Research Article

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Effect of PVA fiber on mechanical properties of fly ash-based geopolymer concrete

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Abstract: The effects of polyvinyl alcohol (PVA) fiber content on mechanical and fracture properties of geopolymer concrete (GPC) were investigated in the present study. Mechanical properties include cubic compressive, prism compressive, tensile and flexural strengths, and elastic modulus. The evaluation indices in fracture properties were measured by using the three-point bending test. Geopolymer was prepared by fly ash, metakaolin, and alkali activator, which was obtained by mixing sodium hydroxide and sodium silicate solutions. The volume fractions of PVA fiber (length 12 mm and diameter 40 μm) were 0, 0.2, 0.4, 0.6, 0.8, and 1.0%. The results indicate that the effects of the PVA fiber on the cubic and prism compressive strengths and elastic modulus are similar. A tendency of first increasing and then decreasing with the increase in the PVA fiber content was observed in these properties. They all reached a maximum at 0.2% PVA fiber content. There was also a similar tendency of first increase and then decrease for tensile and flexural strengths, peak load, critical effective crack lengths, fracture toughness, and fracture energy of GPC, which were significantly improved by the PVA fiber. They reached a maximum at 0.8% PVA fiber content, except the tensile strength whose maximum was at 1.0% PVA fiber volume fraction. Considering the parameters analyzed, it seems that the 0.8% PVA fiber content provides optimal reinforcement of the mechanical properties of GPC.

Keywords: geopolymer concrete, PVA fiber, mechanical properties, fracture performance

1 Introduction

Concrete is widely used in the world because ordinary Portland cement (OPC) as the main binder material has wide sources, simple preparation, and superior mechanical properties. However, the growing demand for concrete results in increased energy consumption and emissions of carbon dioxide to produce a large amount of OPC [1]. The extensive use of OPC is considered one of the main causes of global warming [2], and hence, numerous attempts have been made to find greener alternatives to this material. Professor Davidovits prepared the geopolymer to replace OPC by activating active aluminosilicate materials with high alkali solution. Geopolymer can be produced from industrial wastes and geological sources including fly ash (FA), blast furnace slag, bottom ash, metakaolin (MK), and so on [3,4]. FA-based geopolymer composites have been widely studied because thermal power generation discharges a large amount of FA [5–7]. In addition, MK has attracted considerable attention because of its abundant raw materials and satisfactory activity [8]. Although the early strength of the geopolymer with low calcium FA is lower than that of the MK-based geopolymer, the MK-based geopolymer exhibits worse resistance to elevated temperature than FA-based geopolymer [9–12]. Therefore, to overcome these shortcomings, some researchers have prepared geopolymers by blending MK and FA. Research results showed that MK–FA-based geopolymer exhibited higher compressive and bending strengths and better high-temperature resistance than MK-based or FA-based geopolymer [13–15].

Geopolymer concrete (GPC) is environmentally friendly, is energy saving, and also has similar or better mechanical properties than OPC concrete (OPCC) [16]. Compared to OPCC, GPC has better bond strength under similar compressive strength, higher early strength, and faster speed of strength development [17]. Besides, the fire resistance of GPC is much better than the traditional concrete. As a result, GPC can be used in repairing and strengthening of existing structures, such as bridge structures, pavement structures, building structures, and so on, and rapid repaired strength

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can be obtained. Furthermore, GPC will exhibit better application prospects at some structures in high temperature. Hassan also believes that compared to OPCC, GPC has higher early strength and better durability [18]. The durability of GPC includes freeze–thaw cycle and heat, fire, chloride, sulfate, acid, and efflorescence resistances, which are mainly due to the dense microstructure and migration behavior of GPC [19–21]. Bakri et al. reported that the durability of FA-based GPC was better than that of OPC when exposed to acid [22]. GPC can be used as a high-temperature-resistant material because it can still maintain better mechanical properties than OPC at high temperatures [23]. In addition, the drying shrinkage of GPC is much less than that of OPC, so GPC is more suitable for thick concrete layers or concrete members with heavy constraints [18,24]. Although GPC has better durability and mechanical properties, its tensile and flexural properties were similar or even lower than those of OPC [25,26]. Furthermore, the crack resistance and toughness of the GPC are low. As a result, cracks and brittle fracture easily occur in GPC [27,28]. Therefore, to further improve the applicability of GPC, several studies have been conducted to improve its flexural strength and fracture toughness.

The addition of fibers can significantly improve the tensile properties and toughness of concrete. Several researchers have conducted studies on fiber-reinforced concrete, including variations in metal, synthetic, and natural fibers. With the addition of fibers, the tensile strength of concrete can be improved and the length of cracks in concrete can be reduced. As a result, fiber-reinforced concrete exhibits higher ductility and toughness than OPC without fibers [29–33]. Owing to the good mechanical properties, durability, and environmental protective performance of GPC, which is expected to replace silicate cement concrete, several studies evaluated the performance of fiber-reinforced GPC. Diverse types of fibers have been used in geopolymer composites such as carbon, steel, glass, polyvinyl alcohol (PVA), polypropylene, cotton, and natural fibers [34–40]. From these, PVA fibers have attracted increasing attention in recent years because of their high tensile strength, similar Young's modulus to concrete, and low price [41,42]. Furthermore, PVA fiber has good resistance to acidity and alkalinity, which are also characteristics of geopolymer [43]. As PVA fibers have a positive effect on the durability of GPC [44], they can be considered suitable for GPC [40]. As reported in the previous studies, PVA fiber also improves the mechanical properties and toughness of geopolymer composites. Ohno and Li investigated the mechanical properties of PVA fiber (length 12 mm and diameter 39 μm) reinforced GPC by cubic compressive and dog-

