An experimental study on the cement mortar reinforcement through recycled nylon fibers

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Abstract

We investigate engineering applications of recycled nylon fibers obtained from waste fishing nets, focusing our attention on the use of recycled nylon fibers as tensile reinforcement of cementitious mortars. We begin by characterizing the tensile behavior of both unconditioned and alkali-cured recycled nylon fibers obtained through manual cutting of waste fishing net filaments, with the aim of assessing the resistance of such materials to chemical attacks. Next, we deal with compression and bending tests on cementitious mortars reinforced with recycled nylon fibers, and establish comparisons with the experimental behavior of the unreinforced material. In our analysis of different weight fractions and aspect ratios of the reinforcing fibers, we observe marked increases in the tensile strength and toughness of the nylon reinforced mortar, as compared with the unreinforced material. The presented results emphasize the high environmental and mechanical potential of recycled nylon fibers for the reinforcement of sustainable construction materials.

Keywords: fiber reinforced mortar; recycled nylon; waste fishing nets; flexural strength; toughness.

1 INTRODUCTION

Protection of the sea environment is one of the most serious issues of this time. In addition to the known causes of environmental degradation, such as pollution, overbuilding of the coast, unconscionable fishing, and coastal erosion, the indiscriminate abandonment of fishing nets on the seabed can cause a growing form of desertification of marine ecosystems. While in the past fishing nets were made of biodegradable natural materials such as cotton and linen, nowadays the nets are typically made of plastic. Fishing net plastics are generally not biodegradable, and therefore it is extremely important to enhance their recycling in order to dispose of wastes, lower the cost of the resulting products, reduce energy consumption and emissions of CO_2 into the atmosphere. It is worth noting that recent studies have shown that several waste materials can be profitably employed to manufacture low-cost reinforcement techniques of structural and non-structural materials in the construction industry (refer, e.g., to [1],[2],[3],[4] and the references therein).

Polypropylene (PP) and polyamide (PA) fibers have been successfully used in cementitious materials to control shrinkage cracking, to improve material toughness and impact resistance, and to increase significantly the energy absorption capacity of the material [5],[6],[7]. Such virgin plastic fibers might guarantee better mechanical performance than recycled plastics, but inevitably require larger energy consumption and CO_2 emissions. Among recycled plastics, the reinforcement of cementitious materials through recycled polyethylene terephthalate (R-PET) fibers has received particular attention in the technical literature. Several authors have shown that R-PET fibers can conveniently replace virgin plastic fibers in eco-friendly concretes, providing good mechanical and chemical strengths to the final material [8],[9],[10],[11][12],[13],[14],[15],[16]. More recently, the R-PET reinforcement of cementitious mortars has also received some attention in the literature [17],[18]. It should be noted, however, that the use of recycled materials in cementitious mortars remains only very partially investigated. The same holds with respect to the use of nylon fibers as mortar reinforcements. A recent study by Ozger et al. [19] investigates the recycling of nylon fibers from post-consumer textile carpet waste and their use for concrete reinforcement. Ogzer and coauthors describe the preparation of nylon fiber-reinforced concrete and the identification of its thermo-mechanical properties, such as compressive and tensile strengths, toughness, specific heat capacity, thermal conductivity, thermal expansion, and hygrometric shrinkage. The results presented in [19] highlight that concretes reinforced with recycled nylon fibers have more ductile and tougher behavior than the unreinforced material, and suffer minor drying shrinkage. Such advantages are however balanced by slight reductions of the tensile strength, maximum load-bearing capacity, and modulus of elasticity.

We deal in the present work with the reinforcement of a commercial cementitious mortar (*Disbocret Unitech R4* kindly provided by Caparol GmbH & Co of Vermezzo, Milan) through recycled nylon (R-Nylon) fibers extracted from abandoned and sized fishing nets. The latter were recovered by Omega Plastic srl (Battipaglia, Salerno, Italy) at Italian harbors. It is worth noting that a large quantity of abandoned fishing nets are scattered on the seabed in Italy, causing a growing form of desertification of marine ecosystems. Other abandoned fishing nets are collected on the docks, after the seizure by the Port Authorities. Omega Plastic deals with the recovery of plastic from abandoned and/or seized fishing nets. Such an activity is particularly useful for many Italian Port Authorities that are not currently able to handle such waste materials. After the collection, the fishing nets are cleaned from residues of other products, classified by type of polymer, and cut and packed for storage. The final product is often finished through extrusion and polymerization by companies working in the recycling of plastic materials. The R-Nylon (short) fibers analyzed in the present work are instead obtained through manual cutting of fishing nets kindly provided by Omega Plastic, with the aim of analyzing a purely mechanical recycling process that does not involve energy consumption and CO2 emissions. We begin by performing a preliminary mechanical characterization of the tensile strengths of both unconditioned R-Nylon fibers, and alkali-conditioned R-Nylon fibers, in order to assess their resistance to chemical attacks. Next, we conduct compression and bending tests on mortar specimens reinforced with R-Nylon fibers, comparing the results of such tests to analogous ones referred to the unreinforced mortar. We analyze different fiber weight fractions and aspect ratios of R-Nylon fibers. The given results indicate that the examined R-Nylon fibers significantly improve the tensile and fracture properties of the base material, as we observe up to 35% increases in tensile strength, and a ductile failure mode in the R-Nylon reinforced mortar. The work is completed by comparisons with available literature results on mortars and concretes reinforced through recycled materials.

2 MATERIALS AND METHODS

2.1 R-Nylon fibers and mortar

We analyze reinforcing fibers obtained from waste fishing nets recovered and processed by Omega Plastic srl. Such materials were collected at Italian harbors, cleaned from residual products, and manually cut to obtain reinforcing fibers of convenient length. The examined fishing nets are made of aliphatic polyamide 6 (commonly referred to as “nylon 6”). Such a material is widely used in many industrial applications due to its good mechanical and chemical properties, such as, e.g., enhanced toughness and chemical resistance. We performed the manual cutting of the above fishing nets in order to obtain R-Nylon fibers to be used for different purposes. At the time of supply, nylon 6 fibers were woven in a square mesh with sides equal to 40 mm. We hand-cut such a mesh into fibers of the desired length. In detail, we cut 200 mm filaments, each including four knots, to be used for uniaxial characterization tests; and short fibers of different lengths, not including knots, to be employed for mortar-reinforcing purposes.

