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Assessment of interfacial bonding of recycled polymer fibers from waste fishing nets in concrete

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Abstract: This study investigates the interfacial bonding behavior of recycled polymer fibers derived from discarded fishing nets when embedded in concrete. Utilizing waste fishing nets as reinforcement not only provides a sustainable alternative to conventional synthetic fibers but also contributes to environmental protection and resource efficiency. To assess bond performance, single-fiber pullout tests were conducted on recycled fibers with different geometries. The results demonstrated that fiber geometry, particularly diameter, plays a critical role in fiber-matrix interaction. Larger fibers (1.50 mm) exhibited approximately 46% higher bond strength and nearly seven times greater pull-out energy than finer fibers (0.30 mm), due to their increased contact perimeter, higher stiffness, and more effective stress transfer. These findings indicate that recycled fishing net fibers with moderate to large diameters can significantly enhance bond strength, energy absorption, and post-cracking toughness in cementitious composites. However, potential workability issues associated with larger fibers highlight the need for optimized mixing procedures. Further research employing advanced microstructural techniques is recommended to elucidate the role of fiber surface morphology and to develop surface modification strategies for improving the efficiency of finer fibers. Overall, this research advances the understanding of fiber-matrix interfacial behavior while presenting a viable pathway for recycling marine plastic waste into high-value construction materials.

Keywords: Interfacial bonding; recycled polymer fibers; concrete.

INTRODUCTION

The construction industry has long stood as a foundation of global progress, playing a pivotal role in driving infrastructure development, accelerating urbanization, and fostering socioeconomic growth (Ajayi et al., 2017). However, alongside these achievements, the sector is also associated with significant environmental challenges. The intensive extraction of mineral resources and fossil fuels, coupled with the generation of large quantities of construction and demolition waste, has contributed to severe environmental degradation, including greenhouse gas emissions, resource depletion, and ecosystem disruption (Zhang et al., 2019). Besides, global ecosystems face increasing threats from marine debris, which predominantly consists of plastic-based materials that are either slowly biodegradable or entirely non-biodegradable. Among these, abandoned, lost, or discarded fishing nets represent one of the most hazardous forms of marine litter (Spirkovski et al., 2019). These nets not only endanger marine biodiversity through entanglement and ingestion by aquatic organisms but also pose risks to human activities, such as maritime navigation, by becoming entangled in ship propellers (Richardson et al., 2019). The persistence of such waste materials in marine environments has raised concerns about long-term ecological impacts and potential risks to food security through microplastic contamination in seafood (Wang et al., 2016).

Several studies have explored the recycling of waste fishing nets (WFNs) in construction applications, mainly through their incorporation into soil- or cement-based materials, with the aim of enhancing mechanical strength and ductility as a potential alternative to conventional synthetic polymeric fibers (Orasutthikul et al., 2017) (Kim et al., 2008)(Spadea et al., 2015). Research on the mechanical properties of fishing nets recovered from the seafloor revealed that macro WFNs fibers exhibited approximately 20% lower tensile strength than new (unused) fishing nets that had not been exposed to seawater, while their elongation at break and Young's modulus remained comparable (Bertelsen et al., 2016). The effectiveness of recycled nylon fibers obtained from WFNs as reinforcement was investigated by applying tensile loads to cement mortar specimens (Spadea et al., 2015).

The recycling of WFNs has emerged as a sustainable approach to reduce marine plastic pollution while providing an alternative source of fiber reinforcement for cementitious composites. Although previous studies demonstrated that recycled WFN fibers retain acceptable mechanical properties with only a moderate loss in tensile strength, their reinforcing efficiency in concrete remains insufficiently understood. Therefore, this study examines: (1) the influence of fiber type on bond strength and (2) the effect of fiber type on pull-out energy in concrete.

