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Effectiveness of recycled nylon fibers as reinforcing material in mortar

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Abstract: Disposing of waste fishing nets has been a major issue in the sea environment. Although the storage of such nets has not caused a serious safety hazard to date, it is important to find suitable recycling solutions. In this study, the authors investigate the utilization of recycled waste fishing nets in fiber-reinforced mortar and compare the mechanical properties of such mortar made with recycled waste fishing nets to those of mortar made with PVA (polyvinyl alcohol) short fibers. Two types of recycled nylon fiber were investigated: straight fiber and fiber with a knot at each end. The straight recycled 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 mechanical test results showed improvements in first-crack strength, toughness, and ductility for mortar reinforced with recycled nylon fibers. The addition of recycled nylon fibers improves first-crack strength more than that PVA fibers do. However, the compressive strength decreases with increase in fiber fraction, and decreases with increase in fiber aspect ratio.

Keywords: recycled nylon fiber, waste fishing net, recycled materials, fiber reinforced mortar.

1. 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

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. Spadea 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, MOR), toughness, and ductility. Two decades later, many researchers are studying the use of fiber reinforced mortar (FRM) as a way of achieving higher MOR, fracture toughness, impact resistance, and of controlling shrinkage. The use of synthetic fibers such as polyvinyl alcohol (PVA) and polypropylene was found to be successful in significantly improving the mechanical properties of the base material [4-7]. In recent years, many researchers have become interested in using recycled materials [8-15]. 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. [16] found that the tensile strength of PVA fibers decreases by 44% from alkali exposure.

This study aims to investigate the effectiveness of recycled nylon (R-nylon) fibers retrieved from

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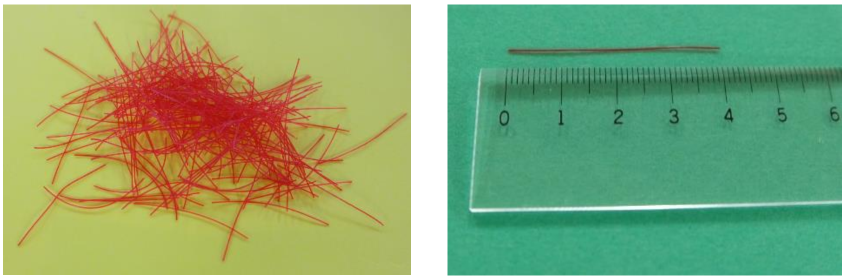
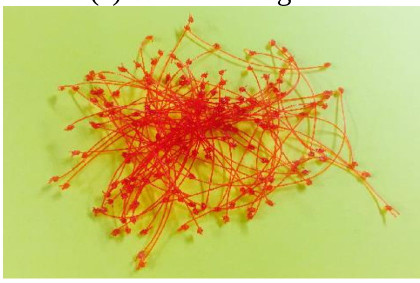
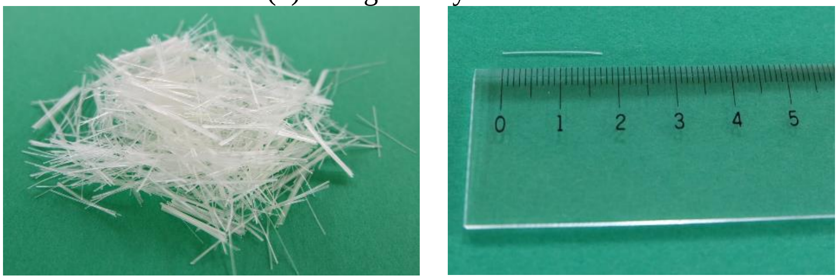
(a) Waste fishing net



(b) Straight R-nylon fibers



(c) Knotted R-nylon fibers



(d) PVA fibers

Fig. 1 – Types of fibers

Table 1 – Mechanical properties of fibers

Fiber type	Diameter (μm)	Tensile strength (MPa)	Young's modulus (GPa)	Density (g/cm^3)
R-nylon fiber	350	440	3.0	1.13
PVA	200	975	27	1.30

waste fishing nets to improve certain mechanical properties of mortar. The authors address the preparation of R-nylon FRM and the identification of its mechanical properties (e.g., compressive strength, MOR, toughness, and residual strength) in comparison to those of PVA FRM. The effects of using different fiber volume ratios and lengths are analyzed.

