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Technical Paper

Influences of nylon fiber geometries and contents on mechanical behavior of reinforced mortar

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Abstract: Used nylon fishing nets were utilized as recycled nylon (RN) short fibers for reinforcing cement mortar. Fishing nets were cut into specified shapes and lengths, then mixed into mortar. In this study, the influences of fiber geometries such as diameter, aspect ratio and the fiber content on the mechanical properties of mortar were emphasized. Changes in flowability of fresh mortar, compressive strength, flexural strength, failure behavior, flexural toughness, residual strength factors were experimentally investigated and compared among various mixes. Experimental results indicated that fiber geometries as well as fiber content directly affect the mechanical properties of mortar. Adding fibers was found to reduce flowability and compressive strength of the mortar. For instance, using sharp-shapes reduced compressive strength by 41% while using cross-shapes improved flexural strength by 44.5%. Improvement in flexural strength and flexural toughness were found in association with the fiber content. RN fiber contributes to the post-peak loading capacity and prevents abrupt failure of concrete structures.

Keywords: Recycled nylon fiber; used fishing nets; fiber reinforced mortar; mechanical behavior.

1 Introduction

Abandoned, lost or discarded fishing gears (ALDFG), particularly fishing nets, in the ocean is becoming environmental issues. It was estimated that more than 705,000 tons of ALDFG were lost in the ocean and more than 100,000 marine lives were killed by ALDFG annually [1]. ALDFG accounts more than 46% of the plastics in the Great Pacific Garbage Patch, and the number of ALDFG is growing rapidly [2]. Recent studies found that ALDFG damages many coral reefs by scraping their tissues [3]. ALDFG can be navigational threats by causing entanglement of ship's propeller causing economic losses [4]. Therefore, there is a demanding issue in finding suitable recycling solutions for ALDFG to mitigate environmental impacts.

Modern fishing nets are usually made of very strong, durable materials such as nylon and high-density polyethylene (HDPE), which make fishing nets basically non-biodegradable. Fishing nets can be utilized into many textile products, such as clothes, carpets, sunglasses, and accessories [1, 5, 6]. However, there are still challenges in recycling used fishing nets because the considerable amounts of energy and resources are required in the recycling process, and the huge amounts of CO_2 are emitted [7].

Synthetic fibers have been widely used as reinforcement in cementitious materials as they improve mechanical properties and durability of concrete [8]. Polypropylene and nylon fibers were found to improve freeze-thaw resistance, splitting tensile strength, flexural strength of the mortar as well as prevent spalling of concrete under high temperature. However, the decrease in workability and compressive strength was reported [9-11]. Polyvinyl alcohol (PVA) fiber helps improving compressive strength, tensile strength, and fatigue and freeze-thaw resistance of the structure [12-14]. Nylon fiber also helped mitigating micro-cracks propagation by the crack bridging effect [15]. In addition, nylon fiber reinforced mortar showed outstanding mechanical properties over the polypropylene due to the better distribution of fiber in the cement mix [16].

Recently, recycled fibers have drawn the interest of engineers due to the relatively low material cost and for environmental preservation. Recycled fibers, such as polyethylene terephthalate (PET) fibers from plastic bottles and recycled nylon (RN) fibers from waste carpets were found to improve both

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mechanical properties and durability of cementitious materials [17-22]. Recycled fibers showed acceptable alkaline resistivity, which ensures safe application for concrete [23-25]. In addition, recycled HDPE fibers express comparable mechanical performance and durability as the new polypropylene fibers in reinforced cement mortar [24]. RN fiber from used fishing nets was found safely applicable for cementitious materials without harmful effects [25]. Orasutthikul et al. reported that RN fiber from used fishing nets improves flexural strength and flexural toughness as well as contributes to post-peak capacity of the mortar under bending loads [26]. The RN fiber from used fishing nets showed the comparable efficiency in reinforcing mortar as of other recycled fibers.

This research utilized used fishing nets as RN short fibers for reinforcing cement mortar. The aim of this study is to investigate the influences of fiber geometries such as diameter, length and shape as well as fiber content on the mechanical behavior of reinforced mortar. Flowability of fresh mortar, compressive strength, flexural strength, failure behavior, flexural toughness, and residual capacity factors were experimentally investigated to evaluate the effectiveness of the reinforcement.