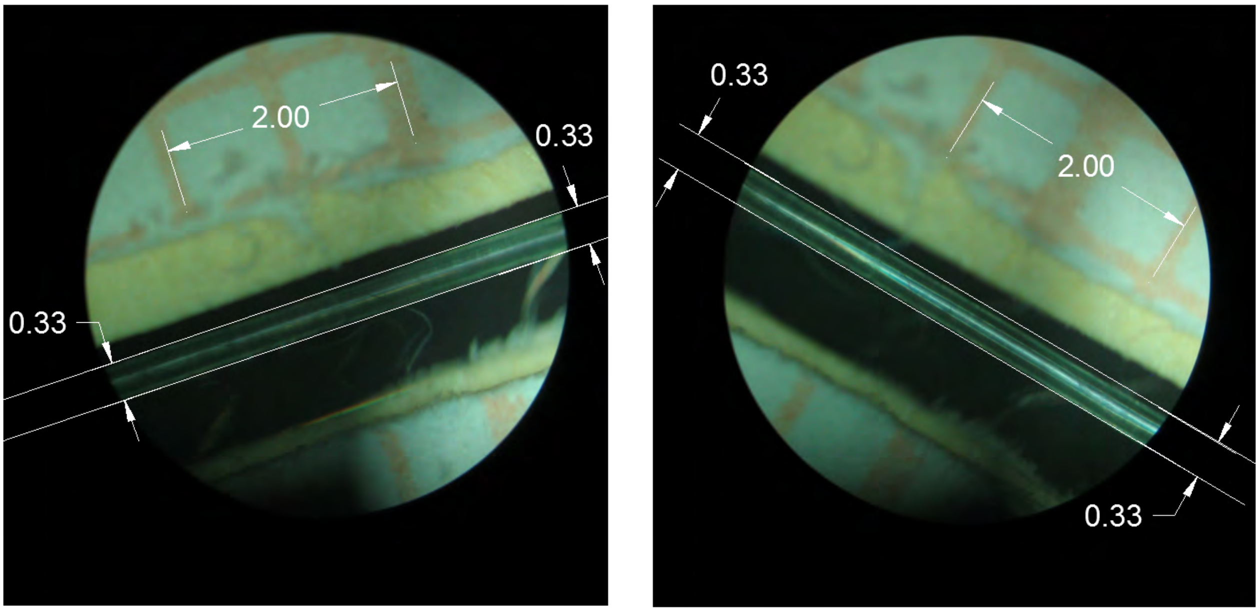
Figure 1 – Examined Nylon 6 waste fishing nets.

The employed mortar consisted of the commercial product *Disbocret Unitech R4*, which was produced and kindly supplied by Italian Caparol GmbH & Co of Vermezzo (Milan, Italy). Such a mortar is aimed at repairing damaged concrete, and includes nanometric reinforcing fibers aiming at enhancing material thixotropy and shrinkage resistance. According to the producer datasheet, the Disbocret Unitech R4 owes the following mechanical properties:

- strength class R4, according to EN 1504;
- bond to existing concrete greater than 2 MPa (EN 1542);
- Young's modulus of elasticity greater than 20 GPa (EN 13412).

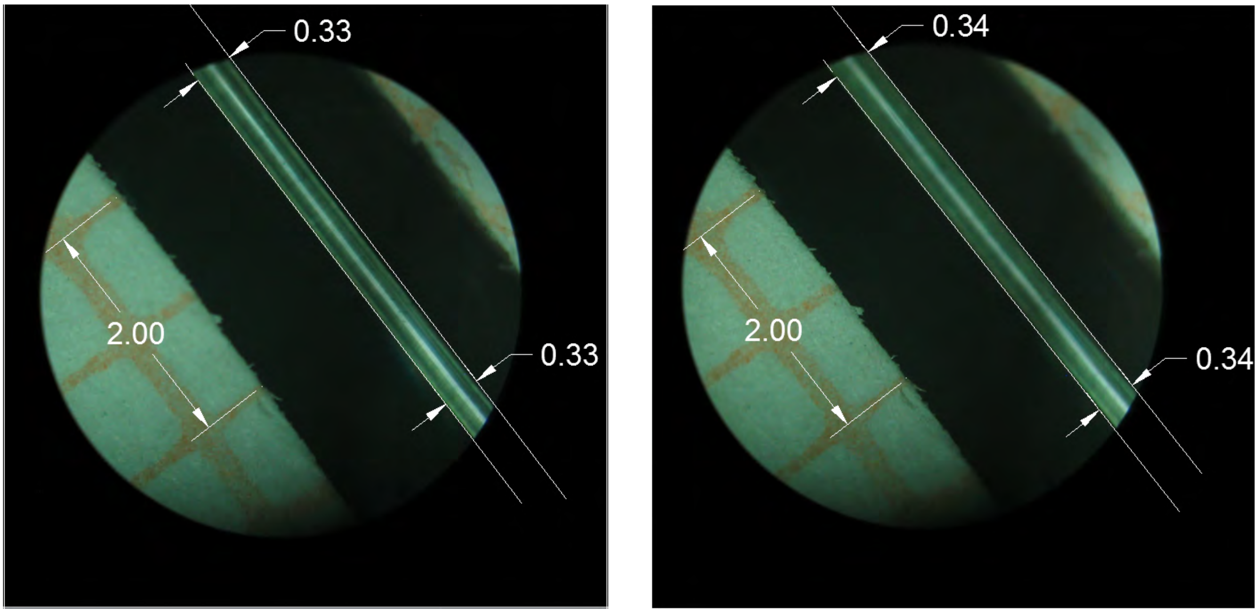
2.2 Alkali conditioning of R-Nylon fibers

We conditioned 200 mm R-Nylon monofilaments in an alkaline environment according to the ASTM D543-06 standard [20]. In detail, we cured such filaments in a solution consisting of 10.4 g of sodium hydroxide immersed in 999 ml of distilled water for 120 hours (5 days), keeping the temperature constant at 60 ± 2 °C through a climatic chamber.



(a) (b)

Figure 2 – Optical microscope images of two alkali-conditioned R-Nylon fibers.



(a) (b)

Figure 3 – Optical microscope images of two unconditioned R-Nylon fibers.

We weighed the fibers using an electronic scale (resolution 1 mg) and inspected them with an optical microscope (ZEISS Axioskop 40) using 5× magnification both before and after the treatment. We observed a slight loss of mass, equal to about 1.7%, but no relevant signs of corrosion on the fiber surface (cf. Figs. 1 and 2). By zooming in the images acquired from the optical microscope, we were able to consistently measure the geometry of the fibers. As shown in Figure 2 and Figure 3, the cross-section appears circular with 0.33 mm diameter, for both conditioned and unconditioned R-Nylon fibers.

2.3 Preparation of Mortar Samples

The preparation of mortar prismatic samples included the following steps:

- weighing of mortar and nylon fibers;
- hand mixing of dry materials in order to uniformly distribute fibers into the mortar premix;
- hydrating the mixture by adding the target quantity of water (180 g of water for each kilogram of mortar);
- mechanical shaking of the mixture at slow speed (for about two minutes) until a homogeneous and workable product of semi-fluid consistency was obtained;
- casting the prismatic specimens into 40 mm × 40 mm × 160 mm molds and accurately vibrating them.

We removed the specimens from the formworks after 24 h curing at room temperature. Next, we cured the unmolded specimens in water at 23 °C for 28 days until testing. We examined two plain mortar specimens, and two specimens in correspondence with six different fiber-reinforcement mixes, thus obtaining a total of 14 prismatic specimens. As described in Table 1, the examined mortar mixes vary due to the content and aspect ratio of R-Nylon fibers. Throughout the paper, we refer to the plain mortar specimens as "UR" and the reinforced mortar specimen as "PA – fiber length in inches – weight fraction" (Table 1).

Table 1 – Specimens designation

	Specimens		Fibers		
Designation	**Quantity**	**Fiber weight fraction**	**Length *l***	**Diameter *d***	**Aspect ratio**
		%	mm (inches)	mm	***L/D***
UR	2	–	–	–	–
PA-0.5-1.0%	2	1.0	12.7 (0.5)	0.33	385
PA-0.5-1.5%	2	1.5	12.7 (0.5)	0.33	385
PA-1.0-1.0%	2	1.0	25.4 (1.0)	0.33	770
PA-1.0-1.5%	2	1.5	25.4 (1.0)	0.33	770
PA-1.5-1.0%	2	1.0	38.1 (1.5)	0.33	1155
PA-1.5-1.5%	2	1.5	38.1 (1.5)	0.33	1155

3 TESTS AND RESULTS

3.1 Uniaxial tensile tests on R-Nylon fibers

We carried out uniaxial tensile tests according to ASTM C1557-03 Standard [21] on both conditioned and unconditioned 200 mm R-Nylon filaments in order to determine the tensile strength and Young's modulus of such elements. The tests were performed under a constant cross-head displacement rate by means of an MTS SANS testing machine equipped with a 1 kN load cell and pneumatic grips. We set testing rates that were sufficiently rapid to possibly obtain the failure strength within 30 s.

