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Original scientific paper

Effect of Different Water-Binder Ratios and Fiber Contents on the Fluidity and Mechanical Properties of PVA-ECC Materials

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Abstract: With the development of fiber-reinforced cement composites, the diversity and complexity of application scenarios require enhanced strength and ductility and tough materials in practical engineering. To explore the effects of different water-binder ratios and fiber contents on the fluidity, bending resistance, tensile properties, fracture toughness, and fracture behavior of polyvinyl alcohol (PVA) fiber cement composites, several groups of high ductility test blocks (PVA-engineering cementitious composites (ECC)) with different mixing ratios were designed in this study. Based on the expansion degree, the mechanical experimental data, and the electron microscopy scanning image results, *K*-value analysis was performed on the strain hardening strength criterion. The effect of the water–binder ratio and the fiber dosing on the PVA-ECC material was determined. Results show that the greater the water-binder ratio is, the better the fluidity of the ECC matrix is. In the same cement system and at the same water-binder ratio, the fluidity of the ECC paste gradually deteriorates with the increase of the fiber content. The water-binder ratio significantly affects the flexural tensile strength of the composite. The flexural and tensile strengths of the PVA-ECC gradually increase as the water-binder ratio decreases, but the ductility gradually decreases. The water-binder ratio of the substrate directly influences the damage behavior of the fibers within the substrate. With the gradual increase of the water-binder ratio, the fiber at the crack interface gradually changes from pull-out morphology to fracture morphology. The strain capacity and the multi-crack cracking performance decrease. To achieve improved working performance in the actual project, the matrix water-binder ratio should be controlled at approximately 0.45, and the PVA fiber dose of 1.7% is optimal. This study can provide a good reference for the optimization of practical engineering components.

Keywords: fiber reinforced cement-based composites; fluidity; mechanical properties; PVA-ECC

1 INTRODUCTION

In recent years, nearly 90% of the major defects in bridges can be traced to the cracks caused by problems such as insufficient material toughness. When the cement matrix of a bridge has cracks of different degrees, the reinforcement will be exposed to air and gradually corroded. The expansion of cracks will further reduce the stiffness and bearing capacity of the members. To improve the performance of cement-based materials, Yang [1] proposed the concept of engineering cementitious composites (ECC) on the basis of "fiber bridging" theory, combining the initial and steady-state cracking criteria. Yang [2] developed polyvinyl alcohol (PVA) fiber reinforced ECC (PVA-ECC) materials. These materials exhibit steady-state cracking and multi-cracking patterns during deformation, increasing the ductility of the member and enhancing the safety, durability, and sustainability of the structure.

ECC materials have been developed on a large scale for building components. The diversity and complexity of their application scenarios require the materials to have high strength, ductility, and toughness. On this basis, scholars have carried out many studies on ECC materials [3]. Different single or mixed fibers have been added, and basic mechanical tests have been performed to obtain the fiber types and content ranges that can strengthen the test piece. In addition, there is an analysis of the different forms of rupture mechanisms [4], as well as a study of the fiber damage process [5]. The current research has made some progress. However, no standard exists for the study of different fiber types and doping levels. The experimental database still needs improvement. Furthermore, few simplified formulas can be used to calculate the fracture toughness parameters in PVA-ECC materials. Further research on the effect of PVA fibers on the mechanical properties of materials is necessary.

Therefore, this study uses mechanical tests and scanning electron microscopy observations for the experiments. Two variables, namely, the water-binder ratio of the base material and the volume of the fiber, are set to explore their influence on the strength and ductility of the material and calculate the *K*-value. Finally, the internal mechanism of the influence law is determined to provide a basis for the optimization and test of engineering components.