bone tensile testing. The tensile ductility of specimens could be increased by 4%, which is several hundred times that of GPC or OPC without fibers [45]. Nematollahi et al. reported that short PVA fibers with 2% volume content significantly improved the flexural strength of GPC [46]. Xu et al. [47] added two different PVA fiber lengths (12 and 8 mm) into geopolymer composite. The two types of fibers enhanced the compressive, tensile, and flexural strengths of the samples. The toughening effect of the geopolymer composite was remarkable, and the long fiber provided a better performance [47].

Fracture performance is an important aspect of evaluating structural safety [48]. Compared with plastic and brittle materials, it is more difficult to analyze the fracture properties of concrete due to the existence of the fracture process zone in concrete [49]. Various fracture calculation modes were established to evaluate fracture performance of concrete, including fictitious crack model, Griffith model, size effect model, and double-K fracture model. The double-K fracture model is widely used because it accurately describes the process of concrete crack propagation, and its calculation is simpler than other models [50,51]. Fracture toughness and fracture energy as indices of fracture performance are utilized to assess the ability of structures to prevent crack propagation. However, previous researches on PVA fiber-reinforced GPC mainly focused on the basic mechanical properties. There have been few systematic investigations on mechanical properties, including fracture performance. In this study, five groups with different fiber contents and a control group were formed to systematically study the influence of PVA fibers on the mechanical properties including the fracture performance of GPC. The cubic compressive, prism compressive, tensile and flexural strengths, elastic modulus, and fracture performance of GPC were evaluated in this investigation. Besides, the fracture performance was assessed by double-K fracture parameters and fracture energy based on the double-K fracture model, which were measured by the three-point bending method.

2 Experimental investigation

2.1 Materials

In accordance with the specification of FA used for cement and concrete (GB T 1596-2017), grade-one FA procured from Luoyang Power Plant in China was utilized in this study. The chemical composition of the FA is

Table 1: Chemical composition of FA

Chemical	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	f-CaO	SO ₃	Others
Component (wt%)	60.98	24.47	6.70	4.90	0.68	0.58	0.52	1.17

Table 2: Chemical composition of MK

Chemical	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO + MgO	K ₂ O + Na ₂ O
Component (wt%)	54 ± 2	43 ± 2	≤1.3	≤0.8	≤0.7

presented in Table 1. MK was provided by Chenxing Industrial Co. Ltd., Shijiazhuang, Hebei Province, China. The main chemical components are SiO₂ and Al₂O₃ (Table 2). Sodium hydroxide (Jinhai Xinwu Fine Chemical Co. Ltd., 99% purity) and sodium silicate (Longxiang Ceramics Co. Ltd., SiO₂/Na₂O = 3.2) were used as alkaline activators. The molar ratio of silicon oxide to sodium oxide of the activator was 1.3, and the weight ratio of sodium oxide was 16.8%. The liquid polycarboxylic acid superplasticizer (Zhongyi Chemical Co., Ltd., 6–8 of pH, 25–40% of water-reducing rate, and 1.08 of specific gravity) produced by Zhongyi Chemical Co., Ltd. was used to reduce the amount of water and to improve the strength of concrete.

Coarse aggregates with particle sizes between 5 and 20 mm and river sand with a fineness modulus of 2.7 were used in this study. The properties of the PVA fibers furnished by Kuraray Co. Ltd., Japan, are presented in Table 3.

2.2 Mix proportions and admixture synthesis

In this study, the mix proportion design of GPC was in accordance with the specification for the mix proportion design of ordinary concrete (JGJ 55-2011). The aim of this article is to study the mechanical properties of GPC with different PVA fiber contents. The control variate method was used, and the dosage of PVA fiber was the only

change. Table 4 presents the mix proportions of the PVA fiber-reinforced GPC in this study. As shown in Table 4, the fiber volume fractions were 0, 0.2, 0.4, 0.6, 0.8, and 1.0%. The usage of PVA fibers in traditional concrete is very popular. However, there is few related research conducted on GPC reinforced with PVA fibers. Referring to the commonly used PVA fiber contents in traditional concrete, the PVA fiber contents of 0.2, 0.4, 0.6, 0.8, and 1.0% were used in this study. A water/binder ratio of 0.4, an aggregate/binder ratio of 3.0, and a sand/aggregate ratio of 0.35 by weight were used for all specimens. Forty percent of the binder material was FA and 60% was MK because the previous research reported that the addition of MK made FA-based GPC more uniform and compact, and 60% MK content brought the best improvement effect [52].