With the aim of accurately defining the gage length and preventing eccentricity of the load and fiber twisting, we preliminarily mounted the specimens on cardboard tabs and cut the tabs sides after fastening the specimens. As shown in Figure 4, three different gage lengths L_0 were adopted (1 in, 1¼ in, and 1½ in). During the tests we continuously acquired force and cross-head displacement, observing a linear elastic behavior of the tested specimens up to failure.

The peak force F_{max} and the elongation to force ratios $\Delta L / F$ exhibited by conditioned and unconditioned fibers are shown in Table 2 and Table 3, respectively. The quantity $\Delta L / F$ is derived using a linear regression for the Force–Displacement segment between 20 and 50% of the failure load. The mean, standard deviation (*SD*), and variance (*CV*) of the tensile stresses are also given in Tables 2 and 3 for each group of specimens.

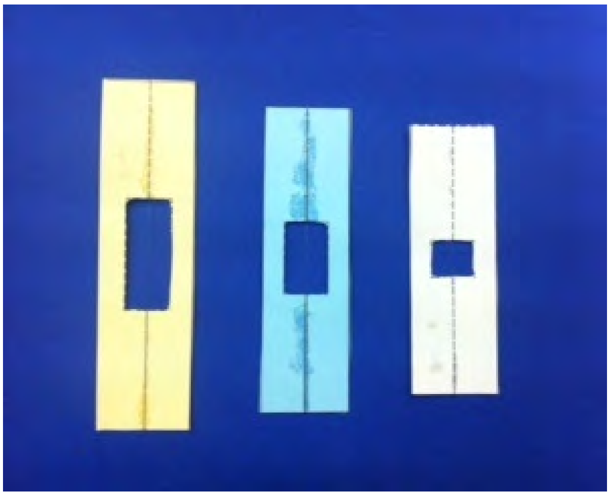


Figure 4 – Cardboard mounting tabs

Table 2 – Results of tensile tests on unconditioned mortar specimens

Gage length L_0		1		2		3		Tensile strength		
		F_{max}	$\Delta L/F$	F_{max}	$\Delta L/F$	F_{max}	$\Delta L/F$	**Mean**	*SD*	*CV*
Inches	mm	kN	mm/kN	kN	mm/kN	kN	mm/kN	MPa	MPa	%
1	25.4	27.0	0.32	30.6	0.33	29.2	0.31	338	21	6.3%
1¼	31.8	30.5	0.38	31.6	0.41	27.2	0.47	348	27	7.7%
1½	38.1	25.4	0.51	27.2	0.49	24.8	0.53	302	15	4.8%

Table 3 – Results of tensile tests on conditioned mortar specimens

Gage length L_0		1		2		3		Tensile strength		
		F_{max}	$\Delta L/F$	F_{max}	$\Delta L/F$	F_{max}	$\Delta L/F$	**Mean**	*SD*	*CV*
Inches	mm	kN	mm/kN	kN	mm/kN	kN	mm/kN	MPa	MPa	%
1	25.4	24.8	0.30	28.5	0.31	28.6	0.32	319	25	7.9%
1¼	31.8	24.8	0.37	30.1	0.39	32.8	0.40	342	48	13.9%
1½	38.1	21.7	0.50	26.7	0.53	25.8	0.49	289	31	10.8%

In the case of 1 in and 1¼ in specimens, we observed satisfactory failure modes and very low dispersion in peak loads. The mean values of the tensile strength results were 338 and 348 MPa respectively for unconditioned specimens and 319 and 342 MPa for conditioned ones. In contrast, the 1½ in specimens showed a considerably lower tensile strength and failure of fibers in the vicinity of grips. This was most probably due to the proximity of the knots to the extreme points of the gage length, which cause local decrease of the fiber mechanical properties.

By restricting our analysis on 1 in and 1¼ in specimens (i.e., neglecting the 1½ in specimens), we observed a very slight decrease in the average tensile strength (about –4%) in conditioned specimens (343 MPa) with respect to unconditioned ones (330 MPa).

We completed the fiber characterization by determining the Young modulus E of such elements through the procedure suggested by ASTM C1557-03 [21]. The adopted method consists of plotting the $\Delta L / F$ experimental values, which provide the inverse of the slope of the force versus cross-head displacement curve, against the corresponding geometric parameter L_0 / A, with A denoting the cross-section area. Assuming a linear elastic constitutive law and uniaxial load conditions, the following analytical expression applies:

$$\frac{\Delta L}{F} = \frac{1}{E}\frac{L_0}{A} + C_S \ . \tag{1}$$

According to Eqn. (1), the linear regression of the experimental data $\Delta L / F$ vs. L_0 / A (cf. Fig. 5) yields a straight line with a constant slope $1/E$ (the inverse of Young modulus) and the intercept C_S giving the system compliance. The above procedure allowed us to determine the average experimental values of the Young moduli, which were found equal to 728 MPa for unconditioned fibers and 724 MPa for the conditioned fibers. The observed minor decreases of tensile strengths and Young moduli due to the alkali conditioning lead us to conclude that the examined R-Nylon fibers show excellent alkali resistance. There is some evidence in the literature that absorbed water may considerably affect the mechanical behavior of Nylon 6, causing stiffness drops together with toughness improvement [22],[23]. Such a phenomenon is demonstrated in the present case by the low Young modulus of the R-Nylon fibers (724-728 MPa), considering that Nylon 6 at the virgin state typically exhibits Young modulus in the range 1-3 GPa [24].

(a)

(b)

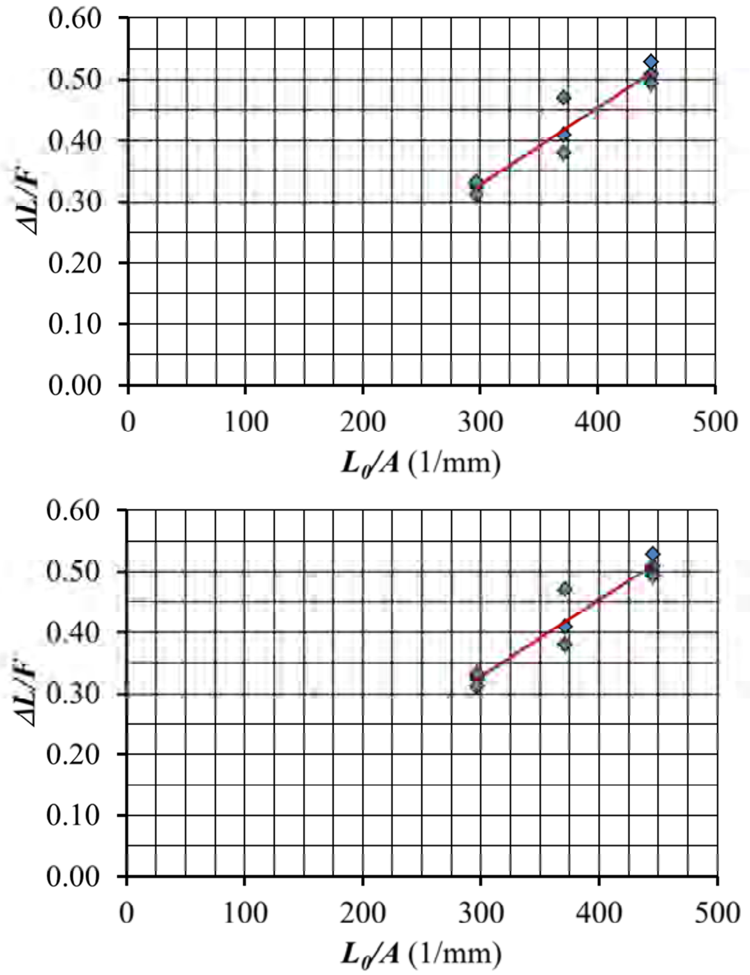


Figure 5 – $\Delta L / F$ vs L_0 / A plots: a) Unconditioned specimens; b) Conditioned specimens.