2 STATE OF THE ART

ECC materials have been developed for nearly 30 years. Scholars have conducted many studies on ECC materials and fiber-reinforced cement materials. Their research results mainly indicate that adding the appropriate number of different fibers to the composite could have a certain gain effect. The research direction was based on the fiber-matrix interface, the basic mechanical properties, curve modeling, and other aspects. The interfacial interaction between fibers and the matrix is one of the key factors in the design of highly ductile materials [6-7]. Kanda T. [8] proposed that interfacial action is related to the water-binder ratio, but detailed research analysis on the law of interfacial properties and the size of the water-binder ratio is lacking. Kwon, S. [9] developed new ultra-high performance hybrid fiber-reinforced cement materials, but the study of the microstructure was not reported. George, M. [10] explored the effect of different types of fiber addition on the strength of ECCs. Alsaif, A. [11] mixed two recycled fibers to find the optimum doping of RTSF and RPF to enhance the flexural properties and ductility of cementitious composites, but the analysis of the microscopic interfacial properties was not exhaustive. Zong, X. [12] pointed out the high significance of the effect of steel fibers on the compressive and splitting tensile strength of concrete. Chen, C. [13] found that adding an appropriate amount of basalt fiber, PVA fiber, and micronized slag powder can effectively improve the mechanical properties of concrete. The above studies mostly focused on the basic mechanical properties of the different fibers incorporated into cementitious materials, but the strain hardening law of the composites still needs further study. Zhou, H. [14] found that the appropriate amount of BF admixture is beneficial to improving the mechanical properties of concrete and established the toughness index and the fracture energy relationship equation, but the requirements of flowability that should be satisfied in practical engineering were not reflected. Zhang, Q. [15] added short alkali resistant glass fibers into the TRC matrix to form a fiber network to enhance the ECC, improving the shortcomings of the matrix, such as easy cracking and poor toughness. Li, T. [16] and Dong, Z. [17] added short fibers to the concrete matrix to improve the crack resistance of the TRC and enhance the restraint effect, but the study of the micromechanism of the reinforcement is not comprehensive enough. Abousnina [18] found the best concrete toughness index at 2% fiber volume admixture, while the generalizability of the equation used in the experiment needs to be further verified. Yan, W. [19] studied stress-strain models and analyzed the equations of stress-strain curves for two types of hybrid fiber-cement matrix composites, steel-polypropylene and PVA-polypropylene, but there was a lack of simplified formulas for studying strain hardening. Li, V. C. [20] reported an ECC reinforced with 2% UHMWPE fiber with a tensile strain capacity of 6-8%.

The performance of fiber cement-based materials is influenced by several factors. Different properties of fibers with different strengths of cementitious materials lead to a wide variation in the strength of fiber-reinforced composites. Despite the maturity of existing experimental and theoretical studies, the database can still be studied further. For example, a unified conclusion has not been drawn from the amount of PVA, the water-binder ratio, and the relationship between the microstructure of the PVA fiber-cement interface. Further studies are needed to investigate the relationship between the fiber and cementitious material matrix interfaces.

This study focuses on the influence of different fiber admixtures, cement types, and water-binder ratios on the mechanical properties of ECCs. The focus is on the effect of the water-binder ratio on the toughening, strengthening, and ducting effects of fibers. The strain-hardening strength condition is calculated, and attention is given to the fiber behavior when the material with a different water-binder ratio is damaged. The aim is to find the precise relationship between the two and the PVA-ECC material and then provide a reference for the design optimization of engineering components.

3 EXPERIMENTS

3.1 Materials

Ordinary Portland cement (OPC, 42.5 grade) and sulphoaluminate cement (SAC) are used. Portland cement has developed into a large area of building materials in various fields due to its reliable performance and low price. Sulphoaluminate cement should be widely used in rush repair projects due to its rapid early hydration. The auxiliary cementitious materials are Grade I fly ash and Grade S95 mineral powder (produced by Beijing Aviation Mineral Products Supplier). Quartz sand is the refined quartz sand produced by the Qinhuangdao Harbor Quartz Sand Factory, with a particle size of 100-200 mesh. The water reducing agent is polycarboxylic acid. The test materials are shown in Fig. 1, and the chemical components are listed in Tab. 1. The physical properties of cement are listed in Tab. 2. The relevant parameters of polyvinyl alcohol fiber are listed in Tab. 3.

