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EFFECTS OF A POLYCARBOXYLATE SUPERPLASTICISER ON THE MECHANICAL PROPERTIES OF A HIGH-STRENGTH ENGINEERED CEMENTITIOUS COMPOSITE

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This study investigates the influence of different dosages of polycarboxylate superplasticisers on the mechanical properties of a High-Strength Engineered Cementitious Composite (HSECC), including the compressive strength, flexural strength, tensile properties, and bending toughness. The distribution of polyethylene (PE) fibres in the hardened body of the HSECC is also analysed using scanning electron microscopy (SEM). The results indicate that the mechanical properties of HSECC present a first decreasing and then increasing trend with the increasing superplasticiser dosage, while the tensile ductility exhibits the opposite trend. The inflection points of the tensile properties are observed within the superplasticiser dosage range of 0.35 ~ 0.4 wt. %. The SEM analysis of the fibre distribution in the specimen cross-section reveals that the addition of a defoaming agent alters the workability of the fresh mortar, resulting in a decrease in the fibre dispersion coefficient from 73.0 % to 65.1 %, a reduction of 10.8 %. Gradually increasing the superplasticiser dosage to 0.35 wt. % increases the fibre dispersion coefficient to 74.5 %. These findings suggest that the optimal dosage of the superplasticiser for HSECC lies within the range of 0.35 ~ 0.4 wt. %, which can enhance the mechanical properties of the HSECC while maintaining good fibre dispersion.

INTRODUCTION

Concrete is widely used in construction due to its low cost and availability. However, its brittleness, susceptibility to cracking, and tensile softening can reduce the durability and load-bearing capacity over time.

To address the above issues, researchers have explored ways how to enhance the ductility of ordinary concrete for decades by adding materials such as steel fibres, polyvinyl alcohol fibres, and polyethylene fibres. For example, Li et al. developed a high-ductility composite material by using polyvinyl alcohol fibres and by adjusting the composition of the concrete matrix. This composite material is known as an engineered cementitious composite (ECC) [1-2]. As a result, ECC exhibits high ductility with a strain of more than 3 % with a strain-hardening ability under tension, where multiple micro-cracks occur in the stressed area, which can be effectively controlled below 100 μm or less [3].

In addition to ECC, researchers have developed High-Strength Engineered Cementitious Composites (HSECCs) with a compressive strength of over 80 MPa by referring to the densely packed model of Ultra-High Performance Concrete (UHPC) with a strain of over 3 % by re-referring to the ECC micromechanics [4-5]. For example, Zhang et al. prepared an HSECC with a strength of 85 MPa and a tensile strain of 4.2 % by adding 2v/v % of polyethylene (PE) fibres [6]. Moreover, Zhou et al. achieved a compressive strength of 100 MPa by adding 2v/v % of PE fibres and by reducing the water-cement ratio [7].

In this study, the composition of HSECC is calculated using a densely packed model [7]. Various dosages of a polycarboxylate superplasticiser are added to the mix to reduce the water-cement ratio of the HSECC. The influence of the superplasticiser dosage on the mechanical properties, including the compressive strength and flexural strength, as well as the fibre distribution of the HSECC, is investigated.

EXPERIMENTAL

Materials

The materials used to prepare the HSECC include PI 42.5 cement, S105-grade slag, 800-mesh fly ash, and silica fume, and their appearance, particle size and specific surface area are shown in Figure 1 and Table 1. Refined quartz sand with a particle size of 50-70 mesh and polyethylene (PE) fibres with a length of 12 mm and a diameter of 24 μm were used. The physical properties of the PE fibres are shown in Table 2. A polycarboxylate superplasticiser (white powder) with a water-reducing efficiency of 40 % was also used.

Composition design

After determining the particle size distribution and specific surface area of the raw materials, a densely packed model was adopted to design the recipe of the HSECCs. A sand-cement ratio of 0.3 and a water-cement ratio of 0.16 were used as shown in Table 3:

Table 1. Specific surface area of the materials.