2. Outline of Experimental Test

The waste fishing nets used in this study were collected by fishermen in Hokkaido, Japan. The fibers were manually cut in three different lengths of 20 mm, 30 mm, and 40 mm, and were mixed in mortar at several different volume fractions.

The volume fractions of the knotted R-nylon fibers (1.0%, 1.5% and 2.0%) were lower than those of the straight fibers (0.5%, 0.75%, and 1.0%), because knotted R-nylon fibers tend to form tenacious clumps. The PVA fibers were included in the mix at 1.0 vol.% and 1.5 vol.%. In the case of the recycled nylon fiber, the authors carried out uniaxial tensile tests according to ASTM C1557-03 standard [17] in order to determine the tensile strength and Young's modulus. The fiber types and the mechanical properties are given in Fig. 1 and Table 1, respectively. Before the fibers were added, cement and sand were mixed in a small mixer. Then, the fibers were gently added to prevent the formation of fiber balls, and all the dry components were mixed by hand in order to obtain a uniform distribution of fibers. Water was gradually added, and a mixing machine was used at low speed for 2 minutes until a homogeneous mixture was achieved. The mortar was cast in prism molds of 40 mm × 40 mm × 160 mm for the bending test and in cylinders of 50 mm diameter × 100 mm in height for the compressive strength test. The specimens were cured in water at 20˚C for 28 days and then tested. For the mortar mixes, various combinations of fiber volume and fiber aspect ratio were used as summarized in Table 2. The unreinforced mortar is notated as UR, and the FRM specimens are notated as SRny (straight recycled nylon fiber), KRny (knotted recycled nylon fiber), and PVA (PVA fiber), followed by "fiber length-volume fraction."

3. Results and Discussions

3.1 Flowability

The flowability test was conducted in compliance with ASTM C 1437 [18]. The flow diameters were measured and are listed in Table 2. It can be seen that flowability tends to decrease with increase in fiber length and amount. A comparison of KRny and SRny40 at 1.0 vol.%, shows that the FRMs mixed with knotted fibers have greater flow diameters, due to the balling of fibers, which leads to fiber–mortar separation. Moreover, a comparison of PVA and SRny30, which have similar aspect ratios, shows fresh FRM containing PVA fibers to have a smaller flow diameter than SRny30 FRMs has, at a

Table 2 – Test results of fresh mortar properties

Specimen type	Fiber fraction by volume (%)	Fiber length, *L* (mm)	Diameter, *D* (mm)	Aspect ratio (*L/D*)	Flow diameter (mm)
UR	-	-	-	-	262
KRny-0.5	0.5	40	0.35	114	247
KRny-0.75	0.75	40	0.35	114	233
KRny-1.0	1.0	40	0.35	114	227
SRny20-1.0	1.0	20	0.35	57	231
SRny20-1.5	1.5	20	0.35	57	226
SRny20-2.0	2.0	20	0.35	57	207
SRny30-1.0	1.0	30	0.35	86	229
SRny30-1.5	1.5	30	0.35	86	216
SRny30-2.0	2.0	30	0.35	86	195
SRny40-1.0	1.0	40	0.35	114	217
SRny40-1.5	1.5	40	0.35	114	207
SRny40-2.0	2.0	40	0.35	114	183
PVA-1.0	1.0	18	0.2	90	213
PVA-1.5	1.5	18	0.2	90	169

given volume fraction, due to greater number of fibers.

