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INORGANIC FIBRE REINFORCED GEOPOLYMER CONCRETE

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Geopolymer concrete (GPC) is a new green building material with low pollution, low energy consumption and high strength; however, it has the disadvantage of being brittle and prone to cracking. Studies have shown that the incorporation of inorganic fibres in GPC can enhance the toughness of GPC and inhibit the development of cracks. There is no clear uniformity in the existing literature on the effect of inorganic fibres to enhance GPC. In this paper, the research reports on the effect of inorganic fibres on the mechanical properties of GPC in recent years, and the prospects of their future research are discussed.

INTRODUCTION

With the growth in the population and the increasing level of modernisation in the world, research into green and sustainable building materials is gaining more and more attention. With the continuous development of engineering construction, the amount of cement being used has also increased. According to statistics, in 2022, the total cement production in China reached 2.13 billion tonnes, ranking it as the largest cement production country in the world [1]. The production of cement is accompanied by a large amount of CO_2 emissions (about 7 % of the total global CO_2 emissions) [2]. China made a commitment to achieve a "carbon peak" by 2030, and the search for green materials that can replace cement is crucial, and the emergence of geopolymer concrete (GPC) provides help in this area.

GPC is a new type of alkali-inspired cementitious material with natural minerals, such as metakaolin or industrial waste materials, such as fly ash, blast furnace slag, and various tailings as the main material for green building materials [3]. The production process of GPC does not require high-temperature calcination. The preparation process is low in pollution and energy consumption, and its carbon emissions are much lower than those of ordinary silicate cement. In addition to the energy savings and environmental protection, GPC also has the advantages of having excellent mechanical properties, heat resistance, and corrosion resistance, making it one of the preferred building materials to replace ordinary silicate cement concrete in the future. However, GPC has some disadvantages, such as brittleness and easy cracking. Numerous studies have shown that the incorporation of inorganic fibres in GPC can effectively improve the brittleness of GPC and enhance its mechanical properties [4]. Inorganic fibres are chemical fibres made from minerals and can be divided into two main categories: one is inorganic and inorganic compound fibres, such as glass fibres, carbon fibres, basalt fibres, ceramic fibres, etc.; the other is metal fibres, such as steel fibres.

Inorganic fibre materials have the advantages of being lightweight, having high-temperature resistance, good thermal stability, low thermal conductivity, and small specific heat capacity. They are usually use in high thermal applications, such as refractory materials [5].

There are many kinds of fibres, and different fibres have different reinforcing effects on GPC. Various scholars have undertaken many relevant experiments and theoretical analysis. However, the results about the effects of inorganic fibres on GPC have not yet been clearly unified, and many conclusions may even contradict each other. For the development of research on the effects of inorganic fibre-reinforced GPC, this paper is composed of several common inorganic fibres: glass fibre, carbon fibre, basalt fibre, and steel fibre. Based on the existing literature, the reinforcing effect of these fibres by themself or mixed together in the GPC are summarised and also provides reference for the development of fibre reinforced GPC for future prospects.