Flaky sodium hydroxide was added to the sodium silicate solution to produce an alkali activator solution. The solution was used to activate the aluminosilicate source materials (FA and MK). The mixing process of the PVA fiber-reinforced GPC is shown in Figure 1. Whether the fibers were distributed evenly in the mixture has a significant effect on the properties of hardened GPC. Before the fibers were added, all the fibers were dispersed by hand in advance. During the first stage of mixing, PVA fibers were added into FA and MK in three batches. After the next batch of fibers was added, the stirring direction of the mixer was changed. The added PVA fibers were mixed about 2 min together with FA and MK. From the prepared fresh mixture, it can be found that the fibers were evenly distributed. The mixture was placed into test molds after being evenly stirred. Then, the test molds with the mixtures were vibrated to eliminate air voids and gaps. The specimens were removed after 24 h staying at ambient temperature because the GPC quickly hardened and reached a high compressive value in a short time. Appropriate reduction of curing humidity is beneficial to polymerization [53]. Deng

Table 3: Properties of PVA fiber

Diameter (μm)	Length (mm)	Young's modulus (GPa)	Elongation (%)	Nominal strength (MPa)	Density (kg/m ³)
40	12	≥42	6.5	≥1,560	910

Table 4: Mix proportions of fiber-reinforced GPC

Mixture ID	Fly ash (kg/m ³)	Metakaolin (kg/m ³)	Alkali activator			River sand (kg/m ³)	Coarse aggregate (kg/m ³)	PVA fiber (%)	Water reducing admixture (%)
			Sodium silicate (kg/m ³)	NaOH (kg/m ³)	Water (kg/m ³)				
M	195.0	274.8	286.3	53.2	66.5	577.4	1072.4	0	2.00
P1	195.0	274.8	286.3	53.2	66.5	577.4	1072.4	0.2	2.00
P2	195.0	274.8	286.3	53.2	66.5	577.4	1072.4	0.4	2.25
P3	195.0	274.8	286.3	53.2	66.5	577.4	1072.4	0.6	2.50
P4	195.0	274.8	286.3	53.2	66.5	577.4	1072.4	0.8	2.75
P5	195.0	274.8	286.3	53.2	66.5	577.4	1072.4	1.0	3.00

reported that 70–80% humidity was the optimal curing humidity in her experiment [54]. Therefore, samples were placed at ambient temperature and low humidity for 3 days after being cured in a standard curing room for 28 days. In general, GPC can obtain higher strength with high-temperature curing than ambient temperature curing based on the current research results. Considering that the curing temperature of the concrete specimens in the actual construction site is always room temperature, the curing temperature of the specimens in this study was chosen as the standard room temperature to make it consistent with the construction practice.

2.3 Cubic compressive strength test

Standard cubic specimens with dimensions of 150 mm × 150 mm × 150 mm were tested following GB/T50081-2002. Three specimens were prepared for each group to ensure the accuracy of the test.

Figure 1: Preparation process of GPC.

2.4 Prism compressive strength test

The prism size for the prism compressive test was 150 mm × 150 mm × 300 mm. The test was conducted in accordance with GB/T50081-2002. The prism compressive strength is closer to actual engineering practice than the cubic compressive strength. The values measured in this experiment were exploited in the elastic modulus testing.

2.5 Elastic modulus test

The size of the specimens used in the elastic modulus test was the same as that in the prism compressive strength test. The test was performed by following GB/T50081-2002, and the test device is shown in Figure 2. Six prisms were prepared for each group to obtain accurate values.

2.6 Splitting tensile strength test

The splitting tensile strength of the GPC was measured under the guidance of GB/T50081-2002. Three cubes with a side length of 150 mm were cast for each mix proportion.

2.7 Flexural strength test

Three-point and four-point loading are the main methods of the flexural test, and the schematic diagram of these two loading modes is shown in Figure 3. In the three-point loading test, the failure surface of the specimen usually appears in the middle of the specimen directly

Figure 2: Testing apparatus of elastic modulus test.

below the loading point. While in the four-point loading test, the failure surface of the specimen is located at the weakest position between the two loading points. Since the fibers may not be completely evenly dispersed and the weakest surface of the specimen may not be at the midpoint, the four-point flexural test used in this study can better reflect the flexural resistance of PVA fiber-reinforced GPC compared with the three-point flexural test. Three $100\text{ mm} \times 100\text{ mm} \times 400\text{ mm}$ prisms for each mix proportion were cast to test.

When the crack on the lower surface is between the two concentrated load action lines, the flexural strength can be calculated by equation (1).

$$f_t = \frac{Fl}{bh^2}, \quad (1)$$

where, f_t is the flexural strength, F is the fracture load, l is the span between supports (300 mm), and b and h are the width and height of the section (100 mm each), respectively.

2.8 Fracture properties test

The wedge splitting, direct stretching, compact stretching, and three-point bending methods have been used to measure fracture performance. The three-point bending method is the most commonly used method because of its simple operation and stable test results [39,55–57]. Five specimens with dimensions of $100\text{ mm} \times 100\text{ mm} \times 400\text{ mm}$ with an initial notch of 30 mm were used according to the

Figure 3: Loading diagram of flexural test: (a) three-point flexural test and (b) four-point flexural test.