3.2 Compressive strength

The compressive strengths of the FRMs are presented in Table 3. The compressive test was conducted in compliance with ASTM C 39 [19]. Table 3 indicates that the addition of the R-nylon fibers causes a reduction in compressive strength of the examined mortars up to 48%. Moreover, it can be clearly seen that the compressive strength decreases with decrease in fiber length, and decreases with increase in R-nylon fiber amount. An explanation is that nylon fibers have a much lower modulus of elasticity than mortar has, and therefore, the inclusion of fibers creates voids in the mortar [20]. Also, the addition of fibers, especially long fibers, leads to increases in the volume of the interfacial transition zone (ITZ), which results in the reduction of strength and stiffness of FRM [21]. This might suggest that the lower compressive strength of the KRny FRM is the result of a greater reduction in the modulus of elasticity of the FRM from the inclusion of knots as shown in Table 3. When the specimens are subjected to compressive load, lateral tensile strain in the mortar occurs due to the Poisson's effect. As the load increases, the longer fibers play a more important role in the mortar's lateral tensile strength than the shorter fibers play. These longer fibers postpone crack enlargement by increasing the mortar's lateral tensile strength [13]. In the case of the PVA fibers, the addition of fibers results in a decrease in compressive strength of the mortar, especially at greater amounts of addition. An explanation is that the modulus of elasticity of PVA fibers and mortar are almost the same, but the fibers are much less dense. Therefore, the mortar was filled with a high amount of fibers, which resulted in reductions in the elastic modulus of the mortar [22].

3.3 Flexural strength

After 28 days of curing, flexural strength tests were conducted in accordance with ASTM C 293 [23]. The authors performed three-point bending tests, and the peak load (P_{cr}), the first-crack strength (i.e., MOR), and other results are listed in Table 3. The results show that the addition of KR-nylon, SR-nylon, and PVA fibers increases the MOR by up to 22%, 41%, and 22%, respectively. Spadea et al. [3] and Orasutthikul et al. [24] 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:

$$M = 3P_{cr}l/2bd^2 \quad (1)$$

where, M = modulus of rupture (MOR) or first-crack strength; P_{cr} = maximum applied load;

Table 3 – Test results of compressive and flexural strength at 28 days

Specimen type	Compressive strength test					Flexural strength test					
	No. of specimens	f'_c (MPa)	*SD*	*CV*	$\%\Delta f'_c$	No. of specimens	P_{cr} (kN)	*MOR* (MPa)	*SD*	*CV*	$\%\Delta MOR$
UR	3	65.67	1.53	2.33	-	2	1.71	4.81	0.06	3.44	-
KRny-0.5	3	56.61	6.86	12.12	-13.80	2	2.08	5.86	0.12	5.66	21.95
KRny-0.75	3	55.96	11.43	20.42	-14.79	2	1.79	5.04	0.06	3.28	4.86
KRny-1.0	3	36.77	5.97	16.24	-44.00	2	1.58	4.45	0.00	0.00	-7.35
SRny20-1.0	3	52.56	1.18	2.24	-19.96	2	2.17	6.09	0.12	5.45	26.84
SRny20-1.5	3	48.66	2.05	4.21	-25.89	2	2.42	6.80	0.24	9.72	41.44
SRny20-2.0	3	34.14	1.70	4.99	-48.01	2	1.58	4.81	0.06	3.43	-0.09
SRny30-1.0	3	53.61	0.57	1.05	-18.36	2	2.04	5.74	0.18	8.66	19.42
SRny30-1.5	3	46.84	1.02	2.19	-28.67	2	2.00	5.63	0.12	5.85	17.06
SRny30-2.0	3	35.06	3.32	9.47	-46.61	2	1.54	4.34	0.18	11.46	-9.75
SRny40-1.0	3	55.54	2.84	5.12	-15.43	2	2.13	5.98	0.18	8.32	24.38
SRny40-1.5	3	48.24	0.57	1.19	-26.54	2	2.29	6.44	0.06	2.47	34.04
SRny40-2.0	3	35.27	1.07	3.02	-46.28	2	1.83	5.16	0.12	6.44	7.32
PVA-1.0	3	61.70	0.52	0.85	-5.87	2	2.04	5.74	0.06	2.87	19.49
PVA-1.5	3	59.57	5.61	9.41	-6.81	2	2.08	5.86	0.12	5.67	21.95

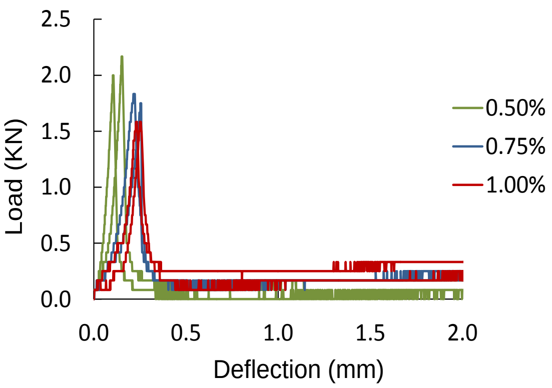
Note: f'_c - compressive strength, *SD* - standard deviation, *CV* - coefficient of variation, $\%\Delta f_c$ - percent difference in compressive strength between control specimens (UR) and FRMs, ΔR - percent difference in modulus of rupture between control specimens (UR) and FRMs.

b = specimen width; d = specimen depth; and l = span length.

