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Research paper

Mechanical properties and microstructure of recycled mortar reinforced with hybrid fiber

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Abstract

This study investigated the hybrid effects of two types of microfiber, namely, polypropylene and nylon, on the mechanical properties of high-strength mortar, which produced fine recycled aggregate (FRA). The amount of microfibers was maintained at a volumetric fraction of 0.6%. The microstructure and mechanical strength properties (compressive strength and flexural strength) of recycled mortar reinforced with hybrid-size microfibers were evaluated at various curing ages. Experimental results show that the inclusion of hybrid fibers significantly influenced the mechanical performance of the recycled mortar. The hybridization fiber at volume fraction 0.3% polypropylene + 0.3% nylon yielded the most promising mechanical performance. Enhancements of 8% on compressive and 11% flexural strength were achieved at 28 days. Scanning electron microscopy observations revealed that reinforcement at the microscale prohibited the initiation and growth of cracks at the micro level. High loads were required to form macrocracks within composites, thereby improving the mechanical strength of the mortar matrix.

Keywords: *Fine Recycled Aggregate; Hybrid Fiber; Nylon Fiber; Polypropylene Fiber; Recycled Mortar.*

1. Introduction

At present, recycled aggregates generated through the reuse and recycling of construction and demolition waste activities are one of the best alternative measures taken by the construction industry to solve natural aggregate deficiencies in some parts of the world and possibly reduce the degradation impact of environmental pollution. In the production process of coarse recycled aggregates, fine fractions (<5 mm) are indirectly produced, and they represent about 40%–50% of the weight of crushed waste. Fine recycled aggregates (FRAs) demonstrate high absorption characteristic compared with coarse aggregates, making this material more difficult to incorporate into concrete due to a large water demand. In addition, the control of mixing water and workability of the fresh mixture will be difficult. Hence, most international standards restricted the use of FRA and replaced it with natural fine aggregate (NFA) in the production of concrete; however, FRAs remain unrestricted in the production of mortars [1]. Many studies have been carried out on the employment of FRAs from crushing concrete waste in the manufacture of new mortar [2-6]. The influence of FRA on mechanical and durability properties of production mortar was analyzed. In general, the mechanical and durability characteristics decrease as the percentage of FRAs increases. In other studies, several authors reported no adverse effects on the mechanical properties of mortar when FRAs are used as replacement at ratios of up to 30% [7], [8]. Cement-based materials (e.g., concrete and mortar) are generally highly brittle with low tensile strength and strain capacity. A wide range of solutions have been proposed to overcome the brittle weakness of cement-based materials. Among these solutions, the inclusion of a certain portion of small fibers randomly mixed into concrete mixture called fiber-reinforced concrete (FRC) is effective in reducing brittleness and enhancing tensile strength of concrete. Fiber distributed in the matrix creates a bridging effect, thereby delaying crack propagation, enhancing the toughness of concrete, and maintaining the ability to carry a load after the first crack appears [9]. In the case of concrete or mortar, the increasing proportion of recycled aggregate will increase the brittleness of concrete or mortar, leading to deteriorated mechanical properties [6], [10]. Previous studies demonstrated that the inclusion of monofiber, that is, steel [11], polypropylene (PP) [12], nylon (NY) [13], and natural fiber [14], can enhance the mechanical properties, restrain the progression of cracks, and convert it into a ductile material, thereby increasing energy absorption. However, the ability of fibers in improving concrete properties with recycled aggregate depends on the type of fibers, content, aspect ratio, surface friction, and tensile strength of fibers [15].