current research results for traditional concrete, and the shape of the specimen is shown in Figure 4. The loading device was the same as that in the flexural test. A schematic diagram of the overall test device is presented in Figure 5. The loading pad is a steel plate with a section size of $5\text{ mm} \times 10\text{ mm} \times 130\text{ mm}$. The load acquisition device is a load sensor with the measuring range of 30 kN and an accuracy of 1 N produced by Bengbu Sensor System Engineering Co., LTD. The crack mouth opening displacement (CMOD) of the crack nozzle was measured by a clip gauge with a range of 10 mm and an accuracy of 0.5 mm produced by Beijing Steel Sodium Gram Co., Ltd. The clip gauge is a kind of sensor to measure the developing distance of a crack or the tensile elongation of a specimen, which is based on that the two clamping pieces of the clip gauge can move freely with the change of the distance of a crack or the tensile elongation of a specimen during the test. The changed distance and tensile elongation can be recorded automatically. Two aluminum sheets with a sharp spout were symmetrically stuck close to the edge of the initial crack on the bottom surface of the specimen. The two sharp spouts were direct to the middle of the initial crack. The lamped extender was fixed between the two sharp spouts with the two measuring sheets of the lamped extender contacting the two sharp spouts, respectively. In this study, a DH3818Y static strain tester (Jiangsu Donghua Testing Technology Co., LTD) was adopted. The static strain tester was

Figure 4: Shape of the specimen.

Figure 5: Loading diagram.

connected to a load sensor and a clip gage and is used to record data of load and crack opening displacement.

The double-K model was used to analyze the fracture performance of PVA fiber-reinforced GPC, and fracture parameters were calculated by equations (2)–(9) [58]. The load–displacement curve method was utilized to determine the initiation load. The load corresponding to the turning point of the load–displacement curve (Figure 6) from the linear elastic to the nonlinear section is the crack initiation load F_Q . The length of the crack is the critical effective crack length a_c under the maximum load F_{max} , which can be calculated by equation (2).

$$a_c = \frac{2}{\pi} (h + h_0) \arctan \sqrt{\frac{tEV_c}{32.6F_{max}}} - 0.1135 - h, \quad (2)$$

where a_c is the critical effective crack length, h_0 is the thickness of the knife edge thin steel plate (2 mm), h and t are the height and width of the specimen (100 mm each), respectively, V_c is the critical opening displacement, E is the elasticity as determined by equation (3), and F_{max} is the critical load.

$$E = \frac{1}{tc_i} \left[3.7 + 32.6 \tan^2 \left(\frac{\pi a_0 + h_0}{2h + h_0} \right) \right], \quad (3)$$

where c_i is the can be expressed by $c_i = V_i/F_i$ ($\mu\text{m}/\text{kN}$) and a_0 is the initial depth of crack (30 mm).

When the external load of the specimen reaches F_Q , the structure is within the elastic range. The initiation fracture toughness K_{Ic}^Q can be calculated by the linear elastic fracture mechanics formula with a_0 and F_Q , as shown in equations (4) and (5).

$$K_{Ic}^Q = \frac{1.5 \left(F_Q + \frac{mg}{2} \times 10^{-2} \right) \times 10^{-3} S \sqrt{a_0}}{th^2} f(a_0), \quad (4)$$

$$f(a_0) = \frac{1.99 - \alpha_0(1 - \alpha_0)(2.15 - 3.93\alpha_0 + 2.7\alpha_0^2)}{(1 + 2\alpha_0)(1 - \alpha_0)^{\frac{3}{2}}}, \quad (5)$$

$$\alpha_0 = \frac{a_0}{h},$$

where K_{Ic}^Q is the initial fracture toughness ($\text{MPa} \cdot \text{m}^{1/2}$), S is the span between two supports (300 mm), F_Q is the initial crack load (kN), and m is the mass of m_1 and m_2 , which

Figure 6: Load–crack opening displacement.

are the mass of the beam between two supports and the weight of the loading device on the beam, respectively.

When structural failure occurs, the concrete material is in a state of viscoelastic stress. However, according to the assumption of asymptotic linear elasticity, the fracture toughness of unstability K_{IC}^S can still be calculated by the formula in linear elastic fracture mechanics [58,59]. Equations (6) and (7) are used for the three-point bending beams.

$$K_{IC}^S = \frac{1.5 \left(F_{\max} + \frac{mg}{2} \times 10^{-2} \right) \times 10^{-3} S \sqrt{a_c}}{th^2} f(\alpha_c), \quad (6)$$

$$f(\alpha_c) = \frac{1.99 - \alpha_c(1 - \alpha_c)(2.15 - 3.93\alpha_c + 2.7\alpha_c^2)}{(1 + 2\alpha_c)(1 - \alpha_c)^{\frac{3}{2}}}, \quad (7)$$

$$\alpha_c = \frac{a_c}{h},$$

where K_{IC}^S is the unstable fracture toughness ($\text{MPa} \cdot \text{m}^{1/2}$) and $F_{\max}$ is the unstable load (kN).

The size effect exists in this study as nonstandard specimens were used. Based on the Weibull brittle failure statistical theory, the approximate conversion between the fracture toughness of standard and nonstandard specimens was conducted using equation (8).

$$K_{IC}^S = \sqrt[3]{\frac{V_{NS}}{V_S}} \sqrt{\frac{h_S}{h_{NS}}} K_{IC}^{NS} \quad (h \leq 750 \text{ mm}), \quad (8)$$

where K_{IC}^S and K_{IC}^{NS} are the fracture toughness of standard and nonstandard specimens, respectively ($\text{MPa} \cdot \text{m}^{1/2}$), h_S and h_{NS} are the height of standard and nonstandard specimens, respectively (m), V_S and V_{NS} are the specimen volumes between the supports of standard and nonstandard specimens, respectively (m^3), and α is the parameter of Weibull ($\alpha = 10$).

