CEMENT MORTAR REINFORCED WITH RECYCLED CARBON FIBER AND CFRP WASTE

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Abstract

This study investigated the effects of recycled carbon fibres (RCF) and carbon fibre reinforced polymer (CFRP) waste of different percentages on the mechanical properties of Portland cement composite through laboratory testing. Portland cement mortars reinforced by either RCF or CFRP waste were tested for flexural strength, stiffness, and fracture toughness by conducting three-point bending test. The influences of dispersing agent and additives for cement including mineral and chemical admixtures on cement reinforced fibre composites for a total of 15 different combinations were evaluated based on the mechanical properties. Experiment results suggested that the strength of the composite grew gradually, and reached a maximum increase of 21.9% with 3% CFRP waste by weight compared to plain material. On the other hand, specimens using 3% CFRP waste or 1.5% RCF fibres has shown a significant increase in stiffness with 20.5% and 15.5%, respectively. Additionally, CFRP offered cement composite a remarkable growth regarding fracture energy up to 5334%.

1. Introduction

In the past few decades, cement mortar reinforced with fibres has been widely used as a construction material. The most popular applications of cement mortar reinforced by fibres are repair materials and shotcrete (see e.g. [1], [2]). In [2], the authors conducted experiments on cement-based repair mortar and showed that polyvinyl alcohol fibre had positive effects on the cohesion at the interface. Additionally, the reinforcing fibres were able to enhance both the mechanical properties and durability of mortar. The addition of polyvinyl alcohol fibres into cement mortar altered the failure to be less brittle.

A great number of research studies have indicated that carbon fibre reinforcement improved the strength of cementitious composites, e.g., improvement in the fracture resistance of cement mortar [3] and critical effectiveness crack length [4]. In [5], Wang and colleagues assessed that the Young's modulus of cement composite and compressive strength increased by 26.8% and 20.6%, respectively with 0.6% carbon fibres by cement powder's weight. Likewise, the strength and modulus of cement composite were estimated to rise by 56% and 39% when adding carbon fibres treated by silane [6]. The findings of Shu et al. [3] suggested that a hybrid-fibres (i.e., micro and meso carbon fibres) could have more merits than an equivalent volume fraction of micro-length fibres. Among three types of fibre reinforcements investigated in the study, the hybrid-fibres mixture improved the fracture resistance of mortar and had a lower air-to-cement mortar ratio than the macro fibres blend.

One of the key factors suggesting studies on RCF and CFRP waste is the positive trend of using recycled materials in the future. The modern recycling technologies (i.e., pyrolysis, oxidation in a fluid bed, and chemical), which recycle carbon fibres from their polymer-matrix composites, may recover the entire

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mechanical properties of carbon fibres ([7], [8]). Spadea and colleagues [9] did their research on the use of recycled nylon fibres from old fishing net to reinforce cement mortar. The authors concluded that the recycled nylon fibres could be safely used as a reinforcement material for cement. Furthermore, the tensile strength of the composite climbed by 35%. The recycled fibres also changed the failure mode of the product from brittle to ductile. Moreover, regarding statistics on the need of CFRP, the consumption of carbon fibres was 35,000 tons in 2008 and doubled by 2014 [10]. There will be a large amount of CFRP waste that will become the main source of raw materials for recycling carbon fibres.

Given the findings of the above review, this study aims to evaluate the effects of RCF and CFRP waste on cement mortar, the influences of admixtures on the cementitious composite, and to determine a standard fabrication process. The mechanical properties of cement reinforced by RCF and CFRP waste were investigated measuring the flexural strength, the stiffness, and the fracture toughness using the three-point bending test. Moreover, a mineral additive (i.e., silica fume), chemical additives (i.e., lignin sulfonate), and high-range water-reducing admixture were assessed to determine their impact on the cement matrix.