3.2 Bending and Compressive Tests

We performed three-point load-bending tests and compression tests on mortar prismatic specimens according to EN 1015-11:2007 [25] using a MATEST electrically operated testing machine with a 200 kN capacity.

Bending tests were carried out under displacement control at a speed of 0.01 mm per second on a clear span of 100 mm. Compression tests were performed on the two portions resulting from the failure the specimens subjected to bending tests, on using a testing device provided with a spherical hinge and two metal plates with dimensions of 40 mm × 40 mm actuated by the testing machine. We ended up with compression tests on ideal cubes with dimensions of 40 mm × 40 mm × 40 mm, applying a loading rate equal to 100 N per second.

As expected, the unreinforced mortar specimen exhibited brittle behavior in bending due to a sudden rupture on reaching the peak load. On the other hand, fiber-reinforced mortar specimens showed considerable post-peak resources.

Figure 6 – Three-point bending test setup.

Figure 7 – Compression test setup.

Load–deflection curves ($P-\delta$) obtained during the bending test are shown in Figures 7, 8, and 9, with reference to the specimen reinforced by 0.5, 1.0, and 1.5 in fibers, respectively. In the same chart we report the curves referring to mixtures containing different percentages of R-Nylon fibers (1.0 and 1.5% by weight).

Typically, the tests show a drop of the load after reaching the peak load. Starting from the post-peak load target, the curves exhibit an almost constant branching or a hardening kind of constitutive behavior depending on the length and quantity of fibers. More specifically, we observe the following:

- a higher percentage of fibers (1.5 rather than 1.0%) causes a less relevant drop of load after the peak value (see Figures 7 and 9);

- fibers of greater length (1.0 and 1.5 in rather than 0.5 in) confer a hardening type of post-peak behavior on the mortar.

Table 4 shows the peak load (P_{cr}) exhibited by each specimen, the corresponding midspan deflection (δ_{cr}), and the values of first crack strength, f_{cr}, calculated as follows (EN 1015-11:2007):

$$f_{cr} = \frac{3}{2}\frac{Pl}{a^3}. \tag{2}$$

For each examined mixture, we also report the mean, standard deviation (*SD*), and coefficient of variance (*CV*) of the first crack strength. In the last column of Table 4 we show the percentage change in the first crack strength in reinforced mortars with respect to the unreinforced ones (Δf_{cr}).

Table 4 and Figure 11 highlight how reinforcing fibers confer to mortar a considerably higher resistance to cracking (up to 35%). Furthermore it is evidenced that longer fibers are most effective, as the increase in strength varies from 16–18% to 32–35% when fibers of 1.0 and 1.5 in rather than 0.5 in are used. Contrarily, the weight fraction of fibers does not seem to be crucial in this sense. Such results bear special relevance, considering that reductions of the first crack strength over the unreinforced material were instead observed in the case of a R-PET reinforcement of the same mortar analyzed in the present study (up to –20% reductions of f_{cr}, [18]), and for the R-Nylon reinforcement of a concrete based on a Portland limestone cement and a 0,35 water/cement ratio (about -11% first-crack strength reductions in four-point bending tests, [19]).

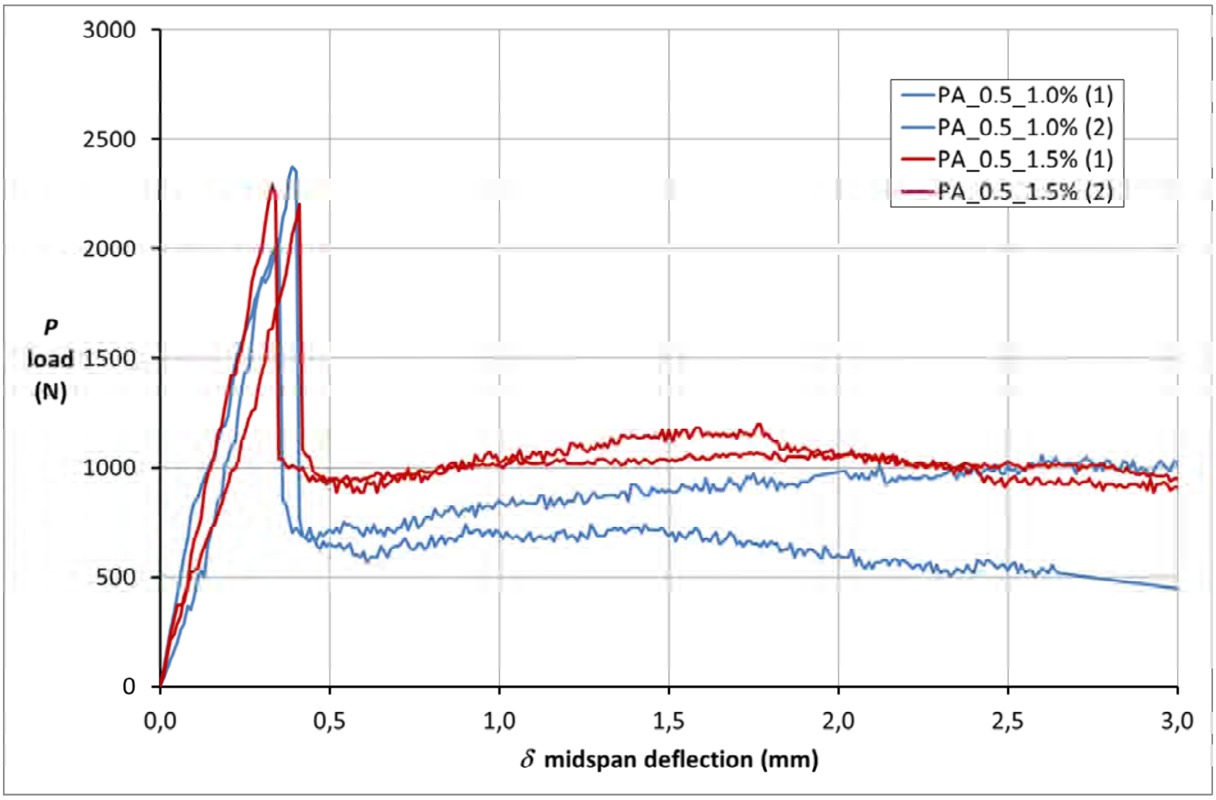


Figure 8 – Load–deflection curves of mortar specimens reinforced with 0.5 in R-Nylon fibers.