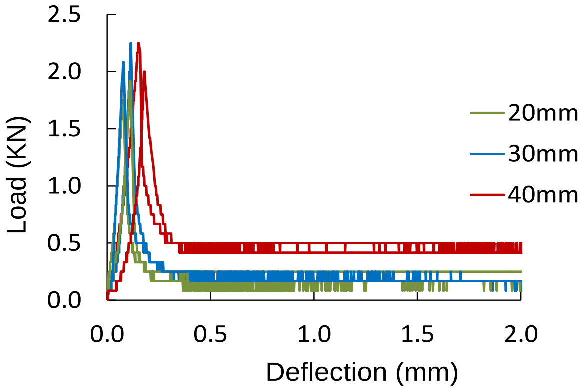
From Fig. 2(a) to (e), it can be clearly seen that R-nylon FRM shows a significant reduction in load after the first crack. This is because the R-nylon fibers used in this study have a smooth surface, so the friction interlocking between the fiber surface and the mortar is poor, which results in low frictional resistance to slippage. When PVA FRMs were subjected to external load, the PVA fibers tended to rupture before the fiber and the matrix debonded from each other. This caused abrupt reductions in the post-peak load of PVA FRMs to nearly the same or slightly lower than that of SRny40 FRM with a 2.0% fiber fraction when mid-span deflection was increasing. After the bending test, the fiber surface was examined to analyze the frictional resistance and interfacial bond between the fiber and the matrix. The R-nylon surface seen in Fig. 3(a) shows the fiber had no serious change in scratching as a result of low frictional resistance between the fiber and the matrix. For the PVA fiber, due to the stronger bond between the fiber and the matrix, some cement paste is seen on the fiber surface as shown in Fig. 3(b).

3.4 Toughness and residual strength

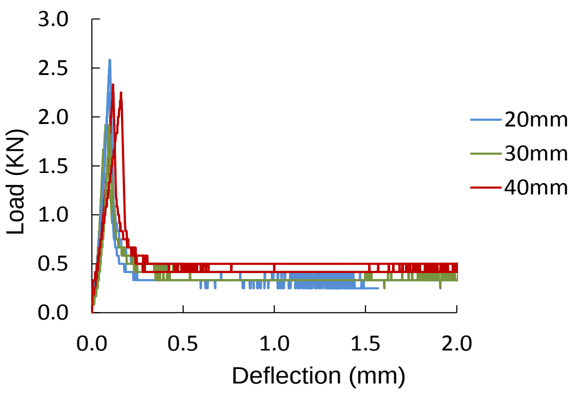
Toughness is an important mechanical characteristic of FRM. In accordance with ASTM C 1018 [25], toughness indices I5, I10, and I20 were obtained by dividing the area under the load-deflection curve up to 3.0, 5.5, and 10.5 times the first-crack deflection, respectively, by the area under the curve up to the first-crack deflection (see Fig. 4). Table 4 summarizes the toughness indices and residual strength factors of FRMs at 28 days. The addition of the fibers to the mortar appears to afford outstanding improvements in toughness, especially for higher fiber fractions and greater fiber lengths (see Fig. 5). The toughness and residual strength of FRMs are dependent on fiber characteristics, such as geometric shape, tensile strength, and modulus of elasticity, as well as on the bond strength between the fiber and the surrounding mortar. SRny30 fiber and PVA fiber have similar aspect ratios, but SRny30 FRMs have lower toughness indices and residual strength factors than PVA FRMs have. However, the fracture toughnesses of



