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MICROMECHANICAL MODELING OF FLEXURAL STRENGTH FOR EPOXY POLYMER CONCRETE

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Epoxy polymer concrete (EPC) has been widely used in civil engineering nowadays due to its excellent mechanical properties and advantages in processing. In this paper, a modelling study has been carried out on the flexural performance of EPC. Two classic micromechanics models, i.e. rule of mixture and Mori-Tanaka method, are introduced to predict the flexural strength of EPC with various epoxy resin contents. The comparison shows that the parallel model based on the rule of mixture attains a good agreement with the measured results when the epoxy resin content is sufficiently high to achieve strong adhesion between the aggregate and the epoxy resin. In contrast, the Mori-Tanaka method with the failure criterion dominated by the weakest phase fails to give acceptable prediction due to the unsuitability of its basic assumptions to EPC, particularly when the epoxy resin content is at relatively high levels.

Keywords: Epoxy polymer concrete; Flexural strength; micro-mechanics.

1. Introduction

Polymer concrete is a type of composites manufactured by blending polymer with aggregate and other fillers, where polymer acts as binder for the other components. The polymer matrices commonly used for polymer concrete include polyester styrene, acrylic and epoxy resin [Fowler, 1999; Haddad and Al Kobaisi, 2012]. A comparative research indicates that polymer concrete using polyester or epoxy resin as binder has superior performance than its cement counterpart [Mani et al., 1987]. Due to its excellent properties such as high strength, short curing time and good weather resistance [Bedi et al., 2013; Davydov et al., 1970], epoxy polymer concrete (EPC) has attracted increasing attention in civil engineering, and found various applications in bridge-deck overlays [Dinitz and Stenko, 2010; Doody and Morgan, 1993], machine tool bed [Cho et al., 2011; Kim et al., 1995] and railway slab [Jeon et al., 2015], etc.

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In the past decades, intensive experimental research effort has been devoted to the characterization of the mechanical properties of EPC. The influences of resin and fillers (e.g. aggregate, fibers and particles) on the compressive performance [Ahn, 2003; Bărbuţă et al., 2010; Czarnecki et al., 1996; Dȩbska and Lichołai, 2015; Gencel et al., 2012; Haidar et al., 2011; Jung et al., 2014; Lokuge and Aravinthan, 2013; Shokrieh et al., 2011], the flexural properties [Abdel-Fattah and EI-Hawary, 1999; Ahn, 2003; Bărbuţă et al., 2010; Czarnecki et al., 1996; Daud et al., 2015; Dȩbska and Lichołai, 2015; Gencel et al., 2012; Haidar et al., 2011; Jung et al., 2014; Lokuge and Aravinthan, 2013; Shokrieh et al., 2011] and elastic modulus [Ahn, 2003; Czarnecki et al., 1996; Gencel et al., 2012; Haidar et al., 2011; Jung et al., 2014; Lokuge and Aravinthan, 2013; Shokrieh et al., 2011] of EPC were studied. The weather resistance of EPC was examined under the conditions of chemical erosion [Reis, 2009; Ribeiro et al., 2002] and high temperature [Jung et al., 2014; Oussama et al., 2012; Reis, 2012]. Reis and his colleagues [Reis, 2006; Reis and Ferreira, 2004a, b, 2005, 2006; Reis et al., 2003] carried out a series of investigation on the fracture properties of fiber reinforced EPC. It was found that the mechanical properties of EPC are closely related to the content of resin [Abdel-Fattah and EI-Hawary, 1999; Haidar et al., 2011; Vipulanandan and Dharmarajan, 1988]. Higher resin content generally leads to better mechanical performance. However, increase of resin content also raises the cost of EPC, which may restrict the applications of EPC in civil engineering [Fowler, 1999]. Therefore, a model that describes the relation between the strength of EPC and the resin content is necessary to the developers and users. Research on the strength model of EPC, unfortunately, still remains rare heretofore. Nguyen et al. [Nguyen et al., 2013] attempted to predict the elastic properties of EPC using the Mori-Tanaka method. Toufigh et al. [Toufigh et al., 2016] proposed a constitutive model of the compressive properties for EPC based on the disturbed state concept.