To further improve the reinforcement effect, the use of hybrid fibers of different types or sizes has been gaining popularity in recent years [16-19]. The benefits of randomly distributed hybrid fibers can combine the complementary benefits that each particular fiber type can impart; this combination can lead to behavioral efficacy or performance that exceeds that induced by each fiber type alone. Moreover, the inclusion of a hybrid combination of fiber reflects that concrete has a complex microstructure with a multiscale structure that contains random features over a wide range of length scales (from nanometers to millimeters). The addition of fibers of different sizes can improve the properties of the composites by chasing the propagation of crack growth at both micro and macro levels [18], [19]. Vineetha and Aravind [20] investigated the effects of a hybrid fiber between PP and NY fibers on the mechanical properties of recycled aggregate concrete. They concluded that the specimen with fiber content of 1% combined with 25% PP and 75% NY fiber presents better performance in terms of the compressive strength, flexural strength, and split tensile strength of concrete compared with other specimens. In another research, Ismail and Ramli [21] observed that a recycled aggregate concrete mix incorporated with hybrid fibers (polyolefin and PP fibers) exhibits higher impact resistance characteristics than single fiber specimens.

Although present studies have analyzed the utilization of hybrid fibers in reinforced recycled aggregate concrete composites, the benefits of hybrid fibers in enhancing the various properties of mortar using FRA remain unclear. Hence, this work aimed to investigate the effect of hybrid fibers on the mechanical properties of high-strength mortar, which was produced with FRA. In this study, two types of microsynthetic fibers (i.e., PP and NY fibers of different sizes) were added in single and hybrid forms in a series of FRA mortar mixtures. The main objective of this study was to evaluate the contribution of various reinforced fiber systems on the compressive and flexural strength properties of the resulting FRA mortar. This study also determined the most appropriate fiber composition that could significantly enhance the performance of FRA mortar. Scanning electron microscopy (SEM) analysis was performed to visualize the microstructural behavior of the fibers and non-fiber mortar mixes in relation to their mechanical strength.

2. Method

The binders for mortar production consisted of type 1 ordinary Portland cement (OPC) and silica fume (see Table 1 for typical chemical compositions of OPC and silica fume). Other materials for preparing mortar mixtures included NFA, FRA, water, fibers, and superplasticizer. The NFA used was uncrushed locally sourced quartzite natural river sand that was manufactured as reference mortar, and FRA was generated from crushed wasted concrete and subsequently sieved with a vibration screen. The sieve analysis results for grading both NFA and FRA are presented in Table 2 and Fig. 1. The grading results indicated no obvious difference in the size distribution of NFA and FRA; both types of aggregates were composed of 70% generally coarse particles with a size that was higher than 600 µm. However, the fine modulus values were slightly higher in FRA than in NFA, which indicated that FRA was slightly coarser than NFA. Table 3 summarizes the properties of NFA and FRA. Physical observations indicated that FRA was more angular and rougher than NFA. In addition, FRA was characterized by its porosity, low density, and high absorption characteristics compared with NFA. The inferior properties of FRA were attributed to the presence of a certain amount of hydrated cement residue in fine fractions that adhered to the FRA particles, which are light and porous in nature. In this study, two microsynthetic fibers of different types and sizes were used: i) PP fiber type (12 mm in length) and ii) NY fibers (6 mm in length). Both fibers are manufactured in multimesh form so that they can be separated into multistrand or individual filaments in mortar during mixing. The detailed specifications of PP and NY fibers are shown in Table 4. To enhance the workability of mortar in this study, we used a chloride-free super plasticizing admixture based on sulfonated naphthalene polymers. To achieve the required workability and be in compliance with specifications of ASTM standard C494, a superplasticizer formulated based on carboxylate polyether with high-range water reducer was used.

All mortar mixtures batched in this study were prepared following the sequences of methods for mixing according to standard procedures prescribed in ASTM Standard 305. In this study, to ensure uniform powder binders, cement and silica fume were initially dry mixed at a low mixing speed by using a rotary mixer for 3 min prior to adding other materials. The slump flow of fresh mortar was carried out to determine mortar workability after the completion of mixing. The slump flow was performed using the flow table complying with specifications prescribed in ASTM Standard C230 and standard testing procedures stipulated in ASTM Standard C1437. All specimens were cast in steel molds and compacted using a vibrating table. The specimens were cured in a humidity-controlled environment at room temperature for 24 h and then demolded. Mortar cube specimens of 50 mm were used to determine the density and compressive strength of hardened mortar mixtures, and both tests were carried out in accordance with the procedures described in BS EN 12390-7:2009 and ASTM Standard C109. Meanwhile, mortar (with dimensions of 40 mm×40 mm×160 mm prism) were casted to determine the flexural strength according to ASTM Standard 348. All the specimens used for the determination of compressive and flexural strength were cured and tested at the age of 7, 14, and 28 days. The compressive and flexural strength at the given curing ages of mortar indicated the average strength of the three specimens tested.

