

Evaluation of carbon fiber reinforced cementitious matrix as a recyclable strengthening material

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ABSTRACT

The use of fiber-reinforced polymer (FRP)-epoxy resin is a common retrofitting technique usually employed by engineers. In the research presented in this paper, a new cement-based material was developed introducing chopped carbon fiber. The carbon-fiber-reinforced cementitious matrix (C-FRCM) containing a cement-based matrix and embedded carbon-fiber mesh is an alternative solution to FRP-epoxy resin, addressing cost, durability, and reversibility issues. The flexural performance of carbon-fiber-reinforced cementitious matrix plates with chopped carbon fibers was explored in this study. A series of three-point bending tests were conducted to investigate the effects of chopped carbon fiber content. The measured mechanical properties of the proposed C-FRCM mix were compared with those made of commercial formulations. The flexural strengths and failure modes of the carbon-fiber-reinforced cementitious matrix plates were obtained and recorded during tests, and then the inter-laminar shear strengths were calculated. Upon the completion of three-point bending tests, scanning electron microscopy was used to observe the microscopic appearance of tested specimens. The optimum content of chopped carbon fibers in the cement-based materials was determined based on the structural behavior and microstructural analysis. The results also show that the carbon fiber mesh is effective in strengthening the carbon-fiber-reinforced cementitious matrix.

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1. Introduction

Fiber-reinforced polymers (FRPs) are composites commonly used to strengthen and improve the flexural and shear capacity of masonry and concrete structures (Italian National Research Council (CNR), 2004). Traditionally, FRPs are bonded to the structures using epoxy adhesive (Bilotta et al., 2015; Ceroni et al., 2014a, 2014b; Aiello, 2008). However, there are some environmentally harmful drawbacks attributed to the organic resins, including toxic health hazards for the installers and the irreversibility of the FRP-epoxy resin waste. Specialized handling equipment and training for installation personnel are compulsory. It is also difficult to remove FRP-epoxy resin without harming the original structure and thus difficult to conduct any repairs on the structure if needed. Additionally, if any construction waste contains FRP-epoxy resin, it is also difficult to recycle the aggregates and FRP since epoxy resin is

difficult to depolymerize in the natural environment. A potential solution for replacing the FRP-epoxy resin strengthening system is the use of carbon-fiber-reinforced cementitious matrix (C-FRCM), which is a composite plate made of carbon fiber mesh and cement-based material (Di Tommaso et al., 2007; Liu, 2006; Wu, 1999; Su et al., in press). Compared to the available epoxy resin on the market, the C-FRCM system has its own advantageous characteristics such as better compatibility, better durability, ease of installation, better fire resistance, and ease of reversibility (Zhu et al., 2018).

In recent years, researchers have investigated the influence of short fibers on various properties of textile-reinforced concrete (Butler et al., 2006a; Hinzen et al., 2007). For example, Barhum et al. (Barhum and Mechtcherine, 2012a) studied the effect of chopped carbon fibers or glass fibers on the tensile properties of textile reinforced concrete (TRC) sheets with different water-cement ratios. This research revealed that the initial cracking stress of the TRC sheet was increased when the fiber volume content was 1.0%. In particular, the short-cut carbon fibers significantly improved the initial cracking stress of the sheet and helped increase the fracture

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energy of the material. Butler et al. (2013) also studied the effect of externally dispersed or undispersed chopped glass fibers on the mechanical properties of TRC sheets. Their results indicated that the number of cracks in the TRC thin plate corresponded with the amount of dispersed chopped carbon fiber. This cracking indicated that the incorporation of undispersed chopped carbon fiber improved the interfacial bonding performance between the carbon fiber mesh and the matrix concrete. Butler et al. (2006b) compared the tensile properties of TRC sheets blended with chopped glass fibers of 6 mm and 12 mm in length. When the volume fraction of chopped fibers was in the range of 0.2%–0.6%, it was found that the fibers could be more evenly dispersed as the fiber aspect ratio (i.e. ratio of length over diameter) became larger. Wang (Wang et al., 2008) investigated the effect of carbon fiber dispersion on the mechanical properties of C-FRCM through measuring the flexural strength, tensile strength, modulus, and compressive strength. Three-point bending testing revealed that the distribution of major elements varied with the variation of the fiber dispersion status.

Little research has been conducted on chopped carbon fibers. Yin et al. (Yin and Xu, 2010) studied the mechanical properties of TRC sheets with short-cut polypropylene fibers through a four-point bending test. They found that when the content of polypropylene fibers was less than 1.0 kg/m³, the stiffness after cracking of the sheets was improved, the crack width was reduced, and the anti-stripping ability of the concrete was improved. Dai et al. (2012) observed that the addition of chopped polypropylene fibers enhanced the tensile strength of the TRC sheet significantly. Xu et al. (2014) discovered that the incorporation of chopped polypropylene fiber improved the bending capacity of the TRC sheet at high temperatures. Shen et al. (2016) analyzed the influence of the types and amounts of short-cut fibers on the flexural capacity and crack development of TRC sheets respectively through the four-point bending test. Zhou et al. (2003) studied the relationship between the compressive strength and splitting strength of the composite material and the amount of carbon fiber content. These studies indicate that there has been significant research from both domestic and foreign scholars on carbon-fiber-reinforced cement-based materials.

