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ECC Mechanical Properties of Reinforced Ultra-high Toughness Cement-based Composites

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Keywords: PVA-ECC Material, Ultra-high Toughness Cement-based Composites, Fly Ash Content, PVA Fiber Content

Abstract: traditional concrete materials are brittle and easy to crack, which is difficult to meet the requirements of crack and leakage prevention of urban rail transit. The ultra-high toughness and excellent crack control ability of PVA fiber reinforced cement-based composite (PVA-ECC) are two orders of magnitude higher than that of concrete. So, supplanting conventional cement with PVA-ECC can extraordinarily work on the solidness of present day substantial design, it can further develop its administration life and lessen the upkeep cost in the help stage. In this paper, the full scale mechanical properties of PVA-ECC were examined by direct malleable test, compressive test and meager plate four point twisting test. This paper extensively investigates the impacts of fly ash content, sand cover proportion, water folio proportion and PVA fiber content on the mechanical properties of PVA-ECC. In this paper, PVA-ECC with various mechanical properties can be acquired by changing various boundaries as per the real designing necessities, and they meet the bridge deck structure for compressive performance, flexural performance and tensile performance. It has good engineering practical application significance. The experimental results show that when the content of PVA fiber reaches 1.5%, when it reaches the tensile strength is relatively low, the secant modulus of PVA-ECC is 101.54mpa, indicating that PVA-ECC with the content of 1.5% PVA fiber has better toughness.

1. Introduction

Engineering fiber reinforced cement-based composites (ECC) have a high level of ductility and toughness, which can effectively resist and withstand various forms of cracking or failure. Its inherent self-healing performance does not sacrifice the internal strength of the crack, which greatly improves the durability of the structure. Looking at the future development direction of green and intelligent construction industry, ECC has broad application prospects. As a kind of fiber reinforced concrete, UHTCC is characterized by strain hardening. Therefore, the test that can best show the characteristics of UHTCC in direct tensile test. In recent years, China's research on PVA-ECC has made continuous progress, which has gradually improved PVA-ECC and finally reached the level of UHTCC.

Based on macro control and micro adjustment, the ultra-high toughness of ECC can show great deformation ability. It has unique strain hardening characteristics and multi crack development characteristics, which can significantly improve the flexural tensile, seismic and fracture resistance of engineering structures. It is often called "bendable concrete". ECC also has good energy absorption capacity, which can be used in structures and components to obtain high seismic and shear performance. Most of areas in China are located in high intensity earthquake areas. The research on new and effective seismic materials and seismic fortification of foundation projects is still a more important topic. ECC has the similar strain hardening ability and crack control ability as metal, which is promising to set off a new wave in the construction industry. ECC makes full use of local resources and industrial waste to add fly ash into the substrate as cementitious material. It not only reduces the amount of cement, but also slightly alleviates the problem of difficult treatment of industrial waste residue, and pays attention to the economic and environmental benefits of secondary utilization. Its concept of "green concrete" conforms to the contemporary theme of protecting ecology and pursuing environmental protection. It belongs to high-performance ecological building materials. When it is used in practical engineering, it can greatly improve the seismic performance of structures or components and prolong the service life of buildings. While its safety and durability are guaranteed, it also practices the sustainable development strategy.

The innovation of this paper is to study the ECC mechanical properties of reinforced ultra-high toughness cement-based composites, which is innovative and practical.

2. Related Work

As a new type of high-performance building material, ultra-high toughness cement-based composite can overcome the shortcomings of poor toughness and difficult to control crack width of concrete. More and more scholars have studied it. Turk K studied the coupling effect, it used limestone powder as part or all substitute of silica sand aggregate in ECC and it used large volume fly ash as binder[1]. The purpose of Fang y research was to improve the mechanical properties of ceramics by adding Y-stabilized ZrO whiskers through flux method and hot pressing technology[2]. Han Y's focused on the potential use of industrial solid waste (ISW). It includes silica fume (SF), fly ash (FA) and ground blast furnace slag (GGBFS), as well as low-cost PVA fibers produced by local synthetic fiber plants [3]. Zhang Z made a multi-scale systematic study on the mechanical properties of two engineering cement-based composites (ECC) with different fly ash content after sub high temperature exposure [4]. Sherir Ma introduced the properties of Engineering cement-based composites (ECCS) using magnesium oxide as expansion self-healing agent to repair microcracks. ECCs can maintain small crack widths of less than 60 m even under ultimate loads, which can stimulate spontaneous healing of cracks and thus improve the mechanical properties of structural elements[5]. Kan l introduced the test results of the influence of Fly Ash Fineness and calcium content on the mechanical properties of ECC[6]. Nematollahi B's study reported the thermal and mechanical properties of sustainable lightweight engineering Geopolymer Composites (EGC) that exhibit strain hardening behavior under uniaxial tension [7]. However, the deficiency of these studies is that the experimental data are not complete, and the existing equipment is difficult to support their research findings.

3. ECC Mechanical Properties of Ultra-high Toughness Cement-based Composites

3.1. Progress of Ultra-high Toughness Cement-based Composites

(1) Overview of material development

In 1992, scholars put forward the theory of steady-state cracking and multi crack cracking of short fiber reinforced cement-based composites, and then developed the corresponding materials and named them "engineered cementitious composite" (abbreviated as ECC). ECC has successfully solved three major problems of ordinary fiber concrete, that is, ECC only uses no more than 2.5% fiber content, the crack of PVA-ECC is basically controlled within 100 microns, and the manufacturing process is simple. These excellent properties make it a hot research topic in the field of building materials [8]. After nearly 30 years of development, ECC has a large number of research results. At present, whether the ultimate tensile strain exceeds 3% is used to distinguish the advantages and disadvantages of ECC. Among them, ECC with ultimate tensile strain exceeding 3% is excellent ECC, which is called "strategic hardening cementitious composite" (SHCC) in Europe and North Africa, "dual fiber reinforced cementitious composites" (dfrcc) in Japan, and "ultra high toughness cementitious composite" (UHTCC) in China.