Rule of mixture and Mori-Tanaka method are two of classic micromechanics models for composite materials. Both of them are frequently-used in cement concrete and asphalt concrete [Hashin and Monterio, 2002; Huang et al., 2003; Yang and Huang, 1996b], functionally graded materials [Chandra et al., 2015; Gulshan TAJ and Anupam, 2013] and Carbon Nanotube-Reinforced Composite [Alibeigloo and Jafarian, 2016; Nejad and Taghizadeh, 2017; Nejati and Eslampanah, 2016; Pouresmaeeli and Fazelzadeh, 2017]. In this paper, the two micromechanics models are employed to establish the relation between the flexural strength of EPC and the contents of aggregate and epoxy resin as well as their mechanical properties. A comparison of the prediction performance is carried out between the two models according to the experimentally obtained results of four-point bending tests.

2. Specimen preparation and testing program

Granite aggregate is supplied by Fujian Shiyufa Stone Co. Ltd.. The size of fine aggregate (45 wt%) is up to 4.75 mm, and the size of coarse aggregate ranges (55 wt%) from 4.75 mm to 9.5 mm. The epoxy binder, which is supplied by Fhuzhou Baisheng

Fine Chemicals Pte. Ltd., 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 and 1.1 g/cm^3, respectively. The Amine Hydrogen Equivalent Weight (AHEW) and density of the hardener are 100 g/equiv and 0.985 g/cm^3, respectively. Table 1 lists the properties of the granite aggregate and epoxy binder used in this study.

Table 1. Properties of the granite aggregate and epoxy binder after curing.

Properties	Granite aggregate	Epoxy binder
Density [kg/m^3]	2.50×10^3	1.17×10^3
Elastic modulus [GPa]	45	5.61
Poisson ratio	0.26	0.33
Tensile strength [MPa]	9.6	44.2

The epoxy resin was first mixed with the hardener following a weight ratio of 2:1. Then the aggregate was added into the mixture, finally moulded into cuboid EPC specimens (50 mm $\times$ 50 mm $\times$ 200 mm). The EPC specimens were cured at 25 ℃ for 72 hours before demoulding. In this study, seven sets of EPC specimens were prepared with the resin weight percentages of 5.7 wt%, 7.4 wt%, 9.9 wt%, 11.5 wt%, 13.0 wt%, 14.5 wt% and 16.0 wt%, respectively.

The four-point bending tests were conducted at a velocity 1mm/min on an Instron 5567 universal tester, as shown in Fig. 1. The flexural strength of EPC is determined according to the following equation,

$$\sigma_b = \frac{PL}{bh^2} \tag{1}$$

where P is the peak load, L is the span (L = 150 mm), b is the width of the specimen (b = 50 mm), h is the height of the specimen (h = 50 mm). For each set of EPC specimens, at least three specimens were tested to eliminate the influence of accidental error.

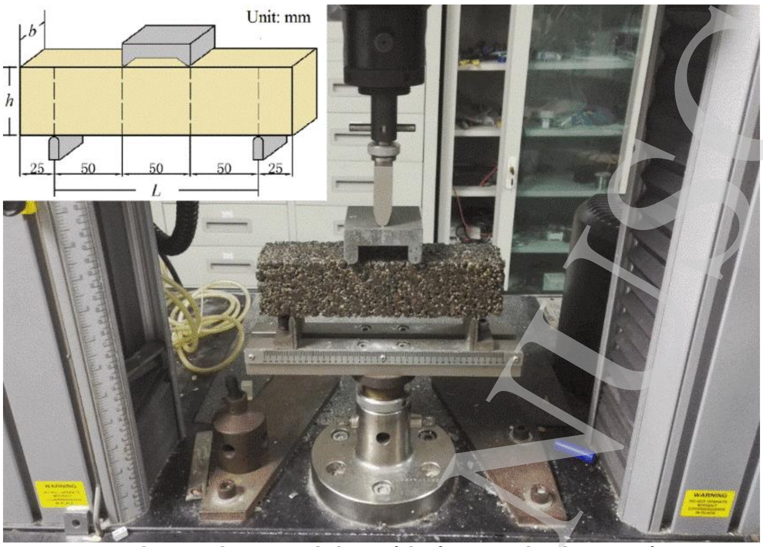

Fig. 1. Schematic diagram and photo of the four-point bending test of EPC.