However, carbon fiber reinforced polymers (CFRP) reinforced cement-based materials have not commonly been used in engineering applications, and require further understanding. One aspect that requires further study is the bending properties of C-FRCM plates incorporating chopped carbon fibers. Therefore, in the research presented in this paper, three-point bending testing

of C-FRCM plates and plates with commercial formulations was performed. The influence of chopped carbon fiber contents on the bending capacity of C-FRCM plates was investigated. The failure mode of the C-FRCM plate was recorded and the flexural strength and interlaminar shear strength were measured. The microscopic morphology of the chopped carbon fibers in the C-FRCM plate was examined by scanning electron microscopy (SEM).

2. Methodology

2.1. Materials

The three-point bending test used Portland cement (PII 52.5R), sand (0–1.2 mm), chopped carbon fibers, silica fume, methylcellulose, defoamer, redispersible polymer, water, and superplasticizer. An illustration of chopped carbon fiber is presented in Fig. 1(a). The mix proportions of cement-based materials are listed in Table 1.

The carbon fiber mesh used in the experiment was woven from a 12K × 12K carbon fiber bundle (i.e. a bundle of vertical or horizontal carbon fiber comprises a total of 12,000 carbon fiber monofilaments), and the mesh size was 10 mm × 10 mm (i.e. the distance between the two bundles is 10 mm), as shown in Fig. 1(b). The mechanical properties of the fiber bundles were tested by tensile test according to GB/T 3362-2005 (Carbon fiber filament ten, 2005), while the tensile device and the failure mode were shown in Fig. 2. The results of the mechanical performance of carbon fiber are provided in Table 2.

The specific calculation is shown below. The tensile strength and elastic modulus of the carbon fiber composites were measured by the tensile loading of the impregnated resin after curing the fiber. Tensile strength is obtained by dividing the failure load by the cross-sectional area of the carbon fiber complex, as shown in Eq. (1). The elastic modulus is determined by the specified strain limit, as shown in Eq. (2).

$$\text{The tensile strength: } \sigma_t = \frac{P \times \rho_t}{t} \times 10^{-6} \quad (1)$$

Where: σ_t = the tensile strength;

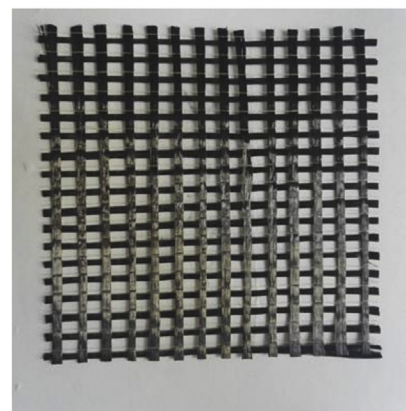
P = the failure load;

ρ_t = the density of carbon fiber;

t = the linear density of carbon fiber.



(a) Chopped carbon fiber (3 mm)



(b) Carbon fiber mesh

Fig. 1. Chopped carbon fiber and carbon fiber mesh.

Table 1
Cement-based material and proportions.

	Cement	Sand	Silica fume	Methylcellulose	Chopped carbon fiber	Water	Superplasticizer	Defoamer	Redispersible polymer
1	1	150%	15%	0.4%	0.8%	46%	2%		
2	1	150%	15%	0.4%	1.2%	46%	2.5%		
3	1	150%	15%	0.4%	1.6%	46%	3%		
4	1	150%	22.22%	0.4%	1.2%	46%	1%	0.53%	11.11%
5	Commercial formulation (cement: admixture: sand: water = 83:17:120:28)								

Note: the percentage of materials is the ratio of material usage to cement usage, and the cement is the standard value.

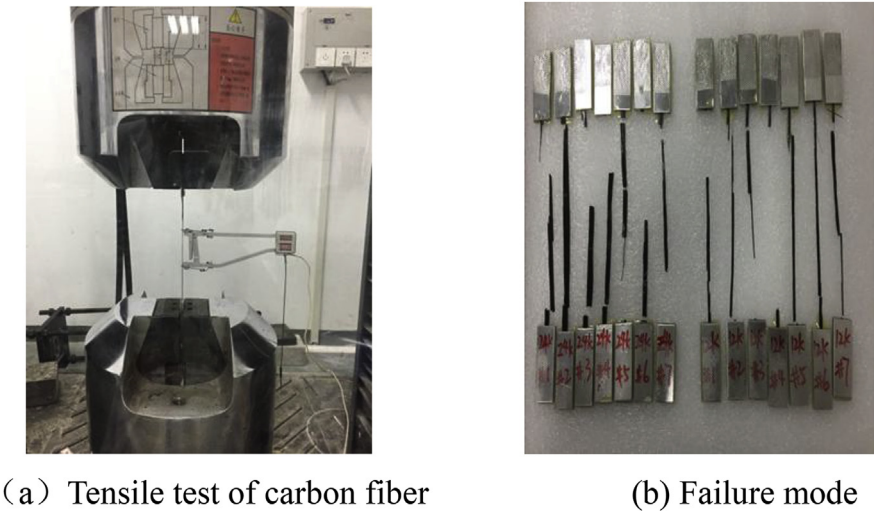


Fig. 2. Mechanical properties of carbon fiber.