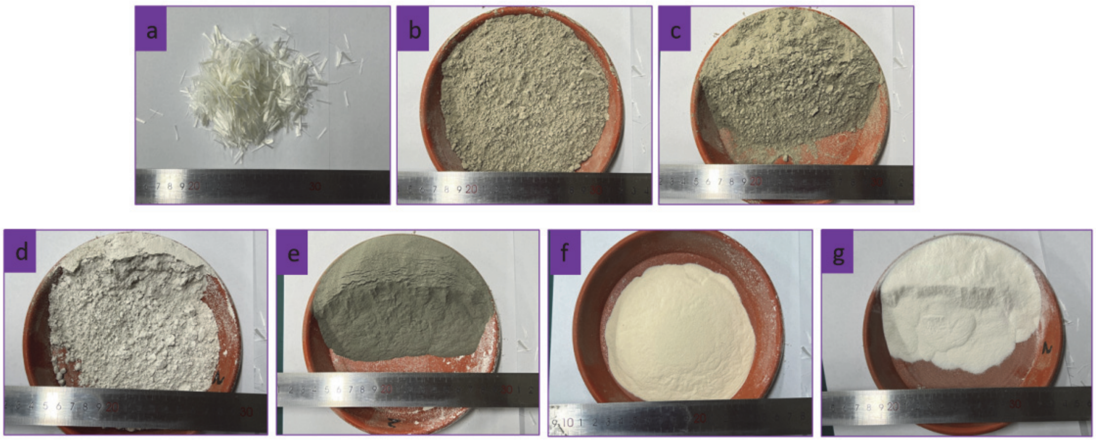

Figure 1 Raw materials for ECC base materials (a) polyvinyl alcohol fiber; (b) ordinary portland cement; (c) fast curing sulphoaluminate cement; (d) s95 grade mineral powder; (e) first grade fly ash; (f) quartz sand; (g) polycarboxylic acid water reducer

Table 1 Chemical composition of ECC dry matter (percent by mass)

Type	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	SO_3
Ordinary Portland Cement (OPC)	60.01	22.67	8.21	4.07	1.07	0.52	0.15	1.14
Sulphoaluminate Cement (SAC)	43.91	5.18	23.14	2.04	1.66	0.38	0.08	11.71
Fly ash (FA)	5.28	45.32	33.16	3.46	1.24	1.20	1.28	0.79
Slag (SG)	36.70	40.83	12.71	1.32	4.85	0.36	0.22	0.68

Table 2 Physical properties of cement

Cement type	Compressive strength / MPa		Flexural strength / MPa		Initial setting time / min	Final setting time / min
	3d	28d	3d	28d		
Sulphoaluminate Cement (SAC)	42.5	45.0	6.5	7.0	25	180
Ordinary Portland Cement (OPC)	25.2	51.9	5.2	7.4	160	220

Table 3 Relevant performance parameters of polyvinyl alcohol fiber

Fiber type	Density / g/cm^3	Tensile strength / MPa	Elastic modulus / GPa	Diameter / mm	Length / mm
Polyvinyl alcohol	1.2	1640	41.8	0.038	12

3.2 Test Method and Material Preparation

Fluidity test: refer to the method specified in Determination of Cement Mortar Fluidity (GB/T 2419-2005). Mechanical property test: refer to the Test Method for Cement Mortar Strength (ISO Method) (GB/T17671-1999). The specimens were maintained indoors for 7 days and then tested for all mechanical properties. The mass ratio of mineral powder to fly ash is 1:1. The water-binder ratio is adjusted to obtain four different substrates, which are referred to as W/B 0.25, W/B 0.35, W/B 0.45, and W/B 0.55. W/B refers to the water-binder ratio, and the number part represents the specific value of the water-binder ratio. Three PVA fiber volume additions (1.5%, 1.7%, 2.0%) were set to blend into four different substrates (i.e., W/B of 0.25, 0.35, 0.45, and 0.55).

A critical value exists for the influence of the fiber content on the fluidity of the newly mixed slurry. When the fiber content exceeds the critical value, the PVA-ECC slurry stops flowing. To ensure fluidity, water reducing agent should be added. The fluidity is poor at low water-binder ratios. The range of expansion is tested with W/B0.25. Fig. 2 shows the effect of adding a water reducing agent on the law of the expansion degree under different amounts.