(2) Factors affecting the compressive properties of ultra-high toughness cement-based composites

There are many elements that influence the compressive properties of super high strength concrete based composites, for example, fiber content, fiber length breadth proportion, water cover proportion, fly debris content, age, temperature, stickiness and others. A few variables are momentarily presented beneath [9].

1) Fibre

Based on the theory of fiber reinforced concrete, fiber toughens the matrix through its bridges stress on the matrix. This force can be used to balance the transverse tensile stress formed by Poisson effect when the matrix is compressed, which correspondingly enhances the compressive strength and strain hardening ability of ECC materials. Fiber strength and fiber versatile modulus are straightforwardly connected with the kind of fiber. The material properties of Japanese PVA fiber are awesome. Concerning the issue of fiber surface harshness, PVA fiber has solid synthetic holding with the grid, which is easy to cause the matrix to scrape the fiber. Fly ash is generally used to solve this problem. Therefore, at present, the more popular research is the influence of fiber length, fiber diameter and fiber content on ECC materials [10].

2) Fly ash

Fly ash material is one of pozzolanic materials. It also plays a very important role in PVA-ECC. Optimization effect of fly ash on compressive ductility of ECC materials. The greater the content of fly ash, the better the ductility of ECC.

3.2. Properties of Engineering Cement-based Composites (PVA-ECC)

As one of the representative products of high-performance cement-based composites, the theoretical basis of ECC includes micromechanics, fracture mechanics and mathematical statistics. Through the mix proportion design of the matrix, the cracking characteristics are controlled, and the appropriate fiber types are matched to realize the high matching of the matrix, fiber and interface and the optimization of fiber toughening efficiency [11]. PVA-ECC is widely used because of its ultra-high toughness and crack control function. The difference between PVA-ECC and traditional fiber reinforced concrete is that coarse aggregate is abandoned in matrix design, which has the mechanical response of strain hardening under tensile stress. At the same time, the cracking mode changes from unsTable Griffith crack cracking mode to steady-state multi crack development mode.

This makes PVA-ECC have extremely high tensile strain (it can stably reach more than 3%). The design of PVA-ECC can also "tailor" the performance design of the materials according to the personalized needs of the actual structure, which is more flexible. It has incomparable excellent performance than traditional fiber reinforced concrete (FRC). The high toughness of ECC can significantly improve the seismic and impact resistance of the structure as a building material. In addition, the characteristics of dispersed cracks and crack width control ability of ECC under large deformation significantly improve the defects of traditional concrete materials that reduce the structural bearing capacity and anti erosion ability of external harmful substances due to easy cracking. It reduces maintenance costs during structural operation [12]. Material Table 1 compares fiber reinforced cement-based materials with fiber reinforced concrete.

Table 1. Comparison between fiber reinforced concrete and fiber reinforced cement-based materials

Matching number	FRC	General HPFRC	ECC
Design method	conventional method	High fiber volume content	Matrix design and fiber content optimization based on micromechanics and fracture mechanics
fibre	Various fibers with low volume content $\leq 2\%$	Mostly steel fiber, volume content $\geq 5\%$	Polymer synthetic fiber, volume content $\leq 2\%$
matrix	ordinary concrete	Ordinary concrete and high strength concrete	No coarse aggregate, coarse sand, fly ash and other cement-based materials with large mineral content
Interface	uncontrolled	Changing the shape of steel fiber and strengthening the physical bonding of interface	The chemical bond strength of the control interface is moderate
Tensile properties	strain softening	Mostly strain hardening	strain hardening
Tensile strain	0.1%	<1.5%	>3%
crack width	beyond control	Typically hundreds of microns	The steady-state cracking stage is generally $<100\mu m$
construction technology	Self compacting can be realized	It is difficult to achieve self compaction, and high-frequency vibration is usually required	Self compacting can be realized
material cost	Lower	normal	High, limited by the price of high modulus synthetic fiber

(1) PVA-ECC compression performance

Figure 1 shows the compressive stress-strain curves of typical concrete, PVA-ECC and pe-ecc under uniaxial compression load. Table 2 shows the typical ECC mix proportion. The water cement ratio of pe-ecc is significantly lower than that of PVA-ECC, which is the main reason why the elastic modulus and compressive strength of the former are higher than those of the latter [13].