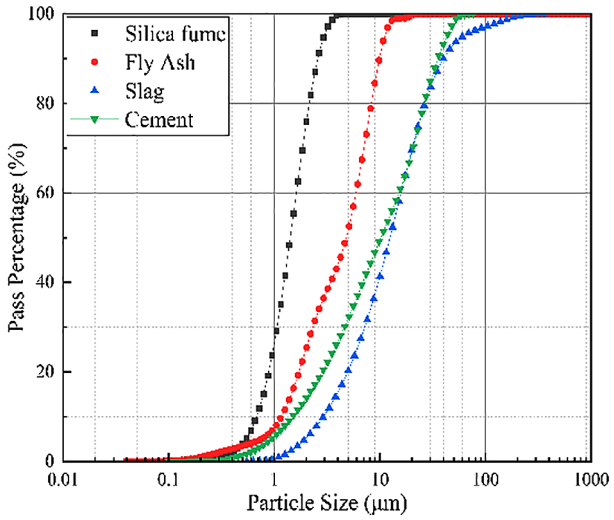
Materials	Cement	Slag	Fly ash	Silica fume
Specific surface area($m^2 \cdot Ml^{-1}$)	2.5	2.5	2.8	5.3

Table 2. Physical properties of the PE fibres.

Length (mm)	Diameter (μm)	Tensile strength (MPa)	Elastic modulus (GPa)	Density ($g \cdot cm^{-3}$)
12	24	3000	120	0.97

Preparation and curing of the HSECC specimens

In this study, the following procedure was followed for the preparation of all the HSECC specimens: (1) The HSECC dry mix was poured into a mixer and stirred for 3 minutes until well mixed. (2) Water was added to the mixer and stirred for 5-6 minutes until the mixture had a flowable consistency. (3) PE fibres were added to the mixer and mixed for an additional 5 minutes before pouring the mixture into the mould. (4) The specimens



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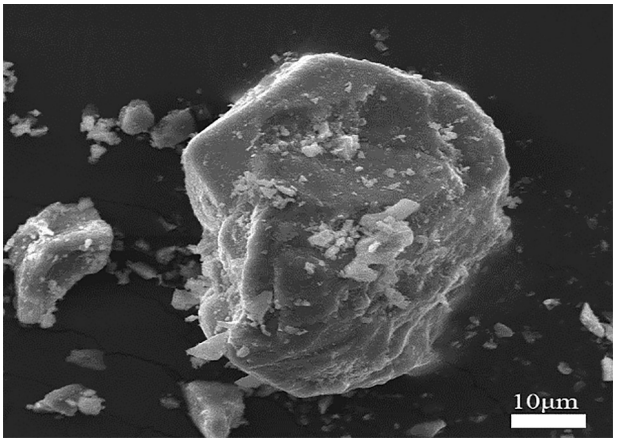

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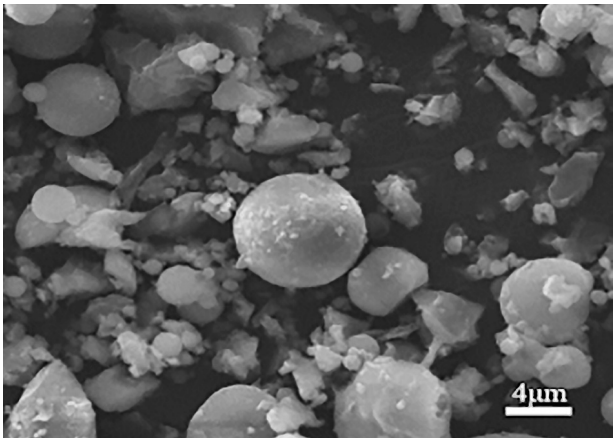

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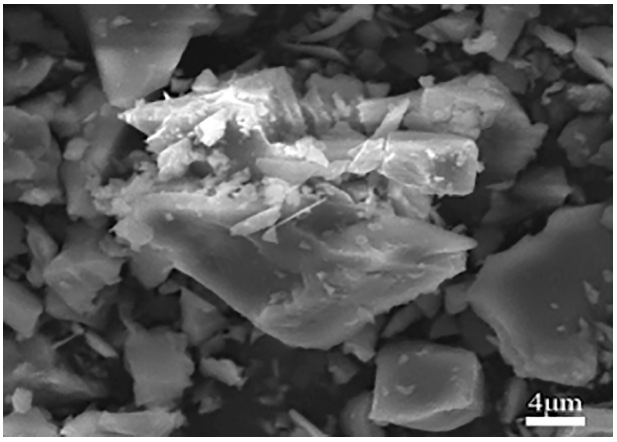