Table 4 Additions of substances in different groups

Number	Water binder ratio	Fiber content	Addition amount of water reducing agent
OPC-W/B0.25-1.5%	0.25	1.5%	6‰
OPC-W/B0.25-1.7%		1.7%	6‰
OPC-W/B0.25-2.0%		2.0%	6.5‰
OPC-W/B0.35-1.5%	0.35	1.5%	5‰
OPC-W/B0.35-1.7%		1.7%	5‰
OPC-W/B0.35-2.0%		2.0%	5‰
OPC-W/B0.45-1.5%	0.45	1.5%	0‰
OPC-W/B0.45-1.7%		1.7%	0‰
OPC-W/B0.45-2.0%		2.0%	0‰
OPC-W/B0.55-1.5%	0.55	1.5%	0‰
OPC-W/B0.55-1.7%		1.7%	0‰
OPC-W/B0.55-2.0%		2.0%	0‰
SAC-W/B0.25-1.5%	0.25	1.5%	3‰
SAC-W/B0.25-1.7%		1.7%	3‰
SAC-W/B0.25-2.0%		2.0%	3‰
SAC-W/B0.35-1.5%	0.35	1.5%	0.4‰
SAC-W/B0.35-1.7%		1.7%	0.4‰
SAC-W/B0.35-2.0%		2.0%	0.4‰
SAC-W/B0.45-1.5%	0.45	1.5%	0‰
SAC-W/B0.45-1.7%		1.7%	0‰
SAC-W/B0.45-2.0%		2.0%	0‰
SAC-W/B0.55-1.5%	0.55	1.5%	0‰
SAC-W/B0.55-1.7%		1.7%	0‰
SAC-W/B0.55-2.0%		2.0%	0‰

Note: OPC refers to the common acid salt cement system, SAC refers to the sulphoaluminate cement system, and the number after W/B refers to the specific value of the water-binder ratio. Each group number corresponds to three different fiber content.

In Fig. 2, the fluidity decreases with the increase of the fiber content. When the fiber content is fixed, the fluidity strengthens with the increase of the water reducer. When the fiber content is 1.5%, 0.2% water-reducing agent is added, and when the fiber content is 2.0%, 0.25% water-reducing agent is added; the fluidity of the slurry will reach saturation. This finding can provide a reference for the amount of water reducer to add.

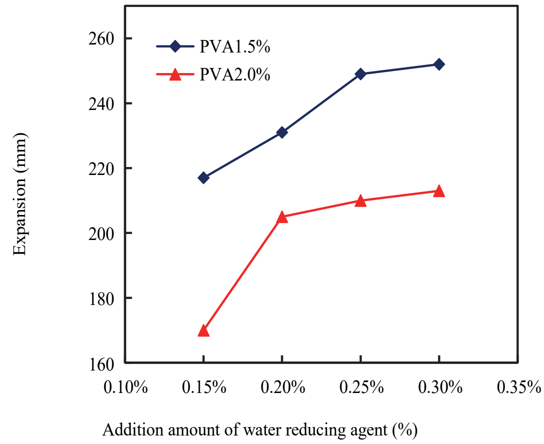

Figure 2 Substrate flowability with low water-binder ratio (0.25)

The results in Fig. 2 indicate that the numbers of substances added in the different groups were developed as shown in Tab. 4.

4 RESULTS ANALYSIS AND DISCUSSION

4.1 Liquidity Analysis

The expansion degree of paste with different fiber content under different water-binder ratio is shown in Fig. 3.