3. Experimental results

Fig. 2 shows the stress-deflection curves of EPC with various resin weight percentages. It can be observed that the flexural stress grows linearly with the deflection during the loading process. After reaching the maximum value, the stress declines sharply and the fracture occurs in the pure bending section of the specimen, indicating a typical brittle behavior. Table 2 gives the measured flexural strength, which shows the clear improvement of flexural strength with increasing resin content.

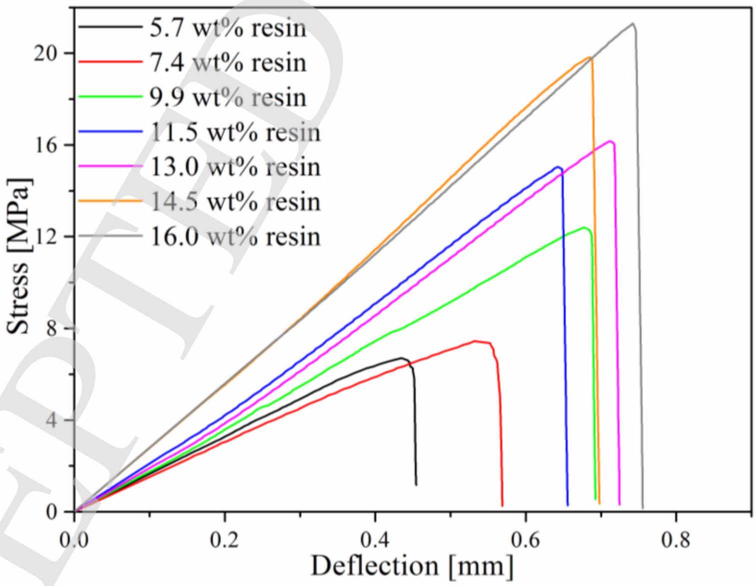

Fig. 2. Stress-deflection curves of EPC with various epoxy resin weight percentages under four-point

bending.

Table 2. Flexural strength of epoxy polymer concrete

Epoxy resin content [wt%]	5.7	7.4	9.9	11.5	13.0	14.5	16.0
Flexural strength [MPa]	7.03 ±0.86	7.90 ±1.48	13.77 ±1.25	15.69 ±0.60	16.46 ±1.04	19.84 ±0.96	21.16 ±1.20

Fig. 3(a) compares the fracture surfaces of EPC specimens with 7.4 wt% and 11.5 wt% resin. The fracture surface of the EPC with 11.5 wt% resin is smooth. No debonding between the aggregate and epoxy matrix is observed, indicating that the aggregate and epoxy matrix rupture almost simultaneously. In contrast, the fracture surface of EPC with 7.4 wt% resin is much rougher and the pull-out of aggregate from epoxy matrix is clearly visible, implying that the aggregate is not sufficiently wetted by the epoxy binder at low epoxy resin content to achieve a strong bonding. Fig. 3(b) gives a zoom-in view of the fracture surfaces of EPC specimens with relatively high resin contents (from 11.5 to 16 wt%). The fracture surface becomes smoother with increasing resin content, demonstrating a strong aggregate/epoxy matrix bonding within the EPC specimens. It is noteworthy that the fracture surfaces of aggregate are flush well with those of epoxy matrix, indicative that the breakage of aggregate and epoxy resin occurs almost simultaneously on the fracture surface.

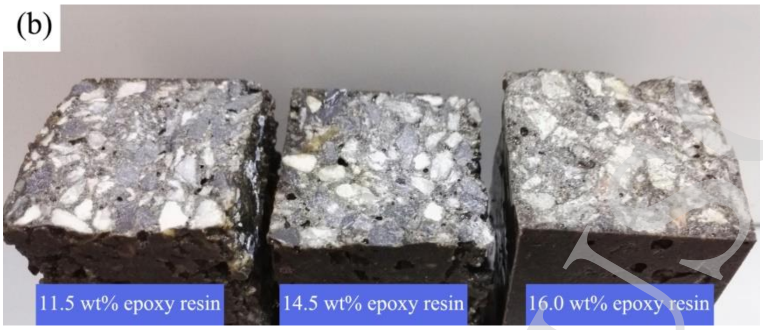

Fig. 3. (a) Fracture surfaces of EPC specimens with 7.4 wt% resin and 11.5 wt% resin after four-point bending test. (b) Zoom-in view of the ffacture surfaces of EPC specimens with relatively high resin contents (11.5-16 wt%).