2 Experimental program

2.1 Test specimens

Nylon used fishing nets used in this study were obtained from local fishermen in Hokkaido. Fishing nets were washed by soaking in water for 72 hours and dried indoor under room temperature. RN fibers were prepared by manually cutting the fishing nets by hand to control their length and shape. Diameter of fiber was measured using microscope, and it is confirmed that no sign of serious deterioration found on the surface of the fiber (Fig. 1). Three different nylon waste fishing nets were used in this study. Type A, type B and type C fibers are the RN fibers cut from each of waste fishing nets. Only the straight parts of the net (i.e. the nodes are not included) were used for RN type A, B and C. For RN type C, other two configurations of cutting were introduced to study the effect of the shapes of fibers which are cross-shapes with a node at the middle (type CS) and sharp-shapes with 4 nodes at the end of each section (type CR). Configuration of fibers are shown in Fig. 2.

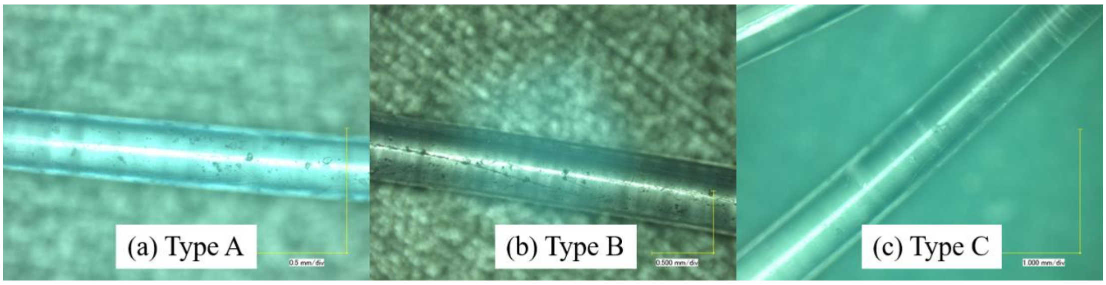
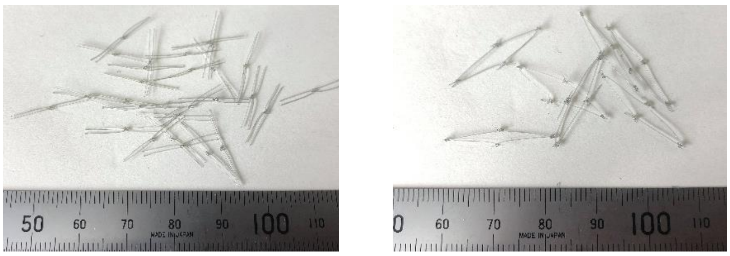


Fig. 1 – Microscope images of the fibers

(a) Type A (b) Type B (c) Type C



(d) Type CR (e) Type CS

Fig. 2 – Types of fibers

Table 1 – Mechanical properties of the fibers

Fiber	Diameter (mm)	Fiber configuration	Tensile strength (MPa)	Failure strain (%)	Young's modulus (GPa)
Type A	0.24	Straight	344	36.5	0.94
Type B	0.52	Straight	246	19.8	1.24
Type C	0.23	Straight	143	34.2	0.42
Type CR	0.23	Cross shapes	143	34.2	0.42
Type CS	0.23	Sharp shapes	143	34.2	0.42

Table 2 – Properties of cement

Density (g/cm^3)	Specific surface area (cm^2/g)	28 days compressive strength (MPa)	Ignition loss %	MgO (%)	SO_3 (%)	Cl^- (%)
3.16	3340	61.6	2.26	1.41	2.10	0.015

Table 3 – Mix proportion of mortar (kg/m^3)

Cement	Sand	Water	Fiber
742	1087	334	11.3

Uniaxial tensile tests following ASTM C1557 [27] were conducted on each type fibers using universal testing machine (UTM) with the constant cross-head displacement at 2 mm/min. The properties of the fibers are given in Table 1. Assuming linear relationship between stress and strain during the test, Young's modulus of fibers were calculated from the ratio of tensile strength and the failure strain.

2.2 Mix design and casting procedures

Mortar prisms with the dimension of 40 mm × 40 mm × 160 mm and the mortar cylinders measuring 50 mm in diameter and 100 mm in length were prepared for the tests. Ordinary Portland cement (OPC) having the density of 3.16 g/cm^3 and the river sand having the fineness modulus of 2.99 were used for the mixing. Properties of the OPC are given in Table 2. The mix proportion of the mortar is presented in Table 3; the water-to-cement ratio was 0.45. The density of RN fiber was set at 1.13 g/cm^3 according to the general value of nylon. The fiber content by volume was set at 1.0% and 2.0% to avoid the formation of fiber cluster during the mixing. Details of the test specimens are given in Table 4. The control specimen, plain mortar without fiber added, is named as NF (non-fiber). In addition, the mix with RN type A and type B fibers at the fiber fraction of 1.0% each was introduced to investigate the combined effect of fiber diameters. The mixes with of types A and B are named as M-20-1.0 and M-40-1.0 for the length of 20 mm and 40 mm fiber, respectively.