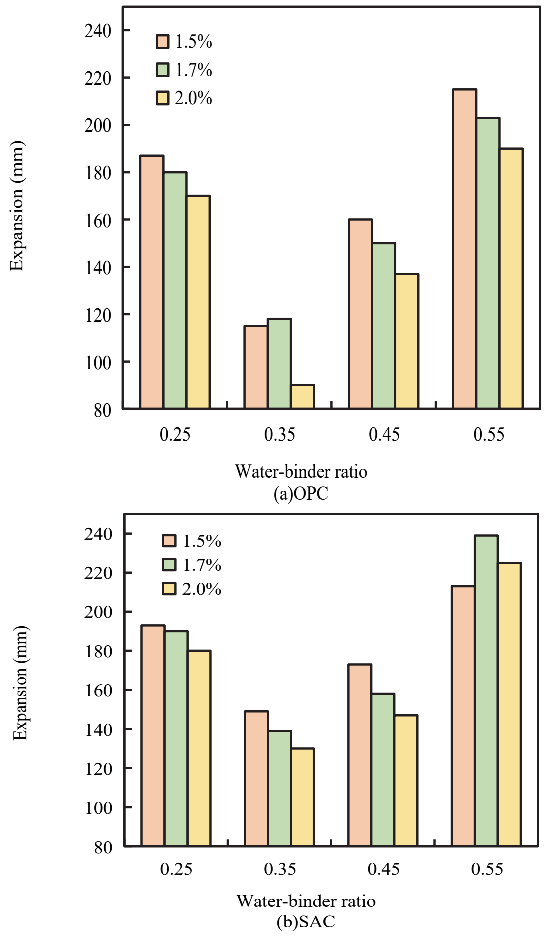

Figure 3 Variation curve of fresh paste expansion with the water-cement ratio under different fiber content (a) OPC; (b) SAC

According to Fig. 3, the expansions of OPC-W/B0.35-1.5%, OPC-W/B0.45-1.5% and OPC-W/B0.55-1.5% are 137 mm, 162 mm and 214 mm respectively. Expansions of SAC-W/B0.35-1.5%, SAC-W/B0.45-1.5% and SAC-W/B0.55-1.5% are 149 mm, 172 mm and 221 mm. The greater the water-binder ratio, the better the fluidity of the ECC matrix. When the fiber content is 1.5%, the range of change in elongation is the largest. The expansion of OPC-W/B0.45-1.5% and OPC-W/B0.55-1.5% is 18.2% and 15.4% higher than that of OPC-W/B0.35-1.5%. OPC-W/B0.45-1.5%, OPC-W/B0.55-1.5% and SAC-W/B0.45-1.5%, and SAC-W/B0.55-1.5% can make the fluidity of the slurry reach more than 130 mm without adding a proper amount of water reducing agent. It shows that ECC matrix with large water-binder ratio is easier to meet the requirements of construction workability.

At the same water-binder ratio, the expansion of the ECC paste will gradually decrease with the increase of the fiber content. In the case of SAC-W/B0.45, V1.7% and V2.0% are 8.67% and 15.03% less expensive than V1.5%. For OPC-W/B0.45, V1.7% and V2.0% are 6.25% and 14.38% less expensive than V1.5%. PVA fiber has a carboxyl group and thus has strong hydrophilicity. The larger the amount of PVA is, the freer water will be absorbed. The surface of the solid particles in the slurry is not wet with enough free water. The friction between particles increases.

4.2 Flexural Properties of Cement Fiber Reinforced Materials

The rule between the crack morphology of the PVA fiber ECC and the water-binder ratio of the matrix is shown in Fig. 4. The surface of the PVA-ECC has produced multiple cracks in varying degrees at a1-a3 (W/B0.55) and b1-b3 (W/B0.45), the width of the cracks is larger, and many fine cracks can be observed next to the main crack with high ductility. A significant reduction in crack width can be observed at d1-d3 (W/B0.25) and c1-c3 (W/B0.35), with few cracks, inconspicuous multi-joint cracking, and weak ductility. The greater the water-binder ratio is, the greater the number of cracks is.

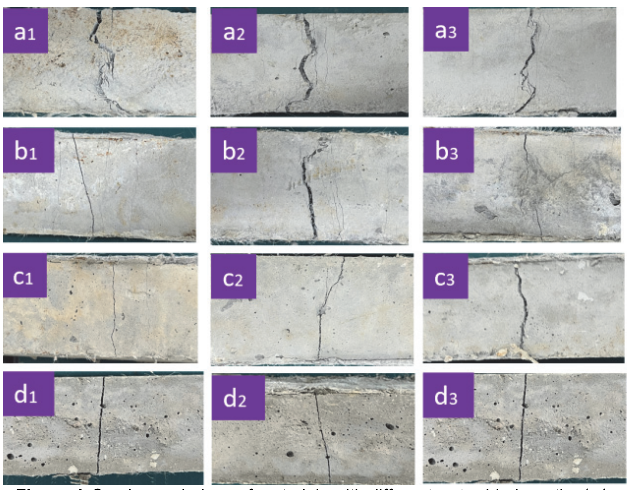

Figure 4 Crack morphology of materials with different water-binder ratio: (a1-a3) W/B0.55 (b1-b3) W/B0.45 (c1-c3) W/B0.35 (d1-d3) W/B0.25

Fig. 5 shows a typical tensile stress-displacement curve for a strain-hardened composite [21]. The vertical coordinate σ / MPa is the stress and the horizontal coordinate δ / mm is the displacement corresponding to the stress.