The experiments on cement mortar reinforced by RCF were conducted using different reinforcement percentage, and treatment methods. With regard to the length, Chung [6] found that hybrid fibres using both short carbon fibres and steel fibres increased the fracture toughness of composite. Additionally, Shu and colleagues [3] evaluated the hybrid effects of carbon fibres on the mechanical properties of cement paste by using two different types of fibre length (i.e., meso and micro fibre). The authors reported that there was an increase in tensile properties and the fracture resistance of cement composite. Furthermore, the pre-peak load tensile performance was improved by using micro carbon fibres. Therefore, in the present research, the mechanical effects of using RCF in range 0.05 - 15 mm were investigated; three weight percentages were tested: 0.5%, 1%, and 1.5% wt. cement. Regarding CFRP waste, the raw materials was crushed in two different mesh sieves (i.e., 3 mm and 6 mm) and used from two to three percent wt. cement. Additionally, the dosage of both lignin sulfonate and the high-range water-reducing admixture were 0.3% by weight according to the technical specifications provided by chemical manufacturers. The dispersion of reinforcements including RCF and CFRP waste in the cement composite was evaluated by conducting scanning electron microscope (SEM) observations of the fracture surface. Moreover, the bonding between matrix phase (i.e., cement matrix) and dispersing phase (i.e., RCF and CFRP waste) were evaluated with SEM images.

2. Materials and Testing Description

2.1. Components

Portland cement PCB40 type I, standard sand which meet the requirements of the Japan Industry Standard JIS R 5201 were used. CFRP waste and RCF were provided by other research projects. The length of fibres was from 0.05 mm to 15 mm (average 2.38 mm) by using the shearing machine model 18S504 manufactured by Kumagai Riki Kogyo Co., Ltd., Japan. In terms of CFRP waste, the raw materials was crushed by a crushing machine (model: NH-34, supplier: Sansho Industry Co., Ltd., Japan) with two different sizes of sieves (i.e., 3 mm and 6 mm).

Two types of chemical additives were used in this research including lignin sulfonate (named M100, provided by Nippon Paper Industries Co., Ltd.) and a high-range water-reduction admixture (named 21WH, provided by KAO Co., Ltd.). Both lignin sulfonate and the high-range water-reducing admixture serve as dispersants and complexing agents in the cement and concrete micro structure [11]. Furthermore, silica fume (SF), supplied by TOMOE Engineering Co., Ltd., was used with high purity SiO2. The SF is a highly reactive pozzolan materials with fine particles which are approximately 100 times smaller than cement particles. Moreover, the SF has a stable pH value and increases the flow of cement and concrete mortar [12], and improves mechanical properties of cement mortar reinforced with carbon fibres [6]. Some details of these can be seen in Table 1.

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2.2. Materials

The preparation of mortar specimens consisted of the following steps:

- Weighting cement powder, water, admixtures, RCF, and CFRP waste.
- Drying mixing materials including sand, cement and RCF/CFRP waste by mixing machine for two minutes, mixing by hand for 30 seconds to better disperse fibres.
- Adding water slowly within 5 seconds.
- Mechanical shaking of the mixture with the mixing machine for three minutes. During this period, the machine was stopped twice to check the uniformity of mortar.
- Casting the prismatic specimens into 40mm x 40mm x 160mm moulds, accurately vibrating for 2 minutes according to the guidance of ISO 679:2009.
- Curing at room temperature (i.e., approximate 26°C) for 24 hours before demoulding. The specimens were then cured in water tank at room temperature. After 7 day curing, having the 90-95% of ultimate compressive strength, the specimens were subjected to three-point bending and fracture toughness tests. The average compressive strength after 28 days of the plain material, measured with three cubic specimens of side 40 mm, was 59.18±1.12 MPa.

Table 1. Some features of the components.

Product name	M100	21WH	SF
Density (g/m3)	-	1.060-1.100	-
pH (5% water solution)	4.4	11.3	3.2
Moisture (%)	100	100	0.32
Solid (%)	49.7	-	-
SiO_2 (%)	-	-	94.7
Ignition loss (%)	-	-	0.08

2.3. Testing Procedures

The three-point bending test according to ISO 679:2009 was conducted on a machine "Autograph AG-I" (load range from 5-100kN) provided by Shimadzu Co., Ltd. (Japan). The purpose was to determine the flexural properties of mixtures compared to the control material. The displacement speed was set to 1 mm/min. Totally 15 combinations were investigated, whose ID names are listed in Table 2 (in the acronyms, the first block of characters indicates the content in % weight of RCF or CFRP, the second block specifies the chemical additive or silica fume). The bending strength and stiffness were estimated, respectively, by:

$$\sigma_b = \frac{3Fl}{2bh^2} \qquad E_b = \frac{ml^3}{4bh^3} \tag{1}$$

Where: σ_b is flexural strength; E_b is the initial bending elastic modulus; F is maximum load; l, b, h are length, width, height, respectively; m is the initial slop of force-displacement curve.