MATERIALS AND EXPERIMENTAL PROCEDURE

Materials

Table 1 provides the mix proportions of the materials employed in this study, expressed as mass ratios of each constituent to cement (C) (Park et al., 2021). A matrix proportioned with a cement-to-sand ratio (C/S) of 1.0:1.5, incorporating 0.0009 superplasticizer and a water-to-cement ratio (W/C) of 0.45. A superplasticizer (SP) containing 25% polycarboxylate ether was employed to enhance the workability of the concrete mixture. Table 2 presents the physical

characteristics of the recycled polymer fibers, where Type 1 fiber (F1) exhibits a smaller diameter (0.3 mm) and lower specific gravity (0.95 g/cm³), while Type 2 fiber (F2) shows a larger diameter (1.5 mm) and higher density (1.20 g/cm³), with both types having the same fiber length of 40 mm. The characterization of WFNs fiber properties and its preparation for incorporation into cementitious composites were conducted in accordance with the procedures outlined in reference (Park et al., 2021).

Table 1. Matrix composition by weight ratio.

C	C/S	SP	W/C	Compressive strength (MPa)	Slump flow (mm)
1.0	1.5	0.0009	0.45	72.86	260

Table 2. Properties of recycled polymer fibers.

Fiber type	Diameter (mm)	Length (mm)	Specific Gravity (g/cm ³)
F1	0.3	40	0.95
F2	1.5	40	1.20

Experimental Procedure

The principal stages of the specimen preparation are described as follows (Park et al., 2021): Cement and silica sand were blended for 2 min before adding water and a polycarboxylate-based superplasticizer, followed by 3 min of mixing. Prior to casting, fibers were positioned in molds with a 10 mm embedment length, and the fresh mortar was slightly vibrated. Samples were then covered with plastic sheets and kept at room temperature for 24 h, demolded, and subsequently cured in water at 20 ± 2 °C for 28 d. Mechanical testing was carried out under dry conditions at 28 d. Figure 1 presents two groups of specimens prepared using fiber types F1 and F2, which are designated as MF1 and MF2, respectively.

The evaluation of concrete workability was conducted in accordance with ASTM C1437. The experimental device consisted of a truncated cone, 60 mm in height, with a base diameter of 100 mm and a top diameter of 70 mm. The matrix without any incorporated

fibers exhibited a slump flow of 260 mm, as summarized in Table 1. Besides, compressive strength testing was performed following ASTM C109/C109M. The specimens were subjected to a loading rate corresponding to a crosshead displacement of 1.0 mm/min, equivalent to a force application rate of 1000 N/s. The pullout response was determined using bell-shaped pullout specimens, following the methodology and procedures reported by Park et al. (Park et al., 2019). For each matrix, three specimens were subjected to pull-out testing, and the average bond strength was subsequently calculated (Park et al., 2021).