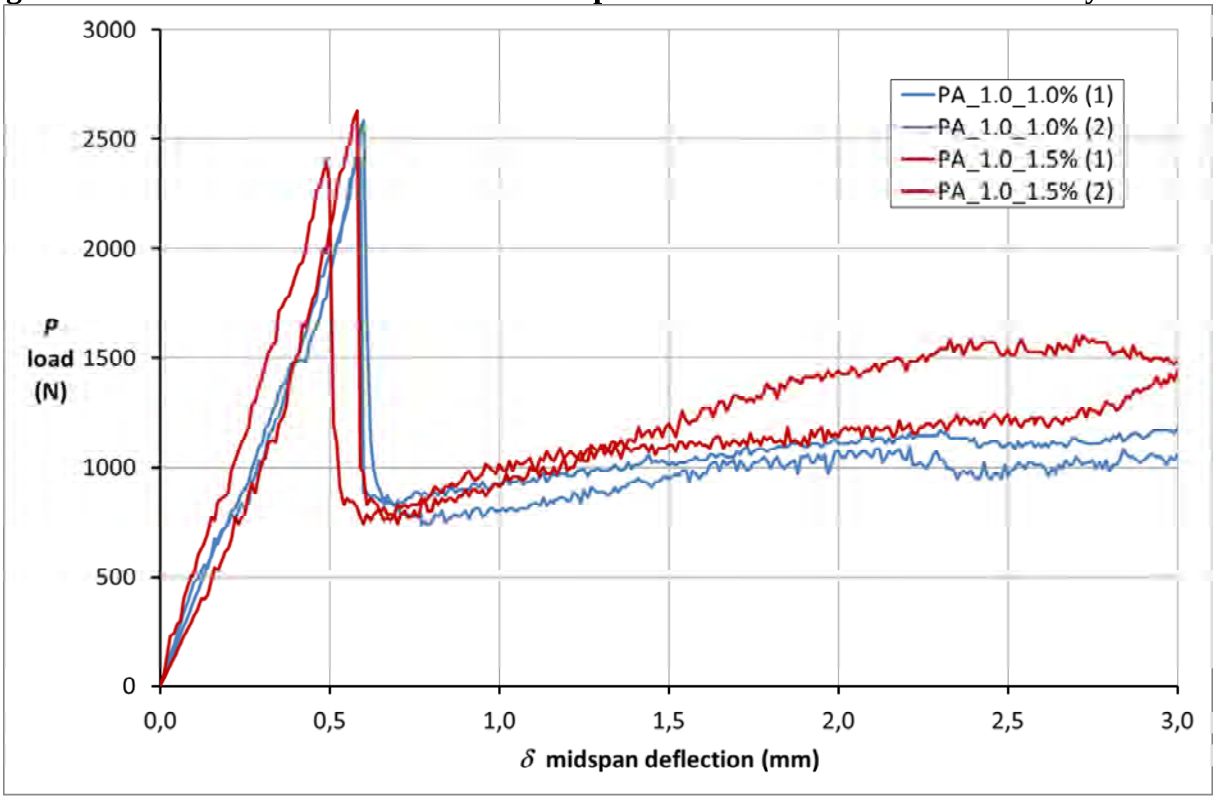


Figure 9 – Load-deflection curves of mortar specimens reinforced with 1.0 in R-Nylon fibers.

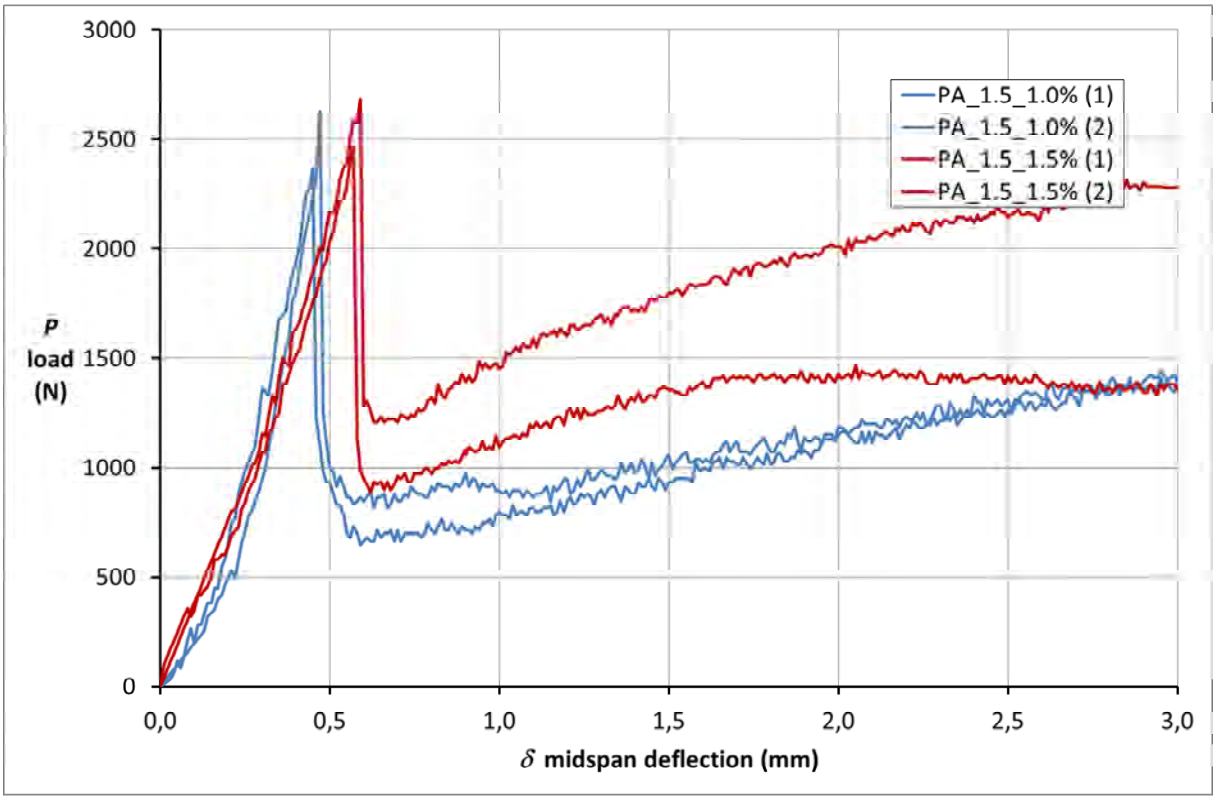


Figure 10 – Load-deflection curves of mortar specimen reinforced with 1.5 in R-Nylon fibers.