Preparation of mortar specimens was conducted according to our previous study [26]. Cement and sand were mixed together for 1 minutes at first, then RN fibers were slowly added during the mixing. Water was subsequently added and mixed for further 2-3 minutes to avoid fiber cluster. Two prism specimens and three cylinder specimens were casted and cured in water for 28 days before the tests.

2.3 Testing methods

Compressive tests were performed as per JIS A 1108 [28], and three-point flexural tests were conducted in accordance with JIS R 5201 [29]. Compressive tests and three-point flexural tests were conducted on the cylinder specimens and the prism specimens respectively. Two linear variable differential transformers (LVDTs) attached on the front and back sides of the specimen were used to measure vertical displacement at the midspan of the specimen during the flexural loading as shown in Fig. 3. The flexural load was applied with the vertical displacement rate of 0.05 mm/min until the vertical displacement reached 2.00 mm.

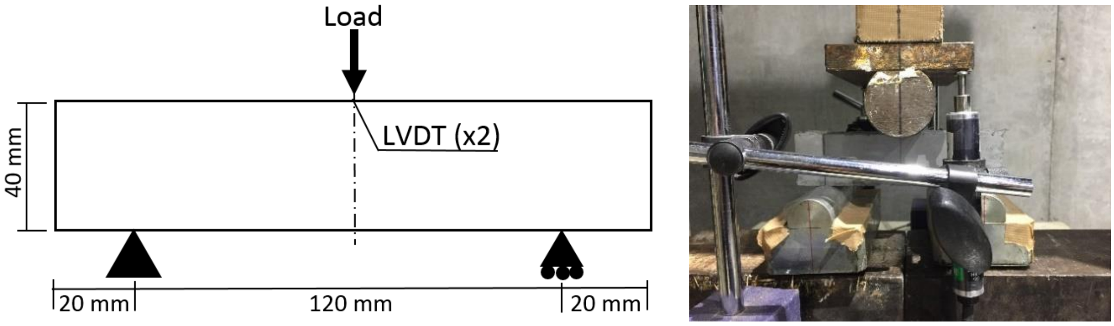


Fig. 3 – Three-point flexural test setup

Table 4 – Details of test specimens

Specimen name	Diameter of fiber, *D* (mm)	Length of fiber, *L* (mm)	Aspect ratio of fiber (*L*/*D*)	Fiber content by volume (%)
NF	-	-	-	-
A-20-1.0	0.24	20	83	1.0
A-20-2.0	0.24	20	83	2.0
A-40-1.0	0.24	40	167	1.0
A-40-2.0	0.24	40	167	2.0
B-20-1.0	0.52	20	38	1.0
B-20-2.0	0.52	20	38	2.0
B-30-1.0	0.52	30	58	1.0
B-30-2.0	0.52	30	58	2.0
B-40-1.0	0.52	40	77	1.0
B-40-2.0	0.52	40	77	2.0
C-10-1.0	0.23	10	43	1.0
C-10-2.0	0.23	10	43	2.0
M-20-1.0	0.24 + 0.52	20	-	1.0 each
M-40-1.0	0.24 + 0.52	40	-	1.0 each
CR-20-1.0	0.23	20	-	1.0
CR-20-2.0	0.23	20	-	2.0
CS-20-1.0	0.23	20	-	1.0
CS-20-2.0	0.23	20	-	2.0

3 Results and discussions

3.1 Mortar flow

The flow diameter of fresh mortar was measured in accordance with JIS R 5201 [29], and the results are given in Table 5. Adding fibers resulted in the reduction of flow diameter ranging from 2 – 22%. The reduction was remarkable for type C, which was 11% to 19%. Using fiber with the higher aspect ratio reduced flowability of fresh mortar in type A and type B mixes as seen in A-40-1.0 and B-40-1.0 that have the aspect ratio of 167 and 77, respectively. However, for type C, regardless of the smaller aspect ratio, fiber cluster was formed during mixing because of relatively small diameter. Increase in the fiber fraction to 2.0% caused further reduction in flow diameter by approximately 1.5 – 2.0 times as observed from the cases of A-20-2.0, C-10-2.0, CS-20-2.0 and CR-20-2.0. Using fibers with the smaller diameter tended to reduce flowability. Moreover, it was observed during the mixing that type A and type C tend to form fiber cluster during the mixing. Longer fibers (i.e. 40 mm) tend to further reduce the flow diameter as observed in A-40-2.0 and M-40-1.0.