Table 2
Mechanical properties of carbon fiber bundles.

	Number of monofilaments (a bundle)	f_{tf} (MPa)	E_f (GPa)	ϵ_u (%)
Carbon fiber	12000	1907	178	1.2

Note: f_{tf} represents tensile strength, E_f represents modulus of elasticity, and ϵ_u represents ultimate strain.

The elastic modulus: $E_t = \frac{\Delta P \times \rho_t}{t} \times \frac{L}{\Delta L} \times 10^{-9}$ (2)

Where: E_t = the elastic modulus;

ΔP = the load value intercepted on the initial line of the stress-strain curve;
 L = the length of the sample between the reinforcing plates;
 ΔL = the length of the sample between the reinforcing plates corresponds to the deformation increment of ΔP .

The shape and size of the sample used to measure the tensile properties of carbon fiber composites are shown in the following Fig. 3. The MTS test machine was used and the loading rate was

1 mm/min.

2.2. Specimens

The testing specimens were all one-way plates. According to GB50010-2010 (Code for design of concrete, 2010), plates supported along two opposite sides shall be calculated as one-way plates; for plates supported on four sides, when the ratio of long side to short side is greater than 3, it may be calculated as a one-way plate along the short side direction. Five types of C-FRCM plates with different cement-based materials having the dimensions of 500 mm × 500 mm × 10 mm were produced. The C-FRCM plates had a single fiber mesh layer, and the carbon fiber mesh was in the center of the plates such that the thickness of the upper and lower protective layers was 5 mm. Fig. 4(a) presents the fabrication of a C-

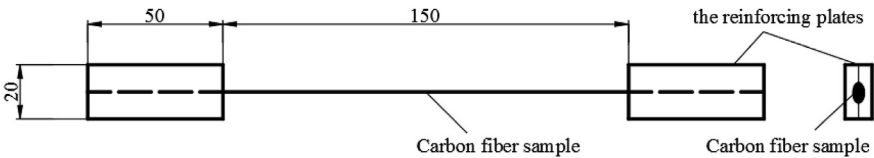


Fig. 3. The shape and size of the specimen.

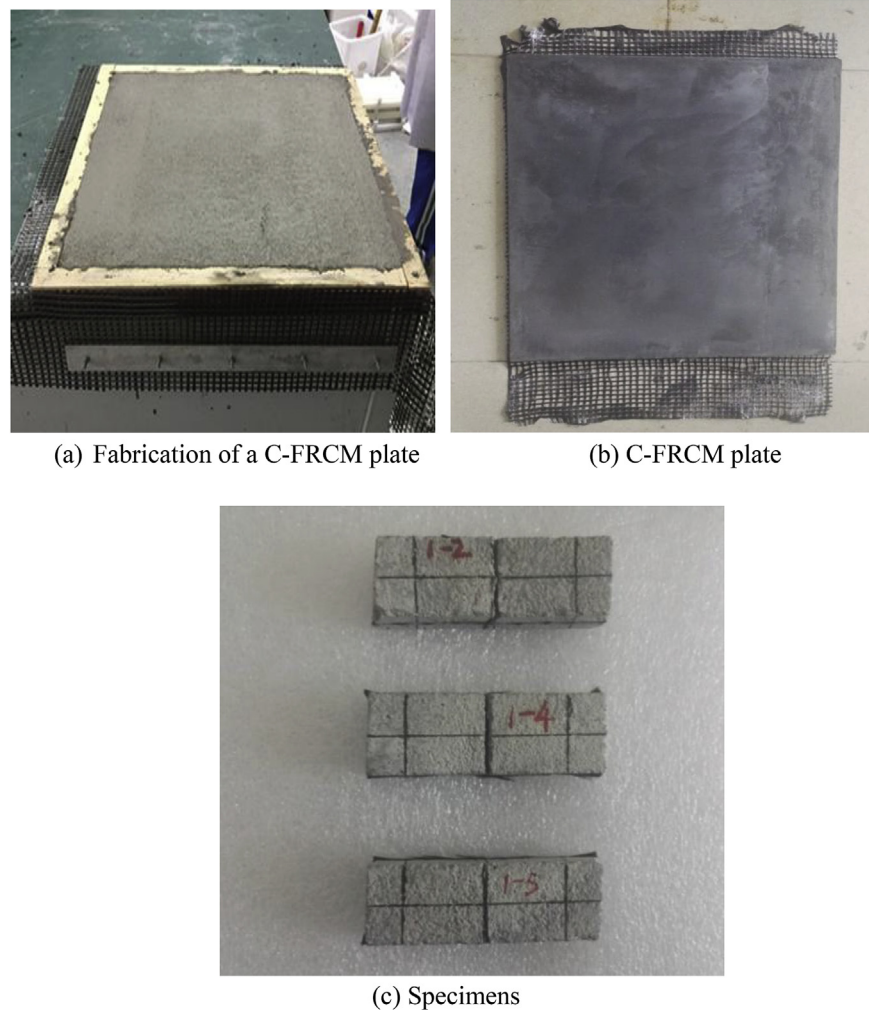


Fig. 4. Manufactured C-FRCM plates.