Table 4 – Results of three-point bending tests

Specimen	P_{cr} N	δ_{cr} mm	f_{cr} MPa	***mean*** MPa	***SD*** MPa	***CV*** %	Δf_{cr} %
UR (1)	2001	0.32	3.61	4.46	0.33	7%	–
UR (2)	1804	0.39	4.23				
PA-0.5-1.0% (1)	2377	0.39	5.57	5.18	0.55	11%	+16%
PA-0.5-1.0% (2)	2044	0.35	4.79				
PA-0.5-1.5% (1)	2292	0.33	5.37	5.27	0.15	3%	+18%
PA-0.5-1.5% (2)	2204	0.41	5.17				
PA-1.0-1.0% (1)	2426	0.58	5.69	5.87	0.27	5%	+32%
PA-1.0-1.0% (2)	2586	0.60	6.06				
PA-1.0-1.5% (1)	2400	0.49	5.63	5.89	0.38	6%	+32%
PA-1.0-1.5% (2)	2629	0.58	6.16				
PA-1.0-1.5% (1)	2378	0.49	5.57	5.86	0.41	7%	+32%
PA-1.0-1.5% (2)	2626	0.47	6.15				
PA-1.0-1.5% (1)	2685	0.59	6.29	6.03	0.37	6%	+35%
PA-1.0-1.5% (2)	2463	0.56	5.77				

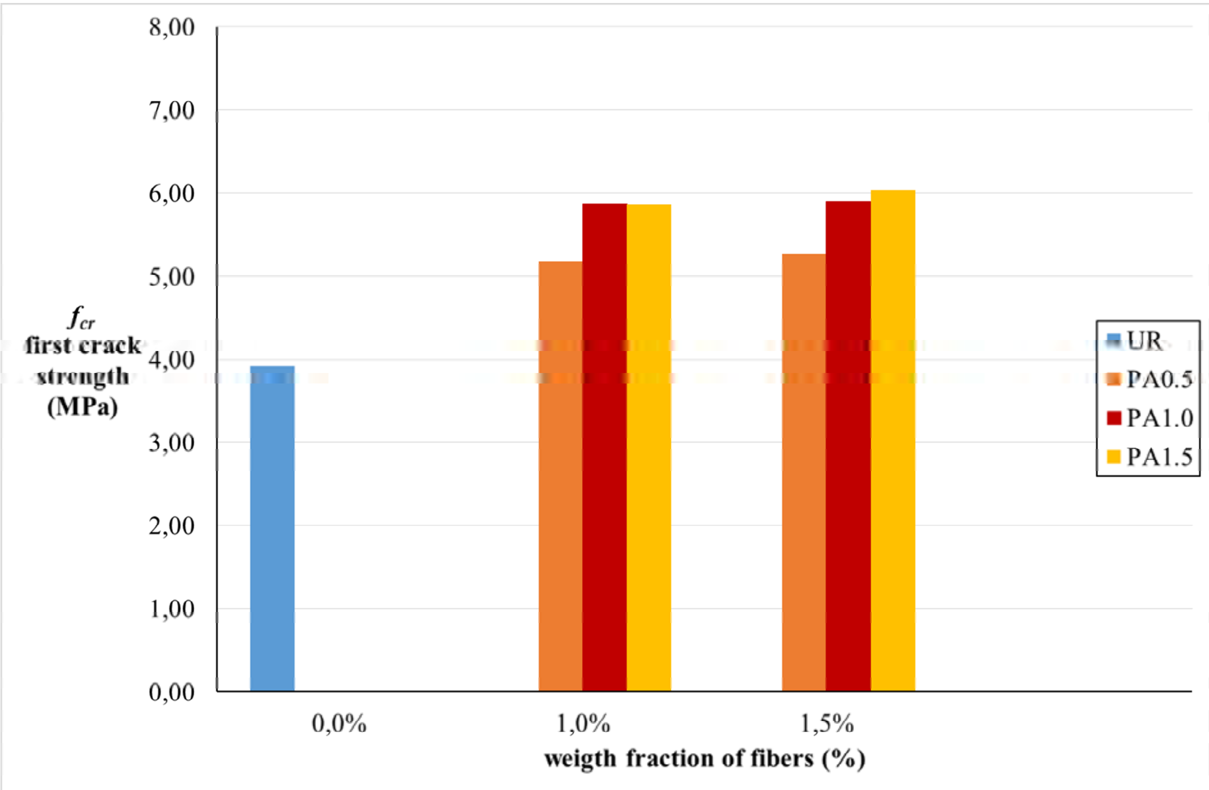


Figure 11 – Average first crack strengths of the analyzed mortars.

Table 5 – Results of compression tests

Specimen	*F* N	f_c MPa	*Mean* N	*SD* N	*CV* %	Δf_c %
UR (1)	70.3	43.9	49.4	3.7	7%	
	80.7	50.4				
UR (2)	82.6	51.6				
	82.5	51.6				
PA-0.5-1.0% (1)	55.3	34.6	32.7	2.0	6%	–34%
	47.9	29.9				
PA-0.5-1.0% (2)	54.1	33.8				
	52.0	32.5				
PA-0.5-1.5% (1)	52.3	32.7	31.3	1.0	3%	–37%
	50.0	31.3				
PA-0.5-1.5% (2)	49.8	31.1				
	48.3	30.2				
PA-1.0-1.0% (1)	65.5	40.9	38.9	2.0	5%	–21%
	59.8	37.4				
PA-1.0-1.0% (2)	64.3	40.2				
	59.2	37.0				
PA-1.0-1.5% (1)	61.3	38.3	36.3	2.4	7%	–27%
	52.4	32.8				
PA-1.0-1.5% (2)	58.8	36.8				
	59.7	37.3				
PA-1.0-1.5% (1)	63.8	39.9	41.5	3.2	8%	–16%
	69.8	43.6				
PA-1.0-1.5% (2)	71.7	44.8				
	60.6	37.9				
PA-1.0-1.5% (1)	61.7	38.6	39.6	1.9	5%	–20%
	67.8	42.4				
PA-1.0-1.5% (2)	62.8	39.3				
	60.9	38.1				

Table 5 shows the cube compressive strength, f_c, calculated as follows (EN 1015-11:2007):

$$f_c = \frac{F}{A}, \tag{3}$$

where F is the maximum compressive force registered during the test and A is the transverse cross-section on which the tests are performed (40 mm × 40 mm). For each kind of mixture considered, we also report the mean, standard deviation (*SD*), and variance (*CV*) of the compressive strength. In the last column of Table 5 we show the percentage change of compressive strength in reinforced mortars with respect to unreinforced ones (Δf_c). The results in Table 5 and Figure 12 show that the addition of R-Nylon fibers causes a decrease in the compressive strength of the examined mortar (up to –37%), especially when very short fibers are employed.