On the contrary, the length and fiber content of type B did not show clear influences on the flowability. For M-20-1.0 and M-40-1.0, the reduction in flow diameter seems to have the same tendency as type A. Fresh mortar with CS fibers showed greater reduction in flow diameter than that with CR fibers because the CS fiber has two knots at its ends (see Fig. 2(e)). Fresh mortar with CR and CS expressed similar trend to that with type C; therefore, the diameter of fiber shows a greater influence on the flowability than the shape of fiber.

The fiber geometry had a great influence on the flowability of fresh mortar. For the same type of fibers, fiber with higher aspect ratio seems to reduce the flowability of fresh mortar. Using fibers with the smaller diameter also reduces the flowability of fresh mortar because more fibers are presenting in the mix at the same fiber content. In addition, thinner fibers tend to be tangle together and form fiber cluster during the mixing. However, this behavior depends on the surface characteristics and the stiffness of the fiber, which needs more confirmations in the future.

3.2 Compressive strength

The results from the compressive strength tests and the three-point flexural tests are summarized in Table 5. These results were averaged from 3 cylinder specimens and 2 prism specimens for compressive and flexural strengths, respectively.

Test results showed that adding fibers reduces the compressive strength of mortar, especially for CR and CS mixes. Increasing fiber content from 1% to 2% causes further reduction of the compressive strength. It was suggested by Lee et al. (2012) and Karahan et al. (2011) that adding fibers reduces the modulus of elasticity and increases air content in cement matrix [11, 30-31]. Moreover, the reduction in compressive strength of CR and CS was probably caused by the knots of fibers, which increases void in the cement matrix. Reduction in compressive strength was observed when applying RN fibers

Table 5 – Flow and compressive and flexural strengths of tested mortar

Specimen	Aspect ratio	Flow		Compressive strength			Flexural strength		
		d (mm)	Δ*d* (%)	f'_c (MPa)	*SD* (MPa)	$\Delta f'_c$ (%)	f_b (MPa)	*SD* (MPa)	Δf_b (%)
NF	-	254	-	45.1	7.7	-	5.3	0.2	
A-20-1.0	83	244	-3.9	48.1	10.8	6.7	5.5	0.8	4.5
A-20-2.0	83	239	-5.9	38.1	4.4	-15.4	5.7	0.5	8.9
A-40-1.0	167	234	-7.9	43.8	14.1	-2.9	6.7	1.2	26.7
A-40-2.0	167	205	-19.3	36.4	4.0	-19.2	5.2	0.0	-2.2
B-20-1.0	38	235	-7.5	42.1	14.1	-6.6	4.9	0.3	-6.7
B-20-2.0	38	240	-5.5	33.0	4.0	-26.7	5.7	0.5	8.9
B-30-1.0	58	238	-6.3	36.0	0.4	-20.2	5.3	0.8	0.0
B-30-2.0	58	244	-3.9	33.1	4.0	-26.7	5.6	0.0	6.7
B-40-1.0	77	249	-2.0	36.9	2.2	-18.2	6.2	0.8	17.8
B-40-2.0	77	238	-6.3	43.3	10.4	-4.0	5.4	0.3	2.2
C-10-1.0	43	226	-11.0	36.3	1.2	-19.4	5.6	0.3	6.7
C-10-2.0	43	206	-18.9	35.3	0.8	-21.8	6.7	0.5	26.7
M-20-1.0	-	247	-2.8	35.9	2.9	-20.3	5.4	0.0	2.2
M-40-1.0	-	210	-17.3	38.0	6.4	-15.7	6.3	0.0	20.0
CR-20-1.0	-	231	-9.1	33.5	0.8	-25.7	6.9	0.5	31.1
CR-20-2.0	-	208	-18.1	30.8	0.7	-31.8	7.6	0.2	44.5
CS-20-1.0	-	224	-11.8	30.6	2.5	-32.0	5.9	0.0	11.1
CS-20-2.0	-	198	-22.0	26.6	1.7	-41.0	5.7	0.8	8.9

Note: *d* – flow diameter, %Δ*d* – percent difference in flow diameter compared with NF, f'_c – compressive strength, *SD* – standard deviation, $\%\Delta f'_c$ – percent difference in compressive strength compared with NF, f_b – flexural strength, and $\%\Delta f_b$ – percent difference in flexural strength compared with NF.

from used fishing nets [25, 26].

