Rehabilitation of corrosion damaged reinforced concrete beams with recycled nylon fiber reinforced sprayed polymer cement mortar

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Introduction

In recent decades, the world has been suffering from the dumping of wastes, especially plastics left in seas and oceans. Waste fishing nets account for some of these wastes: 640,000 tons of fishing nets are disposed of in the ocean annually [1]. As the nets become totally entangled, separating them for disposal is impractical. These nets can be harmful to marine life, such as turtles, seals, and other marine mammals, which can become entangled and suffer injury or drowning [2]. In addition, the marine food web could be disrupted. As abandoned nets and plastic garbage tend to gather at or near the surface of seas and oceans, they keep sunlight from reaching small creatures such as planktons and algae. Therefore, the animals that feed on these small creatures are also directly affected. Although the storage of such nets has not caused a serious safety hazard to date, it is important to find suitable recycling solutions.

Most fishing nets are made of nylon and are non-biodegradable. Even though their storage is not hazardous, it is very important to find suitable ways of recycling these nets. Spada et al. [3] investigated the use of waste fishing nets as recycled nylon fiber for reinforced cement mortar. They found that adding the fibers to mortar significantly improves mechanical properties, such as increased first-crack strength (i.e., the modulus of rupture), toughness, and ductility. In recent years, many researchers have become interested in using recycled materials [4-11]. Not only are they interested in improving the mechanical properties, but they are also concerned with achieving favorable environmental outcomes and realizing economical products. Additionally, durability under alkaline conditions is very important for the fibers, if they are to enhance mortar composites. There is some evidence in the literature that recycled nylon fibers have excellent alkali resistance [3]. However, a test by Ochi et al. [12] found that the tensile strength of polyvinyl alcohol (PVA) fibers decreases by 44% from alkali exposure.

This study aims to investigate the effectiveness of recycled (R-) nylon fibers retrieved from waste fishing nets to improve certain mechanical properties of mortar.

Effectiveness of recycled nylon fibers as mortar strengthening material

In the first stage, the author investigated the utilization of recycled waste fishing nets in fiber-reinforced mortar and compared the mechanical properties of such mortar made with R-nylon fiber from waste fishing nets to those of mortar made with recycled polyethylene terephthalate (R-PET) and PVA short fibers, as shown in Figure 1. Two types of R-nylon fiber were investigated: straight fiber and fiber with a knot at each end. The straight R-nylon fibers were obtained by manually cutting waste fishing nets to the lengths of 20 mm, 30 mm, and 40 mm, and adding them to mortar at the volume ratios of 1.0%, 1.5%, and 2.0%. The 40-mm-long knotted fibers were added to mortar at the volume ratios of 0.5%, 0.75%, and 1.0%. The PVA and R-PET fibers were mixed in mortar at the volume fractions of 1.0% and 1.5%. The properties of fibers are presented in Table 1. The fiber reinforced mortar specimens are noted as “KN”, “SN”, “PE” and “PV,” followed by “fiber length” to represent recycled knotted nylon fiber, recycled straight nylon fiber, recycled PET fiber and PVA fiber, respectively.

Figure 1. Types of fibers
adea et al. [3] also found that compressive stiffness of mortar’s role in mortar’s addition of R-Nylon fibers, this results in reduction in its Young’s modulus [15]. According to Palmquist et al. [16] found that the addition of fiber, especially long fiber, leads to increase in the volume of interfacial transition zone which results in reduction of strength and stiffness of fiber reinforced mortar. Li [17] also investigated the effect of fiber addition on compressive strength of cementitious composites. In this work, it can be explained that a decrease of compressive strength is a result of low resistance to sliding of crack faces which is exerted by bridging force of fiber. Furthermore, when the specimens are subjected to compressive load, it induces lateral tensile strain in mortar due to the Poisson effect. As the load increases, longer fibers play an important role in mortar’s lateral tensile strength than shorter ones. Therefore, the mortar postpone crack enlargement by increasing their lateral tensile strength [18]. This is the reason why the addition of shorter fiber provides lower compressive strength. Spadea et al. [3] also found that compressive strength of mortar with R-Nylon fiber decreased with increase in fiber fraction and decrease in fiber length. For R-PET and PVA fibers, the addition of these fibers into mortar reduces the mortar compressive strength. The moduli of elasticity of PVA and PET fibers are close to mortar; however, these fibers have low density. Therefore, mortar is mixed with large amount of fibers which results in reduction in its Young’s modulus [14]. According to the addition of R-Nylon fiber into mortar, the specimens experienced softening behavior after the peak stress under compression test. On the other hand, plain mortar showed brittle tensile split failure by the formation of the crack parallel to the direction of applied load.