FRCM plate. The casted composite plates were removed from the wooden moulds after 48 h. Afterwards, the C-FRCM plates were cured for 28 days. Fig. 4(b) shows the whole C-FRCM plate. The C-FRCM plates of each group were cut to the thin plate with a size of 60 mm × 20 mm × 10 mm as illustrated in Fig. 4(c). These specimens were used in the three-point bending tests. For each set, three specimens were selected for parallel experiments; a total of 15 specimens were tested.

The specimens for the three-point bending test were numbered according to the type of cement-based material used in the specimen. Using specimen M1-A as an example, “M1” indicates that the matrix material is the first type listed in Table 1, while “A” identifies it as one of the three parallel specimens for this type of matrix material. The geometry of each test piece deviated from design due to the cutting process, thus the geometric dimensions are presented in Table 3.

2.3. Three-point bending test method

The loading method was applied according to the ASTM D2344 standard (Standard Test Method for, 2344) as illustrated in Fig. 5. The three-point bending test was performed on a test machine with a maximum load of 10 kN. The distance between end-supports of the three-point bending test was 40 mm, and loading used

displacement control with a speed of 0.05 mm/min. The load-displacement curve was output through the force sensor of the apparatus. When the load suddenly dropped, or the load dropped to 80% of the ultimate load after exceeding the limit load, loading was stopped. The experimental device is pictured in Fig. 6.

3. Three-point bending test results

3.1. Load-displacement curves

The load-displacement curves for each group are presented in Fig. 7. Each of the load-displacement curves of these C-FRCM plates consists of two parts. The first stage is where the load increases linearly with displacement. The second phase of the curve begins where the load drops rapidly after experiencing the peak of the first phase, then slowly increases with the increase of displacement before it stabilizes near the maximum load, and then finally gradually decreases with the increase of displacement.

Fig. 7(a)–(c) show the load-displacement of C-FRCM plates with chopped carbon fiber contents of 0.8%, 1.2%, and 1.6%, respectively. When the content of chopped carbon fiber was 0.8%, the load in the first stage reached a maximum value when the displacement was about 0.1 mm. At the end of the first phase, cracks appeared suddenly and the specimens were damaged. Subsequently, the curves

Table 3
Geometry of C-FRCM plates.

Specimen number	Length (mm)	Width (mm)	Height (mm)	Number of carbon fibers	Position of carbon fiber (mm)
M1-A	58.67	16.81	10.21	2	6.10
M1-B	60.04	16.14	9.99	2	5.22
M1-C	60.36	16.26	9.96	2	6.08
M2-A	59.93	17.13	9.91	2	5.04
M2-B	59.49	16.02	10.11	2	5.12
M2-C	60.17	15.79	10.15	2	5.24
M3-A	60.20	16.07	10.27	2	5.47
M3-B	60.10	16.50	9.04	2	4.13
M3-C	58.59	16.67	9.70	2	4.75
M4-A	59.61	16.07	7.45	2	4.40
M4-B	60.10	15.90	8.22	2	4.79
M4-C	59.97	15.84	8.16	2	4.36
M5-A	59.04	16.76	12.32	2	6.32
M5-B	59.73	15.80	11.04	2	5.72
M5-C	59.50	15.67	10.96	2	6.02

Note: the position of carbon fiber is the distance from the top surface of the specimen to the carbon fiber layer.

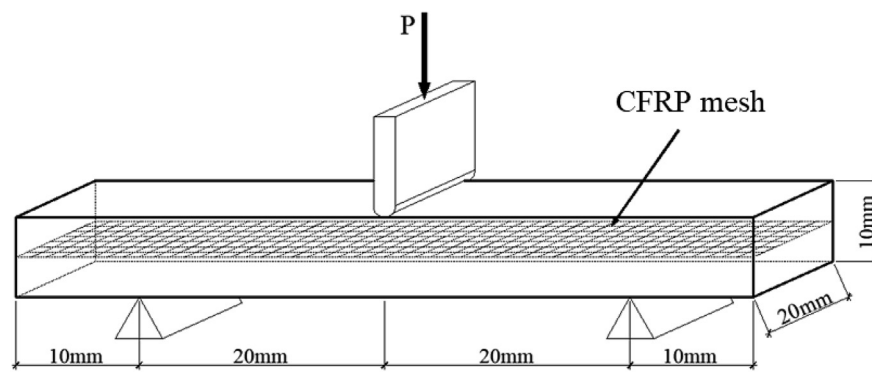


Fig. 5. Three-point bending test schematic.