Mortar mix with the fibers of lower aspect ratio showed considerable reduction in compressive strength as seen from B-20-2.0 and B-30-2.0 that has the lowest compressive strengths among type A, type B and type C. However, A-20-1.0, A-40-1.0 and B-40-2.0 showed relatively less reduction or even increase in compressive strength. This behavior was found by Ozger et al. that short fiber helps improving lateral tensile strength of mortar [32].

3.3 Flexural strength

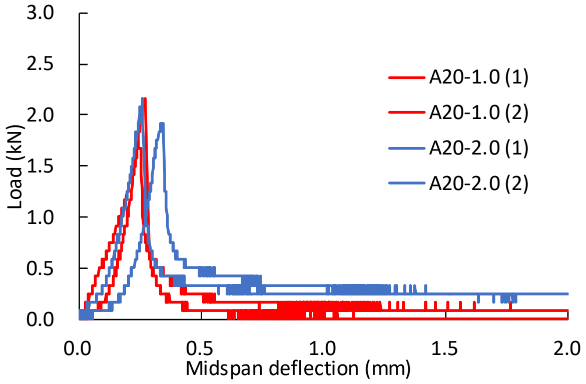
Adding fibers seems to improve flexural strength of the mortar. However, the tendency is still unclear. Mortar reinforced with CR type showed highest flexural strength with the increase of 44% for CR-20-2.0 compared to the plain mortar (NF). C-10-2.0 and A-40-1.0 showed the same level of increment at 27% followed by M-40-1.0 and B-40-1.0. Flexural strength of the CS mix was lower than that of CR, but was still higher than most of the type A and type B that use straight fibers without knots. Orasutthikul et al. [26] explained that the knots at the ends of fiber can form fiber clusters during mixing; therefore, fibers were not uniformly distributed.

Some of the mortar mixes, particularly in type B mixes, showed a comparatively low or even slightly decreased flexural strength compared to NF. It is possible that the voids created by the fiber lower the strength of mortar rather than improve it.

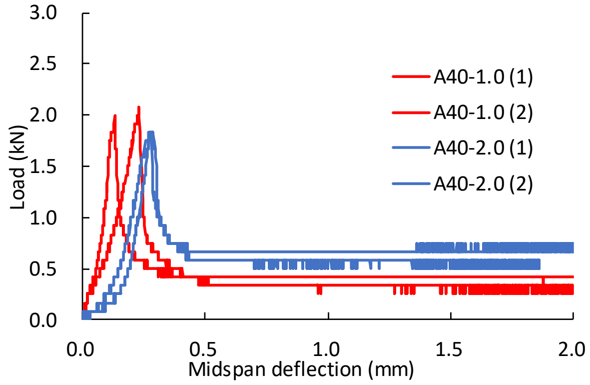
The fiber content and the aspect ratio of fibers did not show clear trend in the increment of flexural strength of mortar, and the effects of those parameters cannot be concluded. The contribution of fibers to flexural strength was found to depend on the surface friction and the bond behavior between fibers and cement substrate [33]. No breakage of fibers was observed during the loading tests; however, the smooth surface of RN fiber may lead to poor bonding between fibers and the cement substrate. The overall results showed that adding fibers gives a positive effect to the flexural strength of mortar.

3.4 Failure behavior

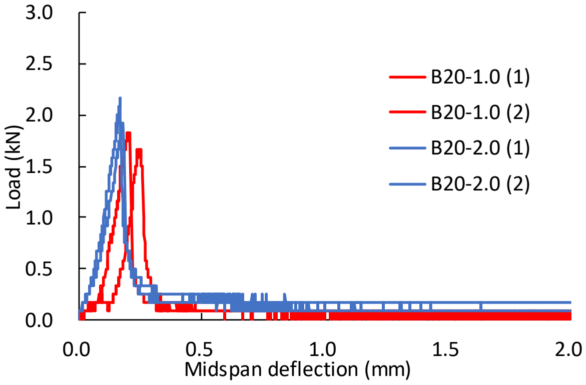
The load-midspan deflection curves from the three-point bending tests are shown in Fig. 4. All fiber-reinforced specimens expressed ductile failure whereas plain mortar (NF) showed brittle failure. The load dropped after the peak load and maintained post-peak loads in the range of 0 – 0.5 kN and 0.5 – 1.0 kN for the fiber fraction of 1.0% and 2.0% respectively. In addition, a hardening stage was observed in which the load increased slightly after the peak as observed in type B and type CR (Fig. 4 (d-f, i)). This behavior indicated that fibers would be able to transfer the loads through cracks and to prevent sudden collapse of concrete. This hardening stage was also found for recycled PET fibers [23, 26] and HDPE fibers [24].