3. Mix design

The mix design of mortar was in accordance with the absolute volume method prescribed in the American Concrete Institute Standard. This mix design was prepared with a binder:aggregate relation maintained at 1:2.25 and an effective water/cement ratio of 0.32 to achieve a targeted compressive strength of more than 50 MPa on day 28. In this study, we attempted to fully optimize the utilization of FRA in mortar mix. Hence, the compositions of fine aggregates in all recycled mortar mixtures were kept constant by substituting the NFA with 100% FRA. Meanwhile, the dosage designs of either individual or hybrid fibers added to the respective recycled mortar mix were also constant at a total volumetric fraction rate of 0.6% (by volume of the mortar mixes) as recommended by the manufacturer. A superplasticizer was added at appropriate dosages to maintain the workability of the mortar mix, considering the water loss caused by the absorption of aggregates and binders during mixing.

In total, nine mortar mixtures were prepared with the following code: i. (CO) – reference mortar, which was produced with NFA). ii. (RO) – recycled mortar composed of 100% FRA, iii) (P1 and N1) - recycled mortar made with 100% FRA and incorporated with single PP and NY fiber respectively; and iv) (H1 to H5) recycled mortar mix made of 100% FRA and then incorporated with various fractions of fiber volume in hybrid combinations. The detailed mix proportions in the material composition of all the mortar mixes are listed in Table 5.

Table 1: Typical Chemical Compositions of the OPC and Silica Fume

Materials	Composition (%)									
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	SO_3	P_2O_5	TiO_2	Others
OPC	16	3.6	2.9	72	1.5	0.34	3.1	0.06	0.17	0.34
Silica fume	90	1.2	2.0	1.0	0.6	0.8	0.5	0.05	0.09	4.8

Table 2: Sieve Analysis of Aggregates

Types of aggregate	Aggregate passing (%) according to sieve size (mm)							Fineness modulus
	0.15	0.3	0.6	1.18	2.36	5	10	
NFA	0.02	0.08	0.23	0.50	0.83	1.00	1.00	3.34
FRA	0.06	0.14	0.24	0.38	0.57	0.91	1.00	3.70

Table 3: Properties of NFA and FRA

Properties	NFA	FRA
Fineness modulus	2.75	2.83
Particle density (Mg/m^3)	2.65	2.30
Water absorption (%)	1.08	2.07
Fineness 75 µm (%)	2.00	6.00

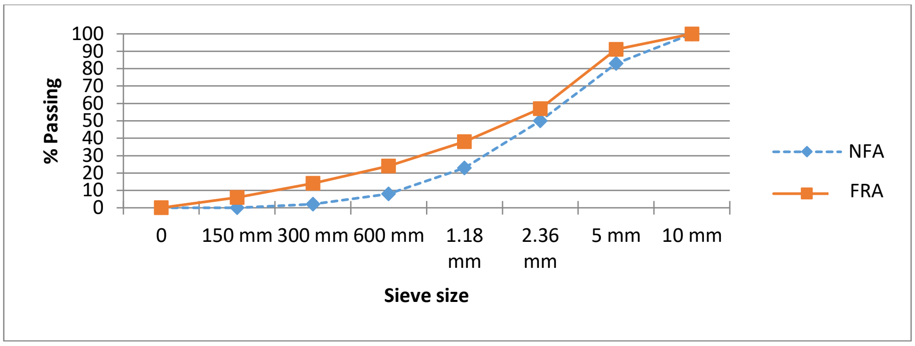

Fig. 1: Particle Size Distributions of NFA and FRA.