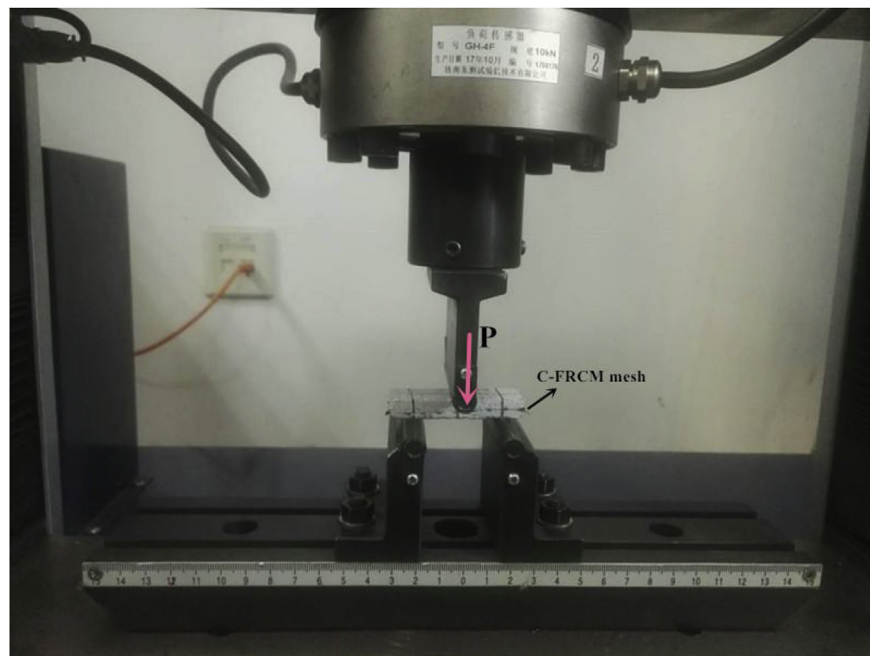
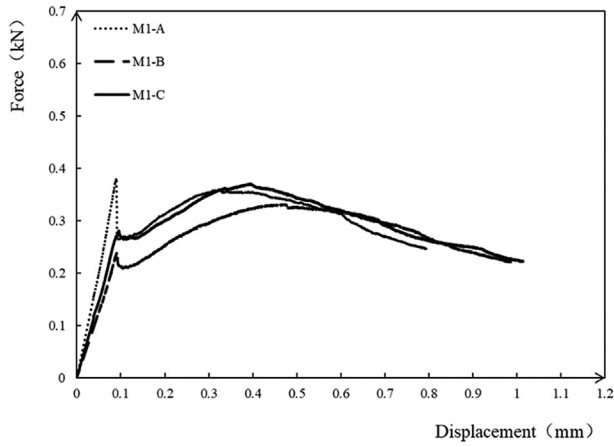
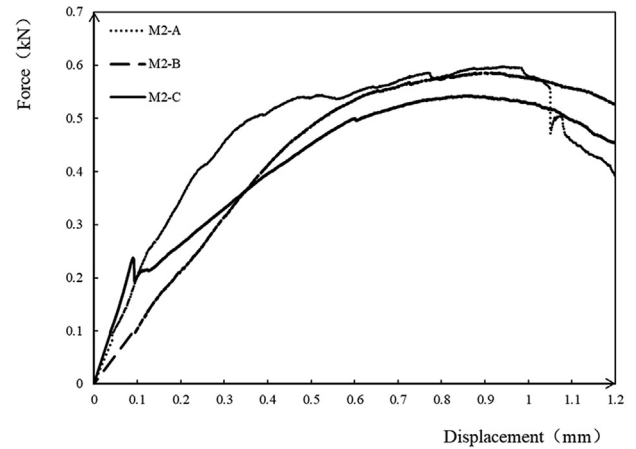


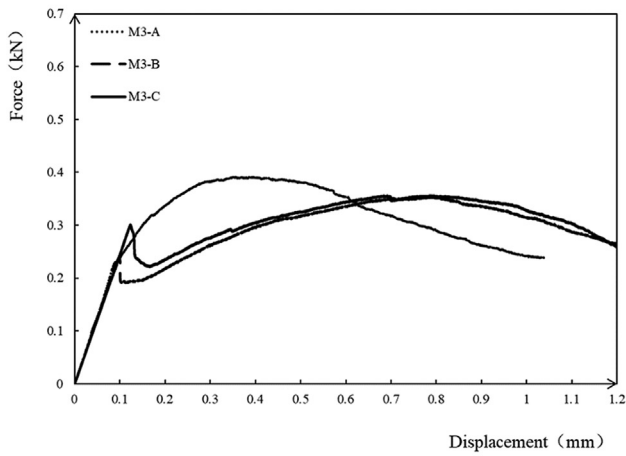
Fig. 6. Three-point bending test setup.