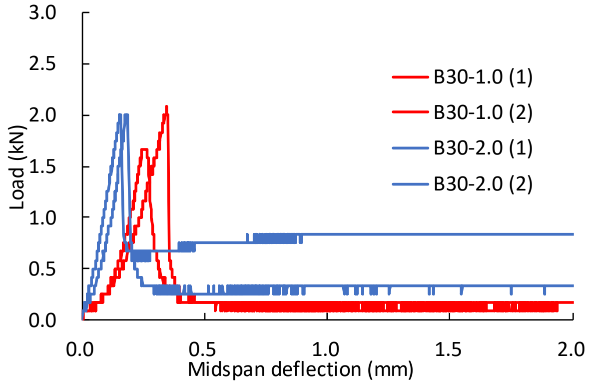
(a) Type A with 20 mm long fiber



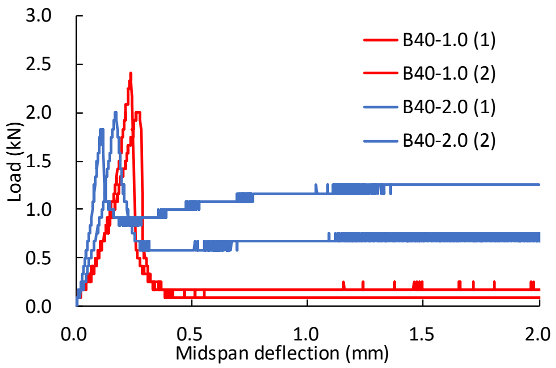
(b)Type A with 40 mm long fiber



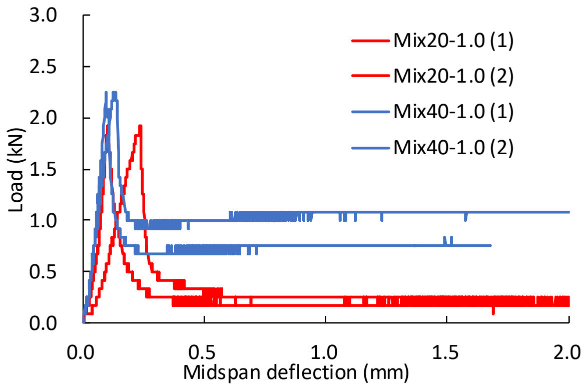
(c) Type B with 20 mm long fiber



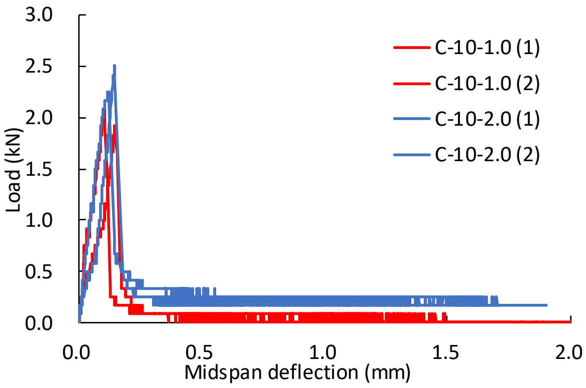
(d) Type B with 30 mm long fiber



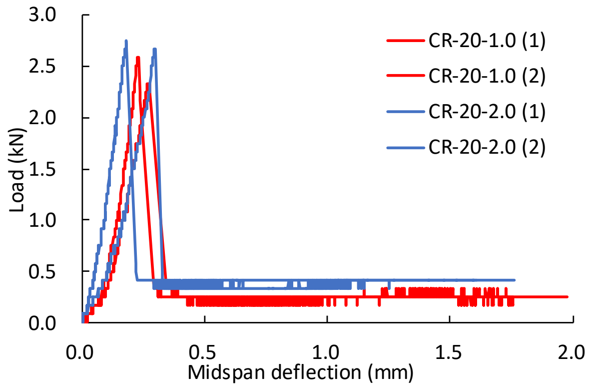
(e) Type B with 40 mm long fiber



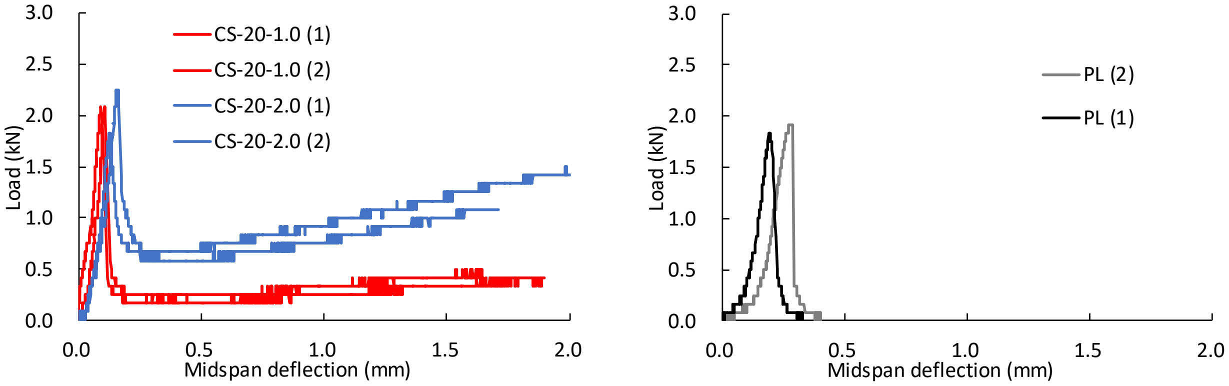
(f) Mix of type A and type B with 20 and 40 mm long fiber



(g) Type C with 10 mm long fiber



(h) Type CR with 20 mm long fiber



(i) Type CS with 20 mm long fiber

(j) Plain mortar (NF)

Fig. 4 – Load-midspan deflection curves

Increasing fiber content (i.e. fiber fraction to 2.0%) as well as increasing the length of fiber improved the post-peak behavior and reduced the drop in post-peak loads. This characteristic indicated that fiber delays the failure as well as prevents sudden collapse of the structure. The diameter of fiber does not show a noticeable effect on the first-rack strength; however, the larger diameter of fiber showed the higher post-peak loads as indicated in Fig 4 (e). The increase in the post-peak capacity of type CS confirmed that the stresses were transferred by the fibers. The knots at the ends of fiber was found to improve bond behavior between fiber and the matrix; thus, the fiber was elongated rather than being pulled out.