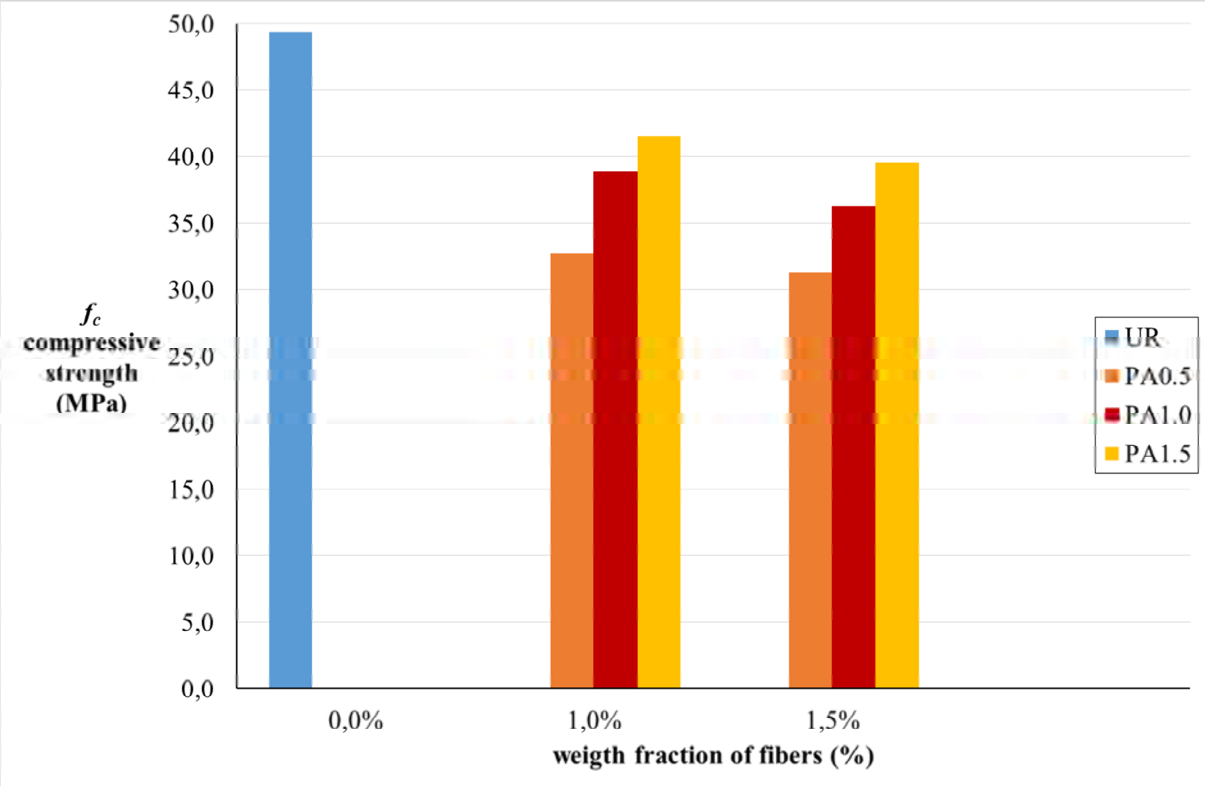


Figure 12 – Average compressive strengths of the analyzed mortars.

The effect of reinforcing plastic fibers in compression is quite often debated in the literature, since different studies report increases [3],[5],[6],[11], decreases [7],[10],[14] or no relevant effects [12],[17],[19] in the compressive strength of fiber-reinforced concretes and mortars, with respect to the unreinforced materials. The decrease of compressive properties has been explained due to the fact that highly deformable plastic fibers might assume the role of voids in the cementitious matrix when compressive forces are applied [7],[10],[14]. On the other hand, it has been shown that sufficiently stiff fibers can increase the lateral tensile strength of the composite material, leading to delayed compression failure [5],[6],[19]. As we already observed, the present R-Nylon fibers suffered a noticeable stiffness drop due to water absorption (cf. Sect. 3.1), and indeed we observe decreases in the compressive strengths of the fiber-reinforced mortars, as compared with the unreinforced material. Such strength drops are nevertheless less relevant in the case of longer fibers, due to a major anchor length (cf. Fig. 11).

3.3 Toughness indices and residual strength factors

The toughness exhibited by mortar specimens in three-point bending tests is typically measured by computing the area under the corresponding load–deflection curve, which is related to the energy absorption capacity of the material. The following equation denotes the area under the load-deflection curve up to a target value of deflection $\bar{\delta}$:

$$T_{\bar{\delta}} = \int_0^{\bar{\delta}} P\delta \, d\delta \,, \tag{4}$$

Although ASTM C 1609-06 [26] is currently accepted as the test method for the analysis of fiber-reinforced concrete, we hereafter consider the ASTM C 1018-97 [27] procedure to analyze the load deflection curve of mortar specimens. Both standards refer to a three-point bending test but the procedure required by ASTM C 1018-97 [27] is better suited to small size specimens, such as the mortar specimens examined in the present study. In line with such a standard, we introduce the following toughness indices:

$$I_5 = \frac{T_{3\delta_{cr}}}{T_{\delta_{cr}}} \,, \tag{5}$$

$$I_{10} = \frac{T_{5.5\delta_{cr}}}{T_{\delta_{cr}}} \,, \tag{6}$$

where δ_{cr} is the deflection corresponding to the first crack strength (Table 4).

We also introduce the residual strength factor:

$$R_{a,b} = \frac{100}{(a-b)}\left(I_a - I_b\right), \tag{7}$$

which is related to the load-carrying capacity of the material after crack onset. Assuming a linear force–deflection response up to δ_{cr} it can be easily verified that a perfectly plastic post-crack behavior corresponds to $R_{a,b} = 100$.

Table 6 – Flexural toughness, toughness indices, and residual strength factors at 28 days

Specimen	$T_{\delta_{cr}}$ N mm	$T_{3\delta_{cr}}$ N mm	$T_{5.5\delta_{cr}}$ N mm	I_5	I_{10}	R_{5-10}
UR (1)	342					
UR (2)	336					
PA-0.5-1.0% (1)	492	542	646	2.4	4.2	36.9
PA-0.5-1.0% (2)	331	537	787			
PA-0.5-1.5% (1)	362	665	860	2.9	5.4	50.7
PA-0.5-1.5% (2)	418	824	1126			
PA-1.0-1.0% (1)	637	1135	1639	2.7	5.1	47.9
PA-1.0-1.0% (2)	693	1079	1535			
PA-1.0-1.5% (1)	576	944	1433	2.7	5.7	59.4
PA-1.0-1.5% (2)	637	1165	2203			
PA-1.0-1.5% (1)	418	711	1211	2.9	6.1	63.0
PA-1.0-1.5% (2)	399	869	1362			
PA-1.0-1.5% (1)	712	1875	3168	3.4	7.3	77.2
PA-1.0-1.5% (2)	595	1333	1941			

Table 6 shows the flexural toughness exhibited by each specimen at three different values of deflection (δ_{cr} , $3\delta_{cr}$, $5.5\,\delta_{cr}$). We also report the average values of toughness indices I_5 and I_{10} as well as the residual strength factor:

$$R_{10,5} = 20\left(I_{10} - I_5\right). \tag{8}$$

Toughness indices and residual strength factors could not be computed for the UR mortar, due to the brittle behavior of such material.

As seen in Table 6, the recycled nylon-reinforced mortar exhibits relevant values of residual strength factors $R_{10,5}$. More specifically, we observe remarkable increments of the residual strength factor both on increasing the percentage of fibers (to 1.5 rather than 1.0%) and on increasing the fiber length (to 1.0 and 1.5 in rather than 0.5 in). This circumstance is consistent with what was observed previously in the load–displacement curves (cf. Section 3.2). Marked increases of the material toughness (compared with the unreinforced material) were also observed in the case of a R-PET reinforcement of the same mortar analyzed in the present study [18]. In both cases, the toughness indexes I_5 and I_{10} increase with the fiber length (cf. Table 4 in [18] and Table 6 in this document). Toughness increments were also observed by Ozger et al. [19] in the case of concrete reinforcement with nylon fibers obtained from post-consumer textile carpet waste.

4 CONCLUSIONS

We analyzed the effectiveness of recycled nylon fibers obtained from waste fishing nets as tensile reinforcement for cementitious materials such as mortars, plasters, and concretes. We considered mortars with different weight fractions and aspect ratios of fibers, establishing comparisons with the behavior of unreinforced mortar and with similar investigations available in the literature.

The outcomes of the experimental campaign indicated that the examined R-Nylon fibers significantly improve the tensile and fracture properties of cement mortars. Thanks to reinforcing fibers, we observed increases in tensile strength (up to 35%) and the transformation of a brittle failure to a more ductile failure mode. We pointed out that a higher percentage of fibers (1.5% rather than 1.0%) causes a less relevant drop in the load after the peak value and higher fiber aspect ratios give the reinforced mortar a hardening-type post-peak behavior. As a consequence, we observed remarkable increments of the toughness indices and of the residual strength factor both on increasing the percentage of fibers (to 1.5 rather than 1.0%) and on increasing the fiber length (to 1.0 and 1.5 in rather than 0.5 in). On the other hand, a decrease in the compressive strength was shown by the reinforced mortar specimen. The loss of strength was particularly relevant (up to –37%) when considering fibers with a very low aspect ratio. In addition, tensile tests performed on conditioned and unconditioned specimens showed that the alkali resistance of recycled nylon fibers used in this work should be considered adequate according to currently recognized standards.