4. Modelling and verification

4.1. *Estimation of cavity volume fraction*

Cavities are introduced into EPC specimens inevitably during the preparation, which makes the obtained EPC a three-phase composite system containing aggregate, epoxy matrix and cavities. Fig. 4 compares the fracture surfaces of the EPC specimens with 5.7 wt%, 7.4 wt%, 9.9 wt%, 13.0 wt% and 14.5 wt% resin, in which the cavities are identified and marked with bright green color. The size of these cavities with irregular shape varies in a range up to about 4 mm. It can be observed that the number of cavities decreases with increasing epoxy resin content. The EPC specimens with relatively low resin contents (from 5.7 to 9.9 wt%) show dense distributions of cavities (Fig. 4(a)-(c)). In contrast, the cavities appear sporadically in the EPC specimens with relatively high resin contents (from 13 to 14.5 wt%), as shown in Fig. 4(d)-(e). The volume fraction of cavities V_h can be estimated through the statistics of the marked areas. Table 3 lists the estimated volume fractions of cavities, along with the volume factions of aggregate V_Ω.

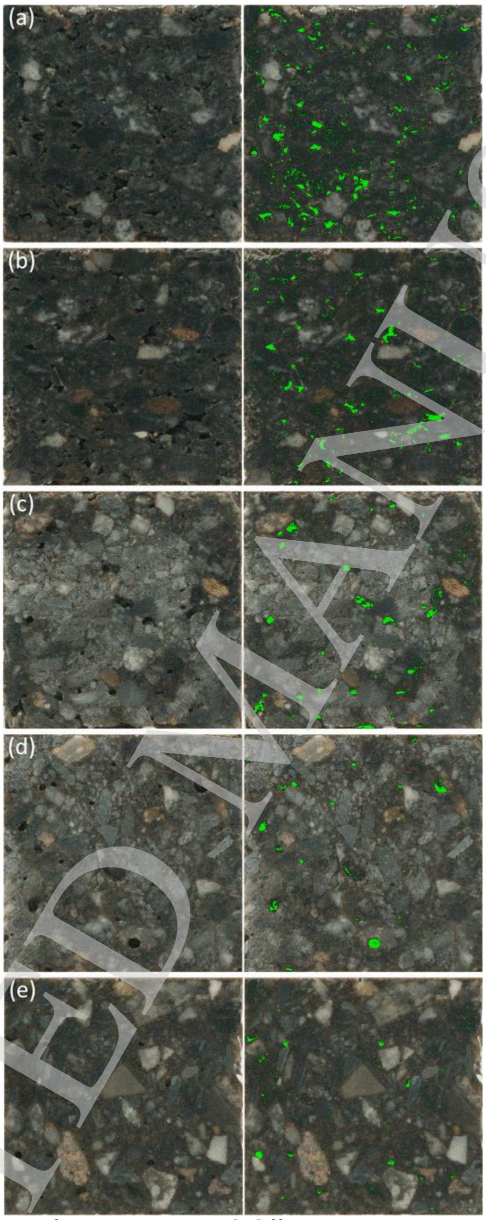

Fig. 4. Fracture surfaces of EPC specimens with different epoxy resin contents: (a) 5.7 wt%, (b) 7.4 wt%, (c) 9.9 wt%1, (d) 13.0 wt%, (e) 14.5 wt%. The cavities are marked with bright green color.