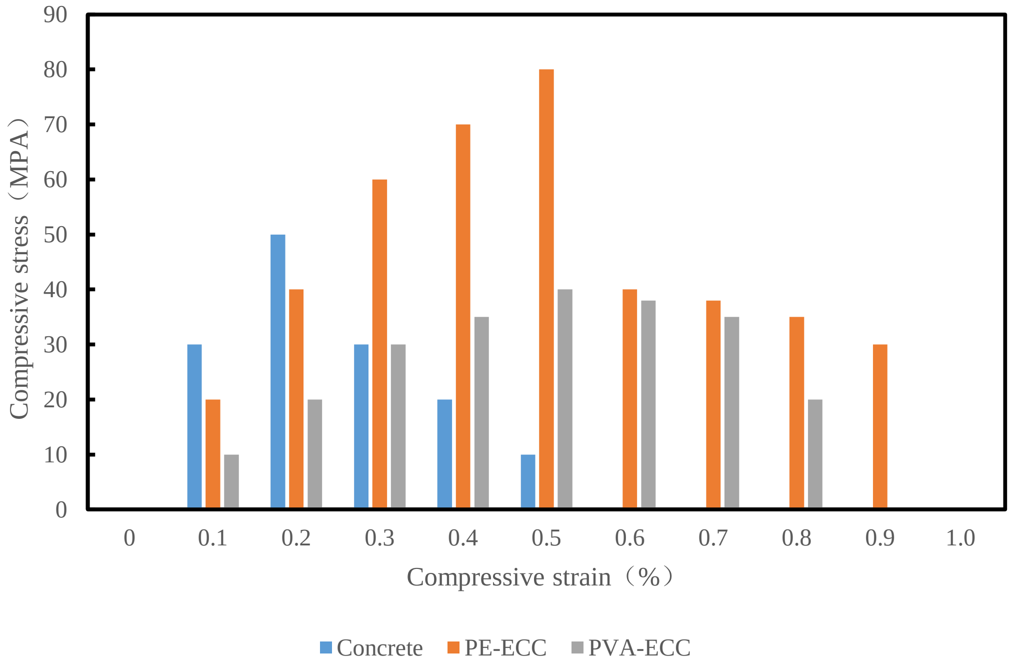
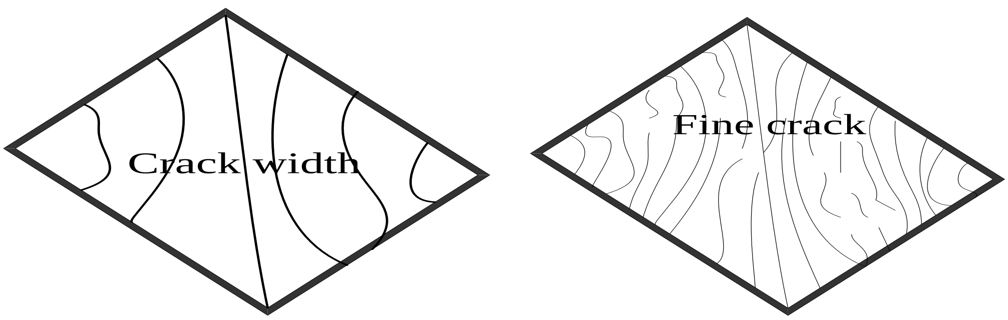


Figure 1. Compressive stress-strain curves of concrete, pe-ecc and PVA-ECC

Table 2. Typical ECC mix

Component	PE-ECC	PVA-ECC
cement	1	1
Fine sand	0.5	1
Fly ash	0	0.11
water	0.27	0.42
Water reducing agent	0.03	0.012
Thickening agent	0.05%	0.048%
Defoamer	0	0.047%
fibre	1.5% by volume	2% by volume

(2) Shear resistance



(a) Conventional concrete (b)PVA-ECC

Figure 2. Comparison of crack modes of concrete and PVA-ECC under in-plane pure shear

The plane pure shear test of PVA-ECC shows that under shear, PVA-ECC slab is different from the typical brittle failure characteristics of ordinary concrete slab in that its cracking process is stable and there will be no sudden drop in stiffness. PVA-ECC plate forms a large number of densely distributed parallel micro cracks under the action of shear. The cracks will not penetrate each other, even if the cracks are located on the same straight line (as shown in Figure 2).

3.3. ECC Quasi Strain Hardening Model and Technical Requirements for Raw Materials

The pressure of the two disappointment methods of brittle failure and quasi brittle failure nearly drops out of nowhere in the wake of arriving at the pinnacle load, or the conditioning segment shows up right away, and the example flops unexpectedly. After the main break shows up, the composites with semi strain solidifying qualities can be connected by strands across the break. It can consistently move the heap to the uncracked part of the network and gradually infer new breaks.

When they failure, the section is full of fine cracks with almost equal distance and width, and the specimen can still maintain good integrity with obvious failure signs, which belongs to ductile failure. In order to improve the high brittleness of cement-based materials and realize high performance and high durability, new fiber-reinforced cement-based composites came into being. ECC falls into this category. Based on micromechanics and fracture mechanics, and the theory of fiber bridging method proposed later, the theoretical support of ECC materials is constantly improving. Starting from the theory, with the help of micromechanical model adjustment and selection of appropriate components and raw material design parameters, fiber-reinforced cement-based composites that meet the expected requirements and functional requirements can be predicted and prepared [14].

(1) ECC quasi strain hardening model

Through the selection of component parameters by micromechanics, ECC achieves the purpose of improving ductility and controlling failure mode, and it has the characteristics of quasi strain hardening and multi crack development. Uniaxial tensile test can directly reflect whether it has the characteristics of quasi strain hardening. Through the area of tensile stress-strain curve, the fracture energy of material can be judged intuitively. Therefore, the quasi strain hardening model can also indirectly explain the reason why ECC has good seismic performance. The design goal of ECC is to improve the fracture energy (i.e. component toughness), and the slip hardening caused by PVA fiber pulling out of the matrix is the main source of ECC energy absorption [15].

(2) Steady state crack criterion

Figure 3 shows the curve of strain hardening characteristic material $\alpha-\delta$. For Cement-based Composites with low fiber content, the critical energy release rate A_{tip} at the crack tip is basically equivalent to the energy consumption A_b in the fiber bridging area, then:

$$A_{tip} = A_b = \alpha_{ss}\delta_{ss} - \int_0^{\delta_{ss}} \alpha(\delta)d\delta \quad (1)$$

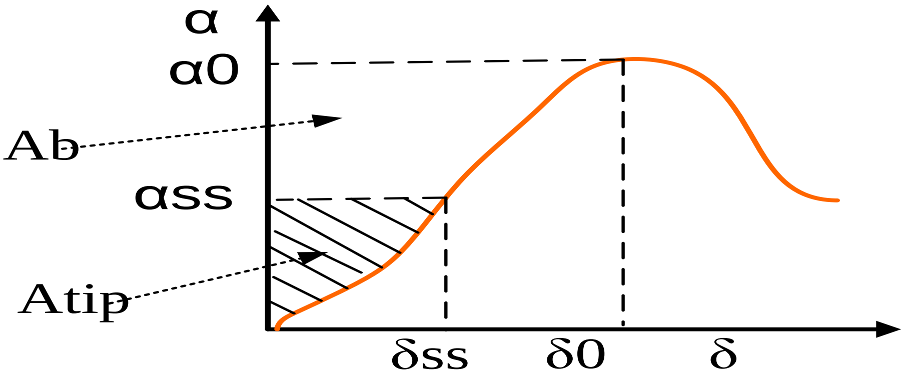


Figure 3. Stress-strain curve of strain hardening material

The shaded part A_b' on the left in the Figure is the curve residual energy. In order to achieve crack cracking in a sTable state, there are

$$\alpha_{ss} \le \alpha_0 \tag{2}$$

When the two are equal, the residual energy reaches the maximum value. At this time, there are:

$$A_b = \alpha_0 \delta_0 - \int_0^{\delta_0} \alpha(\delta) d\delta \ge A_{tip} \tag{3}$$

This formula is usually not satisfied because the A_{tip} at the crack tip is too large or the energy consumption in the rising section of the hardened material curve is insufficient.