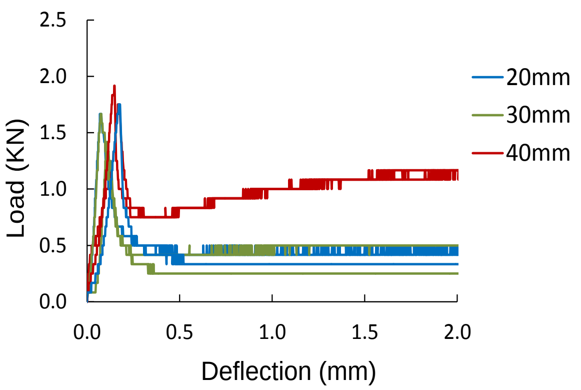
(a) Knotted R-nylon fiber



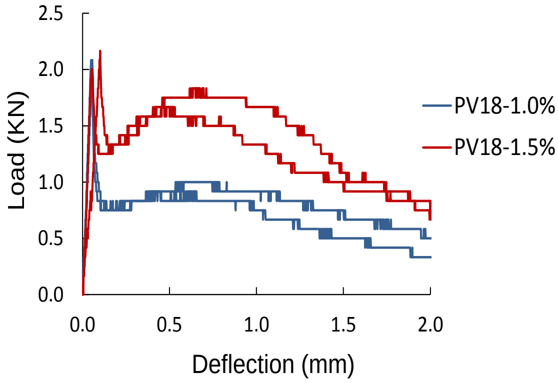
(b) Straight R-nylon fiber with 1.0% fiber fraction



(c) Straight R-nylon fiber with 1.5% fiber fraction

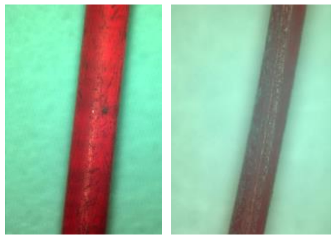


(d) Straight R-nylon fiber with 2.0% fiber fraction

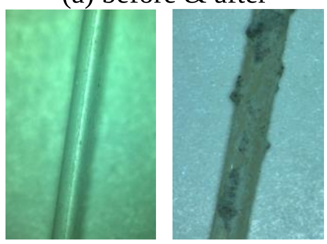


(e) PVA fiber

Fig. 2 – Load-midspan deflection curves of fiber-reinforced mortar specimens



(a) before & after



(b) before & after

Fig. 3 – Fiber surface before and after the flexural test: (a) R-nylon fiber, (b) PVA18 fiber

the SRny40 FRMs with a 2.0% fiber fraction (SRny40-2.0) fall between those of the PVA FRMs with a 1.0% fiber fraction (PVA-1.0) and the PVA FRMs with a 1.5% fiber fraction (PVA-1.5). In this study, the fiber fractions of the KRny fiber are low, and therefore the toughness and residual strength of the FRMs are not effectively improved. The PVA fibers generally have a stronger bond to the surrounding cementitious matrix because it is hydrophilic. Redon et al. [26] found that small-diameter PVA fibers ruptured before achieving their full pullout length. Therefore, when the PVA FRMs were loaded, the PVA fibers broke from tension rather than from pullout.

4. Conclusions

In this study, the effectiveness and potential of using waste fishing nets as recycled nylon fiber to

Table 4 – Toughness indices and residual strength factors at 28 days

Specimen type	Toughness indices			Residual strength factors	
	I_5	I_{10}	I_{20}	$R_{5,10}$	$R_{10,20}$
KRny-0.5	1.61	1.82	2.42	4.20	6.02
KRny-0.75	1.56	2.20	4.00	12.80	18.01
KRny-1.0	1.91	3.27	6.21	27.20	29.43
SRny20-1.0	1.95	2.41	3.45	9.18	10.40
SRny20-1.5	2.40	3.38	5.23	19.60	18.50
SRny20-2.0	2.80	4.17	6.71	27.40	25.40
SRny30-1.0	1.97	2.91	4.79	18.80	18.80
SRny30-1.5	2.86	4.17	6.49	26.20	23.20
SRny30-2.0	3.05	4.23	7.29	23.60	30.61
SRny40-1.0	2.88	4.47	7.71	31.80	32.44
SRny40-1.5	2.49	4.25	7.80	35.18	35.50
SRny40-2.0	3.37	6.02	13.38	53.00	73.60
PVA-1.0	2.77	4.62	8.74	37.00	41.21
PVA-1.5	3.72	7.50	15.74	75.60	82.40