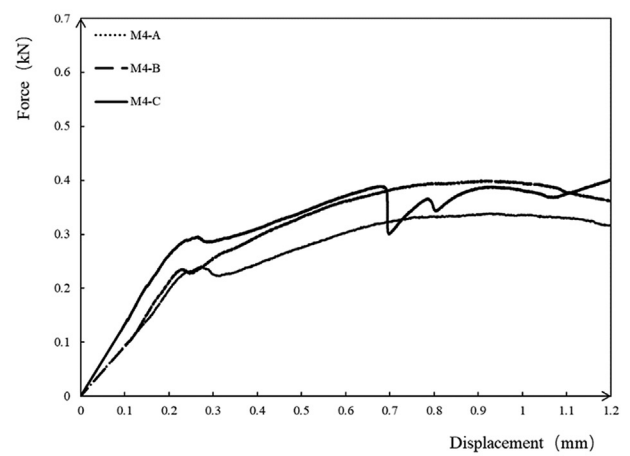
(a) Load-displacement of M1



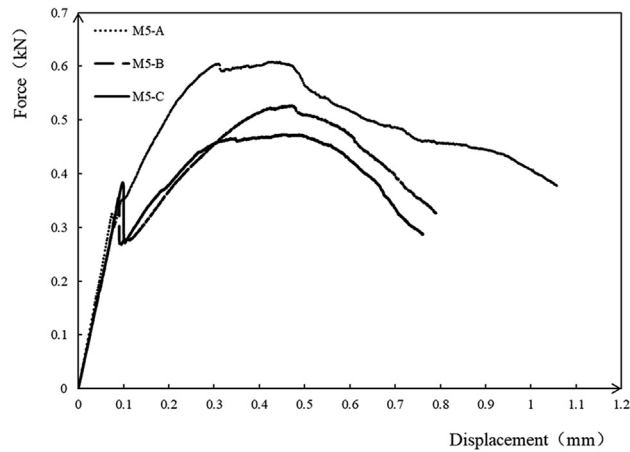
(b) Load-displacement of M2



(c) Load-displacement of M3



(d) Load-displacement of M4



(e) Load-displacement of M5

Fig. 7. Load-displacement curves for the C-FRCM plates.

entered the second stage. As each specimen cracked, the load dropped rapidly, then the load began to slowly rise again due to the presence of the CFRP mesh in the center of the C-FRCM plate. Eventually, the load exceeded the maximum value of the first stage, and then approximately stabilized at about 0.35 kN. Finally, the

width of the crack in the specimen grew larger, and the load began to decline slowly until the specimen completely failed.

When the content of chopped carbon fiber was 1.2%, there were some slight differences in its load-displacement curve as shown in Fig. 7(b) compared to when the content was 0.8%. While

the first stage was similar, the increased content of chopped carbon fiber enhanced the overall load-bearing capacity of the C-FRCM plate. When the curve entered the second stage, the load on the C-FRCM plate did not instantaneously decrease but rather increased slowly to its maximum of about 0.6 kN. Increasing the content of chopped carbon fibers to this level increased the maximum load-bearing capacity of the C-FRCM plate as well as the corresponding displacement. Consequently, the ductility improved as the content of chopped carbon fiber was increased to 1.2%.

When the chopped carbon fiber content was increased to 1.6%, the load-displacement curve shown in Fig. 7(c) was similar to that when the carbon fiber content was 0.8%. This suggests that the load-bearing capacity of the C-FRCM plate does not simply increase as the content of the chopped carbon fiber increases. The probable cause for this effect is that when the content of chopped carbon fiber is too high, the chopped carbon fiber becomes difficult to disperse during the stirring process of the cement-based materials, thereby making it difficult to transfer the load to all the carbon fibers, and the carbon fibers are not fully utilized. This is discussed further with the SEM results in Section 4.

The load-displacement of the fourth set of samples is presented in Fig. 7(d). These load-displacement curves show no clear drop between the first and second stages. These curves are similar to those seen in Fig. 7(b) when the carbon content was 1.2%. When the displacement reached about 0.25 mm, the load was at its maximum value of about 0.25 kN in the first stage. Around this point, cracks were observed, and the maximum load was reached at about 0.4 kN. Although the maximum load of this group was not greater than the maximum load of the second group, the cracking occurred later, and the displacement was greater than that of the second group. Therefore, it can be observed that the increased silica fume content in the C-FRCM plate can increase ductility.

Fig. 7(e) presents the load-displacement of the commercial formulation. Its load-displacement curve is similar to that when the carbon fiber content was 0.8%. In the second stage, the load stabilized around 0.5 kN. It can be observed that the development of the second phase of the commercial formulation was better than the first group, the third group, and the fourth group. However, the whole tendency of the fourth group still does not reach the same level as the second group.

3.2. Failure mode

For all specimens tested, cracks appeared in the specimens when the load was near the maximum value of the first stage in the load-displacement curve. As the test progressed, the crack width progressed until the specimen completely failed. The failure mode for each specimen was observed to be bending failure with intermediate fracture and no interlayer failure. A typical C-FRCM plate specimen after failure is presented in Fig. 8.



Fig. 8. Failure mode of the C-FRCM plates.

3.3. Bending strength and shear strength

In this study, the classical beam theory was used to calculate the bending strength and interlaminar shear strength of C-FRCM plates. The formulae for these strengths are as follows:

$$\text{Bending strength: } \sigma = FL/4W \quad (3)$$

$$\text{Interlaminar shear strength: } \tau = 3P/4bh \quad (4)$$

Where:

- σ = Maximum bending stress;
- F, P = Maximum force value;
- τ = Interlaminar shear strength;
- W = Bending section modulus of the specimen, $W=(bh^2)/6$;
- b = Width of specimen;
- h = Thickness of specimen.