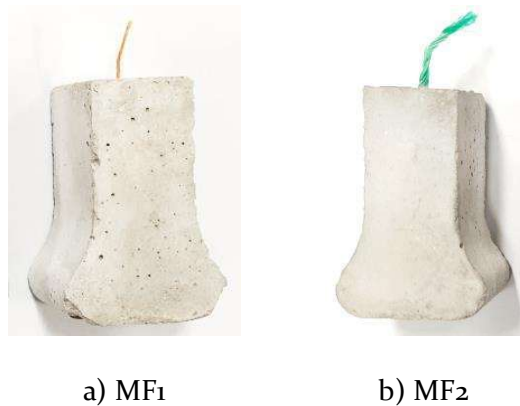


Figure 1. Sample of matrices

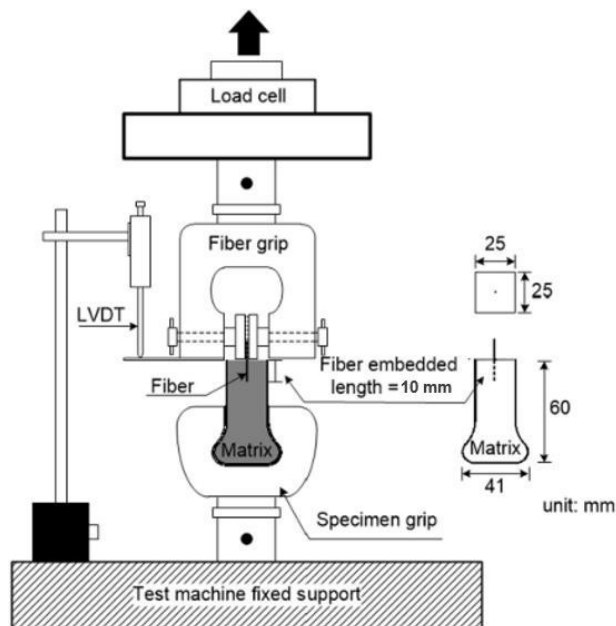


Figure 2 Experimental setup of the pullout test under static loading rate (Park et al., 2019).

A displacement rate of 0.0167 mm/s was adopted for the pull-out test to maintain stable testing conditions and reliably characterize the mechanical behavior of the fiber-concrete interaction (Park et al., 2019). The pull-out force was obtained through a load cell attached to the loading frame, whereas the fiber displacement during testing was monitored using a displacement measuring device (Fig. 2).

Figure 3 shows the pull-out behavior of straight fibers embedded in cement mortar. In this initial stage, the fiber-matrix system behaves elastically. The pullout load increases almost linearly with slip until reaching the critical load (P_{crit}) at displacement Δ_{crit} , where interfacial debonding starts to occur. As slip continues to increase, the pullout load rises further until it reaches the peak load (P_{peak}) at Δ_{peak} . This represents the maximum bond resistance of the interface, after which progressive debonding dominates. Beyond Δ_0 , the interface is fully debonded, and the pullout resistance decreases gradually. The descending branch is governed mainly by frictional sliding and possible mechanical anchorage, while the shaded area under the curve represents the total pullout energy absorbed during the process.

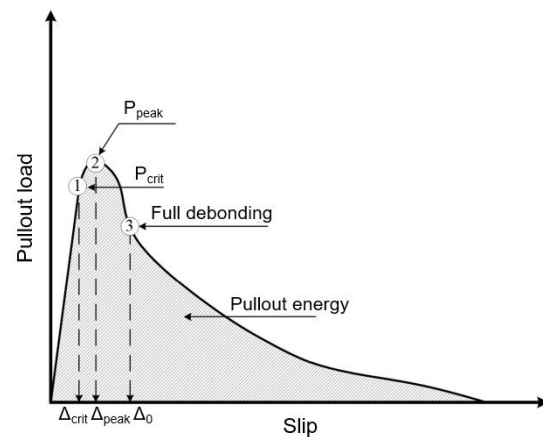


Figure 3. Force–displacement curve of a fiber during the pullout process (Park et al., 2019).

The resistance offered during fiber extraction is governed by the quality of the interfacial bond between the fibers and the mortar matrix. This bond can be categorized into three primary components: chemical,

frictional, and mechanical. The chemical component arises from adhesion between the fibers and the cementitious matrix formed during hydration. The frictional bond originates from the surface roughness at the interface between the fiber and the mortar, while the mechanical bond is attributed to deformation of the fiber geometry during extraction (Park et al., 2020).