With regard to fracture toughness, the three-point bending test for notched beam was considered according to RILEM 1985 TC50-FMC [13], [14], [15]. The dimensions of the specimen were: total length 160 mm, supports span 100 mm, height 40 mm, and width 40 mm. The notch depth was 20mm, and the width was 1 mm. The three-point bending test was conducted by Autograph AG-I. The displacement-loading rate was 0.05 mm/min. Fracture energy was estimated by:

$$G_F = \frac{\left[\int_0^{\delta_0} p(\delta).d\delta + mg\delta_0\right]}{A_{lig}} = \frac{\left(W_0 + mg\delta_0\right)}{A_{lig}} \tag{2}$$

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Where: W_0 is fracture work; m is the weight of specimen between two supports; g is the acceleration of gravity (i.e., 9.8 m/s^2); δ_0 is the span-deflection of specimen at failure; A_{lig} is ligament area.
According to the results in bending test, the combinations which have the best performance were selected for fracture toughness test.
In order to evaluate the effects of reinforcement on cementitious matrix, the fracture surfaces were observed by scanning electron microscope (SEM). This observation provided some information regarding reinforcement and structure at micro level. Additionally, the bonding between dispersing phase (i.e., RCF or CFRP waste) and matrix phase (C-S-H minerals) was figured out and discussed about its impacts on mechanical properties. In this study, SEM machine model JSM-7001FD (by JEOL Co., Ltd., Japan) was used with voltage range from 5kV to 10kV.
Moreover, during testing, images were recorded by a digital high resolution camera (Nikon D3300) for post analysis image correlation by VIC-2D software [16]. For this purpose, one longitudinal side of the specimens was speckled with black and white acrylic paints for two dimensional full field strain measurements with digital image correlation technique (DIC). A cold light source was used to highlight the speckle pattern region meanwhile the digital camera acquired images at a frequency of 1 Hz. The strain field was used to understand the crack development and the relationship between load level and crack evolution during the three-point bending as well as fracture toughness test.

3. Results and Discussion

3.1. Flexural strength and Stiffness

Figure 1 and Table 2 indicate the average flexural strength and stiffness of the different mixings compared to the plain material. The comparison highlights that lignin (M100) had negative effect on bending strength but positive influence on stiffness. For instance, 1RCF-M100 increased stiffness by 9.6% but reduced by 11.3% in flexural strength with respect to the plain sample. On the other hand, specimens that used high-range water-reduction additive (21WH) had a slightly increase in both parameters (i.e., flexural strength and stiffness) with increasing of RCF percentage (e.g., RCF-21WH and RCF-21WH-SF). Especially, the specimen with 1.5% RCF reached maximum increment with 20.7% in stiffness. Additionally, no difference was recorded in flexural strength between specimens with and without SF; cement composite reached the highest strength with 1.5% RCF by 13.5% and 11.6%, respectively. However, there was a drop in stiffness when using SF (e.g., up to 11.4% with 0.5% RCF). With regards to cement mortar reinforced by CFRP waste, in both percentage of reinforcement (i.e., 2% and 3% CFRP waste), short CFRP fibres had greater bending strength than mixed CFRP and long CFRP fibres. Furthermore, specimen with 3% long CFRP fibres gained the highest increase by 22% compared to the plain sample; while 2CFRP(short)-21WH rose by 10.8%. However, there was only a small amount of strength increment in both mixed CFRP fibres (i.e., 2CFRP(mix)-21WH and 3CFRP(mix)-21WH) with 6.5% and 0.5%, respectively. Regarding stiffness, almost specimens reinforced with CFRP waste have an increase of more than 12%. No evident difference between specimens with 2CFRP short fibres and mixed fibres was observed. Nevertheless, the samples with 3% CFRP rose the stiffness when increasing the length of fibres in composite. Consequently, the length of CFRP waste might have a positive effect on stiffness of cement mortar reinforced.
From the results of bending test, specimens with best performance were selected for strain analysis by using the map of maximum principal strain by DIC to determine crack development and load level once crack appeared. According to Figure 2, the initial crack of plain sample appeared suddenly; there was almost the same crack length between initial and final crack. On the other hand, the initial crack of 3CFRP(short)-21WH was very small and developed slowly until the last recording. With regards to load level, the load at crack initiation of plain sample was 0.144kN, while for CFRP(short)-21WH was 0.650kN.
It might be evident to recognize that CFRP waste reinforcement prevented the development of crack in cement composite. The crack in reinforced sample did not increase suddenly; the load level kept rising after the appearance of crack. Therefore, this result might indicate an enhancement of the fracture toughness of reinforced cement mortar with CFRP waste.