3.5 Flexural toughness and residual strength factors

Flexural toughness (I_5, I_{10}, I_{20}) are defined as given in Fig. 5 as per ASTM C1018 [34]. They were calculated from the area under the load-deflection curve where δ stands for the first-crack deflection. The residual strength factors are defined by the following equations:

$$R_{5,10} = \frac{100}{10-5} \quad (I_{10} - I_5) \qquad (1)$$

$$R_{10,20} = \frac{100}{20-10} \quad (I_{20} - I_{10}) \qquad (2)$$

Table 6 lists flexural toughness and residual strength factors. The results confirmed that adding fibers affords the improvement of flexural toughness. The load application was terminated when the vertical mid-span displacement reaches 2.0 mm in some mixes. Therefore, I_{20} and $R_{10,20}$ cannot be calculated for them. Residual strength factor, $R_{5,10}$, seems to be higher for the mix containing fiber with higher aspect ratio. Increasing in fiber content and using longer fiber improves flexural toughness of mortar as seen from A-40-2.0, B-40-2.0, M-40-1.0 and CS-20-2.0 in Fig. 6. Moreover, the residual strength factor of the 40-mm long fibers is higher than those of 20-mm long fibers. Similar behavior of flexural toughness was also found when using recycled PET and PVA fibers [26].