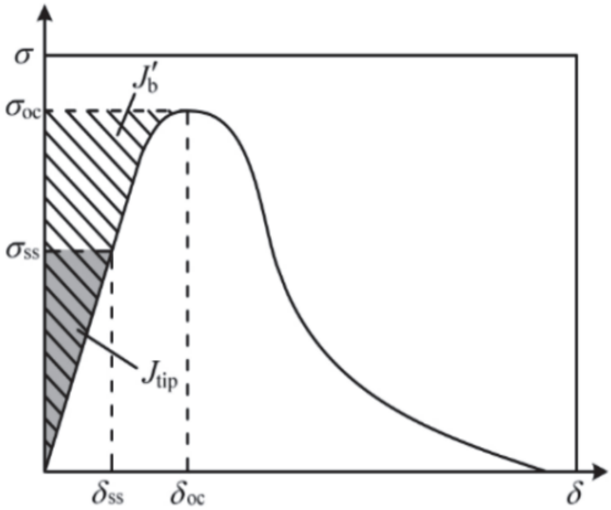

Figure 5 Typical tensile stress-strain curves of strain-hardening composites

In the design theory of ECC, the strength criterion under the stress-strain curve must be satisfied to achieve A multi-slit cracking strain-hardening behavior [22].

Strength criterion formula:

$$\sigma_{oc} > \sigma_{cr} \tag{1}$$

where σ_{oc} is the maximum stress in the material, σ_{cr} is the initial crack strength of the material.

The mechanism of the strength criterion is that when the matrix produces fracture cracks, the fiber does not break and can continue to bear the load. Meanwhile, the stress is transmitted to the surrounding matrix, so the surrounding matrix continues to crack and generate new cracks. Therefore, matrix cracking strength σ_{cr} should be less than the maximum bridging stress of fiber σ_{oc}. The larger the gap between the two is, the easier stable multi-crack development is. A new parameter K is defined as follows:

$$K = \frac{\sigma_{oc}}{\sigma_{cr}} \tag{2}$$

Damage with multiple crack development is likely to occur when the value of K is greater than 1.2. The value is different for different fibers. For fibers with low strength and poor interfacial bonding, large K values should be obtained. For example, PVA fibers should generally have a K value greater than 1.45 [23] because such fibers are prone to fracture and have low probability of producing stable strain hardening.

The corresponding data is extracted from the curve and brought into the equation to solve for it. From the actual measured data, ECC materials with different flexural strengths can be obtained by adjusting the water-binder ratio. The K value for each fit ratio is calculated, and the results are shown in Fig. 6. The horizontal axis is the magnitude of the water to glue ratio, and the vertical axis is the magnitude of the calculated K value.