The flexural strengths and the interlaminar shear strength of the five formulations of C-FRCM plates were calculated and are listed in Table 4 and presented in Fig. 9.

The highest mean bending stress among the five groups of formulations was the fourth group with a value of 22.99 MPa. The maximum bending stress of the first, second, and third groups was largest for the second group with a value of 20.94 MPa. The bending strength of C-FRCM plates increased when the content of chopped carbon fibers increased from 0.8% to 1.2%, but the strength decreased as the content increased further to 1.6%. Therefore, carbon fiber content does not have a singularly positive correlation to the load capacity of C-FRCM plates. Increasing the chopped carbon fiber content leads to greater difficulty in evenly dispersing the fiber during the preparation of cement-based materials. If chopped carbon fibers cannot be well dispersed, the load capacity of C-FRCM cannot be improved. Consequently, the maximum bending strength of the third group is similar to that of the first group. The carbon fiber content of the second and fourth groups is 1.2%. However, compared with the second group, the fourth group had greater silica fume content and a larger bending strength. Thus, it can be observed that an increase of the silica fume content leads to an increase in the load capacity of C-FRCM plates. The fifth group was the commercial formulation and had a maximum bending strength that was similar to that of the third group where the carbon fiber content was 1.6%. Therefore, the flexural strength of C-FRCM plates produced by commercial formulas may be improved.

The interlaminar shear strength of short-beam strength was determined according to the ASTM D2344 standard as previously expressed in equation (4). Similar to the bending strengths, the second group had the largest interlaminar shear strength, followed by the fourth and fifth groups. However, the bending failure of these specimens indicates that the interlaminar shear strength may not be a suitable criterion for evaluating the quality of these formulations. Therefore, the three-point bending test may not provide the best measurements of the mechanical properties of C-FRCM.

4. Microstructural analysis

The strengthening mechanism and dispersion of the chopped carbon fiber were investigated using scanning electron microscopy (SEM) to observe the material morphology of short-cut carbon fiber in cement. Prior to the SEM observation, the samples were dried at 50 °C for 12 h and thin layers of metal palladium were deposited on them. The SEM samples were treated by metal coating method,

Table 4
Bending strength and interlaminar shear strength of C-FRCM plates.

Specimen	Maximum force P_{max} (N)	Maximum bending stress σ (MPa)	Mean bending stress (MPa)	COV	Interlaminar shear strength (MPa)	Mean interlaminar shear strength (MPa)	COV
M1-A	380	13.02	13.04	0.09	1.66	1.64	0.09
M1-B	331	12.33			1.54		
M1-C	370	13.77			1.71		
M2-A	598	21.32	20.94	0.09	2.64	2.63	0.09
M2-B	586	21.46			2.71		
M2-C	543	20.03			2.54		
M3-A	391	13.84	14.41	0.07	1.78	1.74	0.07
M3-B	354	15.77			1.78		
M3-C	356	13.62			1.65		
M4-A	339	22.80	22.99	0.16	2.12	2.28	0.16
M4-B	400	22.32			2.29		
M4-C	420	23.87			2.44		
M5-A	608	14.34	15.28	0.10	2.21	2.18	0.10
M5-B	527	16.42			2.27		
M5-C	473	15.07			2.06		

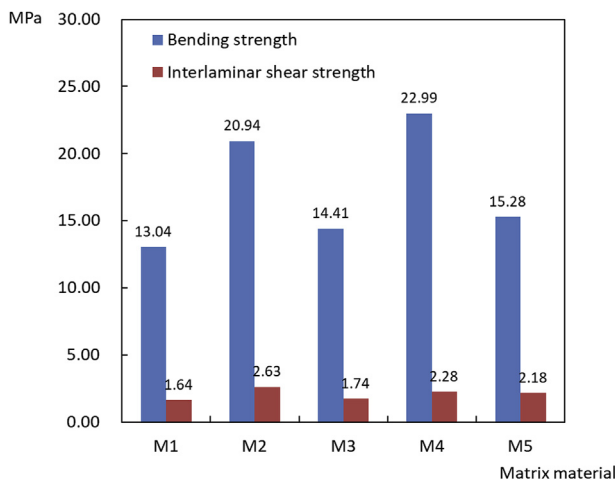


Fig. 9. Bending strength and interlaminar shear strength of C-FRCM plates.

which means the metal (Au, Pt, Ag, Pd) ion sputtering or vacuum evaporation with low resistivity was covered on the surface of the samples by special device (Metin et al., 2017). The failure mechanisms of short-cut carbon fiber can be divided into two types (Shen et al., 2016): tensile failure during loading, and adhesive slippage. The bridging of micro-cracks by fine, well distributed short-cut carbon fiber can inhibit their growth, their merging, and subsequently their forming the first macro-crack. The addition of short fiber reduces the shrinkage of the matrix and, hence, reduces the resulting internal damage in the finely grained concrete (Barhum and Mechtcherine, 2012b).