On comparing the outcomes of the present study with previous literature results [18],[19], we are led to conclude that the toughness and ductility properties of mortars and concretes significantly benefit from the addition of reinforcing fibers to the mix-design. In addition, the present results highlight that R-Nylon fibers are also beneficial in terms of the first-crack strength, as opposed to the R-PET fibers analyzed in [18]. Ultimately the recycled nylon fibers used in this study appear to be much more effective in improving the mechanical qualities of cementitious products compared with recycled nylon fibers obtained from post-consumer textile carpet waste [19] and recycled PET fibers [18]. It is worth noting the environmental benefits related to the recycling of waste fishing nets, especially considering that the reinforcement technique examined in the present work does not require energy consuming processes, such as material re-polymerization and extrusion. The nets just need to be collected, washed, and suitably cut to obtain reinforcing fibers, with substantial reduction of costs and energy consumption. Future extensions of the present research will deal with the multiscale mechanical modeling of materials incorporating R-Nylon reinforcements and other fibers/aggregates recycled from industrial waste, to be conducted through the quasicontinuum method and local maximum entropy schemes [30],[31],[32].

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6 REFERENCES

[1] Sivaraja M, Kandasamy S, Thirumurugan A. Mechanical strength of fibrous concrete with waste rural materials. Journal of Scientific and Industrial Research 2010;69(4):308–312.

[2] Meddah MS, Bencheikh M. Properties of concrete reinforced with different kinds of industrial waste fibre materials Construction and Building Materials 2009;23:3196–3205.

[3] Banthia N, Zanotti C, Sappakittipakorn M. Sustainable fiber reinforced concrete for repair applications. Construction and Building Materials 2014; article in press.
[4] Siddique R, Khatib J, Kaur I. Use of recycled plastic in concrete: a review. Waste Manage 2008;28:1835–1852.
[5] Song PS, Hwang S, Sheu BC. Strength properties of nylon- and polypropylene fibre reinforced concretes. Cement and Concrete Research 2005;35(8):1546–1550.
[6] Nili M, Afroughsabet V. The effects of silica fume and polypropylene fibres on the impact resistance and mechanical properties of concrete. Construction and Building Materials 2010;24(6):927–933.
[7] Karahan O, Atis CD. The durability properties of polypropylene fiber reinforced fly ash concrete. Mater Des 2011;32(2):1044–1049.
[8] Ochi T, Okubo S, Fukui K. Development of recycled PET fiber and its application as concrete-reinforcing fiber. Cement and Concrete Composites 2007;29:448–455.
[9] Kim JJ, Park CG, Lee SiW, Lee SaW, Won JP. Effects of the geometry of recycled PET fiber reinforcement on shrinkage cracking of cement-based composites. Composites Part B – Eng 2008;39:442–450.
[10] Kim SB, Yi NH, Kim HY, Kim J, Song Y. Material and structural performance evaluation of recycled PET fiber reinforced concrete. Cement and Concrete Composites 2010;32:232–240.
[11] Fraternali F, Ciancia V, Chechile R, Rizzano G, Feo L, Incarnato L, Experimental study of the thermo-mechanical properties of recycled PET fiber-reinforced concrete. Composite Structures 2011;93:2368–2374.
[12] Silva DA, Betioli AM, Gleize PJP, Roman HR, Gómez LA, Ribeiro JLD. Degradation of recycled PET fibers in Portland cement-based materials. Cement and Concrete Research 2004;35:1741–1746.
[13] Won JP, Jang CI, Lee SW, Lee SL, Kim HY. Long-term performance of recycled PET fibre-reinforced cement composites. Construction and Building Materials 2010;24;660–665.
[14] Fraternali F, Spadea S, Berardi VP. Effects of recycled PET fibres on the mechanical properties and seawater curing of Portland cement-based concretes. Construction and Building Materials 2014:61:293–302.
[15] Foti D. Preliminary analysis of concrete reinforced with waste bottles PET fibers. Construction and Building Materials 2011;25:1906–1915.
[16] Spadea, S., Farina, I., Berardi, V.P., Dentale, F., Fraternali, F. Energy dissipation capacity of concretes reinforced with recycled PET fibers. S*ubmitted to* Ingegneria Sismica/International Journal of Earthquake Engineering, 2014.
[17] Pereira de Oliveira LA, Castro-Gomes JP. Physical and mechanical behaviour of recycled PET fibre reinforced mortar. Construction and Building Materials 2011;25:1712–1717.
[18] Fraternali F, Farina I, Polzone C, Pagliuca E, Feo L, On the use of R-PET strips for the reinforcement of cement mortars. Composites Part B – Eng 2013;46:207–210.
[19] Ozger OB, Girardi F, Giannuzzi GM, Salomoni VA, Majorana CE, Fambri L, Baldassino N, Di Maggio R. Effect of nylon fibres on mechanical and thermal properties of hardened concrete for energy storage systems. Materials and Design 2013;51:989–997.
[20] ASTM Standard D543. Standard Practices for Evaluating the Resistance of Plastics to Chemical Reagents. ASTM International, West Conshohocken, PA, 2006.
[21] ASTM C1557-03. Standard Test Method for Tensile Strength and Young's Modulus of Fibers. ASTM International, West Conshohocken, PA, 2013.
[22] Boukal, I., Effect of water on the mechanism of deformation of nylon 6. J. Appl. Polym. Sci., 1967, 11: 1483–1494.

[23] Miri, V., Persyn, O., Lefebvre, J.-M., Seguela, R. Effect of water absorption on the plastic deformation behavior of nylon 6, European Polymer Journal, Volume 45, Issue 3, March 2009, Pages 757-762.
[24] Nylon plastics handbook, Kohan MI, editors, Munich: Hanser Pub, 1995.
[25] EN 1015-11. Methods of test for mortar for masonry – Part 11: Determination of flexural and compressive strength of hardened mortar. UNI, 2007.
[26] ASTM Standard C1609. Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading). ASTM International, West Conshohocken, PA, 2012.
[27] ASTM Standard C1018. Standard Test Method for Flexural Toughness and First-Crack Strength of Reinforced Concrete (Using Beam with Third-Point Loading. ASTM International, West Conshohocken, PA, 1997.
[28] Bencardino, F., Rizzuti, L., Spadea, G., Swamy, R.N. Implications of test methodology on post-cracking and fracture behaviour of Steel Fibre Reinforced Concrete. Composites Part B: Engineering 2013, 46, pp. 31-38.
[29] EN 11039-2. Steel fibre reinforced concrete – test method for determination of first crack strength and ductility indexes. Milan, Italy, UNI Editions, 2003.
[30] Knap, J. and Ortiz, M. An analysis of the quasi continuum method. J.Mech. Phys. Solids 2001, 49:1899-1923.
[31] Bompadre, A., Schmidt, B., Ortiz, M., Convergence analysis of mesh free approximation schemes. SIAM J. Numer. Anal. 2012, 50(3):1344-1366.
[32] Fraternali, F., Lorenz, C.D., Marcelli, G. On the estimation of the curvatures and bending rigidity of membrane networks via a local maximum-entropy approach.” J. Comput. Phys. 2012, 231:528-540.