Enhanced flexural performance of epoxy polymer concrete with short natural fibers

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Epoxy polymer concrete (EPC) has found various applications in civil engineering. To enhance the flexural performance of EPC, two kinds of short natural fibers with high specific strength (sisal fibers and ramie fibers) have been incorporated into EPC. The results of mechanical tests show that a small loading of natural fibers (0.36 vol%) can significantly increase the flexural strength of EPC by 25.3% (ramie fibers) or 10.4% (sisal fibers). This enhancement is achieved without any sacrifice of compressive strength of EPC. The reinforcing effects of short natural fibers on the flexural properties and compressive properties of EPC decrease with further increase in fiber content, due to the insufficient wetting of fibers by epoxy resin which results in poor interfacial bonding. The reinforcing mechanisms of short natural fibers are explored according to the observation of fracture surfaces and micromechanical modelling. It is found that the parallel model based on the rule of mixture can be a good approximation to describe the improvement in flexural strength of the short natural fiber reinforced EPC at low fiber volume fractions.

epoxy polymer concrete (EPC), natural fibers, flexural strength, micromechanics models

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1 Introduction

Epoxy polymer concrete (EPC) is a type of polymer concrete in which epoxy resin is used as the binder to replace the traditional cement binder [1,2]. Due to its high strength, good corrosion resistance and rapid setting features, EPC is considered as a promising engineering material in construction and has found various applications, e.g. roadway pavement, building cladding, drain components, and machine beds [3–5]. As Portland cement-based concrete, polymer concrete shows outstanding performance under compression, whereas its tensile strength is relatively poor and sometimes in-

sufficient to applications [6–8]. This vulnerability substantially affects the flexural performance of polymer concrete because failure will occur prematurely in the region subjected to tension. To improve the flexural performance of polymer concrete, short fibers have been incorporated as an additional reinforcing phase. Broniewski et al. [9] found that addition of 3.5 wt% short steel fibers leads to a significant increase in flexural strength of EPC by about 40%. In the work reported by Vipulanandan et al. [10], addition of 3 wt% short glass fibers increases the flexural strength of polyester polymer concrete by around 32%. Similar improvement was observed by Griffiths and Ball [11] who dispersed 1.5 wt% short glass fibers into polyester polymer concrete and attained a 19% increase in flexural strength. Moreover, the

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flexural performance of EPC with artificial crack, i.e. the fracture toughness of the notched EPC beam under three-point-bending condition, can be considerably enhanced by the incorporation of short glass fibers [12–14] or short carbon fibers [13].

Natural fiber reinforced composites have attracted growing interest as a kind of eco-friendly engineering material nowadays [15–17]. Compared with synthetic fibers, natural fibers impose much less impact to the environment in both manufacturing stage and recycling stage. Moreover, natural fibers are usually byproduct of agriculture, which makes them a cost-efficient option. In the past decades, various natural fibers have been introduced into traditional cement concrete in order to enhance the tensile and flexural properties of concrete [18–22]. However, the study of natural fiber reinforced polymer concrete remains limited heretofore. Reis et al. [23] incorporated several kinds of natural fibers (i.e. coconut, sugar cane bagasse and banana fibers) into EPC. It was found that coconut fibers contribute positively to the flexural and fracture performance of EPC, sugar cane bagasse fibers only increase the fracture toughness, whereas banana fibers make the EPC weaker. He also tried to add the textile cutting wastes consisting of cotton, polyester, silk and rayon into EPC, but these additives unfortunately result in deterioration of both flexural and compressive performance of EPC [24].

In this paper, short sisal fibers and ramie fibers are incorporated into EPC. The two kinds of natural fibers have the highest specific tensile strengths and Young's moduli among the cellulose-based natural fibers [25,26]. The mechanical properties of the natural fiber reinforced EPC (NFREPC) are studied through four-point-bending tests and compression tests. Based on the experimental results, the reinforcing mechanisms are explored combining the observation of fracture surfaces and micromechanical modeling of short fiber reinforced polymer composites.