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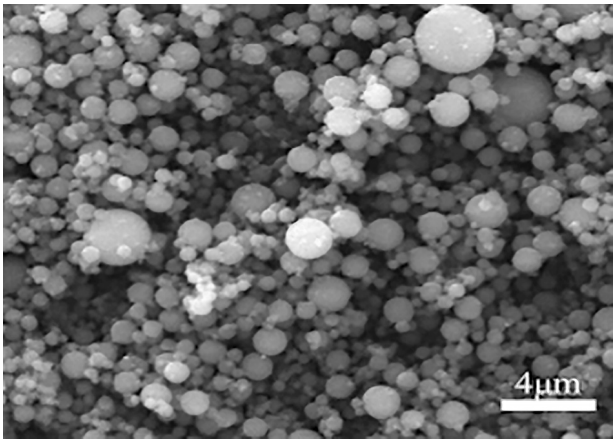

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Figure 1. Appearance and particle size of the materials.

Table 3. HSECC recipes.

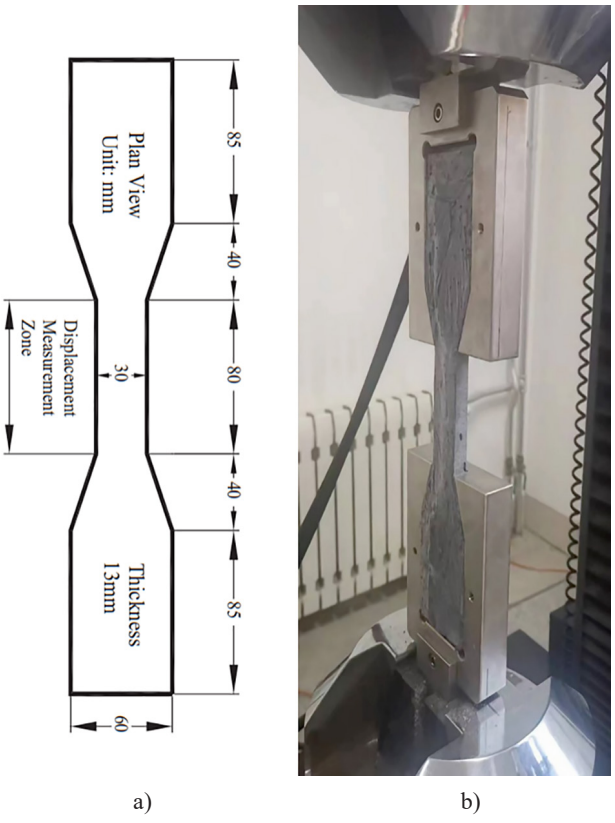
Item	Cement	Slag	Fly ash	Silica fume	Superplasticiser	Defoaming agent
Ref	790	660	220	170	0.20 %	0 %
D1	790	660	220	170	0.20 %	0.1 %
D2	790	660	220	170	0.25 %	0.1 %
D3	790	660	220	170	0.30 %	0.1 %
D4	790	660	220	170	0.35 %	0.1 %
D5	790	660	220	170	0.40 %	0.1 %

were vibrated 60 times on a vibrating table to reach a smooth surface. During the curing stage, the moulded specimens were kept in an environment with a relative humidity above 95 % and a temperature of 20 ± 2 °C for 24 hours before demoulding. The demoulded specimens were then cured in tap water at room temperature.

Experimental methods and analysis

Mechanical property analysis

The dimensions of the specimens for the uniaxial tensile test were in accordance with JC/T-2461, the standard test method for the mechanical properties of ductile fibre reinforced cementitious composites. The detailed dimensions of the specimens and the testing apparatus are shown in Figure 2. A compressive strength test and three-point bending test were conducted using specimens with dimensions of 40 × 40 × 160 mm, and were loaded at rates of 2.4 kN·s^{-1} and 2 mm·min^{-1}, respectively, until the specimens failed. The load-deflection curve of the three-point bending test was obtained, and the toughness index of the specimens was calculated according to ASTM C1018 [8].



a) b)

Figure 2. Dimensions of the dog-bone specimens (a) [9], photograph of a uniaxial tensile testing apparatus (b).