(3) Initial crack stress criterion

The initial crack stress criterion requires that the initial tensile stress α_{gc} of the composite material should be less than the maximum bridge joint stress α_0 of the fiber, that is:

$$\alpha_{gc} \le \alpha_0 \tag{4}$$

The significance of this inequality is to avoid the fiber fracture or pullout failure caused by the bridge stress of the fiber unable to resist the excessive tensile stress. At this time, the fiber has not played its bridging role, and the load cannot be transmitted, so new cracks cannot be generated [16].

(4) Function of ECC components and selection principle of raw materials

The mechanical relationship of fiber bridging, that is, the relationship between fiber bridging stress $\alpha(\delta)$ and crack displacement opening δ, is the guarantee of the constitutive relationship and basic mechanical properties of basic materials. It is also the link between material properties and micromechanics, namely:

$$\alpha(\delta) = \alpha_0 \left[2\left(\frac{\delta}{\delta_0}\right)^{\frac{1}{2}} - \left(\frac{\delta}{\delta_0}\right) \right], \delta \le \delta_0 \tag{5}$$

$$\alpha(\delta) = \alpha_0 \left[1 - \frac{2\delta}{L_g} \right]^2, \delta_0 \le \delta \le \frac{L_g}{2} \tag{6}$$

$$\alpha(\delta)=0, \frac{L_g}{2} \leq \delta \tag{7}$$

Bringing the three formulas into formula 3, and when the fiber does not break and the failure is only pull-out failure, there are:

$$R_g \geq R_g^{crit} = \frac{12W_2^m / E_m}{h\iota \left(L_g / d_g \right) \delta_0} \tag{8}$$

The purpose of fiber reinforced cement-based composites is to use the minimum fiber volume content to achieve the strain hardening effect of the material. It can be seen from the formula that only when the fiber volume rate R_g is greater than or just at the critical fiber volume rate R_g can it have sTable hardening characteristics [17]. The critical volume ratio of fiber R_g^{crit} can guide the design and adjustment of micro parameters and realize the macro tensile stress of composites. These include: matrix characteristics (matrix fracture toughness W_m, matrix elastic modulus E_m), fiber characteristics (fiber diameter d_g, fiber length L_g) and interface characteristics (buffer factor h, interface bonding friction stress ι).

3.4. Test Process for Measuring PVA-ECC Fluidity

According to the orthogonal test design Table and referring to the test method for fluidity of cement mortar (GBT 2419-2005), the test method in the specification shall be adjusted appropriately. The test of PVA-ECC fluidity and time loss is carried out. The specific operation is shown in Figure 4:

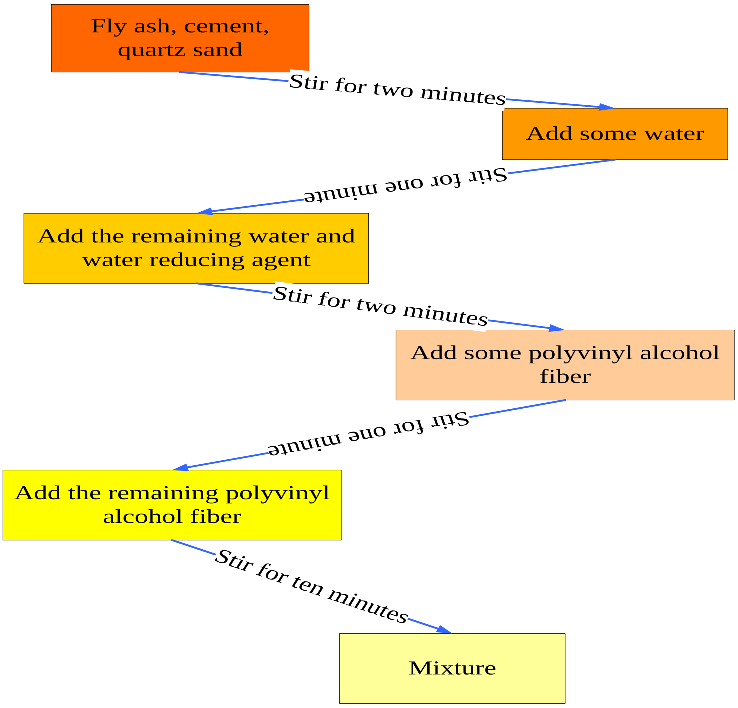
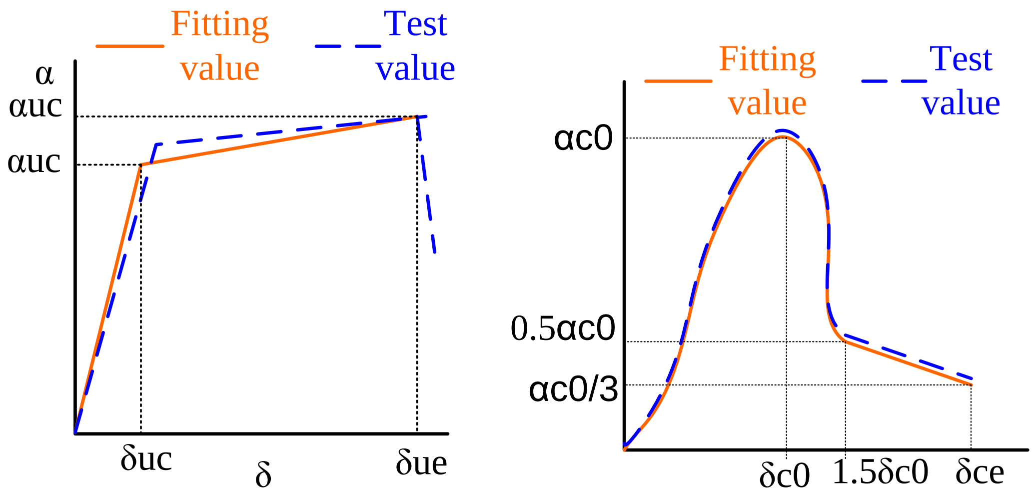