2 Sample preparation and testing program

The raw sisal and ramie continuous fibers are supplied by Yiwu Yangjin Ltd, China. Before being chopped into 10 mm-long pieces, the two kinds of fibers were soaked in the solution with 1% sodium hydroxide (NaOH) for 30 min for surface treatment (Figure 1), then washed with water and dried in oven. Table 1 lists the physical and mechanical properties of the two kinds of fibers. The densities were measured using an analytical balance (Mettler Toledo ME 104E) equipped with density determination kits. The diameters are determined from the micrographs acquired by an optical microscope (Olympus BX51M). The strength of the continuous fibers was obtained through the tensile tests on a universal testing machine (Instron 5567).

Figure 1 (Color online) (a) Surface treatment of the two kinds of natural fibers; (b) chopped pieces of sisal fibers and ramie fibers.

Table 1 Physical and mechanical properties of sisal fibers and ramie fibers

Fiber type	Sisal fiber	Ramie fiber
Density (g cm^{-3})	1.43	1.48
Diameter (mm)	0.25	0.12
Tensile strength (MPa)	418.77	525.97

The granite aggregate is provided by Fujian Shiyufa Stone Co., Ltd. The weight percentage of the fine aggregate with average size less than 4.75 mm is about 45%. The weight percentage of the coarse aggregate with average size in the range of 4.75–9.5 mm is about 55%. The epoxy binder is supplied by Fuzhou Baisheng Fine Chemicals Pte. Ltd. It is composed of bisphenol-A resin (BS5461A) and amine hardener (BS5462). The Epoxy Equivalent Weight (EEW) and density of the epoxy resin are 200 g equiv^{-1} and 1.1 g cm^{-3} , respectively. The Amine Hydrogen Equivalent Weight (AHEW) and density of the hardener are 100 g equiv^{-1} and 0.985 g cm^{-3} , respectively.

Prior to the preparation of NFREPC specimens, all the materials are dried in oven at 40°C for 4 h. The epoxy resin was first mixed with the hardener following a weight ratio of 2:1. Then the short natural fibers were added into the mixture and stirred to disperse uniformly. Afterward, the aggregate was mixed into the epoxy binder. Finally, the mixture was moulded into cuboids ($50 \text{ mm} \times 50 \text{ mm} \times 200 \text{ mm}$) and cylinders ($\phi 100 \text{ mm} \times 100 \text{ mm}$) for bending tests and compression tests, respectively. The NFREPC specimens were cured at 25°C for 72 h before demoulding. In this study, the weight percentage of epoxy matrix is controlled to be 11.5 wt% (about 22.9 vol%). The fiber volume fraction is set in a range

of 0.12–0.60 vol%. The EPC without natural fibers is used as the control sample.

The flexural properties of the NFREPC are evaluated through the four-point-bending test on an Instron 5567 testing machine at a loading speed of 2 mm min^{-1} , as illustrated in Figure 2(a). The flexural strength of concrete specimens is calculated according to

$$\sigma_b = \frac{PL}{bh^2}, \quad (1)$$

where P is the peak load, L is the span ($L=150 \text{ mm}$), b is the width of the specimen ($b=50 \text{ mm}$), h is the height of the specimen ($h=50 \text{ mm}$). The compressive properties of the NFREPC are measured through the axial compression test on a D2-051 2000KN hydraulic pressure testing machine at a loading speed of 2 mm min^{-1} , as illustrated in Figure 2(b). For each set of EPC specimens, at least three specimens were tested to eliminate the influence of accidental error.

3 Results and discussion

3.1 Bending and compression tests

Figure 3 shows the flexural stress-deflection curves of the NFREPC with sisal fibers and ramie fibers, respectively. During the loading process, the bending stress increases almost linearly with the deflection. Then it drops sharply after attaining the peak load, indicating a brittle characteristic of

the two kinds of NFREPC. The compressive stress-displacement curves of the two kinds of NFREPC demonstrate the similar behavior.