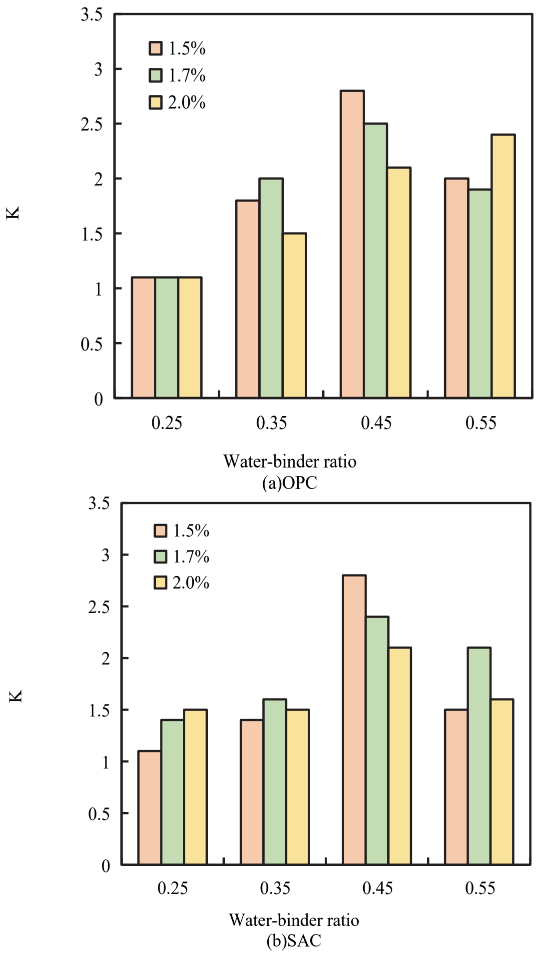

Figure 6 *K*-value bar chart (a) OPC; (b) SAC

OPC-W/B 0.25-1.5%, OPC-W/B 0.25-1.7%, OPC-W/B 0.25-2.0%, all with K values below 1.45. The lower water-binder ratio OPC material does not have strain hardening properties. SAC-W/B 0.25-1.5%, SAC-W/B 0.25-1.7% and SAC-W/B 0.35-1.5%, when *K* values are below 1.45. SAC composites with lower water-binder ratio and fiber dose do not have strain hardening properties. The data indicate that by increasing the fiber doping, strain-hardening conditions can be set for the substrate, thus increasing the material toughness. As the water-binder ratio increases, the *K* value continuously increases. The *K* value reaches the maximum value when the water-binder ratio is 0.45. The highest degree of multi-joint cracking is found in ECCs at this water-binder ratio. In comprehensive consideration, the ECC material has the best water-binder ratio of 0.45, and the optimal fiber content is approximately 1.7%.

4.3 Tensile Properties of Fiber Reinforced Cement-Based Materials

With the gradual increase of the water-binder ratio, the cracking pattern of the compound material changes from a main crack in the main body to a small number of micro-cracks and finally the formation of multi-slit cracking. The fracture section is shown in Fig. 7 (i.e., W/B0.55 crack morphology). In addition to one main crack, many small cracks can be observed, resulting in the high ductility of the composite. W/B0.45 cracks are main cracks, with few microcracks, and the ductility is lower than that of the W/B0.55 series. The W/B0.25 crack is a main crack, without multiple cracks, indicating brittle failure.

Figure 7 Crack morphology of specimen in a direct tension test

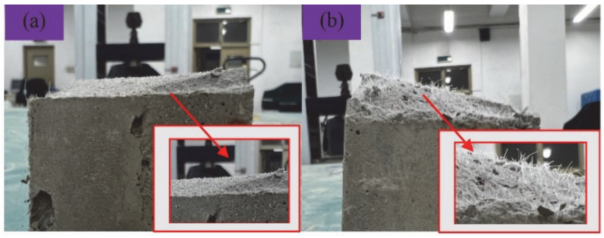

Figure 8 Fiber morphology of the section of the straight drawn sample: (a) W/B0.25; (b) W/B0.55

In Fig. 8, the fiber of section W/B0.25 shows fracture failure, and the fiber of section W/B0.55 shows pull-out failure. The low water-binder ratio makes the friction bond strength of the PVA fiber and the matrix far greater than the apparent tensile strength of the PVA fiber itself. When the load reaches the cracking strength of the base material, the fibers in the matrix cannot continue to bear the load transferred to directly fracture. When the water-binder ratio is large, the fiber and the matrix have an appropriate friction bonding strength. The fiber can play a bridging role, causing multiple cracks in the base material and greatly improving the tensile strain of the ECC. On the basis of the results of the axial tension test, the average value of each data is calculated. The tensile strength under different water-binder ratios is compared as shown in Fig. 9.

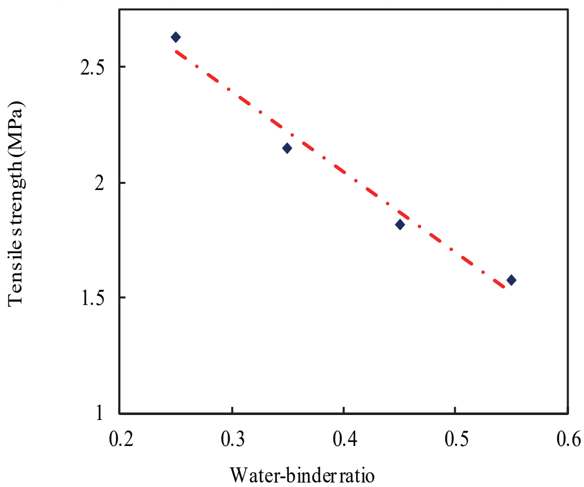

Figure 9 Tensile strength - Water-binder ratio change diagram

When the fiber content is fixed, the tensile strength of the composite is negatively related to the water–binder ratio. The tensile strength of W/B0.55 at the age of 5 days is 1.58 MPa, and those of W/B0.45, W/B0.35, and W/B0.25 respectively reach 1.82, 2.15, and 2.63 MPa, indicating an increase of 15.2%, 36.1%, and 66.5% compared with that of W/B0.55.