Table 3. Volume fraction of cavities (V_h) and the adjusted volume fraction of aggregate (V_Ω) in EPC with different epoxy resin contents

Epoxy resin content [wt%]	5.7	7.4	9.9	13.0	14.5
V_h	0.0320	0.0215	0.0148	0.0066	0.0066

V_Ω	0.8580	0.8356	0.7977	0.7523	0.7287

Fig. 5 shows the relation between V_h and V_Ω. By fitting the measured data points, V_h can be expressed as a function of V_Ω.

$$V_h = 1.83\times10^{-8}\times 28.64^{4.96V_\Omega} + 2.79\times10^{-3} \tag{2}$$

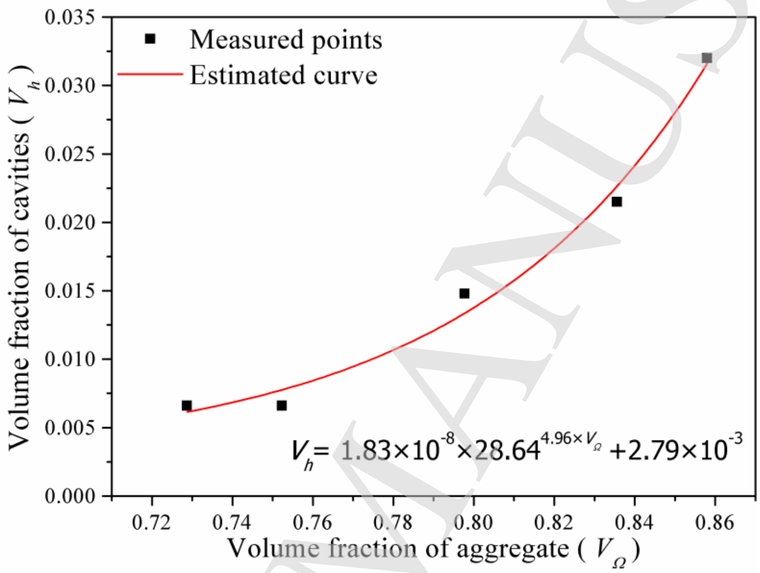

Fig. 5. Relation between volume fraction of cavities (V_h) and volume fraction of aggregate (V_Ω)

4.2. ***Parallel model based on the rule of mixture***

The parallel model based on the rule of mixture for composite materials can be expressed as [Ahmed and Jones, 1990]:

$$E_c = V_\Omega E_\Omega + V_m E_m \tag{3}$$

where E_c is the modulus of composite, E_Ω and E_m are the moduli of the reinforcement and matrix, respectively. V_Ω and V_m represent the volume fraction of reinforcement and matrix, respectively. It can be seen in Fig. 2 that the stress-strain curves of EPC specimens keep a quasi-linear manner in four-point bending test before the stress reaches the ultimate strength. Thus the flexural strength of EPC can be described in a similar form of Eq. (3):

$$\sigma_c = V_\Omega \sigma_\Omega + V_m \sigma_m \tag{4}$$

where σ_c is the flexural strength of EPC, σ_Ω and σ_m are the tensile strengths of aggregate and epoxy matrix for the EPC specimens start to fail in the region subjected to tension.

It should be mentioned that the premise of Eq. (4), 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. The failure of EPC specimens during the bending tests actually includes a series of events: the aggregate breaks first, then the remained epoxy matrix takes all load and reaches its limit soon afterward. Fortunately, this process is found to finish in extremely short time. It can be observed in Fig. 2 that all the stress-strain curves show a smooth quasi-linearly increasing stage followed by a steep drop, without any secondary stress drop related with the failure of aggregate or epoxy matrix. The smooth fracture surfaces in Fig. 3(b) also indicate that the epoxy matrix in EPC does not experience discernible further deformation after the breakage of the aggregate. Therefore, Eq. (4) can be considered as a close approximation to the situation.

Taking account of the cavities in EPC, Eq. (4) can be extended to include three phases

$$\sigma_c = V_\Omega \sigma_\Omega + V_h \sigma_h + \left(1 - V_\Omega - V_h\right)\sigma_m \tag{5}$$

where $\sigma_h = 0$, i.e. the cavities are regarded as a type of special phase without strength. Substituting the material constants and volume fraction into Eq. (5), the flexural strength of EPC can be predicted theoretically, as shown in Fig. 6. Table 4 lists the predicted values along with the measured results. The parallel model based on the rule of mixture provides quite accurate prediction when the resin content is higher than 11.5 wt%, with the relative error less than 10%. However, apparent overestimation can be found at low resin contents (especially less than 7.4 wt%), when the assumptions of perfect bonding are no longer satisfied, as indicated in Fig. 3(a). Fortunately, the EPC with low resin content seldom appears in practical applications due to its poor mechanical performance.