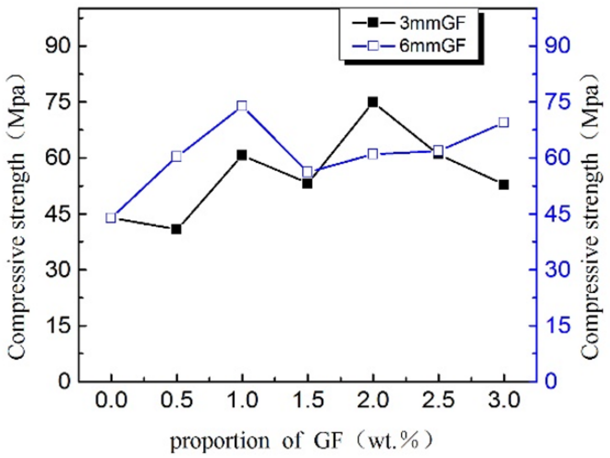
RESULTS AND DISCUSSION

Inorganic fibre

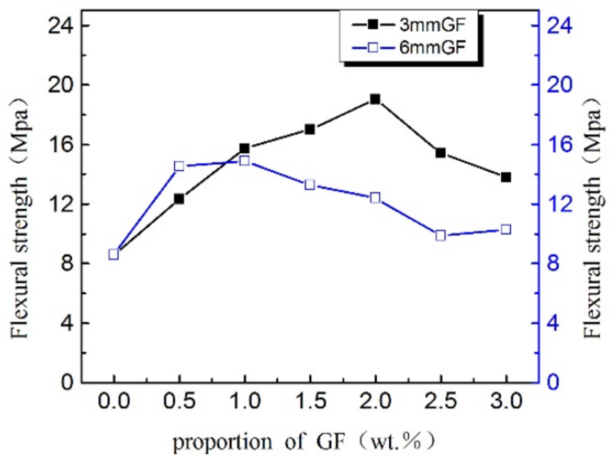
Glass Fibres

Glass fibres (GFs) have the advantages of having high mechanical strength, good insulation, good heat resistance, and good corrosion resistance, and is widely used in construction materials [6].

The addition of GFs can increase the compressive strength of GPC, as was confirmed by Alves et al. [7] and Mermerdaş et al. [8]. Alves' study showed that the increase in the compressive strength is due to the decrease in porosity. At the same time, the addition of GF affects the amount of pores in the mixture; the specimens without added fibres have higher porosity values, resulting in a lower compressive strength. Mermerdaş found that the increase in the compressive strength was due to the GF controlling the cracking during loading, which increased the strength. Also, he found that the splitting tensile strength increased with the increase in the amount of fibres.



a) Compressive strength



b) Flexural strength

Figure 1. Compressive strength and flexural strength of the GPC with 3 mm and 6 mm GFs at different doping levels [10].

Nematollahi et al. [9] studied the effect of GFs with different volume fractions (0.50, 0.75, 1.00 and 1.25 %) on the GPC. It was shown that the compressive and flexural strengths of GPC doped with 1.25 % GF increased by 8.5 % and 34 %, respectively, compared to that of GPC without GF.

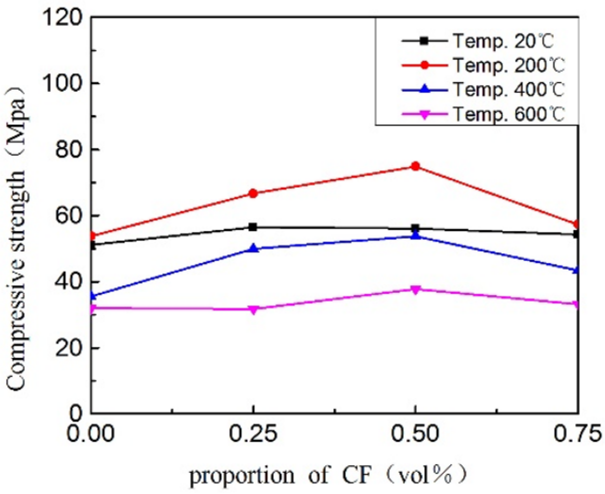
Dianar [10] concluded that GFs increase the flexural strength of GPC mainly because of the good interfacial bonding state between the GFs and the GPC matrix, while the increase in the compressive strength can be attributed to the delay in the formation and extension of microcracks, and may also be caused by the interaction between the water content of the GPC and the moisture content of the fibres. Meanwhile, she experimentally found that the flexural strength increased and then decreased when increasing the mass fraction of the GFs (0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 %), and the compressive strength also showed a similar trend to the flexural strength. Dianar also investigated the effect of the length of the GFs (3 and 6 mm) on the mechanical properties of the GPC and found that the best mechanical properties were found at 3 mm, as shown in Figure 1. Midhun [11] investigated the effect of the incorporation of two different GF lengths (6, 13 mm) on the GPC. He showed that the 13 mm fibres were more effective than the 6 mm fibres in improving the flexural strength, splitting tensile strength, and fracture properties of the GPC.