Characterisation of the fibre distribution in the specimens

After the uniaxial tensile test, the dog-bone specimens were cut at the fracture site and divided into 9 sections [10]. The fibre distribution on the cross-section was observed using a scanning electron microscope (SEM), and the number of fibres in each section was counted. The deviation between the number of fibres and the average number of fibres in each section was calculated, and the negative e-exponent of the deviation was taken as the fibre dispersion coefficient. A larger dispersion coefficient indicates better fibre dispersion. The calculation formula is shown in Equation 1.

$$\alpha = \exp\left[-\frac{1}{x_0}\sqrt{\frac{\sum(x_i - x_0)^2}{n}}\right] \quad (1)$$

where x_0 represents the average number of fibres in each section, x_i represents the actual number of fibres in each section, and n is the number of sections.

RESULTS AND DISCUSSION

Mechanical properties

The effect of superplasticiser dosage on the compressive and flexural strength of the HSECC

Figure 3 shows the effect of the dosages of the superplasticiser on the compressive strength of the HSECC at 3, 7, and 28 days of curing. The compressive strength of the HSECC does not change significantly at 3 days. However, before the superplasticiser content reaches 0.4 wt. %, with the dosage gradually increased, the strength of the HSECC gradually decreases at 7 and 28 days. When the superplasticiser content reaches 0.4 wt. %, the strength of the HSECC increases. At the same time, D1 with 0.2 wt. % of the superplasticiser has the highest 7- and 28-day compressive strength followed by D5 with 0.4 wt. %. Even the 3-day compressive strength does not change drastically, as one can obser-

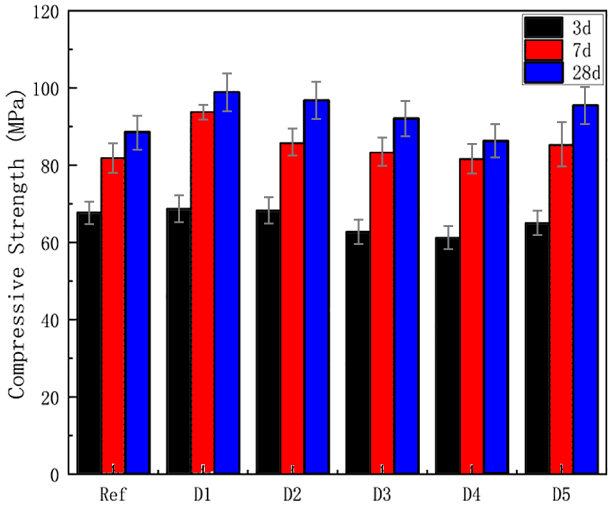


Figure 3. Effect of the superplasticiser dosage on the compressive strength.

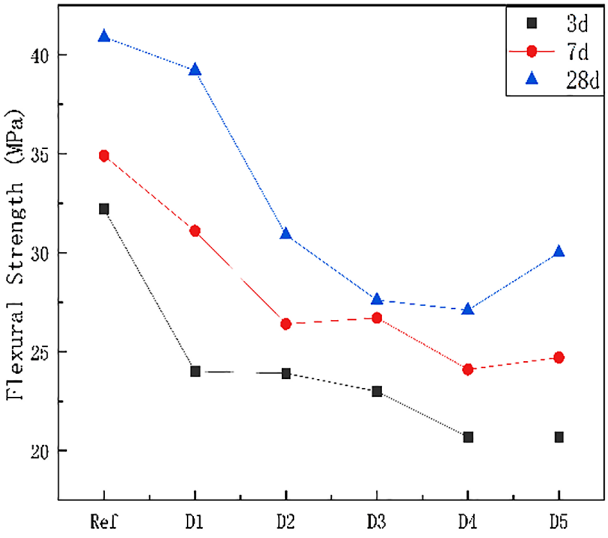
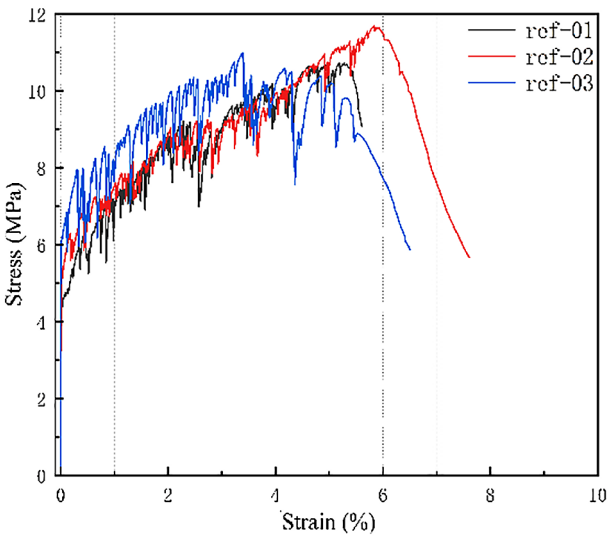