Fig. 6 and Table 4 also give the prediction made with two-phase model, ignoring the influence of the cavities. As the volume fraction of the cavities stays at a low level (up to 3.2 vol%), the simplification to two-phase model results in small deviation (negligible at high resin contents), compared with the three-phase one.

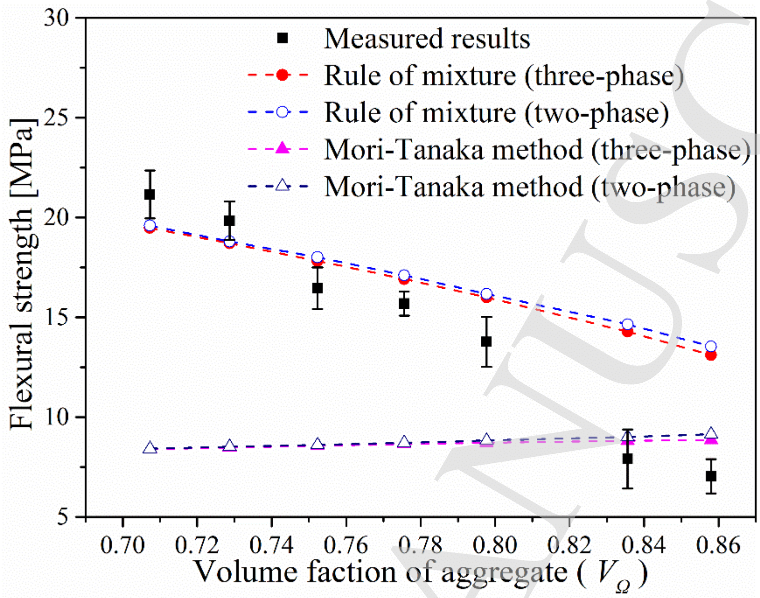

Fig. 6. Predicted flexural strength of EPC based on the rule of mixture and the Mori-Tanaka method with the weakest phase-dominated failure criterion, in comparison with the measured results.

Table 4. Flexural strength of epoxy polymer concrete predicted with the rule of mixture together with the measured data

Resin content [wt %]	Volume fraction of aggregate	Measured strength [MPa]	Predicted strength (Three-phase) [MPa]	Relative error [%]	Predicted strength (Two-phase) [MPa]	Relative error [%]
5.7	0.858	7.03	13.11	86.5	13.54	92.6
7.4	0.836	7.90	14.28	80.8	14.65	85.4
9.9	0.798	13.77	16.00	16.2	16.17	17.4
11.5	0.776	15.69	16.92	7.8	17.11	9.1
13.0	0.752	16.46	17.83	8.3	18.01	9.4
14.5	0.729	19.84	18.71	5.7	18.80	5.2
16.0	0.707	21.16	19.48	7.9	19.60	7.4

4.3. *Mori-Tanaka method with the weakest phase dominated failure criterion*

Mori-Tanaka method [Mori and Tanaka, 1973] is a classic equivalent inclusion model developed to describe the modulus or strength of composites [Benveniste, 1987; Christensen, 1990; Yang and Huang, 1996a]. Yang and Huang [Yang and Huang, 1996b] proposed a micromechanics model combining the Mori-Tanaka method with the failure criterion dominated by the weakest component. The model, which successfully predicted the compressive strength for the concrete made of cement matrix and artificial cement aggregate, has been adopted by the other researchers to study the mechanical responses of concrete [Caporale et al., 2014; Ke et al., 2014; Lin, 2013].

Considering the cavities as a kind of special inclusion without stiffness and strength, the two-phase model proposed by Yang and Huang can be extended to a three-phase one.