Flexural strength
After 28 days of curing, three-point bending tests were conducted in accordance with ASTM C 293. The results show that the addition of R-knotted nylon, R-straight nylon, and PVA fibers increases the MOR by up to 22%, 41%, and 22%, respectively. Spadea et al. [3] and Orasutthikul et al. [19] proposed that using R-nylon fibers from waste fishing nets is very effective at reinforcing mortar, with the MOR found to be improved by up to 35% and 42% in the respective reports.

The first-crack strength can be calculated as follows:

\[ M = 3P_{cr}l^2/2bd^2 \]  

where, \( M \) = modulus of rupture (MOR) or first-crack strength; \( P_{cr} \) = maximum applied load; \( b \) = specimen width; \( d \) = specimen depth; and \( l \) = span length.

It can be clearly seen in Figures 3 (a) – (f) that mortar reinforced with R-Nylon shows a significant reduction in load after the first crack. The second rising portion of the load-deflection curves prior to the second peak, corresponded to the hardening of bond-slip behavior. This phenomenon is very beneficial as long as the fiber does not break. The main reason why the R-PET fiber mortar is superior in the post peak load to other types of fiber may

<table>
<thead>
<tr>
<th>Fiber type</th>
<th>Diameter (mm)</th>
<th>Length (mm)</th>
<th>Tensile strength (MPa)</th>
<th>Young’s modulus (GPa)</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-Nylon</td>
<td>0.35</td>
<td>20, 30, 40</td>
<td>440</td>
<td>3.0</td>
<td>1.32</td>
</tr>
<tr>
<td>R-PET</td>
<td>0.70</td>
<td>30, 40</td>
<td>450</td>
<td>20</td>
<td>1.32</td>
</tr>
<tr>
<td>PVA (18 mm)</td>
<td>0.20</td>
<td>18</td>
<td>975</td>
<td>27</td>
<td>1.30</td>
</tr>
<tr>
<td>PVA (30 mm)</td>
<td>0.66</td>
<td>30</td>
<td>900</td>
<td>23</td>
<td>1.30</td>
</tr>
</tbody>
</table>

Table 1. Properties of fibers

Figure 2. Reduction in compressive strength of fiber reinforced mortar specimens

Compressive strength
Figure 2 illustrates the reduction in compressive strength of fiber reinforced mortar. The results show that the compressive strength decreases as the length decreases and as the amount of R-Nylon fibers increases. This can be explained that Young’s modulus of mortar was reduced with the dosage of fibers with low Young’s modulus, especially R-Nylon fibers [13, 14]. The Young’s modulus of R-Nylon fiber is very low compared with that of mortar; therefore, inclusion of the fiber creates voids in mortar [15]. This might suggest that the lower compressive strength of the KN mortar is the result of a greater reduction in Young’s modulus of the fiber reinforced mortar from the inclusion of knots. Additionally, poor fiber distribution according to easy forming ball of KN fiber, this results in reduction in compressive strength of KN mortar. The results show that mortar reduces the mortar compressive strength of the KN mortar is the result of a decrease of compressive strength is a result of low resistance to sliding of crack faces which is exerted by bridging force of fiber. Furthermore, when the specimens are subjected to compressive load, it induces lateral tensile strain in mortar due to the Poisson effect. As the load increases, longer fibers play an important role in mortar’s lateral tensile strength than shorter ones. Therefore, the mortar postpone crack enlargement by increasing their lateral tensile strength [18]. This is the reason why the addition of shorter fiber provides lower compressive strength. Spadea et al. [3] also found that compressive strength of mortar with R-Nylon fiber decreased with increase in fiber fraction and decrease in fiber length. For R-PET and PVA fibers, the addition of these fibers into mortar reduces the mortar compressive strength. The moduli of elasticity of PVA and PET fibers are close to mortar; however, these fibers have low density. Therefore, mortar is mixed with large amount of fibers which results in reduction in its Young’s modulus [14]. According to the addition of R-Nylon fiber into mortar, the specimens experienced softening behavior after the peak stress under compression test. On the other hand, plain mortar showed brittle tensile split failure by the formation of the crack parallel to the direction of applied load.
Figure 3. Load-midspan deflection curves of fiber-reinforced mortar specimens
be concerned with the fiber geometry. The R-PET fiber used in this study had an embossed surface that significantly increases bond strength between the fiber and mortar.