Tables 2 and 3 list the measured flexural strength and compressive strength of the NFREPC with the two kinds of short natural fibers. It can be seen that a small loading of natural fibers can significantly improve the flexural strength of EPC. The flexural strength of EPC with 0.36 vol% sisal fibers and ramie fibers increases by 10.4% and 25.3% respectively, compared with the control sample. Compared with other natural fibers, such as coconut fibers (25.1%) and sugar cane fibers (3.5%) [23], sisal fibers and ramie fibers show excellent enhancement effects. This improvement is not at compromise with the compressive strength. The compressive strength of the two kinds of NFREPC increases by 5.9%–7.5% when the fiber volume fraction is 0.36 vol%. Further increase of the fiber volume fraction leads to a decrease in the reinforcing effects of natural fibers. The flexural strength and compressive strength of sisal fiber reinforced EPC become lower than those of the control sample when the fiber volume fraction reaches 0.60 vol%. The strength of the 0.60 vol% ramie fiber reinforced EPC falls back to the level of control sample.

Figure 4 compares the fracture surface of the bending specimens of the NFREPC with 0.36 vol% and 0.48 vol% natural fibers. It can be seen in Figure 4(a) and (b) that the breakage of aggregate, epoxy matrix and natural fibers occur

Figure 2 (Color online) Setup of (a) four-point-bending test and (b) compression test for NFREPC.

Figure 3 (Color online) Typical flexural stress-deflection curves of the EPC reinforced with (a) short sisal fibers and (b) short ramie fibers.

Table 2 Flexural strength and compressive strength of the sisal fiber reinforced EPC

Sisal fiber (vol%)	Flexural strength (MPa)	Coefficient of variation (%)	Compressive strength (MPa)	Coefficient of variation (%)
0	15.45±0.77	4.33	59.61±1.21	2.86
0.12	16.62±0.30	1.60	58.32±2.95	4.48
0.24	16.78±0.18	0.47	N/A	N/A
0.36	17.05±0.37	0.80	64.08±1.49	2.07
0.48	15.49±0.29	1.02	N/A	N/A
0.60	14.56±0.81	5.22	40.32±2.63	5.73

Table 3 Flexural strength and compressive strength of the ramie fiber reinforced EPC

Ramie fiber (vol%)	Flexural strength (MPa)	Coefficient of variation (%)	Compressive strength (MPa)	Coefficient of variation (%)
0	15.45±0.77	4.33	59.61±1.21	2.86
0.12	17.62±1.34	6.99	60.99±1.14	1.71
0.24	18.25±0.67	3.21	N/A	N/A
0.36	19.36±0.85	4.37	63.15±2.29	3.15
0.48	16.54±0.42	1.96	N/A	N/A
0.60	16.09±1.04	5.70	58.91±1.44	2.38

Figure 4 (Color online) Fracture surfaces of the NFREPC with (a) 0.36 vol% sisal fibers, (b) 0.36 vol% ramie fibers, (c) 0.48 vol% sisal fibers and (d) 0.48 vol% ramie fibers. The exposed fibers on the fracture surfaces are marked with circles.

almost simultaneously in the bending specimens with 0.36 vol% natural fibers, whereas substantial pull-out of fibers are visible on the fracture surface of the NFREPC with 0.48 vol% natural fibers (Figure 4(c) and (d)). This phenomenon indicates that the wetting of fibers could be poor when the fiber volume fraction is at a relatively high level, leading to a weak bonding between the fibers and matrix.

Figure 5 shows the fractured compressive specimens of the NFREPC with 0.36 vol% natural fibers. The failure behavior of the two kinds of NFREPC is quite similar to the traditional cement concrete. The main cracks propagate in the direction along the compression direction. This fracture mode in-

validates the enhancing effects of short fiber because of the poor resistance of natural fiber to shear force.

3.2 Reinforcing mechanisms

The reinforcing effect of natural fibers on the flexural strength of EPC can be described by the micromechanics models developed for the composites reinforced with synthetic short fibers. In this study, natural fibers are incorporated at very low loadings, and the fracture of all specimens starts in the tension region during the four-point-bending tests. Thus the Halpin-Tsai equations [27], which

Figure 5 (Color online) Fractured NFREPC specimens under compression with (a) 0.36 vol% ramie fibers and (b) 0.36 vol% sisal fibers.