Table 4: Properties of PP & NY

Type	Mega Mesh II - Multi-lament	Scancem's Nycon fibres
Material	100% Virgin polypropylene	100% Virgin Nylon
Color	White	Yellow
Length	12 mm	6 mm
Mass (Denier)	15 denier	8 denier
Specific Gravity	0.90 kg/dm³	1.15 kg/dm³
E-modulus	3,500 N/mm²	1.57 Gpa
Tensile Strength	400 N/mm²	300 Mpa
Melting Point	160 - 170°C	225°C
Thermal Conductivity	Low	Low
Electrical Conductivity	Low	Low
Acid and Alkaline Resistance	High	High

Table 5: Mix Proportions

Speci-men	Cement kg/m^3	Silica fume kg/m^3	Water kg/m^3	NFA kg/m^3	FRA kg/m^3	SP (%)	Fraction of fiber (kg/m^3)		Mortar flow (mm)
							PP	NY	
CO	651	57	227	1593	0	0.8	-	-	145
RO	651	57	227	0	1433	0.9	-	-	140
P1	651	57	227	0	1433	1	0.6	-	155
N1	651	57	227	0	1433	1	0.6	-	160
H1	651	57	227	0	1433	1	0.5	0.1	160
H2	651	57	227	0	1433	1	0.4	0.2	150
H3	651	57	227	0	1433	1	0.3	0.3	150
H4	651	57	227	0	1433	1	0.2	0.4	165
H5	651	57	227	0	1433	1	0.1	0.5	150

4. Results and discussion

4.1. Density of hardened mortar

The flow values of fresh mortar and their respective required dosage of superplasticizer are presented in Table 5. The flowability of the mortar mixes was affected when the NFA was fully replaced with the FRA. This relation was due to the porosity and high-absorption characteristics of FRA, which absorbed more water during mixing and decreased the workability of mixes. Hence, adequate dosages of superplasticizer were used to maintain the slump of mixes within the desired range. Meanwhile, the results show that mortar mixes including single and hybrid fiber contents exhibited similar slump levels at a constant superplasticizer dosage of 1%.

4.2. Density of hardened mortar

Fig. 2 shows the saturated surface density (SSD) of hardened mortar at 28 days. In this figure, the mean density was lower in recycled mortar than in reference or ordinary mortar. The dry density of fine FRA was 14% lower than that of NFA due to the presence of hydrated cement residue on FRA, thereby resulting in lower specific gravity in FRA than in NFA. The replacement ratio of NFA by 100% of FRA significantly reduced the density of mortar. Meanwhile, results showed a slight inconsistency in density results among recycled mortar mixes. This phenomenon was strongly governed by particle density of FRA rather than by the inclusion of fibers. Various amounts of adhered old cement paste on FRA may be due to FRA generated from different sources of parent concrete strength, resulting in inconsistencies in density of FRA and hardened density of recycled mortar.

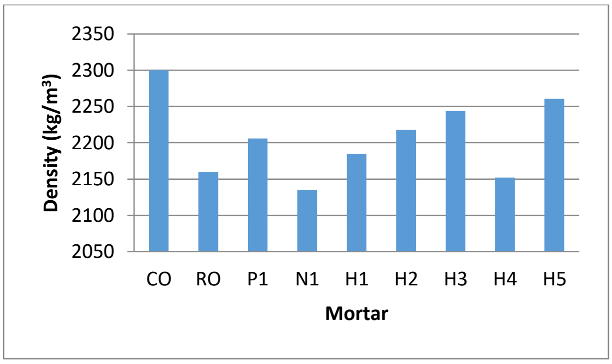

Fig. 2: Density of Hardened Mortars.