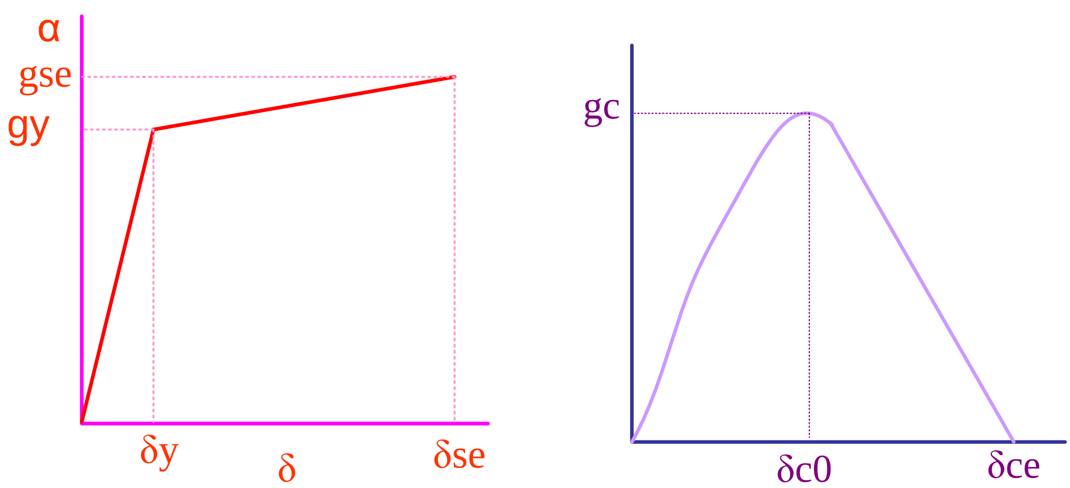
Figure 4. PVA-ECC production flow chart

3.5. Theoretical Calculation

(1) Stress-strain relationship of matrix



(a) ECC uniaxial tension (b) ECC uniaxial compression



(c) Reinforced (d) concrete

Figure 5. Material stress-strain curve

For the matrix constitutive relationship selected in this paper, the test values are fitted first, and then the model is simplified to characterize its constitutive relationship, as shown in Figure 5 (a) and Figure 5 (b). The constitutive equation of ECC under tensile load is expressed by double broken lines. The first segment is the initial crack strain from 0 to ECC, and the second segment is the initial crack strain from ECC to the ultimate tensile strain of ECC. The constitutive equation of ECC under uniaxial compression load is expressed by four segments. The first segment is a straight line and the strain range is 0 to 0.000913. The second segment is a curve segment, and the corresponding strain range is 0.000913 to 0.004, which is also the peak strain of the material. The third segment is the peak stress with the stress reduced to half, and the corresponding strain interval is 0.004 to 0.006. The last section is the peak stress when the stress drops to one third, and the strain also reaches the limit strain. At this time, the strain range is 0.006 to 0.018.

The tensile stress-strain curve can be expressed as:

$$\alpha_u = \frac{\alpha_{uc}}{\delta_{uc}}\delta, 0 \le \alpha \le \alpha_{uc} \tag{9}$$

$$\alpha_u = \alpha_{uc} + (\alpha_{ue} - \alpha_{uc})\left(\frac{\delta - \delta_{uc}}{\delta_{ue} - \delta_{uc}}\right), \delta_{uc} \le \delta \le \delta_{ue} \tag{10}$$

Among them, α_u represents the strength at the beginning of cracking; δ_u represents the strain at the beginning of cracking; ∂_{ue} represents the stress under ultimate tension; δ_{ue} represents the tensile strain corresponding to the ultimate tensile stress [18].

The compressive stress-strain curve can be expressed as:

$$\alpha_c = E_0\delta, 0 \le \delta \le \delta_{0.4} \tag{11}$$

$$\alpha_c = E_0\delta(1-\beta), \delta_{0.4} \le \delta \le \delta_{c0} \tag{12}$$

$$\alpha_c = \alpha_{c0} - 0.5\alpha_{c0}\left(\frac{\delta - \delta_{c0}}{0.5\delta_{c0}}\right), \delta_{c0} \le \delta < 1.5\delta_{c0} \tag{13}$$

$$\alpha_c = \frac{1/6\alpha_{c0}}{1.5\delta_{c0} - \delta_{ce}}(\delta - \delta_{ce}) + \frac{\alpha_{c0}}{3}, 1.5\delta_{c0} \le \delta \le \delta_{ce} \tag{14}$$

Among them, E_0 is the elastic modulus of; α_{c0} is the peak stress; δ_{c0} is the peak strain; δ_{ce} is the ultimate compressive strain; $\delta_{0.4}$ is the strain corresponding to 40% ultimate strength of the rising section, equal to $0.4\alpha_{c0}$; β is the elastic modulus reduction coefficient of the second curve segment, which can be expressed by the following formula:

$$\beta = \frac{a\delta E_0}{\alpha_{c0}} - b \tag{15}$$

a, b are constant. Through the fitting of test data, the values are 0.308 and 0.124 respectively.