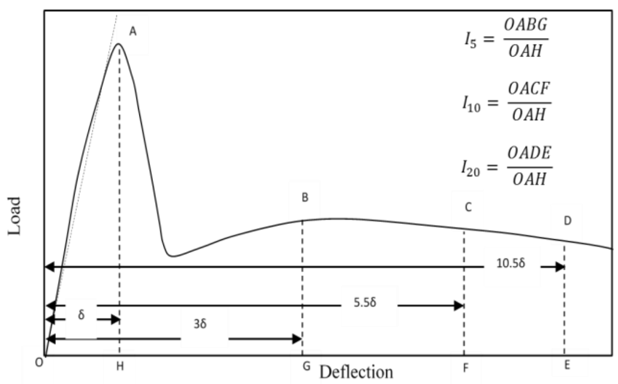


Fig. 4 – Toughness as defined by ASTM 1018

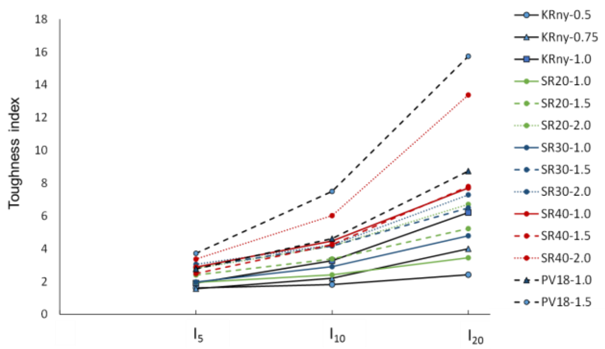


Fig. 5 – Toughness indices of FRMs

reinforce mortar were experimentally tested and discussed. Compressive and three-point bending tests were performed to investigate compressive strength, peak load, modulus of rupture, toughness indices, and residual strength factors. This study found the effects of adding R-nylon fibers to mortar to be as follows.

(1) The addition of R-nylon short fibers recycled from waste fishing nets to mortar improves the mechanical properties of the mortar, except for compressive strength, which decreases as a result of that addition.

(2) The addition of R-nylon fibers, whether straight or knotted, results in a reduction in mortar workability. Mortar flowability tends to decrease with increase in the fiber fraction. Mixes that incorporate longer fibers demonstrate smaller flow diameters than those with shorter fibers.

(3) The addition of R-nylon fibers to mortar affords a more ductile mode of failure than the addition of plain mortar affords. Post-cracking ductility is enhanced, which results in an increase in the load carrying capacity of FRM in bending. The post-peak loads are observed to be higher with higher fiber fractions and longer fibers.

(4) Mechanical analyses show that the addition of fibers leads to reductions in compressive strength of 14-44% for KR-nylon fiber and 20-48% for SR-nylon fiber. The MOR increased by up to 22% for KRny FRM and by up to 41% for SRny FRM.

(5) The addition of PVA fibers to mortar causes a greater reduction in flow diameter than the addition of R-nylon fibers at a similar fiber aspect ratio and the same fiber fraction.

(6) Post-peak load, toughness indices, and residual strength factors differ significantly according to fiber characteristics such as geometric shape, tensile strength, and modulus of elasticity, as well as according to the bond between the fiber and the cementitious matrix. As evidenced by

the flexural test, R-nylon fiber shows a significantly lower post-peak load than PVA fiber affords, due to the smooth surface of R-nylon fiber. Despite the stronger chemical bond between the PVA fiber and the matrix, the PVA fibers tended to rupture instead of pulling out. This caused the post-peak load of the PVA FRM to dramatically drop after the peak, due to breaking of the fiber. However, R-nylon fiber shows greater MOR improvement than PVA fiber affords.

(7) For every type of fiber, its addition to the mortar results in a decrease in compressive strength, especially the addition of fibers with a low modulus of elasticity, such as R-nylon fiber.

It must be noted, however, that the R-nylon FRMs analyzed in this study have been proven beneficial in terms of mechanical properties as PVA fiber, even if a higher amount of fibers may be required to match the performance. Moreover, the use of waste fishing nets as recycled nylon fibers results in an environmental benefit.

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