4.3. Compressive strength of mortar

The overall compressive strength of all mortar samples based on the curing ages of 7, 14, and 28 days are presented in Fig. 3. Table 6 presents the relative compressive strength of all mortar samples (expressed as a percentage of that corresponding to the CO specimen) for the entire testing period. In general, the results obtained from this investigation show that the compressive strength of overall mortar samples continuously increased until 28 days of the curing period. However, the replacement of NFA with 100% FRA noticeably affected the compressive strength of mortar. The recycled mortar in the RO mixtures showed the lowest compressive strength among mortar specimens for all testing ages. In addition, the compressive strength of RO mortar did not meet the design strength target of 50 MPa at 28 days, and it was 20% lower than that of reference mortar (CO). By contrast, recycled mortar prepared with the addition of fibers performed better than non-fibrous recycled mortar. At 28 days, the compressive strength of monofiber mixes represented by P1 and N1 mortar were 96% and 94%, respectively, and these values were relatively close to the compressive strength of CO mortar. Notably, the length of PP fiber was advantageous for mortar strength because it could resist cracks and their propagation compared with NY fiber. However, the compressive strength of high-strength recycled mortar containing full FRA could be further enhanced by adding various volume fractions of fibers in hybrid form. Table 6 shows that certain recycled mortar series with hybrid fibers exhibited improved compressive strength compared with single-fibrous recycled mortar and demonstrated higher strength than CO specimens. Among all hybrid fiber specimens, H3 with a balanced combination of short and long fibers in (combination of 0.3% NY + 0.3% PP fiber) recycled mortar mix presented the highest strength. Table 6 indicates that the compressive strength of H3 over reference mortar increased by 18%, 13%, and 8% at testing ages of 7, 14, and 28 days, respectively. This improvement may be due to the possible function of the homogenous distribution of different lengths and sizes of microfibers leads to inhibit the initiation of crack growth and limiting the crack width at multiscale level either in micro and sub micron scale or millimeter scale in the mortar matrix structure [22-25]. Moreover, the weak link in recycled mortar caused by the low quality of FRA, which potentially created paths of cracks, could at least be compensated to strengthen the matrix and control by synergistic effect produced by hybrid fiber.

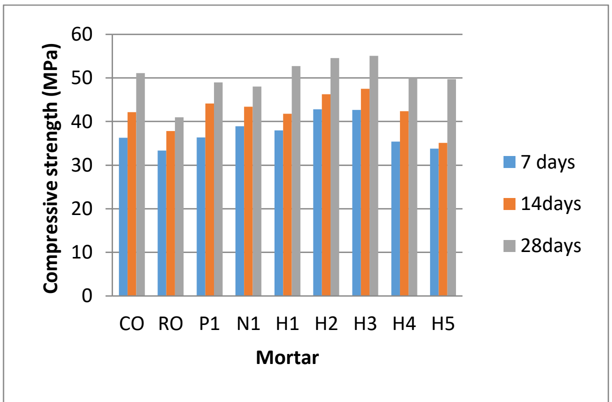

Fig. 3: Compressive Strength versus Curing Age for All Tested Specimens.

Table 6: Compressive Strength Relative to the Reference (CO)

	7 days	14days	28days
CO	1.00	1.00	1.00
RO	0.92	0.90	0.80
P1	1.00	1.05	0.96
N1	1.07	1.03	0.94
H1	1.05	0.99	1.03
H2	1.18	1.10	1.07
H3	1.18	1.13	1.08
H4	0.98	1.00	0.98
H5	0.93	0.83	0.97