The interfacial bond strength of steel fibers was evaluated using Equations (1) and (2). In these equations, τ_{eq} denotes the equivalent bond strength, calculated from the work performed during the fiber pull-out process, whereas τ_{peak} corresponds to the bond strength determined from the maximum pull-out load (P_{peak}). The exposed perimeter ($p_{exposed}$) is defined as the effective perimeter of fiber bundles that is directly in contact with the matrix, reflecting the actual surface curvature of the bundled fibers, as expressed in Equation (3). The parameter E_p was derived under the assumption that the bond strength remains constant along the entire embedment length (L_{em}) (Park et al., 2020).

$$\tau_{eq} = \frac{2E_p}{p_{exposed}L_{em}^2}; \quad (1)$$

$$\tau_{peak} = \frac{P_{peak}}{p_{exposed}L_{em}}; \quad (2)$$

$$p_{exposed} = 2\pi R \frac{0.5\pi d_f}{d_f} = \pi^2 R. \quad (3)$$

where: R denotes the estimated radius of the fiber bundle, whereas d_f specifies the diameter of the constituent individual fibers forming the bundle.

RESULTS AND DISCUSSIONS

Influence of fiber type on the bond strength of concrete

Table 3 summarizes the properties of the recycled polymer fibers, showing a marked difference in diameter between F1 (0.30 mm)

and F2 (1.50 mm) while maintaining similar embedded lengths (10 mm).

Table 3. Mechanical properties of matrices in pullout test

Matrix	Peak bond strength (MPa)	Equivalent bond strength (MPa)	Pullout energy (N.mm)
MF1	1.71	1.67	99.19
MF2	2.50	2.44	691.25

The experimental results indicate a clear influence of fiber type on the interfacial bond strength between recycled polymer fibers and the cementitious matrix. Specifically, the peak bond strength (τ_{peak}) for MF2 was 2.50 MPa, which is approximately 46% higher than that of MF1 (1.71 MPa), as shown in Figure 4. Similarly, the equivalent bond strength (τ_{eq}) for MF2 reached 2.44 MPa, compared to 1.67 MPa for MF1 (Fig. 4). These findings confirm that variations in fiber geometry, particularly fiber diameter, play a decisive role in governing bond performance. Larger fiber dimensions lead to an increased maximum pullout load, a trend consistent with previously reported findings (Qi et al., 2019).

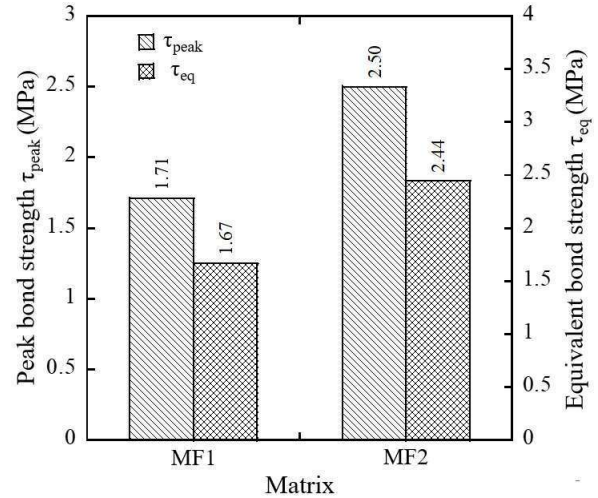


Figure 4. Comparison of bond strength between MF1 and MF2

Slender fibers are often considered beneficial due to their relatively high surface-to-volume ratio, which theoretically enhances interfacial adhesion and mechanical interlock (Wiemer et al., 2020). However, when the fiber

cross-section becomes excessively small, this advantage is offset by a reduced absolute contact perimeter with the surrounding matrix. In the case of MF1, the F1 fibers exhibited a high aspect ratio ($L/d \approx 133.33$), yet their fine diameter (0.30 mm) limited the effective area available for stress transfer. As a result, once interfacial debonding was initiated, the stress level dropped abruptly, leading to reduced pull-out resistance and lower energy absorption capacity (Park et al., 2020). In contrast, the thicker F2 fibers (diameter = 1.50 mm, $L/d \approx 26.67$) offered a substantially larger perimeter and higher stiffness, which facilitated a more uniform stress distribution along the embedded length. This enhanced contact area improved frictional resistance during pull-out and enabled the fibers to sustain higher bond stresses before failure.