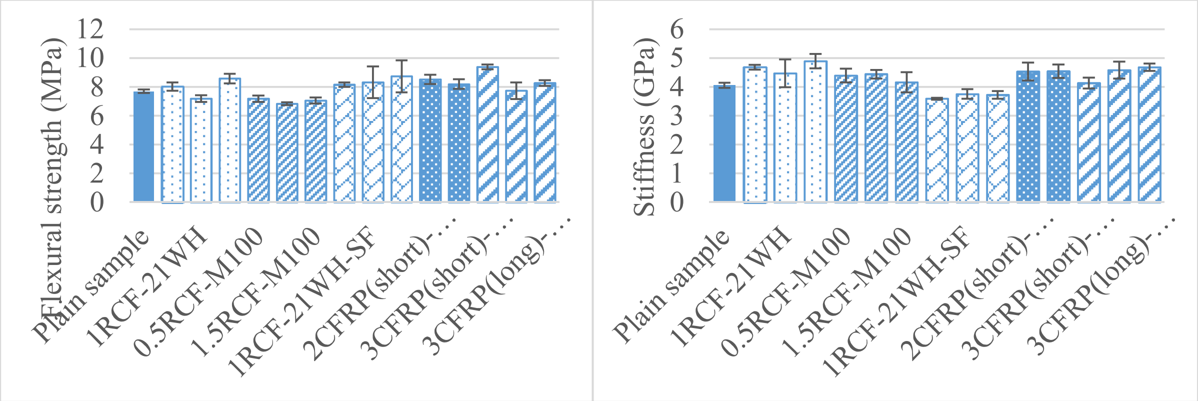

Figure 1. Flexural strength (left) and stiffness (right). Average and standard deviation (error bars) of three tests.

Table 2. Flexural strength and stiffness, and their variation with respect to the plain material.

Material ID	Strength (MPa)	Strength Variation (%)	Stiffness (GPa)	Stiffness Variation (%)
Plain sample	7.69	-	4.05	-
0.5RCF-21WH	8.01	4.2	4.68	15.6
1RCF-21WH	7.18	-6.6	4.47	10.4
1.5RCF-21WH	8.58	11.6	4.89	20.7
0.5RCF-M100	7.18	-6.6	4.39	8.4
1RCF-M100	6.82	-11.3	4.44	9.6
1.5RCF-M100	7.05	-8.3	4.16	2.7
0.5RCF-21WH-SF	8.15	6.0	3.59	-11.4
1RCF-21WH-SF	8.32	8.2	3.75	-7.4
1.5RCF-21WH-SF	8.73	13.5	3.72	-8.1
2CFRP(short)-21WH	8.52	10.8	4.53	11.9
2CFRP(mix)-21WH	8.19	6.5	4.54	12.1
3CFRP(short)-21WH	9.38	22.0	4.13	2.0
3CFRP(mix)-21WH	7.73	0.5	4.58	13.1
3CFRP(long)-21WH	8.26	7.4	4.68	15.6