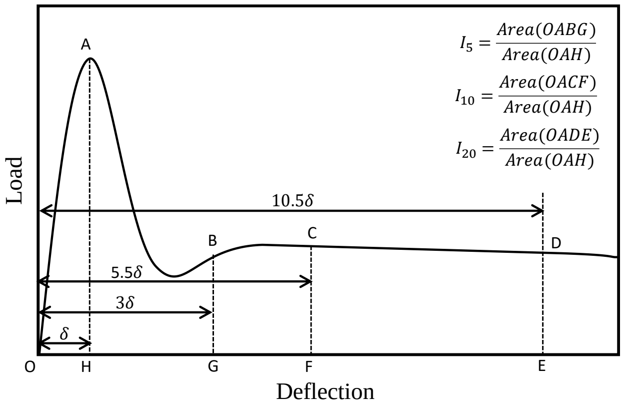


Fig. 5 – Load-deflection curves as defined by ASTM C 1018

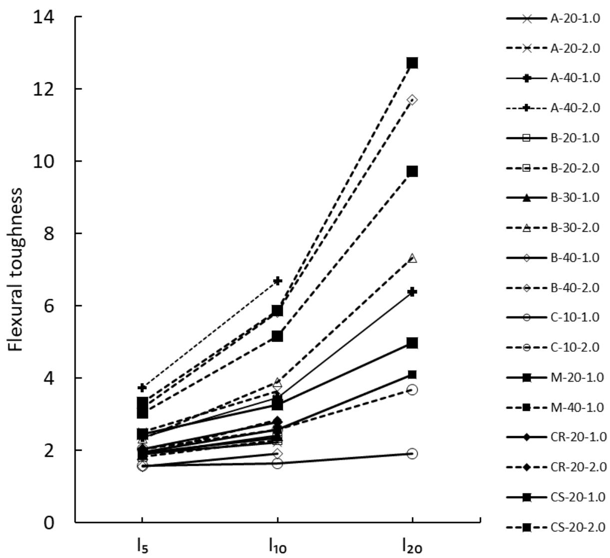


Fig. 6 – Toughness indices of fiber reinforced mortar

Table 6 – Toughness indices and residual strength factors

Specimen	**Aspect ratio**		I_5	I_{10}	I_{20}		$R_{5,10}$	$R_{10,20}$
NF	-		-	-	-		-	-
A-20-1.0	83		1.92	2.23	-		6.2	-
A-20-2.0	83		2.52	3.64	-		22.4	-
A-40-1.0	167		2.36	3.47	6.39		22.2	29.1
A-40-2.0	167		3.73	6.7	-		59.4	-
B-20-1.0	38		1.93	2.35	-		8.4	-
B-20-2.0	38		1.83	2.28	-		9.2	-
B-30-1.0	58		1.88	2.42	-		10.8	-
B-30-2.0	58		2.33	3.89	7.32		31.2	-
B-40-1.0	77		1.56	1.92	-		7.2	-
B-40-2.0	77		3.19	5.83	11.7		52.8	58.7
C-10-1.0	43		1.58	1.64	1.90		1.18	2.61
C-10-2.0	43		2.04	2.58	3.67		10.8	10.8
M-20-1.0	-		2.46	3.26	4.98		16.0	17.2
M-40-1.0	-		3.04	5.16	9.72		42.4	45.6
CR-20-1.0	-		2.04	2.79	-		15.0	-
CR-20-2.0	-		1.89	2.85	-		19.2	-
CS-20-1.0	-		1.95	2.58	4.10		12.6	15.2
CS-20-2.0	-		3.32	5.86	12.71		50.8	68.5

4 Conclusions

Recycled nylon fibers from used fishing nets were mixed in cement mortar with various fiber configurations and contents. The experimental results confirmed that fiber geometries as well as the fiber contents have significant influences on the mechanical properties of mortar, such as flowability, compressive strength, flexural strength, failure behavior, flexural toughness and residual flexural strength. From this study, the following conclusions were drawn:

(1) Adding fibers considerably reduces the flow diameter of fresh mortar in the range of 2 – 22%. Fibers with higher aspect ratio as well as high content of fibers greatly reduce the flowability of mortar. In addition, fiber cluster tends to form during the mixing when using the small diameter of fibers or fibers with knots (CR and CS).

(2) Significant reduction of compressive strength is expected with the addition of fibers. Adding fibers that have lower aspect ratio or the fiber with knots (CR and CS) reduces the compressive strength of mortar up to 41%. The reduction in compressive strength becomes severe as the fiber content is increased.

(3) Adding fibers tends to improve flexural strength of the mortar. However, its influence is still unclear. Cross-shapes fiber shows highest performance at 45% increment in flexural strength among all fiber types.

(4) Adding fibers contributes to the post-peak behavior in which the beam can retain some loads after the peak. Increasing in diameter, length and volume fraction of fiber improves post-peak capacities. The post-peak load is increased with the addition of the sharp-shape fiber. Fiber helps preventing abrupt failure of mortar.

(5) Flexural toughness of the mortar is improved with the addition of fiber. Increase in fiber content as well as the length of fiber yields higher flexural toughness. Using fibers with higher aspect ratio also improves the residual strength factor.

Recycled nylon fibers from waste fishing nets have potential to be used in cementitious materials. The addition of fiber causes both positive and negative effects simultaneously to the mechanical properties of mortar. Therefore, careful consideration should be taken before applying recycled nylon fibers. Further studies are still needed to understand the behavior of recycled fiber reinforced mortar.

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