can fit the experimental results well for the short fiber reinforced composites with low fiber volume fractions, are employed to establish the relation between the flexural strength of NFREPC and the tensile strength of natural fibers. Assuming that the natural fibers are uniformly dispersed in the NFREPC with random orientation and a good bonding between the fibers and matrix is achieved, the Halpin-Tsai equations can be used to predict the modulus of composite [28]:

$$\frac{E_c}{E_m} = \frac{1}{5} \left(\frac{1 + \frac{2l}{d} \eta_L V_f}{1 - \eta_L V_f} \right) + \frac{4}{5} \left(\frac{1 + 2\eta_T V_f}{1 - \eta_T V_f} \right), \quad (2)$$

$$\eta_L = \frac{\frac{E_f}{E_m} - 1}{\frac{E_f}{E_m} + \frac{2l}{d}}, \quad \eta_T = \frac{\frac{E_f}{E_m} - 1}{\frac{E_f}{E_m} + 2},$$

where E_c represents the modulus of composite. E_m and E_f are the modulus of polymer matrix and fiber, respectively. l , d and V_f are the length, diameter and volume fraction of short fibers, respectively. η_L and η_T denote the efficiency coefficients of the fibers in the direction parallel and perpendicular to the tensile load applied on the composite, respectively. It is found in Figure 3 that the flexural stress-deflection curves of NFREPC specimens keep a quasi-linear manner in the four-point-bending test before the stress reaches the ultimate

strength. Thus, the flexural strength of NFREPC can be described in a similar form of eq. (2):

$$\frac{\sigma_c}{\sigma_m} = \frac{1}{5} \left(\frac{1 + \frac{2l}{d} \eta_L V_f}{1 - \eta_L V_f} \right) + \frac{4}{5} \left(\frac{1 + 2\eta_T V_f}{1 - \eta_T V_f} \right), \quad (3)$$

$$\eta_L = \frac{\frac{\sigma_f}{\sigma_m} - 1}{\frac{\sigma_f}{\sigma_m} + \frac{2l}{d}}, \quad \eta_T = \frac{\frac{\sigma_f}{\sigma_m} - 1}{\frac{\sigma_f}{\sigma_m} + 2},$$

where σ_c and σ_m represents the flexural strength of NFREPC and EPC without natural fibers respectively, considering the EPC without natural fibers as approximately homogeneous and isotropic matrix. σ_f denotes the tensile strength of natural fibers.

Figure 6 compares the flexural strength predicted by eq. (3) and the measured results of the two kinds of NFREPC. The theoretical prediction can reproduce the trend observed in the experimental data, i.e. the flexural strength of NFREPC increases with the fiber volume fraction in a specific range (e.g. 0–0.36 vol%). However, the predicted values are considerably lower than the measured ones. The maximum relative deviation is found to be 7.4% for sisal fiber reinforced EPC and 18.0% for ramie fiber reinforced EPC, respectively. The possible reason can be attributed to that the natural fibers in the concrete are not randomly oriented. According to the observation of fracture surfaces for the bending specimens (Figure 4(a) and (b)), it can be assumed that most fibers on the fracture surface are in the similar direction of the tensile load. Thus eq. (3) can be reduced to

$$\frac{\sigma_c}{\sigma_m} = \frac{1 + \frac{2l}{d} \eta_L V_f}{1 - \eta_L V_f}. \quad (4)$$

Since the aspect ratio of the short natural fibers (l/d) used in this study is quite large, ranging from 40 to 83, eq. (5) can be further simplified to the parallel model based on the rule of mixture [29], i.e.

$$\sigma_c = \sigma_f V_f + \sigma_m (1 - V_f). \quad (5)$$

Figure 6 (Color online) Measured flexural strength and the results predicted by the micromechanics models for the NFREPC with (a) short sisal fibers and (b) short ramie fibers.