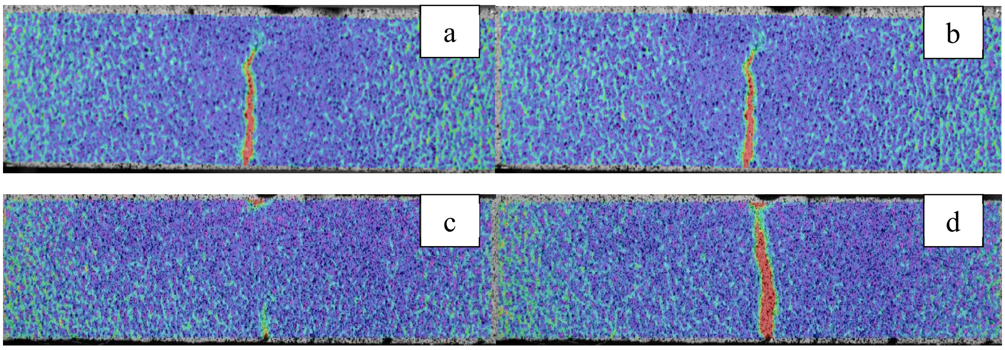

Figure 2. (a, b) Plain sample, (c, d) 3CFRP(short)-21WH. (a, c) initial crack; (b, d) final crack.

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3.2. Fracture energy

Figure 3 shows a marked increase in fracture energy in all specimens using 3% CFRP including short, mixed, and long fibres. The plain sample had a typical failure mode of brittle materials (i.e., the load level rises sharply to the maximum value and decline suddenly). Therefore, the deflection was very small (nearly 0.4mm). Moreover, cement mortar reinforced by short CFRP fibres also had a similar pre-peak trend. However, with mixed and long CFRP fibres, composites offered a post-peak less brittle failure behaviour in which the load level decreased gradually until nearly zero after reaching the peak load; the final deflection was about 18.7mm.

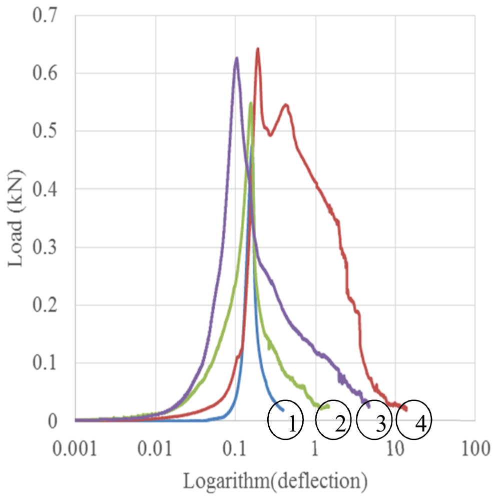

Figure 3. Load-deflection curves for fracture toughness tests. (1) plain sample, (2) 3CFRP(short)-21WH, (3) 3CFRP(mix)-21WH, (4) 3CFRP(long)-21WH

It can be seen that the fracture energy increases when increasing the length of CFRP waste fibres. The reason might come from the ability in crack bridging of long fibres. This was also showed in the result of strain analysis by DIC. Additionally, Table 3 figured out a huge increase in terms of fracture energy (Eq. 2) of cement composite compared to the plain sample. Regarding CFRP reinforced cement composite, there was a growth in all three mixtures including 3CFRP(short), 3CFRP(mix), 3CFRP(long) by 275%, 1729%, and 5334%, respectively. This finding suggested that CFRP can improve the fracture toughness of cement composite. Furthermore, according to the difference among fracture energy of CFRP waste reinforced cement mortars tested, long fibres can have a more positive effect than short fibres.

Table 3. Fracture energy and deflection.