The fracture energy can be calculated by equation (9) from the curve of load–CMOD [59].

$$G_F = \frac{W_0 + 0.0375mg \times \frac{V_c}{a_c}}{b \times (h - a_0)}, \quad (9)$$

where G_F is the fracture energy; W_0 is the area between the P-CMOD curve, the X-axis, and the straight line $x = \text{CMOD}_{10\%}$ (N·m); and $\text{CMOD}_{10\%}$ is the CMOD value corresponding to 10% peak load.

3 Results and discussion

3.1 Compressive strength

As shown in Figure 7, the cubic compressive strength of the GPC was improved by adding PVA fibers from 0.2 to

Figure 7: Cubic compressive strength versus PVA fiber contents.

0.6%, but was reduced with higher volume fractions. The cubic compressive strength of GPC without the PVA fiber was 43.4 MPa, and that of the fiber-reinforced GPC at 0.2% PVA fiber content reached the maximum value of 52.2 MPa. The cubic compressive strength continuously decreased for PVA fiber volume fractions above 0.2%. The strength of the mixture with 0.6% PVA fiber was almost the same as the benchmark strength. When the content of PVA fiber reached its maximum, the cubic compressive strength of GPC reached the minimum value. Previous researches also reported that the cubic compressive strength increased first and then decreased with the increasing PVA fiber content [60,61]. In the study by Yuan *et al.*, 0.3% PVA fiber content achieved the best enhancement of cubic compressive strength of GPC [62]. As for OPC, the maximum cubic compressive strength mostly appeared between 2 and 3% PVA fiber volume fraction [63–66]. Figure 7 exhibits that the growth rate is higher than the deceleration; thus, the best content for the maximum cubic compressive strength may be a little less than 2% in this study.

Concrete was improved by adding slight PVA fibers as fibers could bridge cracks, hinder crack propagation, and support loads in the matrix and the microstructure determines the concrete performance. However, excessive fibers were difficult to disperse and tended to agglomerate. Superfluous fibers also caused more voids and flaws into the matrix, which resulted in the stress concentration of the mixture under pressure load and the reduction in the cubic compressive strength [67]. As shown in Figure 7, there is a decreasing tendency from 0.2 to 0.6% fiber contents, but the cubic compressive strength is still higher than the benchmark strength;

thus, the influence of fibers on this characteristic of the GPC was positive. However, the improvement provided by fibers cannot compensate for the damage to the matrix when excessive fibers are added. Therefore, in this study, the cubic compressive strength at 0.8 and 1.0% PVA fiber content was lower than that of GPC without PVA fibers. As presented in Figure 8, the addition of PVA fibers significantly delayed the expansion of cracks in the matrix, improved the deformation ability of the mixture, and changed brittle failure to plastic failure. A previous study also showed that fibers did not perform well in improving the strength of concrete. The main function of fibers is to increase the toughness of concrete, control cracks, and absorb energy [68].

As shown in Figure 9, similar to the cubic compressive strength, the prism compressive strength also increased first and then decreases with the increase in the PVA fiber content. The optimal content of PVA fiber for the prism compressive strength was 0.2%. Different failure patterns of specimens with diverse volume fractions are shown in Figure 10. Specimens with fibers at 0, 0.2, and 0.4% exhibited brittle failure and were severely damaged. With high contents of PVA fiber, the specimens exhibited several cracks and one main crack running through the top and bottom. As shown in Figure 8(d), the middle of the specimen was raised, but no peeling phenomenon occurred because the PVA fiber provided a good bridging in the matrix, enabling it to bear some

(a)

(b)

(c)

(d)

Figure 8: Cubic compression failure patterns of specimens. (a) Without PVA fiber, (b) 0.2% PVA fiber, (c) 0.4% PVA fiber, and (d) 1.0% PVA fiber.

Figure 9: Prism compressive strength versus PVA fiber contents.

tensile stress around the specimen such that the specimens still had good integrity after failure [69]. Some researchers believe that there are chemical interactions between PVA fibers and the matrix. The formation of hydrogen bonds among molecules due to PVA fibers containing hydroxyl (OH) results in significant changes in the surface bond strength between PVA fibers and the matrix [70]. This is beneficial for highly elastic fibers to bridge matrix materials. However, excessive fibers reduced the prism compressive strength of the GPC due to agglomeration and the introduction of air voids.

As shown in Figure 11, the prism compressive strength is lower than the cubic compressive strength under the same mix proportion. Under uniaxial compression, the test block was compressed longitudinally and expanded laterally. However, the upper and lower surfaces of the specimen would produce shear force because of the friction between the surfaces of the specimen and the press plate. The shear stress acted as a binding band to prevent lateral displacement [71]. Fotouhi *et al.* reported that shear stress propagated inward from the surface at 60° [72]. There is no shear stress in some areas in the middle of the specimen, where spalling failure occurred, and it is confirmed in Figure 12. Previous researches have shown that as the height–width ratio of the specimen increased, the influence of shear stress on the middle part of the specimen decreased and then the compressive strength decreased [73]. Therefore, the prism compressive strength in this test is less than the cubic compressive strength.