Carbon Fibres

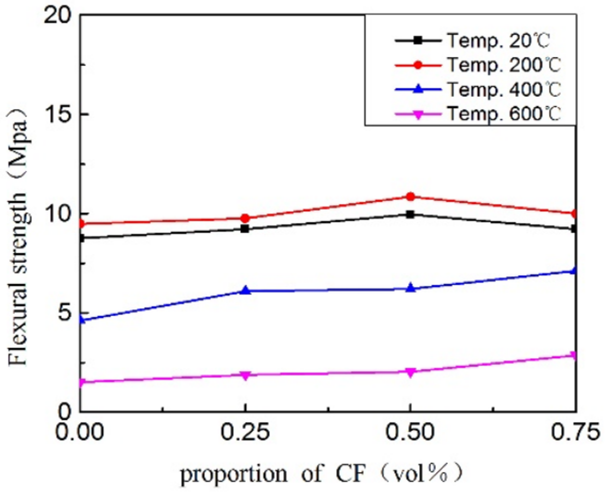
Carbon fibres (CFs) have the characteristics of low density, high stiffness, electrical conductivity, high temperature resistance, and corrosion resistance, which has a broad application prospect in aerospace and civil engineering [12].

The results of Shen et al. [13] and Panjasil et al. [14] showed that the fluidity of GPC decreased with an increase in CF content. Luna-Galiano et al. [15] found the reason for this is that as the CF content increases, its lap gradually forms a three-dimensional spatial structure, which hinders the free flow of the slurry and increases the cohesiveness of the slurry.

Shen concluded that CFs can significantly improve the compressive strength of the GPC by varying the amount of the CF admixture, and Luna-Galiano attributed the improvement of the compressive strength to the good compatibility of the CFs with the matrix interface, which allows them to act as load transmitters that can block the cracks and strengthen the material. Hu et al. [16] studied the effect of CFs with different volume contents (0, 0.25, 0.50, 0.75 %) on the compressive strength of GPC. Authors concluded that the beneficial effect is no longer enhanced when the CF content reaches 0.75 %, which may be due to the increase in the CFs leading to an increase in the porosity of the GPC, and the enhancement effect of the CFs on the compressive strength with the decrease in the compactness brought about by the increase in the porosity which was gradually offset. Panjasil et al. [14] found that the compressive strength of GPC showed an increasing trend with an increasing CF content followed by a decreasing trend and that the optimum CF concentration was at 0.5 %. Subsequently, he drew a different conclusion and the new test results showed that the addition of CF slightly decreased the compressive strength of the GPC, which he analysed as that the possible reason was the agglomeration of CF during the addition process [17]. The author's analysis was due to the higher strength of the matrix used by Panjasil to do the tests, which made the effect of the fibres to improve the GPC less than the effect of the increase in the porosity which led to the decrease in the strength, thus reducing the overall strength of the GPC.



a) Compressive strength



b) Flexural strength

Figure 2. Compressive strength and flexural strength of the GPC with different volume fractions of CF at high temperatures [16].

Chen et al. [16] also studied the effect of CFs with different volume contents (0 %, 0.25 %, 0.50 %, 0.75 %) on the flexural strength of GPC, and the experiments showed that the CF addition could enhance the flexural capacity of the GPC mortar. According to their analyses, this improvement may be due to the good connection between the CFs and the GPC mortar making the CFs play a role of transferring and taking up the force. Moreover, they found that the compressive strength and flexural strength of GPC after exposure to high temperatures also follows the law of increasing and then decreasing with the CF content, as shown in Figure 2. Therefore, the GPC would shrink under the effect of high temperature, and the tightness of the CFs and the GPC mortar would decrease, and when the CF content was too high, the void ratio increased, which reduced the mechanical properties of the GPC.