It is noteworthy that the premise of eq. (5), i.e. the deformation of aggregate and epoxy matrix keeps consistent, is not rigorously satisfied due to the extraordinary difference in mechanical properties between the aggregate and epoxy matrix. Unlike traditional composites, in which the reinforcements with higher modulus and strength carry more load, the aggregate in EPC has high modulus but low strength whereas the epoxy matrix has low modulus but high strength. In this context, the failure of NFREPC specimens during the bending tests can be considered as a few sequentially occurred events. The aggregate breaks first, then the epoxy matrix with natural fibers takes the whole load and reaches its limit in extremely short time. Figure 3 shows that all the stress-strain curves increase quasi-linearly before a steep drop, without any secondary stress drop related with the failure of aggregate or epoxy matrix with natural fibers. Furthermore, the smooth fracture surfaces in Figure 4(a) and (b) indicate that the epoxy matrix with natural fibers does not experience discernible further deformation after the breakage of the aggregate. Therefore, eq. (5) can be regarded as a close approximation to the situation.

The flexural strength of sisal fiber reinforced EPC predicted by eq. (5) agrees well with the measured results (Figure 6(a)), indicating that the parallel model based on the rule of mixture is a good approximation for the sisal fiber reinforced EPC. The predicted strengths of ramie fiber reinforced EPC are closer to the measured results, compared with prediction given by eq. (3), as shown in Figure 6(b). The maximum relative deviation is reduced from 18.0% to 10.7%, which can be regarded as an acceptable level. The discrepancy between the predicted results and measured results in ramie fiber reinforced EPC may be associated with the characteristics of ramie fibers. It is found that a piece of as-received individual ramie fiber is a bundle of fine fibers with relatively weak adhesion. During the tension test of individual ramie fiber, the fine fibers are observed to detach from the main bundle and break early, which makes the measured tensile strength of ramie fiber scatter in a wide range. Consequently, a simply picked mean value may lead to considerable underestimation of fiber strength and the strength of composites.

The failure of EPC under compression mainly follows split mode. In this situation, the load-bearing capacity of natural fibers subjected to shear is much less than their tensile strength. Therefore, the addition of natural fibers has insignificant effect on the compressive strength of EPC unless the insufficient wetting of fibers occurs at relatively high fiber volume fractions.

4 Conclusions

The reinforcing effects of short sisal fibers and ramie fibers

on the flexural performance of epoxy polymer concrete have been studied through four-point bending tests. It is found that the two kinds of natural fibers with small volume fraction (0.12–0.36 vol%) can lead to a significant increase in the flexural strength of EPC. Ramie fibers demonstrate better reinforcing efficiency than sisal fibers. Incorporation of 0.36 vol% ramie fibers into EPC results in a 25.3% increase in the flexural strength, compared with 10.4% increase by 0.36 vol% sisal fibers. In addition, this improvement in flexural performance is achieved without sacrifice of the compressive properties. The compressive strength of the two kinds of NFREPC increases slightly with the addition of short natural fibers. However, the reinforcing effects of short natural fibers decay with further increase of fiber content. At the fiber volume fractions higher than 0.36 vol%, the flexural properties of NFREPC begin decreasing. Both flexural and compressive strength of NFREPC deteriorate to a level even below those of neat EPC when the fiber volume fraction reaches 0.60 vol%. According to the observation of fracture surfaces, this reduction of reinforcing effects is ascribed to the insufficient wetting of fibers by epoxy resin, which causes a poor bonding between the fibers and epoxy matrix.

The reinforcing mechanisms of the natural fibers are explored by introducing the micromechanics models developed for the polymer composites reinforced with short fibers. The discrepancy between the measured results and the values predicted by the Halpin-Tsai model suggests that the short natural fibers work as the reinforcement is not randomly oriented in the EPC. The orientation of natural fibers may be more like the one parallel to the tensile load on the cross-section of bending NFREPC specimen, which makes the prediction of the parallel model based on the rule of mixture attain a good agreement with the experimental data. The availability of the micromechanics model in this situation also indicates a strong fiber-matrix bonding achieved at low fiber volume fractions.

Sisal fibers and ramie fibers are agricultural products of low price. The incorporation of the two kinds of short natural fibers into EPC requires small modification of the procedure of EPC manufacturing. This cost and processing efficiency endows NFREPC with high possibility of large scale use in engineering. For instance, the pavement of highways and bridges is subjected to compression load and bending load simultaneously under its service condition. It could be one of the potential applications of the EPC reinforced with sisal fibers and ramie fibers.

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