Previous researches reported that the compressive strength decreased rapidly when the height–width ratio

increased from 1 to 2, while changed little from 2 to 4 [74]. Therefore, the prism compressive strength of prisms was closer to the actual strength of compressed structures in practical engineering. Several researchers have found that the cubic compressive strength and prism compression are linear. For OPC, the average of f_{cp}/f_c (f_{cp} and f_c are the prism and cubic compressive strengths, respectively) is 0.76, and the ratio is suggested to be 0.67 in Chinese standards. In this study, the ratio of f_{cp}/f_c was between 0.83 and 0.91; the average value of f_{cp}/f_c was 0.866. In practical engineering, for safety consideration, it is suggested to multiply the coefficient by 0.88 like OPC. The following relationship (equation 10) for PVA fiber-reinforced GPC is recommended:

$$f_c = 0.76f_{cp}. \quad (10)$$

3.2 Elastic modulus

Figure 13 depicts the elastic modulus of PVA fiber-reinforced GPC with different volume fractions. With the increase of PVA fiber content, a tendency of first increase and then decrease of the elastic modulus of GPC can be observed. According to the composite material theory, each component can affect concrete. The PVA fiber has a high elastic modulus and can reduce microcracks in the mixture during hydration. A suitable volume of PVA fiber had a positive influence on the elastic modulus. The relation of elastic modulus and compactness of concrete has been reported [75]. However, PVA fibers also caused tiny air voids into the matrix [76]. In addition, excessively clumping fibers caused an uneven distribution of stress in the GPC. As a result, the PVA fibers had little improvement in the elastic modulus, and high contents had a negative impact. A similar result was also reported for PVA fiber-reinforced high-strength concrete by Nuruddin *et al.* [77]. The main reason why PVA fiber decreased the elastic modulus of GPC is that the fiber can support much higher compressive and tensile deformation than brittle GPC, and the addition of PVA fibers makes the GPC stressed as a whole. Namely, after incorporated PVA fiber with low elastic modulus, the rigidity of the GPC decreased and the ductility increased, which can keep GPC from damages under large deformation.

Comparing with OPC, it can be found that when the compressive strength is similar, the elastic modulus of GPC is smaller than that of OPC. The elastic modulus corresponding to the compressive strength of 52.2 is 23.3. Olivia and Nikraz reported that when compressive

Figure 10: Prism compression failure patterns of specimens: (a) without PVA fiber, (b) 0.2% PVA fiber content, (c) 0.4% PVA fiber content, and (d) 1.0% PVA fiber content.

was from 54.04 to 59.08, the elastic modulus of GPC was from 25.33 to 29.05, which was 14.9–28.8% lower than that of OPC [78]. Moreover, the elastic modulus of geopolymer mortar is lower than that of the ordinary cement mortar. Therefore, the low elastic modulus of geopolymer may be the main reason for the low elastic modulus of GPC [79]. In addition, high-temperature curing is also beneficial to the development of elastic modulus of GPC, so the ambient curing in this study is also a reason for the low elastic modulus [78].

For concrete, there is a relationship between the elastic modulus and the cubic compressive strength. Empirical relationships between these two quantities for OPC have been established by different countries. In

the present study, based on the regression analysis, the elastic modulus model of fiber-reinforced GPC is proposed as shown in equation (11). As shown in Figure 14, the correlation between the fitted curve and the test data is good, $R^2 = 0.95813$. The basis of the proposed relationship is derived from the study by Noushini et al. [80].

$$E = -24,829 + 6,643\sqrt{f_c}, \quad (11)$$

where E is elastic modulus of fiber-reinforced GPC (MPa) and f_c is the cubic compressive strength (MPa). It is noted that the measuring of elastic modulus for GPC is more difficult than the measuring of compressive strength of GPC. Using the regression function obtained in this study, the elastic modulus of GPC can be obtained easily just

Figure 11: Cubic and prism compressive strength with different PVA fiber contents.

based on the compressive strength. So the troublesome casting specimens and measuring in elastic modulus of specimens can be avoided in practical engineering, which can save a lot of manpower, material resource, and construction cost of the practical engineering.

3.3 Tensile strength

As shown in Figure 15, the tensile strength of GPC increases with an increase in the PVA fiber content

Figure 13: Elastic modulus versus PVA fiber contents.

from 0 to 1.0%. The tensile strength of GPC is 2.64 MPa with no fiber and 3.11 MPa at 1.0% PVA fiber content, which is the maximum value at the highest volume fraction. The increasing tendency of GPC with PVA fibers from 0 to 0.4% is not evident. A similar observation has been reported, in which lower volume fractions of PVA fiber can only produce a slight improvement in the tensile stress resistance of the matrix [77]. Li et al. reported that the bridging effect was more obvious under tension [81]. In this study, it was also confirmed that the tensile performance of PVA fiber-reinforced GPC improved much more than the compression performance. With regard to OPC, PVA fibers also significantly improved the tensile

Figure 12: Stress distribution: (a) cubical specimen and (b) prism specimen.

Figure 14: Elastic modulus versus cubic compressive strength.

Figure 15: Tensile strength versus PVA fiber contents.

performance of concrete, and the negative effect of fibers will be perceived when the PVA fiber content is high. Wei et al. found that the tensile strength of OPC increased with the PVA fiber content from 0.9 to 1.5% [82]. Khan and Ayub reported that the tensile strength of PVA fiber-reinforced OPC achieved the maximum between 2 and 3% PVA fiber content [83]. Therefore, it is suggested that future studies on the tensile strength of GPC should be carried out in the range of high PVA fiber content, so as to find the optimal PVA fiber volume fraction.