Based on the fact that CF doping can significantly improve the electrical conductivity of GPC, Meng [15] and Panjasil [17] obtained the same conclusion that the resistivity of GPC composites decreased significantly with increased CF doping. Xianjian Meng concluded that this is due to the lap between the CF and GPC matrix to provide an effective path for the electron migration, which enhances the electron migration rate and thus reduces the resistivity of the GPC.

Zhu et al. [18] concluded that CF can significantly increase the toughness of GPC under impact loading as shown with impact compression tests with different volume fractions (0, 0.1, 0.2, 0.3 %) of CF reinforced GPC. Wang et al. [19] added different contents of CF to the GPC in order to improve the toughness of the GPC under impact loading, and the experimental results showed that the CFs had the best effect on the enhancement and toughening of the GPC when the fibre content was 0.2 %.

Basalt Fibres

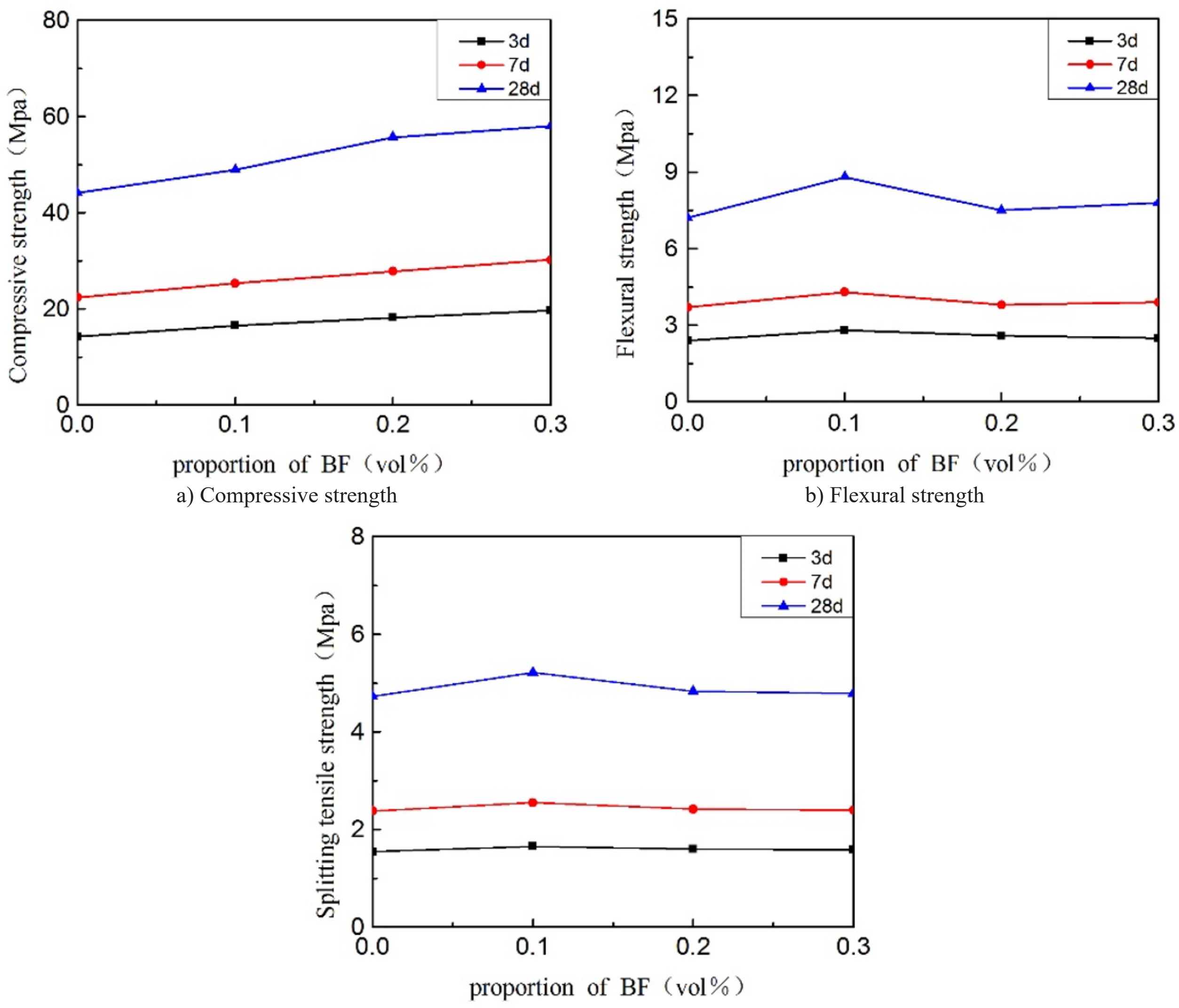
Basalt fibres (BFs) are an inorganic fibre material having high strength, corrosion resistance, high-temperature resistance, and other high performances.