Figure 4. Effect of the superplasticiser dosage on the flexural strength.

ve the same trend. As shown in Figure 4, the flexural strength of the control group is the highest. Under the action of the defoaming agent, the trend of the flexural strength is consistent with that of the compressive strength. This is because the superplasticiser forms an adsorption film on the surface of the cement particles, which can improve the fluidity of the fresh mixture, but also affects the hydration of the cement particles, leading to a decrease in the compressive and flexural strength of the specimens [11]. However, when the dosage of the superplasticiser was increased to 0.4 %, the fluidity of the fresh mixture was greatly improved, which could fill some of the voids introduced by adding the PE fibres, resulting in a decrease in the porosity of the specimens and an increase in the compressive and flexural strength [12].

The effect of the superplasticiser dosage on the tensile strength of the HSECC

During the uniaxial tensile test, a stress concentration is easily generated by the defects inside the specimens, and cracks generally originate from the defects and propagate into the matrix [13]. Figure 5 shows the stress-strain curve of the HSECC after 28 days of curing. It can be seen that the tensile strength and strain capacity of the D1 group is significantly lower than those of the reference group. From D1 to D5, as the dosage of superplasticiser increases, the tensile strain capacity of the specimens increases. When the dosage of superplasticiser increased to 0.35 %, the tensile strain capacity of the specimens reaches a maximum of 9.5 %.



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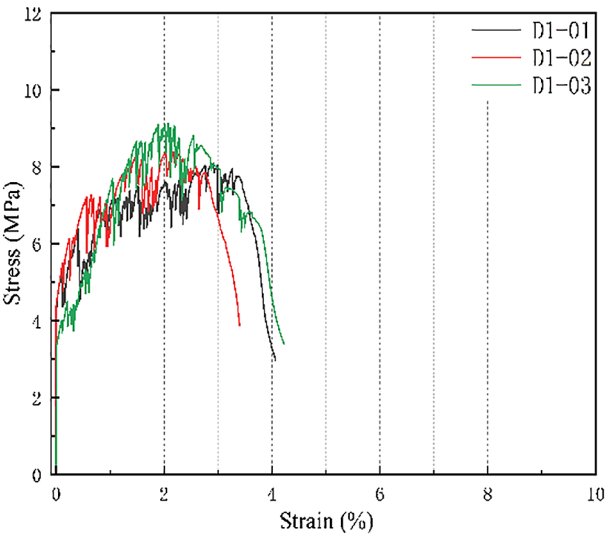

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Figure 5. Influence of the superplasticiser dosage on the tensile ductility. *(Continue on next page)*