From the tendency shown in Figure 15, it can be predicted that there is a threshold between 0.4 and 0.6%. When the fiber content is less than this dosage, it is difficult to affect the tensile resistance because only a few fibers played a bridging role, which could only limit a

small amount of crack expansion. When the fiber content exceeds this dosage, there were more cracks that been limited, which was enough to significantly improve the tensile performance of GPC.

As shown in Figure 16, specimens with PVA fiber contents of less than 0.6% exhibited brittle failure, which could be explained by the fact that only a few nondirectional fibers were distributed in the tensile direction to restrict the development of cracks. When a crack occurred in the matrix, the tensile stress at the crack was completely borne by PVA fibers, and the crack continued to grow where there was no fiber. As the PVA fiber content increases, more fibers are pulled out or broken. Most of the fibers were pulled out because of the high elastic modulus and tensile strength of PVA fibers [84,85]. Moreover, with the increase of PVA fiber content, more fibers played a bridging role, and fibers that were not pulled out or destroyed became more and more. So, the specimen with 1% volume fraction of PVA fiber still maintained good integrity after being destroyed.

3.4 Flexural strength

The flexural strengths with different PVA fiber contents are presented in Figure 17. The flexural strengths of GPC at 0 and 0.8% PVA fiber are the minimum and maximum, respectively. The addition of 0.8% PVA fiber content improved the flexural strength of GPC, which was 45% higher than the benchmark flexural strength. The same tendency was reported by Hossain et al. utilizing PVA fibers to reinforce self-consolidating concrete [39]. Due to the different mix ratio and fiber aspect ratio used in this study and in the study by Hossain et al., the optimal mixing amount is different. The flexural strength of the mixture decreases at 1.0% PVA fiber because unevenly dispersed fibers had insufficient bonding with the matrix and could not form an effective bridge. By comparing Figures 15 and 17, it can be found that the optimal PVA fiber contents corresponding to the tensile strength and flexural strength are different. In the tensile test, all the PVA fibers across the damaged section of the specimen are in tension. However, in the flexural test, only the PVA fibers in the tensile region of the beam specimen are in tension, and other fibers are in compression. As shown in Figure 17, 0.2% PVA fiber content significantly improved the resistance to flexure of GPC compared to no fiber added. However, there is basically no promotion in the tensile strength at 0.2% PVA fiber content. A reason speculated is that a high elastic modulus led to a low

Figure 16: Splitting tensile failure patterns of specimens: (a) without PVA fiber, (b) 0.4% PVA fiber content, (c) 0.6% PVA fiber content, and (d) 1.0% PVA fiber content.

deflection of the prism [86]. When the PVA fiber content exceeds 0.2% and is less than 0.8%, the flexural strength of the GPC continues to increase while the elastic modulus and cubic compressive strength of the mixtures decrease. Therefore, the flexural strength depends on the tensile strength of the tensile zone located at the lower part of the specimen. With the increase in fiber volume fractions, the bonding and friction between fibers and the matrix bore more tensile stress and restrained more cracks in the concrete [84]. As a result, the flexural strength continued to increase from 0.2 to 0.8% fiber content. The flexural strength of GPC with 1% content PVA fiber is lower than that with 0.8% content, but the tensile strength of GPC with 1% volume fraction of PVA fiber is higher. This indicates that 1% PVA fiber causes agglomeration and introduces defects into the matrix. It

also indexes that the flexural resistance of GPC is more sensitive to defects than the tensile resistance, that is, the existence of defects in the matrix has a greater impact on the flexural resistance.

The f_t/f_c (tensile strength/cubic compressive strength) and f_l/f_c (flexural strength/cubic compressive strength) ratios prove the toughness of concrete. The increasing tendency of both curves is shown in Figure 18, which indicates that the addition of PVA fiber enhanced the toughness of GPC. Lin *et al.* also reported that fibers improved the toughness of concrete [35]. A small value of f_l/f_c at 0.2% content may be noticed because the cubic compressive strength is too high. The toughness of the mixture was improved at fiber volume fractions higher than 0.4%, shown in Figure 18. Higher contents of PVA fiber allow fractural specimens to have certain integrity.

Figure 17: Flexural strength versus PVA fiber contents.

Figure 19: Critical effective crack lengths versus PVA fiber contents.

3.5 Fracture properties

The critical effective crack lengths versus the PVA fiber contents of the GPC are shown in Figure 19, and the crack initial and peak loads of the specimens are presented in Figure 20. It is clear that the PVA fibers improved the crack resistance and load-bearing capacity of GPC. The critical effective crack length increased when the PVA fiber content increased and then slightly decreased at 1.0% PVA fiber volume fraction. As shown in Figure 20, the crack initial and peak loads also increased first and then decreased, but there was a significant decrease at 1.0% volume fraction. In addition, the difference between the peak and crack initial loads increases with

the increasing PVA fiber content, which indicates that PVA fibers have a higher influence on the peak load than on the initial crack load of GPC. This indicates that fibers began to work after cracks appeared because the initial load was borne by the GPC matrix, and the load was gradually transferred to the bridged fiber as the deformation increased [87].