4.4. Flexural strength of mortar

The overall gains of flexural strength across the curing age are illustrated in Fig. 4. Table 7 presents the relative flexural strength of all the mortar mixtures (expressed as a percentage of that corresponding to the CO mortar) for the entire test period. In general, the results indicate that similar trends were observed in the compressive strength; flexural strength of mortar decreased when incorporated with the FRA. At 7, 14, and 28 days, the percentage decreases in the flexural strength of the RO mortar were 7%, 9%, and 5%, respectively, compared with the reference mortar. However, the drop in flexural strength was slightly lower than that in compressive strength. This possible factor might be due to the bonding mechanism of matrix in mortar composites, which played an important role in dealing with carrying load in flexural tests rather than in compressive tests. Physical FRA exhibited an angular shape and rough texture compared with the NFA. These features may lead to an enhanced interface bond between the cement paste and FRA particles, thereby improving the flexural strength of mortar. Meanwhile, the inclusion of fibers could enhance the flexural strength of recycled mortar. Notably, mortar mixed with long fibers indicated slightly higher strengths compared with mortar containing short fibers. The large contact area of long fibers with the surrounding matrix may increase their ability in controlling crack propagation under a flexural load. The stiffness of fiber also played an important role in carrying flexural load because PP showed more stiffness than NY. Hence, mortar with monofiber present by P1 produced higher flexural strength than N1 mortar. The profile gain in the flexural strength rate for the entire testing age was remarkable in the hybrid form series with the maximum PP fiber content. However, the homogeneous mixture blended with a balanced combination ratio between PP/NY fiber was beneficial for carrying the flexural load of recycled mortar. At 28 days, the highest flexural strength was recorded in the H3 specimens, in which their overall strength was close to 20 MPa or 11% higher than reference mortar. The balance combination of different lengths (short and long) between PP and NY fibers demonstrated a synergetic effect for increased reinforcing efficiency in preventing multiscale crack propagation in mortar matrix.

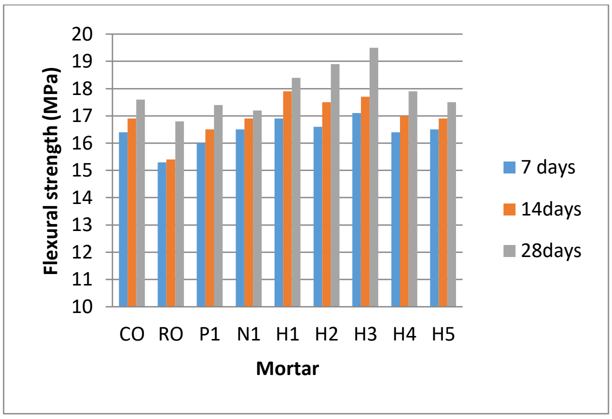

Fig. 4: Flexural Strength versus Curing Age of Tested Specimens.

Table 7: Flexural Strength Relative to the Reference (CO)

	7 days	14 days	28days
CO	1.00	1.00	1.00
RO	0.93	0.91	0.95
P1	0.98	0.98	0.99
N1	1.01	1.00	0.98
H1	1.03	1.06	1.05
H2	1.01	1.04	1.07
H3	1.04	1.05	1.11
H4	1.00	1.01	1.02
H5	1.01	1.00	0.99

4.5. SEM

SEM images of normal and recycled mortar samples after 28 curing days are shown in Fig. 5 and 6 respectively. A dense interface transition zone (ITZ) with few loose particles was observed in reference mortar. This result indicated a good bond between the cement paste and NFA in reference mortar (Fig. 5). Meanwhile, SEM scans for recycled mortar showed a porous layer and cracks between the aggregate and cement paste (Fig. 6). The ITZ thickness layer of FRA ranged from 3µm to 10µm around the aggregate, which consisted of a high concentration of $Ca(OH)_2$ and ettringite. This phenomenon might be attributed to the high absorption capacity of FRA caused by the presence of adhered old cement paste on FRA. The presence of this paste caused free water to be greatly absorbed during mixing, thereby causing more water to flow from the cement matrix to the aggregate particles. Consequently, less water flowed to the hydrating cement, which allowed the premature formation of unhydrated product in the ITZ. SEM analysis was conducted on the fracture surface of samples with fibers in the mortar matrix. Fig. 7 indicates that the fibers inhibited the initiation and growth of microcracks in the matrix.