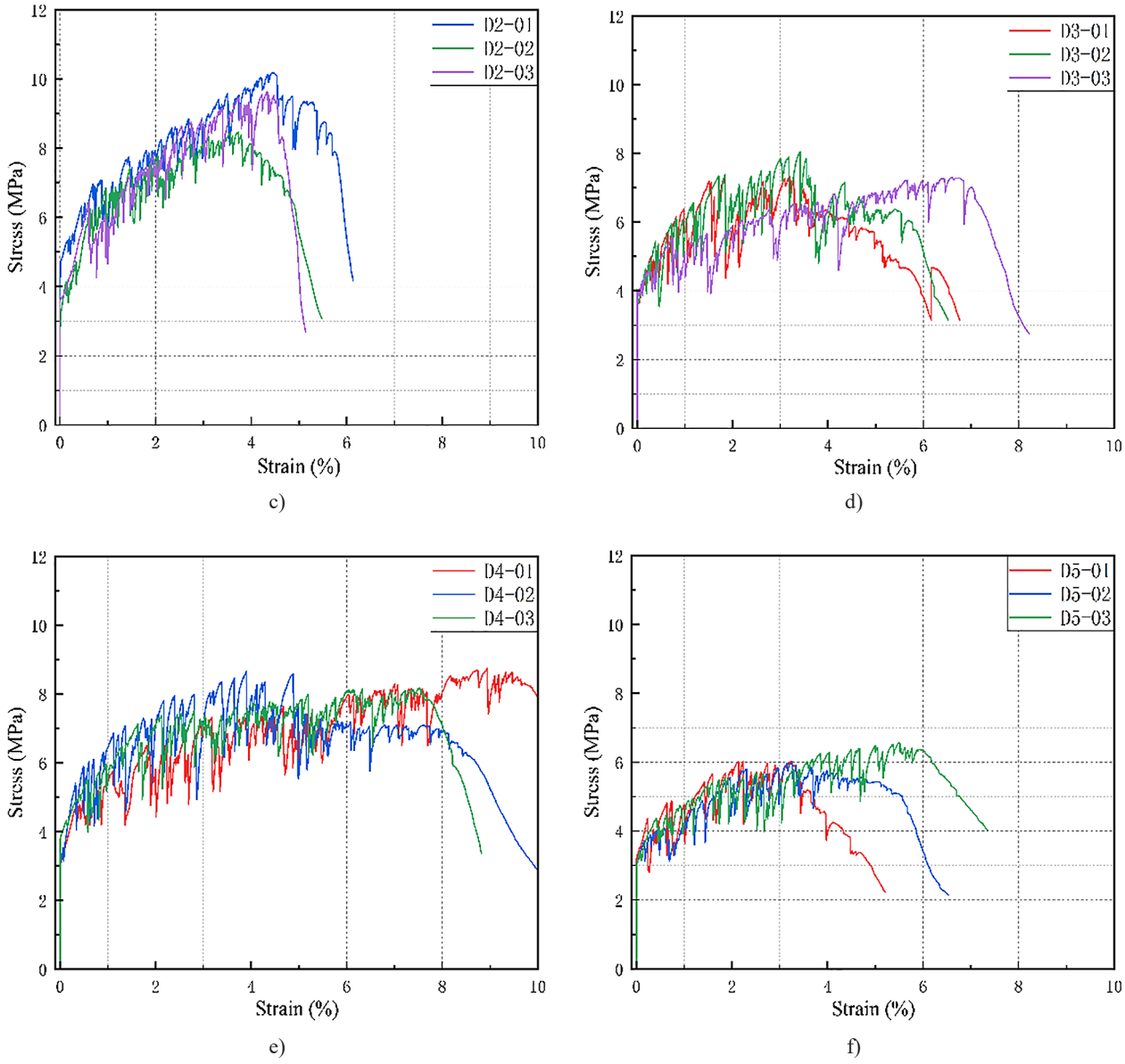

Figure 5. Influence of the superplasticiser dosage on the tensile ductility.

However, when the dosage of superplasticiser is further increased to 0.4 %, the tensile strain capacity of the specimens decreases. It can be seen from Table 4 that the decrease in the tensile ductility of the D1 group is due to the decrease in the fibre dispersion inside the specimens [14-15]. As the dosage of the superplasticiser increases, the fibre dispersion gradually improves, and the hydration process is hindered to some extent by the superplasticiser, leading to the increased tensile strength of the specimens [16]. However, when the dosage of superplasticiser is too high, reaching 0.4 %, fibre agglomeration occurred inside the specimens, resulting in an uneven fibre dispersion and a decrease in the tensile ductility of the specimens [14-15, 17]. Overall, the tensile strength of the specimens shows a negative relationship with the compressive strength.

Flexural modulus

Load-deflection curve

Figure 6 shows the load-deflection curves of the specimens during the three-point bending test. The ultimate load capacity of each group is basically consistent with the trend of the compressive strength and flexural strength. Under the action of the defoamer, the ultimate load capacity of the D1 group is lower than that of the reference group. From D1 to D5, as the dosage of the superplasticiser increases, the ultimate load capacity of the specimens increases. However, when the dosage of the superplasticiser reaches 0.4 % in the D5 group, the ultimate load capacity of the specimens reaches a maximum. In addition, although the load-deflection curves of each group show a negative relationship with

the tensile ductility, typical strain hardening phenomena were observed in the curves, indicating that the composite material has good deformation ability under bending.