(2) Reinforcement stress-strain relationship

Figure 5 (c) shows the stress-strain curve of reinforcement [19], which adopts the double oblique line elastic-plastic model, and the expression is as follows:

$$\alpha_s = E_s\delta_s, \delta_s \le \delta_y \tag{16}$$

$$\alpha_s = g_y + (\delta_s - \delta_y)E'_s, \delta_y \le \delta_s \le \delta_{se} \tag{17}$$

$$E'_s = \frac{g_{se} - g_y}{\delta_{se} - \delta_y} \tag{18}$$

(3) Stress-strain relationship of concrete

The compression of concrete is shown in Figure 5 (d). The first segment is a quadratic parabola, and the second segment is an oblique straight line, which can be expressed as:

$$\alpha_u = g_c\left[\frac{2\delta}{\delta'_{c0}} - \left(\frac{\delta}{\delta'_{c0}}\right)^2\right], 0 \le \delta \le \delta'_{c0} \tag{19}$$

$$\alpha_u = g_c\left[1-\left(\frac{\delta-\delta_{c0}}{\delta'_{ce}-\delta'_{c0}}\right)^2\right], \delta'_{c0} \le \delta \le \delta'_{ce} \tag{20}$$

Among them, δ'_{c0} represents the peak strain of concrete, taking 0.002; δ'_{ce} represents the ultimate compressive strain of concrete, taken as 0.006; then g_c represents the peak stress of concrete [20].

4. Uniaxial Direct Tensile Test of PVA-ECC Sheet

The tensile properties of concrete materials play an important role in the safety of concrete structures. Many investigations have shown that the breaking disappointment of cement is basically brought about by the low elasticity and poor malleable durability of cement. For example, the bridge deck pavement, bridge deck connecting plate and bridge deck expansion joint are subject to long-term vehicle load and temperature secondary internal force, which are extremely easy to crack and lead to reinforcement corrosion. It seriously affects the normal service of bridge deck structure. In this paper, PVA fiber supported concrete (PVA-ECC) with high versatile modulus short fiber has the ductile qualities of multi break breaking and strain solidifying, which can take care of the issues of substantial design harm and sturdiness brought about by substantial weak disappointment. The examination on the elastic properties of PVA-ECC isn't extremely complete, and the exploration on the ductile properties of PVA-ECC assumes an imperative part in addressing the pragmatic utilization of PVA-ECC [21].

4.1. Uniaxial Direct Tensile Test of PVA-ECC Sheet

Through the uniaxial direct pliable trial of 11 gatherings of PVA-ECC with various blend extent, different burden distortion bends are estimated in this paper. The heap is separated by the cross-sectional region of the example, and the elastic twisting is partitioned by the all out malleable length of the example to compute the pliable distortion rate. In this paper, the pressure strain bends of PVA-ECC with various blend extents are gotten to Figure out the elasticity and extreme pliable strain, as displayed in Table 3.

Table 3. Calculation results of tensile strength and ultimate tensile strain of PVA-ECC with 11 groups of different mix proportions

Group number	Tensile strength (MPA)	Ultimate tensile strain (%)
1	1.31	0.67
2	2.78	0.98
3	2.38	2.60
4	1.31	1.45
5	1.75	1.75
6	2.24	2.99
7	3.05	4.06
8	3.39	4.02
9	1.55	0.45
10	3.23	4.16
11	2.55	4.65

4.2. PVA-ECC Tensile Strength

(1) Effect of sand binder ratio and water binder ratio on tensile strength of PVA-ECC

The ratio of sand to cement refers to the mass ratio of sand to gel material in concrete. The sand used in this experiment is quartz sand, and the gel material is fly ash and cement. Quartz sand can reduce the shrinkage deformation of concrete [22].

The proportion of water to fastener alludes to the proportion of how much water in the substantial to the mass of the gel material. The water fastener proportion straightforwardly influences the smoothness of cement. The bigger the water fastener proportion is, the more modest the interior grating of the combination is, and the substantial blending is more uniform. In particular, fiber reinforced concrete, due to the addition of fiber, which brings great difficulty to the mixing of concrete. It is necessary to appropriately increase the water binder ratio to obtain a uniformly mixed concrete mixture. However, the larger the water binder ratio is, the looser the concrete is formed, and the more initial micro cracks are in the concrete, which has an adverse impact on the strength of the concrete.