Material ID	G_F (N/mm)	G_F Variation (%)	Final Deflection (mm)
Plain sample	0.044	-	0.40
1.5RCF-21WH	0.117	164	0.49
3CFRP(short)-21WH	0.167	275	1.34
3CFRP(mix)-21WH	0.813	1729	3.22
3CFRP(long)-21WH	2.415	5334	14.90

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3.3. SEM Observations

SEM observation was conducted on the fracture surface of samples with RCF and CFRP waste fibres in the cementitious matrix. Figure 4a indicates that the crack in matrix was stopped and deviated once it faced CFRP fibres. This point might explain the increment of fracture energy of CFRP wasted reinforced mortar. In addition, a good bonding between RCF and C-S-H minerals (i.e., calcium silicate hydrate mineral which is the main product of reaction between Portland cement and water) in cement matrix was observed (Figure 4b). Furthermore, the surface of RCF was not damaged during mixing procedure.

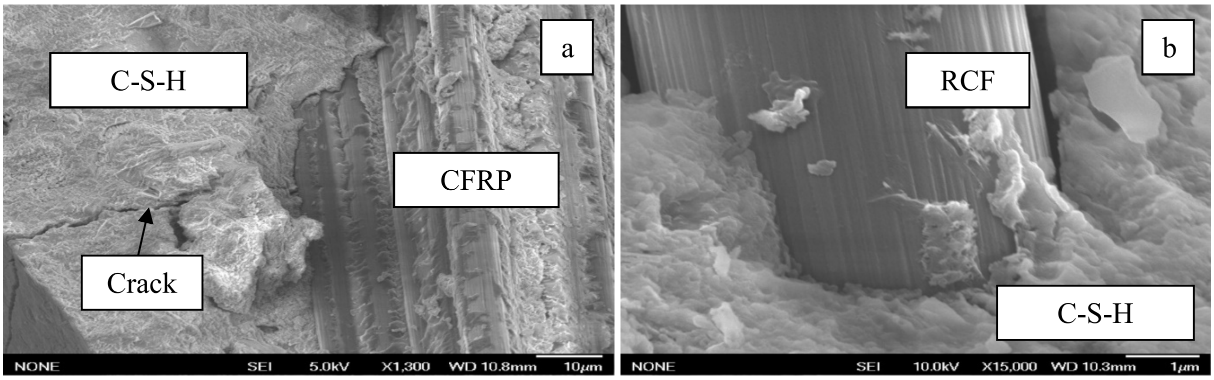

Figure 4. Fracture surface of reinforced mortars: (a) CFRP reinforced, (b) RCF reinforced mortar.

4. Conclusions

An experimental investigation was conducted to understand the effect of RCF and CFRP waste with different percentage and length as reinforcement of Portland cement mortar. The reinforced cement mortars with different combinations were tested for mechanical properties including flexural strength, stiffness, and fracture energy. According to the results, the following conclusions and further research can be suggested.

1) Both RCF and CFRP waste have positive effects on cement composite in terms of flexural strength and stiffness. With regards to flexural strength, among 15 combinations evaluated, two combinations including 1.5RCF-21WH and 3CFRP(short)-21WH had greatest increase by 11.5% and 21.9%, respectively. Additionally, 1.5RCF-21WH also provided a growth in stiffness by 20.5%. On the other hand, 3CFRP(long)-21WH had a better performance regarding stiffness than 3CFRP(short)-21WH with an increase by 15.5% in comparison to the plain material.
2) From strain maps analysis, mortar reinforced with CFRP has a better crack tolerance than the plain one. The crack in the plain sample grew sharply after appearing; while in reinforced samples increased slowly.
3) Regarding fracture energy, there was a remarkable growth of reinforced mortar with CFRP waste. The specimens with 3% CFRP of short, mix, and long fibres increased by 275%, 1729%, and 5334%, respectively in comparison to the plain sample. Furthermore, the mortar reinforced with RCF also indicated an improvement in fracture energy by 164%; however, the failure mode is still brittle.
4) SEM pictures indicated that CFRP fibres might offer a chance to delay the crack development in cement matrix. In addition, both CFRP and RCF had a good bonding with C-S-H minerals in cement matrix.

From the findings of this study, the future research work will aim to investigate the other mechanical properties (e.g. shrinkage) of cement reinforced by CFRP waste and RCF. The further purpose is the behaviour at micro scale to deeply understand about the local mechanisms leading to the global improvement of the mechanical properties.

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