Effect of fiber type on pull-out energy of concrete

The pull-out energy exhibited a consistent trend with bond strength. For MF2, the pull-out energy was 691.25 N-mm, compared with only 99.19 N-mm for MF1 (Fig. 5). These results indicate that fiber diameter plays a critical role in energy absorption capacity. In particular, F2 fibers exhibited nearly seven times greater pull-out energy than F1 fibers, reflecting their ability to mobilize higher peak shear resistance and sustain prolonged frictional sliding after debonding. The superior performance of F2 can also be attributed to the surface morphology of recycled polymer fibers. In the case of fibers with larger diameters, the interaction with the cementitious paste becomes more effective, thereby improving micro-mechanical interlock and resistance to sliding. This mechanism is likely responsible for the markedly higher pull-out energy recorded in MF2 (Sigrüner et al., 2023).

This study suggests that recycled polymer fibers with moderate to large diameters (≈ 1.5 mm) are more suitable for enhancing bond strength and energy absorption, which in turn contributes to improved post-cracking toughness of cement-based composites. However, the influence of fiber size must be balanced against workability concerns, as the

use of larger fibers may necessitate refined mixing approaches to minimize agglomeration. In addition, further research utilizing advanced characterization methods, such as scanning electron microscopy (SEM), X-ray diffraction (XRD), and mercury intrusion porosimetry (MIP), is essential to clarify how fiber surface features influence the bonding process and to design surface modification techniques that can improve the efficiency of recycled polymer fibers.

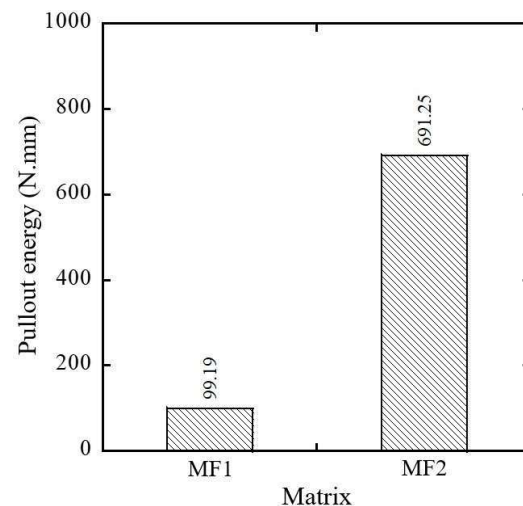


Figure 5. Comparison of pullout energy between MF1 and MF2 matrix

CONCLUSIONS

This study examined the bond performance of recycled polymer fibers derived from waste fishing nets (WFNs) in cementitious composites, with particular attention to the influence of fiber type on interfacial bond strength and pull-out energy. Two fiber types were tested: F1 (0.30 mm) and F2 (1.50 mm), both with the same embedded length (10 mm). Based on the experimental results, the following conclusions can be drawn:

- Fiber geometry, particularly diameter, plays a key role in bond behavior. Larger F2 fibers (1.50 mm) achieved approximately 46% higher bond strength than finer F1 fibers (0.30 mm).
- Pull-out performance was strongly dependent on fiber size, with F2 fibers

exhibiting nearly seven times greater pull-out energy than F1 fibers, attributed to increased contact perimeter, higher stiffness, and improved stress transfer.

- Recycled polymer fibers with moderate to large diameters are more effective in enhancing post-cracking toughness of cementitious composites, though workability concerns must be addressed. Further studies using advanced microstructural techniques are recommended to optimize fiber surface properties, particularly for finer fibers.

This study investigated the effects of various recycled polymer fibers on the bond strength and pullout behavior of concrete. Environmental factors, including humidity and temperature, which may influence fiber-matrix interactions, were not considered. Besides, the tensile strength and flexural strength of concrete containing recycled polymer fibers were not evaluated. Therefore, future research should examine these variables to achieve a more comprehensive understanding.

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