06	3.98	19.29	11.37
R-PET 2.26	3.10	5.51	9.43	56.72	39.25
R-PET 3.50	3.47	7.12	13.90	72.88	67.84
R-PET-CLM	5.2	10.5	(28.8)	104.2	(91.9)

Table 4
Average flexural toughness indices and residual strength factors at 28 days.

Material id	I_5	I_{10}	I_{20} (I_{30})	$R_{5,10}$	$R_{10,20}$ ($R_{10,30}$)
R-PET 1.13	2.25	3.39	4.08	22.74	14.29
R-PET 2.26	3.13	5.96	11.91	57.22	59.35
R-PET 3.50	5.29	12.05	27.13	135.22	150.80
R-PET-CLM	5.1	9.8	(27.3)	86.3	(87.5)

increase with the curing period in all the R-PET reinforced mortars analyzed in the present study. The highest increase rates are observed in the R-PET 3.50 mortar.

6. Concluding remarks

We have expanded the investigation presented in [13] on the reinforcement of cement-lime mortars through hand cut R-PET strips, on considering a high-performance, cement-based mortar (Disbocret Unitech R4) distributed by Caparol Italiana GmbH & Co. KG of Vermezzo (Milan, Italy), and R-PET strips of various lengths. The outcomes of the present study indicate that the reinforcement through hand cut R-PET strips may lead to different beneficial effects in presence of different mortar matrices. In the case of the Disbocret Unitech R4 mortar, we have observed slight decreases of the first-crack strength due to the R-PET reinforcement (up to 28 days of curing), which vary with the strip length and become almost negligible in presence of R-PET 3.50 strips. On the contrary, the results presented in [13] indicate marked increases of the same property when the R-PET 3.50 strip reinforcement is applied to a cement-lime mortar. It is worth noting that the latter owes a base value of the first-crack strength (1.03 MPa at 28 days) much lower than the first-crack strength exhibited by the Disbocret Unitech R4 mortar (2.88 MPa at 28 days). For what concerns flexural toughness indices and residual strength factors, we instead observe that the analyzed R-PET reinforcement is more effective in the cement-based mortar Disbocret Unitech R4 than in the cement-lime mortar analyzed in [13]. Reviewing the reinforcing properties of the different R-PET strips analyzed in the present work, we conclude that the R-PET 3.50 strips feature the best reinforcement performance, ensuring essentially the same first-crack strength of the base Disbocret Unitech R4 mortar at 28 days, and an excellent post-crack response. The latter shows a load drop followed by a hardening branch and a nearly horizontal plateau after the first-crack load (cf. Fig. 3). The reinforcement with R-PET 2.26 strips instead leads to a slight decrease of the first-crack strength (−1.73% at 28 days), as compared to the UNR case, and determines a reasonably good post-crack response, which features a load drop and a nearly horizontal plateau after the first-crack peak. Finally, the reinforcement with R-PET 1.13 strips leads to a noticeable decrease of the first-crack strength over the UNR case (−19.79% at 28 days), a marked load drop and a slightly softening behavior in the post-crack regime. It has to be remarked, however, that all the R-PET reinforcements analyzed in the present study prove to be beneficial in terms of material toughness. The alkali resistance of such reinforcements is comparable with that of the PP monofilaments analyzed in [8].

In future work we intend to enrich the experimental analysis presented in this study, on considering alternative R-PET reinforcements of cement-based mortars (R-PET monofilament reinforcements; different aspect ratios of reinforcing fibers/strips, etc.), and carrying out investigations on the optimal reinforcement strategy through evolutionary algorithms [15]. We also plan to develop mechanical models of the flexural response of fiber-reinforced concretes and mortars, by combining crack-bridging approaches with variational fracture models [16–19].

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