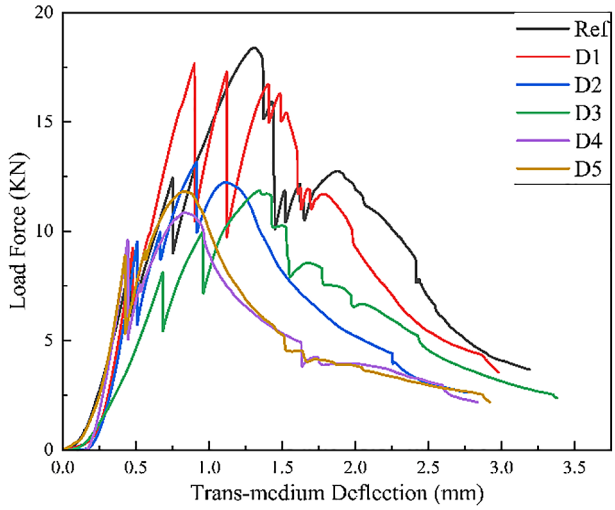

Figure 6. Load-deflection curves of the specimens.

Toughness index

The toughness index of the HSECC is calculated according to the ASTM C1018 standard. The toughness index and residual strength are denoted as I and R, respectively. The calculation of the toughness index is as follows: as shown in Figure 7, δ_{cr} represents the initial cracking deflection, and the area under the load-deflection curve corresponding to the initial cracking situation is calculated as the reference area for calculating the toughness index. Then, the area under the load-deflection curve corresponding to 3 δ_{cr} and 5.5 δ_{cr} is calculated. Finally, the toughness index I_5 and I_{10} are obtained by calculating the ratio of the area under the load-deflection curve corresponding to 3 δ_{cr} and 5.5 δ_{cr} to the reference area, respectively. The formulas for calculating I_5 and I_{10} are shown in Equations 2 and 3, respectively.

$$I_5 = \frac{S_{OACB}}{S_{OAB}} \tag{2}$$

$$I_{10} = \frac{S_{OAEF}}{S_{OAB}} \tag{3}$$

In the above formula, S_{OAB}, S_{OACD} and S_{OAEF} represent the area of the graph enclosed by the points of O, A, C, D, E and F.

Hence, the residual strength $R_{5,10}$ can be obtained by using Equation 4.

$$R_{5,10} = 20\,(I_{10} - I_5) \tag{4}$$

The toughness index I_5 and I_{10} and the residual strength $R_{5,10}$ of each group calculated using the above equations are shown in Table 3. For an ideal elastic-plastic material, its toughness index I_m should not be less than the value of m, and the residual strength $R_{5,10}$ should be greater than or equal to 100 [18]. For the HSECC, the larger the values of the toughness index I_m and residual strength R, the higher the flexural toughness of the HSECC. As shown in Table 4, only the reference, D1, and the D2 groups meet the criteria for an ideal elastic-plastic material, indicating that when the dosage of the superplasticiser exceeds 0.25 %, the superplasticiser delays the cement hydration, resulting in a decrease in the strength of the matrix and the adhesion force between the fibres and the matrix. This leads to a decrease in the ultimate bending load that the specimen can withstand, which reduces the area under the load-deflection curve and decreases the residual strength and toughness index of the material.

Table 4. Flexural toughness index of the HSECC.

Item	I_5	I_{10}	$R_{5,10}$
Ref	9.78	18.69	178.2
D1	9.88	17.77	157.8
D2	10.18	15.44	105.2
D3	7.30	10.16	57.2
D4	5.86	9.63	75.4
D5	8.01	12.04	80.6

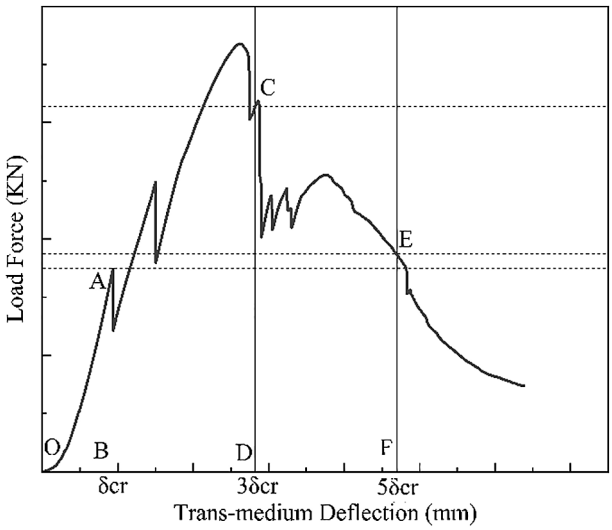

Figure 7. Sample diagram for calculating the flexural toughness.