Nawar et al. [20] compared fibreless specimens with BFs blended at 1 % by mass and found that adding BFs to the GPC significantly improved its flexural strength. Şahin et al. [21] obtained the same conclusion and their results showed that the flexural and compressive strength of the GPC increased with an increase in the percentage of the BFs. The reason for this is that BFs can transmit the load efficiently and, thus, slow down the development of cracks in concrete. They also found that the BFs positively affected the strength of the GPC exposed to freeze-thaw. They concluded that this was because the addition of BFs prevented the development of microcracks, leading to a reduction in the pore space after the freeze-thaw process.

Li et al. [22] studied the mechanical properties of a BF-reinforced GPC at high temperatures. They found that the reinforcing effect of the fibres after high temperature action gradually decreases with an increase in the temperature until 600 °C. Beyond this temperature, the fibres will lose their reinforcing effect. They concluded that the reason for the loss of reinforcement effect is due to the destruction of the aggregate at high temperatures. On the other hand, the bond between the aggregate and the base material decreases with the increase in the temperature, which leads to a reduction in the concrete strength, thus offsetting the reinforcement effect of the fibre. Xu et al. [23] concluded that the reason for the loss in the reinforcement effect is that 600 °C is higher than the melting point of the BFs, and the melting fibres lead to a large number of voids in the GPC concrete specimens, thus, the appearance of a large number of voids.

Liu et al. [24] studied the effect of BFs with different volume fractions (0.1, 0.2, 0.3 %) on the GPC at different ages. They found that the BFs increased the compressive strength of the GPC the most, followed by the flexural strength and tensile strength, as shown in Figure 3. The best performance of the GPC was obtained when the BF dose was 0.1 %.

Wang et al. [25] investigated the fracture characteristics of basalt fibre–reinforced fly ash geopolymer concretes (FAGCs) with different fibre contents (0.025, 0.05, 0.1, 0.15 %). It was found that the incorporation of BFs significantly improved the fracture toughness of the GPC and significantly inhibited the crack development and was most effective at its doping level of 0.05 %. Wang [26] also investigated the mechanical and fracture properties of the GPC doped with different BF lengths (3, 6, 12 and 18 mm). It was shown that the compressive



a) Compressive strength

b) Flexural strength

c) Splitting tensile strength

Figure 2. Compressive strength, flexural strength and splitting tensile strength of the GPC with different volume fractions of BF incorporated at different ages [24].

strength, splitting tensile strength and fracture toughness of the GPC were maximised when the BF was at 6 mm. He concluded that the proper BF length can slow down the crack extension by a bridging action. When the fibres are too long, bunching will occur, leading to the formation of cavities and gaps at the interface between the BFs and the substrate, weakening the bond quality.

While Nawar et al. [27], in their experiment to study the mechanical properties of biased kaolin-based polymer mortars doped with 12 mm and 24 mm BF lengths, found that the 24 mm long BF reinforced specimens were better than the 12 mm long BF reinforced specimens. He concluded that the longer fibres can transfer loads and redistribute stresses more effectively in the crack zone, significantly reducing concrete cracks and increasing their strength. He also found, in his experiments, that incorporating BFs significantly improved the abrasion resistance of the GPC concrete.