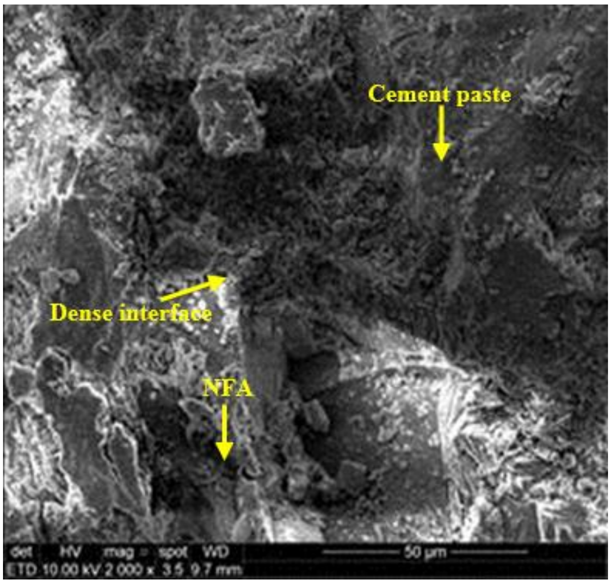

Fig. 5: SEM Micrograph of ITZ between FRA and Cement Paste.

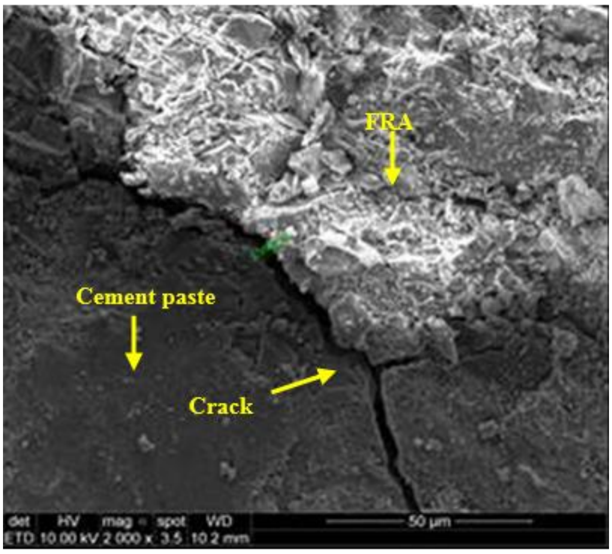

Fig. 6: SEM Micrograph of ITZ between FRA and Cement Paste.

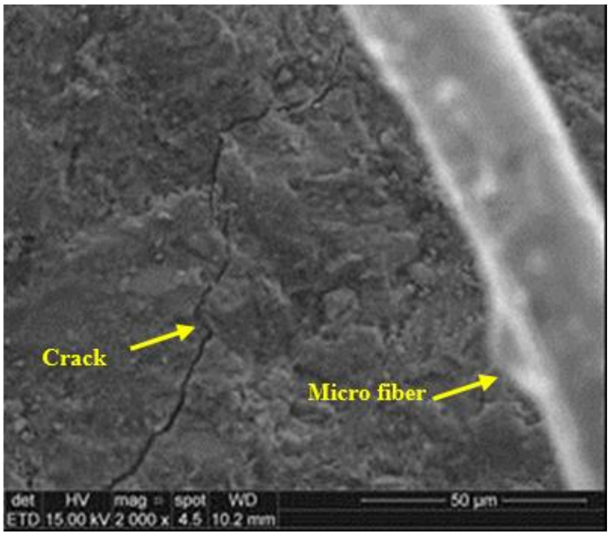

Fig. 7: Roles of Micro Fiber in Resisting Crack Propagation.

5. Conclusion

Based on the experimental testing performed on investigate mechanical properties and microstructure of recycled mortar reinforced hybrid-size micros fibers, the following conclusions can be drawn.

1) The mean SSD of hardened mortar at ages of 28 days decreased slightly when replacing 100% NFA by using FRA. It attributed due to the dry density of the FRA was 13% lower than that of the NFA.
2) The compressive and flexural strength of recycled mortar was significantly affected due to incorporation of hybrid fibers. The balance combination ratio of 0.3 % of polypropylene (long) fibers with 0.3 % of nylon (short) fibers represented the highest enhancement of the compressive and flexural strength was noted. This results were attributed due to the most homogenous distribution of the short and long fibers in the matrix lead to enhance the reinforcing efficiency at different level, either can arresting in the micro or sub micro cracks level.
3) SEM investigation supported the improved reinforcing efficiency of hybrid fiber over controlling propagation of cracks in recycled mortar matrix.

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