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Recycled nylon fibers as cement mortar reinforcement

Saverio Spadea [a,*], Ilenia Farina [a], Anna Carrafiello [b], Fernando Fraternali [a]

[a] University of Salerno, Department of Civil Engineering, Via Giovanni Paolo II, 84084 Fisciano (SA), Italy
[b] Omega Plastic srl, Via Udine 6, 84091 Battipaglia (SA), Italy

HIGHLIGHTS

- Recycled nylon fibers from waste fishing nets are employed as mortar reinforcement.
- Possible impacts of contaminants released by recycled fishing nets are evaluated.
- Marked increases in the first crack strength and toughness are observed.
- Comparisons with recycled and virgin plastic fiber reinforced mortars are established.
- The high technical potential of recycled nylon fibers is highlighted.

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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. Special attention is also given to evaluating the workability of fresh mortar and the possible impacts of contaminants released by waste fishing nets into the environment. 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 and with results given in existing literature. In our analysis of different weight fractions and aspect ratios of the reinforcing fibers, we observe marked increases in the tensile strength (up to +35%) and toughness (up to 13 times greater) 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 cement mortars.

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 and lower the cost of the resulting products. 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 [1–4]. In fact, the research in the field of cement mortar is strongly oriented towards the development of suitable materials for the repair and rehabilitation of existing concrete structures [5,6].

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 [7–9]. Habib et al. [10] have carried out an investigation focusing on the effects of synthetic fibers (glass, nylon, and polypropylene) on the mechanical properties of mortars. Such industrial plastic fibers might guarantee better mechanical performance than recycled plastics. However, they inevitably lead to

* Corresponding author. Tel./fax: +39 089 964342.
E-mail address: sspadea@unisa.it (S. Spadea).

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higher energy consumption and emissions. According to the method proposed by the Intergovernmental Panel on Climate Change (IPCC) in 2007 [11], it is estimated that 1.91 kg of equivalent CO_2 is needed to produce 1 kg of nylon.

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 [12–21]. More recently, the R-PET reinforcement of cementitious mortars has also received some attention in the literature [22,23]. 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. Some recent studies [24,25], investigate the recycling of nylon fibers from post-consumer textile carpet waste and their use for concrete reinforcement. In detail, Ogzer and coauthors [25] 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 [25] 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.

According to the EU green paper [26], waste patches in the Atlantic and the Pacific Oceans are estimated to be in the order of 100 million tons, about 80% of which is plastic. Most of this plastic is due to the indiscriminate abandonment of fishing nets on the seabed, which causes an increasingly common form of desertification of marine ecosystems. A large quantity of fishing nets are also scattered in the Mediterranean Sea or collected on the docks of sea harbors, following seizure by the port authorities.

In the present work, we deal with the reinforcement of a commercial cementitious mortar through recycled nylon (R-nylon) fibers, obtained from waste fishing nets. We begin by assessing that fiber are not potentially harmful for human health by mean of leaching tests. We also perform 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 both recycled and virgin plastic fibers.

2. Materials and methods

2.1. R-nylon fibers and mortar

We analyzed reinforcing fibers provided by Omega Plastic srl, a company that recovers fishing nets (Fig. 1a) seized by southern Italian port authorities (Anzio, Barletta, Castellabate, Giulianova, Giovinazzo, Lipari, Maratea, Marsala, Marina di Camerota, Milazzo, Mola di Bari, Molfetta, Palermo, Ponza, Sapri, Salina, Trani, and Termoli). After collection, residues of other products are cleaned from the nets. These nets are then classified by type of polymer, cut into pieces, and packed for storage. The final product is generally obtained via a process of extrusion and polymerization performed by plastic material recycling companies. In this case, however, the aim was to analyze a purely mechanical recycling process that does not involve energy consumption and CO_2 emissions.

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 fishing nets in order to obtain R-nylon fibers to be used as mortar reinforcing fibers. At the time of supply, nylon 6 fibers of 0.33 mm diameter were woven into a square mesh with 40 mm sides (Fig. 1b). We hand-cut this mesh into fibers of the desired length. This entailed cutting 200 mm filaments, each with four knots, to be used for uniaxial characterization tests. We also hand-cut short fibers of different lengths (12.7 mm, 25.4 mm and 38.2 mm), to be employed in the mortar-reinforcing process (see Table 2 for details).

We employed the commercial mortar *Disbocret Unitech R4*, produced by Italian Caparol GmbH & Co, for the sake of comparing the present results with those deriving from the reinforcement of the same kind of mortar with PET stripes [18]. This product is aimed at repairing damaged concrete, and includes PVC micrometric reinforcing fibers (diameter of about 50 μm, length of about 1 mm) aimed at enhancing material thixotropy and shrinkage resistance rather than mechanical properties. According to the producer datasheet, the mortar owes the following mechanical properties:

- strength class R4, e.g. compressive strength greater than 45 MPa (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. Leaching tests on waste fishing nets

The leaching test is intended to simulate the release of contaminants by placing a reagent in contact with a leaching agent for a defined period of time. In the present case, we conducted the test on 100 g of the disposed fishing net (cut into small pieces with a maximum length equal to 4 mm), without previously washing the fibers. As per the standard leaching test EN 12457-2 [27], they were placed into an agitation apparatus consisting of one liter of CO_2-saturated water for 24 h at a temperature of 20 ± 5 °C. Finally, the liquid was filtered in order to obtain the eluate, which we subjected to chemical analysis. The results of the test are shown in Table 1, together with the limit values in UNI 10802:2013 [28] – the standard giving the acceptance criteria for recycled aggregates in construction. These results show that R-Nylon fibers may not lead to overall adverse environmental or human health impacts. As such, they can be safely used in the reinforcing phase for cement materials.

2.3. Alkali conditioning of R-nylon fibers

We conditioned 200 mm R-nylon monofilaments in an alkaline environment according to the ASTM D543-06 standard [29]. In detail, the filaments were cured in a solution consisting of 10.4 g of sodium hydroxide immersed in 999 ml of distilled water for 120 h (5 days), keeping the temperature constant at 60 ± 2 °C through a climatic chamber.

Table 1
Results of leaching tests on R-nylon fibers.

Compound		Current value	Limit value
Nitrate	mg/l	5.9	50
Fluoride	mg/l	<0.1	1.5
Sulfate	mg/l	3.6	250
Chloride	mg/l	2.2	100
Cyanide	mg/l	<0.1	50
Barium	mg/l	<0.1	1
Copper	mg/l	<0.01	0.05
Zinc	mg/l	<0.1	3
Beryllium	μg/l	<0.1	10
Cobalt	μg/l	<0.1	250
Nickel	μg/l	0.3	10
Vanadium	μg/l	<0.1	250
Arsenic	μg/l	<0.1	50
Cadmium	μg/l	<0.1	5
Chromium	μg/l	0.3	50
Lead	μg/l	0.2	50
Selenium	μg/l	<0.1	10
Mercury	μg/l	<0.1	1
Asbestos	mg/l	<0.01	30
COD	mg/l	12.6	30
PH	–	8.2	>5.5 < 12.0