Saloni et al. [28] found that BFs improved the performance of the GPC by experimentally replacing rice husk ash with different BF mass admixtures (0, 10, 20, 30 and 100 %) on the GPC. As the BF content increases, the Ca content in the slurry increases, and multiple gels such as CSH, CASH, and NASH develop, leading to a denser and homo-geneous hybrid slurry structure. This idea is in agreement with Xu [29]. Also, Xu found that the initial and final setting time of BF-GPC mixed with BF increased with the increase in the BF admixture, and the flowability decreased with the increase in the BF admixture.

Steel Fibres

Steel fibres (SFs) are an emerging and rapidly developing construction material in recent years, widely used as a reinforcement for concrete due to its high hardness and strength, good corrosion resistance, and excellent ability to improve the mechanical properties [30].

Huang et al. [31] investigated the effect of SFs at 0.5, 1.0 and 1.5 % on the mechanical properties of GPC, they found that appropriate amount of SFs increased the compressive strength of the GPC and significantly improved the splitting tensile and flexural strength of the GPC concrete. At the same time, excessive fibres led to excessive microporosity and agglomeration in the concrete, which had undesirable effects. The presence of fibres allows the concrete to maintain its integrity in the event of damage.

Ye et al. [32] investigated the effect of SFs on the dynamic compressive strength of GPC of different strengths (C50, C60, and C70), and the tests showed that the SF addition had a greater effect on the dynamic compressive strength of lower strength GPC, while the effect on the higher strength GPC was not significant. Pan et al. [33] also explored the effect of SFs on GPC of different strengths (C50, C60, and C70), and concluded that the elevation of the peak strain of SFs on the higher strength GPC was significantly higher than the effect on the lower strength concrete due to the poor plasticity of the higher strength GPC itself. They also found that the SF addition slightly increased the modulus of elasticity of the C50 GPC, but decreased that of the C60 and C70 GPC. Raphaela et al. [34] tested a GPC with strength C30 and found that the SF addition decreased the elastic modulus of the GPC with the increasing fibre volume ratio. Zada et al. [35] added 6 mm and 12 mm SFs to a GPC and, after 90 freeze-thaw cycles, they found that both SF lengths increased the freeze-thawed GPC of the GPC after 90 freeze-thaw cycles, and the degree of improvement was not much different between the two, with the 6 and 12 mm SF increasing the average compressive strength of GPC by 10.5 and 10.6 %, respectively.

Guo et al. [36] investigated the strengthening effect of 0.4 % SF doping on a GPC at different temperatures (25, 100, 300, 500, 700 and 900 °C). It was shown that when the temperature was below 300 °C, the compressive strength of the GPC with the SF addition increased with the increase in the temperature and reached the highest value at 300 °C, while its flexural strength first showed a decrease and then an increase. When the temperature continued to rise, the compressive and flexural strength of the GPC decreased, and started to decrease significantly when it reached 700 °C. When the temperature reached 900 °C, the SFs were burned to failure. However, regardless of the temperature, the compressive strength and flexural strength of the GPC with the fibres are higher than those of concrete without the fibres.

Liu et al. [37] investigated the effect of SFs with different volume fractions (0, 1, 2, 3 %), different lengths (6, 8, 13 mm), different diameters (0.12 and 0.20 mm) and different aspect ratios (6/0.12, 8/0.12, 13/0.12, 13/0.20) on an ultra-high performance GPC, and they experimentally found that the reinforcement efficiency of the fibres is not only controlled by the aspect ratio, but also by the size (length and diameter) and the actual amount of fibre filaments, and finally concluded that longer length and smaller diameter fibres have better reinforcement and toughening effects, and that, by increasing the fibre blending, it can improve the strength and toughness of the ultra-high performance GPC.