Namely, the average of the disturbance of the three kinds of stresses is zero within a representative volume element

$$V_\Omega \langle \sigma \rangle_\Omega + V_h \langle \sigma \rangle_H + (1 - V_\Omega - V_h)\langle \sigma \rangle_M = 0 \tag{6}$$

where $\langle \sigma \rangle_M$, $\langle \sigma \rangle_\Omega$ and $\langle \sigma \rangle_H$ denote the stress disturbance caused by the matrix, aggregate and cavities, respectively. $\langle \sigma \rangle_M$, $\langle \sigma \rangle_\Omega$ and $\langle \sigma \rangle_H$ can be expressed as

$$\begin{aligned} \langle \sigma \rangle_M &= -V_\Omega C(S-1)\langle \varepsilon^* \rangle - V_h C(S-1)\langle \varepsilon^{**} \rangle \\ \langle \sigma \rangle_\Omega &= (1-V_\Omega) C(S-1)\langle \varepsilon^* \rangle - V_h C(S-1)\langle \varepsilon^{**} \rangle \\ \langle \sigma \rangle_H &= -V_\Omega C(S-1)\langle \varepsilon^* \rangle + (1-V_h) C(S-1)\langle \varepsilon^{**} \rangle \end{aligned} \tag{7}$$

where C is the modulus of epoxy matrix, S is the fourth-order Eshelby's tensor. $\langle \varepsilon^* \rangle$ and $\langle \varepsilon^{**} \rangle$ are eigenstrains of the aggregate and cavities, respectively.

$$\begin{aligned} \langle \varepsilon^* \rangle &= \left(\alpha_2 \alpha_4^{-1} \alpha_1 - \alpha_3\right)^{-1} \times \left(\left(C^{*-1} - C^{-1}\right) + \alpha_2 \alpha_4^{-1}\left(C^{**-1} - C^{-1}\right)\right)\sigma^0 \\ \langle \varepsilon^{**} \rangle &= \left(\alpha_1 \alpha_3^{-1} \alpha_2 - \alpha_4\right)^{-1} \times \left(\left(C^{**-1} - C^{-1}\right) + \alpha_1 \alpha_3^{-1}\left(C^{*-1} - C^{-1}\right)\right)\sigma^0 \\ \alpha_1 &= V_f C^{**-1} C(S-1) - V_f (S-1) \\ \alpha_2 &= V_h C^{*-1} C(S-1) - V_h (S-1) \\ \alpha_3 &= (1-V_f) C^{*-1} C(S-1) + V_f (S-1) - S \\ \alpha_4 &= (1-V_h) C^{**-1} C(S-1) + V_h (S-1) - S \end{aligned} \tag{8}$$

where C^* and C^{**} represent the moduli of the aggregate and cavities ($C^{**} \approx 0$).

The average stresses in the epoxy matrix and in the aggregate can be written as

$$\begin{aligned} \sigma^{(M)} &= \sigma^0 + \langle \sigma \rangle_M \\ \sigma^{(\Omega)} &= \sigma^0 + \langle \sigma \rangle_\Omega \end{aligned} \tag{9}$$

where σ^0 is the applied stress far from the representative volume element. As the cavities are supposed not to fail under the action of stress, the failure criterion is controlled by the other two phases, i.e., the epoxy matrix and the aggregate. Thus, the flexural strength of EPC σ_s is dominated by the weaker one between the epoxy matrix and the aggregate,

$$\sigma_s = \min\left\{\sigma^{(M)} - \langle\sigma\rangle_M, \sigma^{(\Omega)} - \langle\sigma\rangle_\Omega\right\}$$

$$= \min\left\{\begin{array}{l} \begin{bmatrix} 1 - V_\Omega C(S-1)\left(\alpha_2\alpha_4{}^{-1}\alpha_1 - \alpha_3\right)^{-1}\left(\left(C^{*-1} - C^{-1}\right) + \alpha_2\alpha_4{}^{-1}\left(C^{**-1} - C^{-1}\right)\right) \\ -V_h C(S-1)\left(\alpha_1\alpha_3{}^{-1}\alpha_2 - \alpha_4\right)^{-1}\left(\left(C^{**-1} - C^{-1}\right) + \alpha_1\alpha_3{}^{-1}\left(C^{*-1} - C^{-1}\right)\right) \end{bmatrix}^{-1} \sigma^{(M)}, \\ \begin{bmatrix} 1 + \left(1 - V_\Omega\right) C\left(S-1\right)\left(\alpha_2\alpha_4{}^{-1}\alpha_1 - \alpha_3\right)^{-1}\left(\left(C^{*-1} - C^{-1}\right) + \alpha_2\alpha_4{}^{-1}\left(C^{**-1} - C^{-1}\right)\right) \\ -V_h C(S-1)\left(\alpha_1\alpha_3{}^{-1}\alpha_2 - \alpha_4\right)^{-1}\left(\left(C^{**-1} - C^{-1}\right) + \alpha_1\alpha_3{}^{-1}\left(C^{*-1} - C^{-1}\right)\right) \end{bmatrix}^{-1} \sigma^{(\Omega)} \end{array}\right\} \tag{10}$$