Fig. 10 presents the dispersion of short-cut carbon fibers at microscopic scales. The dispersion of the chopped carbon fiber in the second group was observed to have the most evenly. This more evenly distribution can explain why the load capacity of the C-FRCM plate for the second group is stronger than that of the first and third groups. It was also observed that there were some chopped carbon fibers that had been pulled off, which are highlighted by red circles. The pulling-off mechanism is observed because while the carbon fiber tensile strength is high, its diameter is small, and the limit of the filaments' tensile strength is less than the strength of the bond between the matrix and filament. Therefore, a certain amount of short-cut carbon fiber can effectively reduce the expansion of micro-cracks, increase the initial crack load

of the matrix concrete, and enhance the second stage load-bearing capacity.

Microscopic investigation of fracture surfaces by means of SEM showed that short fibers are frequently linked to multifilament yarns, as shown in Fig. 11. As the previous studies of Barhum (Barhum et al., 2013), cross-linking of chopped carbon fiber filaments can increase the anchoring force between long fiber bundles and matrix concrete, and improve the interfacial adhesion between fiber woven mesh and matrix.

The yellow circles in Fig. 10 indicate the silica fumes in the cement-based material. It can be observed that several silica fume particles were inserted into the cement-based layers and disrupted the interaction among the layers. It can be deduced that microscopic silica fume particles play an effective role in mechanically separating the cement-based layers during the mixing process and finally enhancing the mechanical performance of the layers.

5. Conclusions

This study aims to optimize the cement-based material mixing and to investigate the mechanical performance of C-FRCM composite plates with chopped carbon fibers. In this research, the flexural strengths and interlaminar shear strengths of different cement-based materials were obtained by the three-point bending tests of C-FRCM composite plates. Microstructural analysis based on SEM observations was also carried out. The conclusions are summarized below:

1. During bending tests, the loads of the specimens continued to increase after the occurrence of visible cracks. This indicates that the carbon fiber mesh in the center of C-FRCM plates enhances the plasticity of cement-based materials. Also, the increase of silica fume content in the mixing slightly enhances the ductility of C-FRCM plate.
2. The C-FRCM plate obtained the highest flexural capacities when the chopped carbon fiber concentration was 1.2% of the cement weight, even higher than the C-FRCM plate comprising the commercial formulation. It was determined that there is an optimum content range for chopped carbon fiber content, enabling the effective dispersion of chopped fibers in the cement-based material. Uniform dispersion of fibers leads to better cross-linking effects, which were found by the SEM observation.

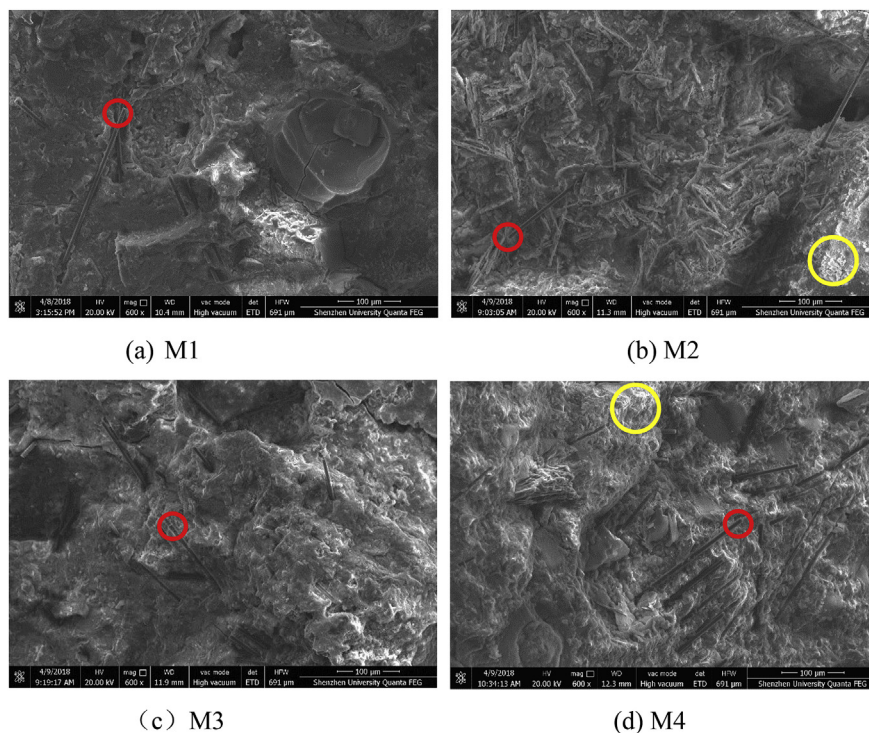


Fig. 10. Microstructure of short-cut carbon fiber in specimens M1–M4.



Fig. 11. Carbon fibers linked to multifilament yarns of a textile layer.

3. The proposed cement-based material satisfies the properties for structural strengthening and therefore could be an effective alternative solution replacing the conventional bonding material, epoxy resin.

Declarations of interest

None.

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