Gao et al. [38] investigated the effect of the fibre length on the GPC. The tests showed that the GPC doped with long fibres exhibited higher compressive strength compared to short ones, which he attributed to the higher efficiency of the long SFs in inhibiting macroscopic crack growth. He also investigated the effect of fibre doping (0, 0.25, 0.5, 0.75, 1 %) on the GPC. He concluded that the final mechanical properties are the result of the combined effect of the SFs and the porosity. On the one hand, the fibre addition can effectively inhibit the crack generation and extension, thus improving the mechanical properties

Table 1. Optimal SF doping when the mechanical properties of the GPC are optimised.

Types of GPC studied	The volume fraction of SF in the experiment	The mechanical properties studied	Optimal dose
Slag based GPC [39]	1, 1.5 and 2.0 (vol. %)	Compressive strength and splitting tensile strength	1.5 vol. %
100 % ground blast furnace slag-based GPC [35]	0, 1.25 and 2.5 (vol. %)	Compressive strength	1.25 vol. %
Red mud-based GPC [40]	0 ~ 1.25 (vol. %)	Compressive strength, flexural strength and splitting tensile strength	1 vol. %
Fly ash-metakaolin GPC [41]	0 ~ 2.5 (vol. %)	Compressive strength	2.0 vol. %
Fly ash-metakaolin GPC [41]	0 ~ 2.5 (vol. %)	Flexural strength and splitting tensile strength	2.5 vol. %
Fly ash GPC [42]	1, 3, 5 and 7 (wt. %)	Compressive strength and flexural strength	7 wt. %
Fly ash-fine blast furnace slag GPC [43]	0.5, 1, 1.5, 2 and 2.5 (vol. %)	Compressive strength, flexural strength and splitting tensile strength	2.5 vol. %

overall, while, on the other hand, the increased porosity due to the fibre addition may lead to a decrease in strength. The crack bridging behaviour caused by the fibre addition during the study seems to exhibit a stronger effect than the porosity increment, thus the mechanical properties show an overall increase. However, the compressive strength increase was no longer significant beyond 1 % fibre incorporation. He analysed that this may be due to the higher the fibre content, the more obvious the effect of the increase in the porosity on the crack bridging effect.

Different conclusions were obtained by Zada et al. [35] on the effect of the fibre length on the GPC, who found that the GPC with short SFs (6 mm) incorporated performed better in terms of compressive strength, while GPC with long SF (12 mm) incorporated performed better in terms of the bending strength. Also, he found that the GPC incorporated with short SFs (6 mm) outperformed the GPC incorporated with long SFs (12 mm) regardless of the seawater erosion or high temperature effect.

The above analysis shows that the mechanical properties of the GPC shows an overall increase and then a decrease with the increase in the SFs. Table 1 summarises the optimal doping of SFs when the mechanical properties of the GPC are optimised in the different literature sources.

Comparison between fibres

Different inorganic fibres have different reinforcement effects on the GPC, and Table 2 summarises the excellent degree in the mechanical property improvement between the different fibres.

Effect of fibre intermixing on the GPC

In addition to the single blending of fibres in the GPC, many scholars have also studied the reinforcing effect of different fibres blended together in the GPC on concrete. Bakthavatchalam et al. [47] blended different BF (0.2, 0.5, 1.0, 1.5 %)

Table 2. Comparison of the different mechanical properties of the different fibres acting on the GPC.

The fibres studied	Volume doping of the studied fibres	Mechanical properties studied	Optimal dosing of CF	Optimal dosing of GF	Optimal dosing of BF	Optimal dosing of SF	Comparison of fibre enhancement of GPC at optimal doping level
GF, CF and BF [44]	0.1, 0.2 and 0.3 %	Compressive strength	0.3 %	0.3 %	0.3 %	-	BF > GF > CF
		Flexural strength	0.1 %	0.2 %	0.2 %	-	GF > BF > CF
SF and BF [45]	0.2, 0.4, 0.6, 0.8, 1.0, 1.5 and 2.0 %	Compressive strength	-	-	0.2 %	1.0 %	SF > BF
		Splitting tensile strength	-	-	0.2 %	1.0 %	SF > BF
SF and BF [46]	0.2, 0.4, 0.6, 0.8, 1.0, 1.5 and 2.0 %	Fracture toughness	-	-	1.5 %	2.0 %	SF > BF