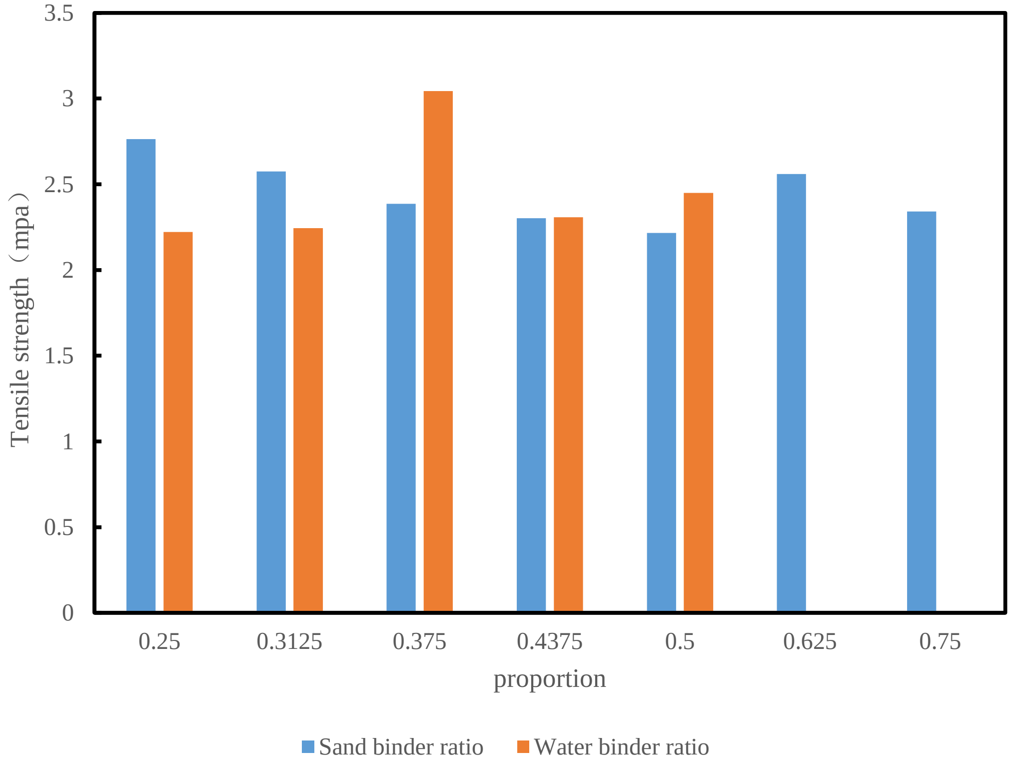


Figure 6. Effect of water binder ratio and sand binder ratio on tensile strength of PVA-ECC

As should be visible from Figure 6, when the sand binder proportion is 0.25, the greatest rigidity is 2.764mpa. At the point when the sand fastener proportion is 0.50, the base rigidity is 2.216 MPa, the normal worth is 2.454 MPa, and the absolute decrease range is 19.8%. The water binder proportion certainly affects the elasticity of PVA-ECC. From the investigation results, the best worth of water fastener proportion is 0.375.

(2) Effect of fly ash content and PVA fiber content on tensile strength of PVA-ECC

Fly ash can improve the fluidity of concrete, reduce the water binder ratio, it improves the compactness of concrete, and increases the strength of concrete. It is a necessary admixture for high-strength concrete at present.

When PVA-ECC uniaxial tension reaches the peak load, cracks have appeared. It mainly relies on PVA fiber to bear the tensile stress. Countless PVA strands are scattered on the two sides of the break and associate the concrete mortar network on the two sides, which makes the pliable pressure of PVA-ECC rise "crisscross". So, the principle factor for the predominant ductile properties of PVA-ECC is the expansion of PVA fiber.

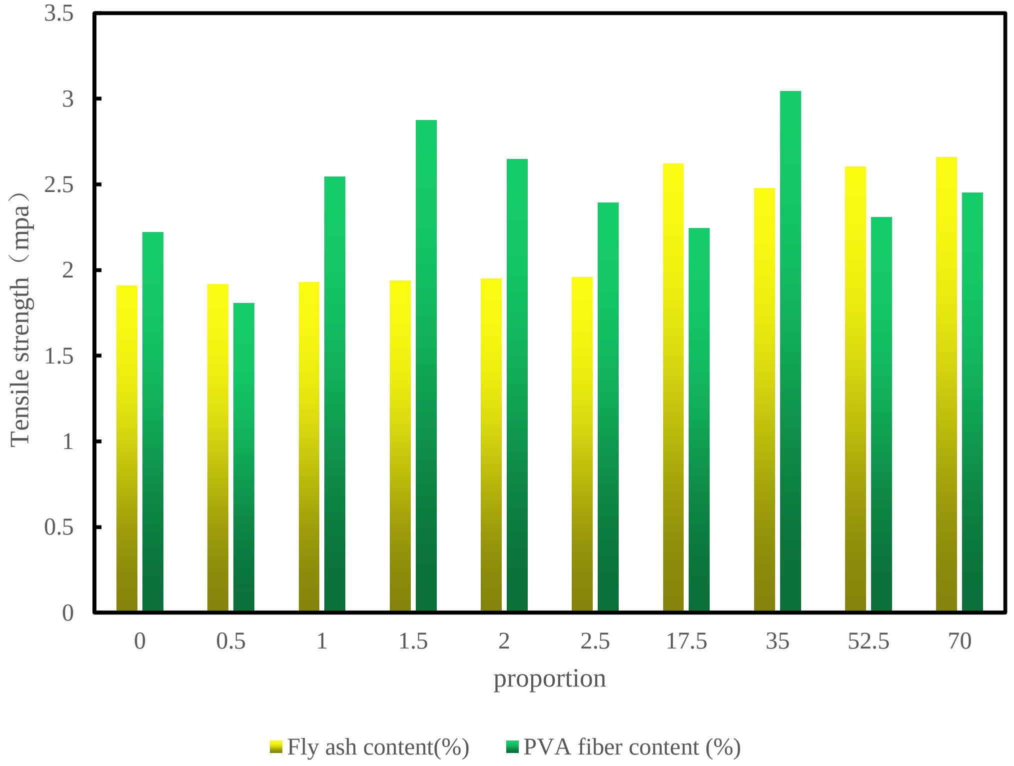


Figure 7. Effect of fly ash content and PVA fiber content on tensile strength of PVA-ECC

As should be visible from Figure 7, the rigidity of PVA-ECC without fly ash is 1.908mpa, which is lower than that of PVA-ECC with fly ash. The tensile strength of PVA-ECC with different content of fly ash has little difference, the lowest is 2.476mpa, the highest is 2.658mpa, the difference is only 0.182mpa, and the average tensile strength is 2.59mpa. It shows that the expansion of fly ash can marginally work on the elasticity of PVA-ECC. All in all, fly debris can well help PVA fiber to play a spanning job in PVA-ECC under strain, so as to improve the tensile strength of PVA-ECC. From the computation results, it can be seen that as long as the content of fly ash is greater than 17.5%, the impact is self-evident.

The effect of PVA fiber on tensile strength is reflected in two aspects. First, PVA fibers randomly distributed in the cement mortar matrix can form a spatial grid structure to bear the tensile stress under uniaxial tension. Even if PVA-ECC cracks, it will not break, so as to improve the tensile strength. At the same time, PVA-ECC has large uniaxial tensile deformation, which can realize the stress characteristics of multi crack development and strain hardening. On the other hand, because PVA fiber is soft, it is easy to bend. When the PVA fiber content is high, the PVA fibers are intertwined into clusters. The more fibers, the more serious the mutual agglomeration, and the more initial defects of PVA-ECC, which reduces the tensile strength of PVA-ECC. From the analysis results, when the content of PVA fiber is 1.5%, the tensile strength of PVA-ECC is the highest, which is 2.874mpa.