**Toughness and residual strength**

Toughness indices $I_5$, $I_{10}$ and $I_{20}$ were obtained by dividing the area under the load-deflection curve up to 3.0, 5.5, and 10.5 times the first-crack deflection, respectively, by the area under the curve up to the first-crack deflection, as illustrated in Figure 4. The residual strength factors, $R_{5,10}$ and $R_{10,20}$, were determined according to ASTM C1018 by the following equations:

$$ R_{5,10} = \frac{100}{(5-10)} (I_5 - I_{10}) $$

$$ R_{10,20} = \frac{100}{(10-20)} (I_{10} - I_{20}) $$

It is obvious that the addition of the R-Nylon fiber to the mortar appears to afford outstanding improvements in toughness, especially for higher fiber fractions and greater length of fiber as shown in Figure 5. According to the embossed surface of the R-PET fiber, the R-PET fiber mortar performed outstanding post peak behavior; particularly the mortar with higher aspect ratio fiber (PE-40) exhibited higher toughness indices and residual strength factors. This implies that not only fiber length but also fiber geometries govern the bond characteristics between the fiber and cement matrix. The opposite result was obtained for the PVA fiber mortar: the smaller the aspect ratio of the fiber, the higher the post peak load. Redon and Li [20] conducted a pull out test, where two types of PVA fiber having 0.044 mm and 0.700 mm diameter were investigated. They found that the smaller diameter fiber broke before the full pullout length, while most of the larger diameter fiber were fully pulled out. Moreover, the larger diameter fiber embedded in the mortar decreased in its diameter according to abrasions. Therefore, the PV30 mortar exhibited higher post peak load than the PV18 mortar did. As evidenced by the results, the toughness and residual strength of KN fiber mortar presented worst performance because the fiber fraction is limited to low amount. Moreover, easily forming ball shape of KN fiber leads to poor fiber distribution, which directly affects toughness and residual strength of fiber reinforced mortar.

**Application of recycled nylon fiber reinforced polymer cement mortar**

In the second stage, the author discusses the applicability of R-nylon fiber sprayed polymer cement mortar (SPCM) to the section repair of corrosion damaged reinforced concrete (RC) beams. In this study, a novel R-nylon fiber SPCM (SPCM_RN, see Figure 5 (a)) was compared with two types of SPCM: polyethylene (PE) fiber SPCM (SPCM_PE, see Figure 2 (b)), and non-fiber containing SPCM (SPCM_NF). The geometry and reinforcement of the beams are shown in Figure 7. For flexural reinforcement, two reinforcing bars of 10 mm in diameter were used as lower reinforcement and two reinforcing bars of 6 mm were used as upper reinforcement. Stirrups are arranged with 6-mm-diameter reinforcing bars at 90 mm intervals. The concrete was made with ordinary Portland cement (OPC), and its compressive strength was 33 MPa. The experiments involved the removal of concrete to three depths, to represent three repair methods: removal to a depth of 10 mm, removal of all the cover concrete, and removal to a depth of 20 mm over the tensile reinforcements, as illustrated in Figure 8. Four-point bending tests, as shown in Figure 9, were conducted on 44 RC beams whose flexural behaviors (load carrying capacity, flexural stiffness and ductility) were investigated.

**Conclusions**

In this study, the effectiveness and potential of using waste fishing nets as R-nylon fiber to reinforce mortar were experimentally tested and discussed. Compressive
and three-point bending test were performed to investigate compressive strength, peak load, modulus of rupture, toughness indices, and residual strength factors. The compressive strength of the mortar with R-nylon fiber decreased with increase in fiber fraction and length. The post peak load, toughness and residual strength depended on the properties of fiber such as Young’s modulus, tensile strength, and geometry as well as the bond strength between fiber and matrix.

Moreover, in this study, an experimental investigation was conducted on the use of SPCM for repairing corrosion-damaged RC beams. The effects of mixing R-nylon fiber into SPCM on the repair effectiveness was investigated in comparison with two common SPCM types: SPCM without fiber and SPCM with PE fiber. SPCM containing R-nylon fiber was found to afford increases in load carrying capacity for the beams whose tensile reinforcement was reduced by 10% to 18% from corrosion, and it was found to provide higher ductility than the two other types of SPCM as well as non-damaged and non-repaired beams. The beams repaired with SPCM containing either of the fibers showed higher stiffness than those repaired with SPCM without fibers. It was found that, for the beams whose tensile reinforcement was reduced by 10% from corrosion, removing the whole concrete covering is suitable for improving flexural behavior and can be a better choice in terms of economic efficiency. Furthermore, for beams that have lost 10% to 18% of their tensile steel mass, it is recommended that concrete over the tensile reinforcements be removed to a depth of 20 mm and replaced by SPCM containing either type of fibers. It is noted that for the beams whose tensile reinforcement was reduced more than 18% from corrosion, only replacement with SPCM is not sufficient for load carrying capacity recovery.

References