Fibre distribution in specimen

There are generally two methods to improve the fibre distribution in HSECC specimens: one is to change the mixing procedure. Zhou et al. suggested reserving some mixing water and adding the reserved mixing water after the fibre dispersion in the slurry can improve the fibre dispersion and increase the dispersion coefficient of the fibres [17, 19]. The other is to adjust the

viscosity of the fresh mixture. Within a suitable range of viscosity, the dispersion coefficient of the fibres inside the specimen is significantly improved [20-23]. As can be seen from Table 4, the dispersion coefficient of the reference group is 73.0 %. However, with the addition of the defoaming agent, the dispersion coefficient of the fibres in the D1 group decreases to 65.1 %, resulting in a decrease in the tensile ductility. As the dosage of the superplasticiser increases, the fibre dispersion coefficient in the HSECC specimens increases. When the dosage of the superplasticiser reaches 0.35 wt. %, the dispersion coefficient of the fibres reaches a turning point at 74.5 %, where the viscosity of the fresh mixture is within the appropriate range. From Table 5 and Figure 5, it can be concluded that the tensile ductility of the specimens is positively correlated with the fibre dispersion coefficient in the cross-section. The higher the fibre dispersion coefficient of the specimen, the higher its tensile ductility. Figure 8 is a representative scanning electron microscopy image of the cross-sectional area of a specimen, with the black dots indicating the PE fibres and the grey areas indicating the matrix. In the areas where the black dots tend to cluster, there may be a tendency towards fibre agglomeration, which can negatively impact the performance. Additionally, the cross-section of holes in the test piece can be observed in the image. Under stress, a specimen generally cracks first from the holes, then the matrix, and finally, the fibres bridge the gap to resist the crack tendency. Hence, an even distribution of fibres is helpful in achieving better composite material performance.

Table 5. Fibre dispersion coefficient of the HSECC specimens.

Item	Ref	D1	D2	D3	D4	D5
Dispersion coefficient (%)	73.0	65.1	73.4	73.8	74.5	73.0

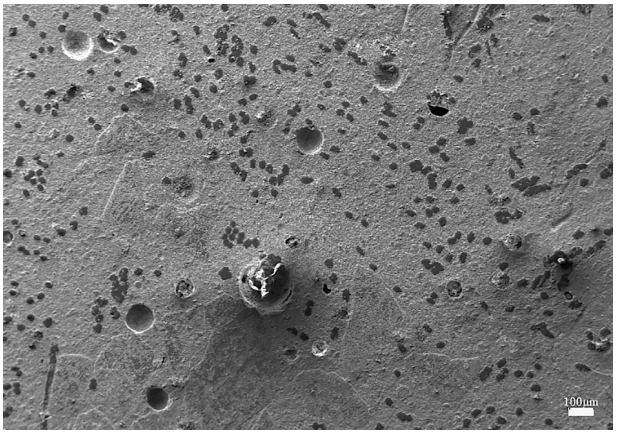

Figure 8. The microstructure of the cross-section of the specimen.

CONCLUSIONS

In this study, new HSECCs were developed by adding a small amount of a defoaming agent and a superplasticiser and the influence of the dosage of the superplasticiser on the mechanical properties of the HSECC was investigated. The following conclusions are drawn:

- An HSECC with excellent compressive strength, flexural strength, and flexural strength is obtained in the D1 group by adding 0.1 wt. % defoamer and 0.20 wt. % superplasticiser. According to the results, the compressive strength reaches about 100 MPa, and the flexural strength is as high as 39 MPa.
- With the increase in the dosage of the superplasticiser, the compressive strength, flexural strength, toughness index, and residual strength of the HSECC decrease, but the tensile ductility of HSECC could be improved within a certain range.
- The fibre dispersion degree in the D4 group specimens with 0.35 wt. % of superplasticiser is the highest, resulting in a significant strain hardening phenomena in the load-deflection curve and stress-strain curve. The highest tensile ductility is 9.5 %.

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