4.4 SEM Observation of Damage Morphology

Samples were taken from the base material of each water-binder ratio. The micro-enhancement mechanism was analyzed by taking electron microscope photos.

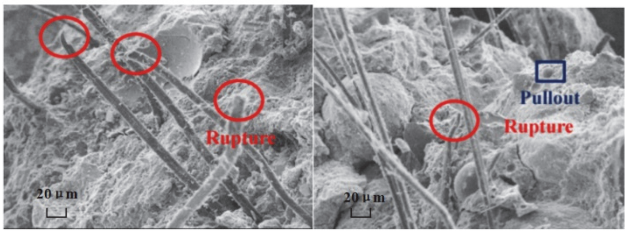

Figure 10 Fiber failure behavior of crack section

In Fig. 10, the fibers on the crack interface of the samples with various water-binder ratios are mainly in pull-out and fracture forms. Some fiber bundles are unopened. This phenomenon explains why the mechanical properties of the material do not change much as the large fiber content continues to increase. In W/B0.55, W/B0.45, and W/B0.35, the PVA fibers with different proportions exhibited pull-out failure. The larger the water-cement ratio is, the longer the fiber pull-out length is. Most of the W/B0.25 interfacial fibers show a fracture morphology.

Different failure behaviors of PVA fibers lead to different mechanical properties of ECC composites. When the water-binder ratio is small and the substrate is undamaged, the fiber will break. The reinforcement and toughening of the fiber cannot be displayed, and the fiber shows fracture. When the water-binder ratio is large, the friction bond strength between the fiber and the matrix is less than the apparent tensile strength of the fiber itself. The substrate cracks first during loading. After the load is transferred to the fiber, the fiber continues to slide under the force until the fiber is pulled out. The fiber gives full play to its bridging role in the matrix to prevent the formation of new cracks and the propagation of the original microcracks in the matrix.

The water-binder ratio, the apparent strength of the fiber, and the friction and adhesion strength of the fiber and the substrate are the main factors that affect the failure morphology of the fiber. In practical engineering, the law between the strength of the substrate and the fiber should be considered to optimize the engineering components.

5 CONCLUSIONS

The effect of the water-cement ratio and fiber doping on the flow and mechanical properties of PVA-ECC materials was investigated, and the relationship between the substrate strength and the fiber damage morphology is revealed. Starting from composite material proportioning, a combination of mechanical and microscopic tests was used. Two different cement systems with different water-binder ratios and fiber admixtures were analyzed.

(1) When the water-binder ratio is not less than 0.45, the workability of the fresh paste is good, and additives are unnecessary to adjust the fluidity of the matrix to meet the construction workability requirements.

(2) The water-binder ratio will significantly affect the mechanical properties of the material. With the decrease of the water-binder ratio, the bending and tensile strength of ECC will gradually increase, but the ductility of ECC will gradually decrease. Meanwhile, the water-binder ratio also directly affects the damage behavior of the fibers in the matrix. With the decrease of the water-binder ratio, the fiber at the crack interface gradually changes from pull-out morphology to fracture morphology, and the strain capacity and the multi-crack cracking performance decrease.

(3) By increasing the water-binder ratio and the number of fibers, the substrate can be strain-hardened, thus increasing the toughness of the material. The best toughness is achieved when W/B is 0.45. In the actual project, considering the strength and performance of the specimen, 0.45 is the suggested water-binder ratio of the ECC material, and the optimal fiber content is approximately 1.7%.

This study combined indoor experiments with theoretical research and proposes the optimal water-binder ratio and optimal fiber doping of PVA fiber-reinforced ECCs. This proposal has practical significance for the application of ECC materials. Given the lack of actual engineering field performance test data, a better understanding of the mechanism of PVA-ECCs will be achieved in future studies by combining actual application data with the contents of this study and supplementing the conclusions.

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