The curves of load–CMOD and fracture energy are presented in Figures 21 and 22, respectively. As shown in Figure 21, 0.6–1.0% fiber content effectively slowed down the post-peak curve and improved the toughness of GPC, but 0.2 and 0.4% PVA fiber content had little effect on the post-peak behavior of GPC. The curve did

Figure 18: Ratios versus PVA fiber contents.

Figure 20: Crack initial and peak loads versus PVA fiber contents.

Figure 21: Load-CMOD curve.

Figure 22: Fracture energy versus PVA fiber contents.

not continue from 0 to 0.4% PVA fiber contents because specimens ruptured in a brittle fracture. GPC could still bear certain tensile stress after tensile failure with PVA fiber volume fractions higher than or equal to 0.6%. The envelop area under the load-CMOD curve was larger with a higher content of PVA fiber, and with the increase of PVA fiber volume fraction, the fracture energy increased correspondingly, as shown in Figure 22. The fracture energy of the PVA fiber-reinforced GPC was considerably higher than that without the PVA fiber. In other studies, fibers also significantly improved the fracture energy of GPC by 5 to 10 times [88,89]. As shown in Figure 22, the fracture energy significantly increased when the PVA fiber content was 0.4 to 0.6%. This phenomenon also

appeared in PVA fiber-reinforced OPC. However, in Hosain's investigation, the fracture energy of OPC significantly increased with the PVA fiber content from 0.2 to 0.3% [90]. The changing trend of fracture energy with fiber contents is similar to the trends of tensile strength and flexure strength, which both reached the maximum at 0.8% content because the improvement of these properties was benefited from fiber bridging. It has been pointed out that there are mainly three kinds of interaction between fibers and matrix: bonding, friction, and mechanical occlusion [87]. As for the PVA fiber, there are mainly adhesion and friction between fibers and GPC. As the fibers were added, more energy was required to break the bond between fibers and the matrix and then pull the fibers out or to rupture fibers apart. However, when the PVA fiber content was too high, the negative effect brought by the fiber agglomeration and the stomata introduced by PVA fibers would be more obvious, so there was a decrease when the PVA fiber content is 1.0% [89].

Figure 23 presents initial and unstable fracture toughness varied with different contents of PVA fiber. Although the two tendencies are similar, the increase and decrease range of unstable fracture toughness are considerably larger than that of the initial fracture toughness. The influence of PVA fiber on initial fracture toughness is not significant, but the improvement of unstable fracture toughness is significant. Previous studies by us and others have also shown that the influence of fibers on the instability fracture toughness of concrete is much greater than the fracture toughness of initiation, whether PVA fiber or basalt fiber [59,91,92]. As the initial crack

Figure 23: Fracture toughness versus PVA fiber contents.

load was quickly reached, peak load was reached with a small value of CMOD. Stress at the crack tip rapidly developed because of the initial damage inside the concrete. In contrast, although fibers reduced some cracks and enhanced internal adhesion, they also introduced small air voids into the GPC, which had a negative effect. When microcracks occurred, PVA fibers hardly reached the stress state and helped the matrix to resist tensile stress because they were erratically distributed. Therefore, the PVA fiber had little influence on initial fracture toughness of GPC. The bridging action of fibers clearly improved the toughness of concrete when the cracks stably expanded [91]. The adhesion and friction between fibers and matrix considerably improve the tolerance of tensile stress. As a result, with the increase of the PVA fiber content from 0 to 0.8%, the unstable fracture toughness of GPC continuously increased. The fracture toughness of initiation and instability of concrete decreased at 1.0% content of PVA fiber as presented in Figure 23. One of the reasons may be that excessive PVA fibers increased the amount of agglomerates and brought air voids, which decreased the compactness of specimens and increased the initial defect of concrete [93]. In addition, comparing the flexural resistance and fracture performance of GPC with different contents of PVA fiber, the same tendency can be found between them; thus, the flexural strength can also reflect the fracture performance.

4 Conclusion

The effect of the PVA fiber on the cubic and prism compressive strengths, elastic modulus, tensile and flexural strengths, and fracture performance of GPC was investigated in this study. The following conclusions can be drawn:

- A tendency of increasing first and then declining was found in the elastic modulus and cubic and prism compressive strengths. The addition of 0.2% PVA fiber content provided the best enhancement of the above properties, increasing the cubic and prism compressive strengths and elastic modulus by 20.3, 16.7, and 27.4%, respectively. Other contents of PVA fiber had little influence on GPC.
- PVA fibers significantly enhanced the tensile and flexural strengths of GPC. With the increasing content of PVA fiber, there was a continuous increase in the tensile strength, whereas an initial increase and decrease later were observed in the flexural strength. The tensile strength of GPC was maximally improved by 17.8 at

1.0% PVA fiber content, and the flexural strength of the GPC was enhanced by 45% at a PVA fiber content of 0.8%.

- The critical effective crack length, initial crack load, peak load, initial fracture toughness, unstable fracture toughness, and fracture energy of the PVA fiber-reinforced GPC first increased and then decreased with an increase in the PVA fiber volume fraction. These parameters reached maximum values at 0.8% PVA fiber content. The unstable fracture toughness and fracture energy were significantly improved. At 0.8% PVA fiber volume fraction, the fracture energy and unstable fracture toughness were enhanced by 1284.2 and 128.6%, respectively.
- The volume fraction of 0.8% was suggested to get optimal tensile properties and toughness while ensuring the compressive performance of concrete.

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