4.3. PVA-ECC Tensile Elastic Modulus

Through SPSS statistical analysis software, a single factor general linear model is established to analyze the influence of PVA fiber content on the elastic modulus when PVA-ECC reaches tensile strength. The results are shown in Figure 8.

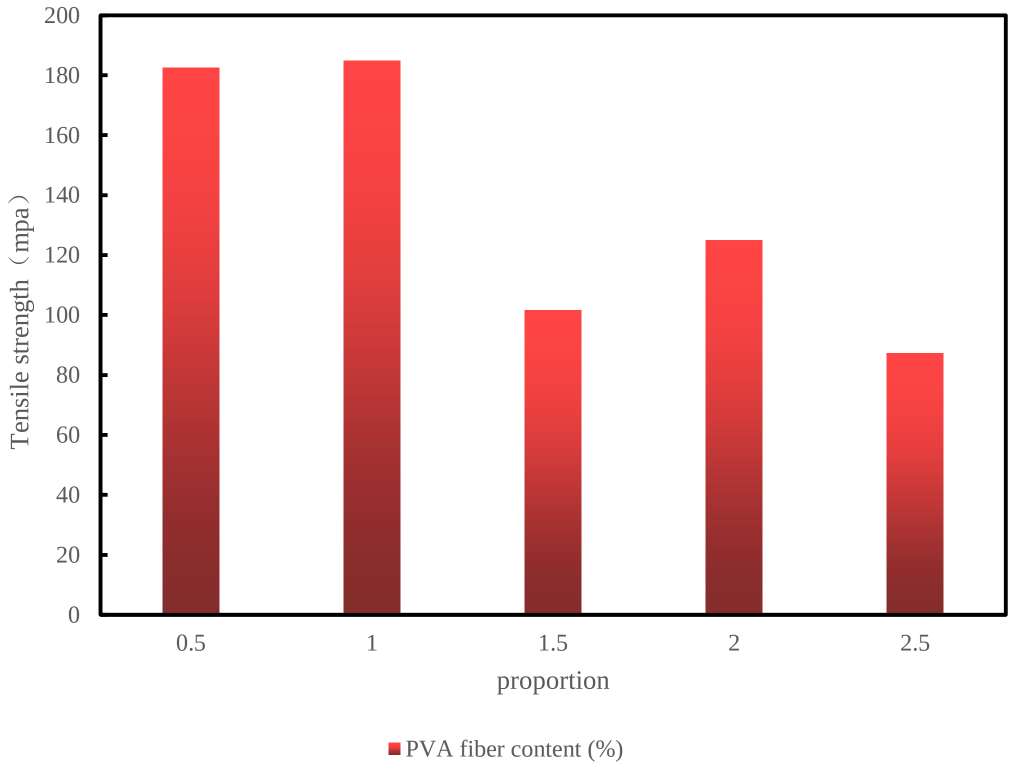


Figure 8. Effect of PVA-ECC on elastic modulus

It can be seen from the analysis results that the increase of PVA fiber content will reduce the secant modulus when PVA-ECC reaches the tensile strength, and the lower the secant modulus. It shows that the toughness of PVA-ECC is better. As can be seen from Figure 8, when the PVA fiber content reaches 1.5%, the secant modulus of PVA-ECC when it reaches the tensile strength is relatively low, which is 101.54mpa. It shows that PVA-ECC with 1.5% PVA fiber content has better toughness.

5. Discussion

Because of its brittleness and easy cracking, traditional concrete materials are difficult to fully meet the requirements of crack and leakage prevention of urban rail transit. PVA fiber reinforced cement-based composites (PVA-ECC) have two orders of magnitude higher toughness and excellent crack control ability than concrete materials. Therefore, the service life of modern concrete can be greatly improved by replacing the traditional concrete with PVA-ECC. PVA-ECC provides a new choice to improve the current challenges faced by concrete because of its incomparable high toughness and crack control ability of traditional concrete materials.

In terms of rail transit, concrete support structures have been widely used in subway stations, tunnels and track foundations. However, concrete materials are easy to crack and the crack width after cracking is difficult to control. This greatly reduces the durability of concrete, such as impermeability, frost resistance, protection of reinforcement from corrosion and corrosion resistance, and reduces the actual service life of concrete structure. Once cracks occur, chemical grouting is needed, and the maintenance cost will be greatly increased. The environmental impact of urban subway construction is complex, facing various complex engineering and hydrogeological environments. On the other hand, with the technological innovation and industrial development of rail transit, the construction of transportation infrastructure is required to be faster, more environmental friendly and safer, especially with better durability and longer service life.

The challenges faced by the concrete structure of rail transit show that the concrete materials in the future need to have the following characteristics: (1) high crack resistance and high crack control ability, especially in the case of large deformation. (2) Good durability: during the service period after construction, the structure will maintain its due building structural functionality. (3) Environment friendly, low energy consumption in the production of materials: it can digest a large number of wastes generated in other industries. It makes full use of resources.

6. Conclusion

This paper mainly solves the physical and mechanical research of PVA-ECC, while the durability of PVA-ECC needs to be further studied. In addition, the application of PVA-ECC in practical engineering will be different from the effect of experimental research. A very important reason is the pretreatment of PVA fiber. The effect of pretreatment directly affects the mechanical properties of PVA-ECC. Through the examination of this paper, the impacts of various variables on the physical and mechanical properties of PVA-ECC are gotten, which has a good reference value for making PVA-ECC with different properties. It is hoped that the consideration of cost economy can be further added in the future to produce PVA-ECC with low cost and good performance.

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Data Availability

Data sharing is not applicable to this article as no new data were created or analysed in this study.

Conflict of Interest

The author states that this article has no conflict of interest.

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