In Eq. (10), the strength of EPC equals to the applied stress σ^0, which causes the weaker one of the two phases to reach its limit. Thus, the values of $\sigma^{(M)}$ and $\sigma^{(\Omega)}$ are set as the tensile strength of epoxy matrix and aggregate, respectively. When V_h vanishes, the three-phase model downgrades to the two-phase one.

Fig. 6 shows the flexural strength predicted by substituting the material constants in Table 1 and volume fractions of epoxy resin into Eq. (6)-(10). The model, unfortunately, does not work at most volume fractions of aggregate. Even the trend of the measured data cannot be correctly reproduced by this model.

To explore the reasons of this unexpected poor performance, the lower and upper limit of the prediction are examined. The predicted strength of EPC should attain its lower limit and higher limit when the volume fraction of aggregate is 100% and 0%, respectively. In the cased of $V_\Omega \approx 1$, the predicted strength is equal to the strength of aggregate. However, the predicted strength is far less than the strength of epoxy matrix when $V_\Omega = 0$. This irrational result is associated with the assumption of the failure criterion, in which the strength of concrete is defined as the applied stress when the weakest phase in EPC reaches its limit. In this situation, the strength of EPC can be significantly reduced by the existence of even a single small aggregate in the epoxy matrix. Therefore, the weakest phase-dominated failure criterion may work well only when the weaker phase (i.e. the aggregate) occupies a high volume fraction in EPC. It can be seen that the strength model gives a close prediction at the volume fraction of 0.836 (14.5 wt% resin). Nevertheless, the prediction shows considerable deviation at higher aggregate volume fraction compared with the measured result. As mentioned in the previous section, low epoxy resin content leads to the insufficient wetting of aggregate, which invalidates the assumption of perfect bonding between the aggregate and epoxy matrix, i.e. one of the bases to apply the Mori-Tanaka method. Therefore, the Mori-Tanaka method accompanied with the weakest phase-dominated failure criterion, though fits cement concrete, is not suitable for modeling the strength of EPC.

5. Conclusion

Two micromechanics models of flexural strength have been proposed for EPC. The prediction performance of the two models is verified according to the measured results obtained in four-point bending tests. The follow conclusions can be drawn:

(1) The parallel model based on the rule of mixture is a good approximation when the epoxy resin content in EPC is higher than 11.5 wt%. The prediction given by the proposed three-phase model, which includes the aggregate, epoxy matrix and cavities, agrees well with the measured results. At relatively low epoxy resin contents ($\leq$9.9 wt%), the flexural strength predicted by the rule of mixture-based model shows large deviation. This discrepancy is attributed to the poor wetting of the aggregate by the insufficient epoxy resin, which invalidates the implicit assumption of perfect bonding between the phases.

(2) Distinguished from conventional composites, the aggregate in EPC occupies high moduli and low strength, whereas the epoxy matrix has low modulus and high strength. One of the basic assumptions of the rule of mixture, i.e. consistent deformation of phases, is not strictly satisfied due to this extraordinary feature of EPC. However, the failure of EPC is found an extremely short process, which makes the rule of mixture a close approximation to the real situation. It may also be applicable to other composites with the similar characteristics and mechanical behaviors.

(3) The Mori-Tanaka method accompanied with the failure criterion dominated by the weakest phase is a popular model for cement concrete. However, this model is found unsuitable for the flexural properties of EPC. At high epoxy resin contents, namely low volume fraction of aggregate, the influence of the aggregate (weakest phase) is overestimated, making the predicted results much lower than the measured ones. When the volume fraction of aggregate is high enough, the poor bonding between the aggregate and epoxy matrix also invalidates the model.

Acknowledgments

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