and SF (1.8, 1.5, 1.0, 0.5 %) fibres so that their total volume blends were 2 %, and the effect of their mutual blending on the GPC was studied. The study showed that with the addition of the BF content, the workability performance of the GPC was not affected, but it decreases when the SF doping increased. At the same time, he found that the compressive strength of the GPC was highest when the BF doping was 0.5 % and the SF volume doping was 1.5 %, and the splitting tensile strength and flexural strength of the GPC were the highest when the BF doping was 1.5 % and the SF volume doping was 0.5 %. The experimental data showed that the fibre intermixing was better than the single admixture, the analysis was due to the fact that the SFs change the internal structure of the concrete by affecting the macroscopic strength, while the BFs connect the matrix by creating a good interfacial bond. Thus, the two fibres produced positive synergistic effects in the hybridisation.

Abid et al. [48] investigated the fracture toughness of a GPC with two different fibres (GF and SF) without, single (1.6 % by volume) and blended (0 and 1.6 % and 0.3 and 1.3 % by volume, keeping the total fibre volume at 1.6 %). The experimental results showed that the steel single fibre blend (abbreviated as S1.6) and the steel-GF blended fibre blend (SF1.3 %, GF0.3 %, referred to as S1.3G0.3) were the mixtures with the highest fracture toughness values in the experiments. S1.3 G0.3 had the highest disc fracture toughness values, while S1.6 had the highest cubic fracture toughness values.

Guler et al. [49] investigated the performance of a fly ash-based GPC with GF or BF alone and intermixed GF and BF under high-temperature action, and the results showed that the mixture of the GF and BF was more effective than single GF and BF in terms of residual compression and flexural strength of the GPC mortar specimens under high-temperature action.

In summary, the intermixing of fibres may bring a positive synergistic effect, making the reinforcement effect higher than that of fibre single-mixed ground-polymer concrete. However, any related studies still need to be more extensive and deeply investigated.

CONCLUSIONS

Based on the existing literature, this paper summarised the effects of several standard inorganic fibres (GFs, CFs, BFs, and SFs) on the GPC.

1. Doping with GF, CF, BF, and SF in the GPC can enhance the mechanical properties of the GPC, such as the compressive strength, flexural strength, and splitting tensile strength. CFs can improve the electrical conductivity of the GPC, BFs can improve the wear resistance of the GPC, and SFs have a positive effect on the GPC after freeze-thaw or under seawater erosion.

2. Fibres have an optimal amount for the GPC to achieve the best performance, and the reinforcing effect on the GPC will be reduced when the fibre dosing exceeds this optimal amount. On the one hand, the addition of fibres can effectively inhibit the generation and expansion of cracks, thus improving the overall mechanical properties; on the other hand, the increase in the porosity due to the addition of fibres may lead to a decrease in strength. Therefore, the mechanical properties of the GPC are jointly acted by the fibres and porosity.

3. The degree of influence of the different fibre sizes on the GPC varies. The reduction in the fibre diameter contributes to improving the mechanical strength of fibre-reinforced GPC. GPC, with the addition of short SFs, performed better in the compressive strength, while the GPC, with the addition of long SFs, performed better in the bending strength.

4. The reinforcing effect of different fibres for the GPC is different. For example, regarding the compressive strength, SF > BF > GF > CF.

5. The intermixing of fibres may bring a positive synergistic effect and make the reinforcement effect higher than that of GPC with fibres alone, e.g., when the BF dose is 0.5 % and the SF volume dose is 1.5 %, the compressive strength of the GPC is higher than that of the GPC with an SF or BF dose of 2 % alone.

Prospects

Although some of the above conclusions on the performance of fibre-reinforced GPC is still controversial, by and large, the mechanical properties of GPC played an enhanced role. China's research on fibre-reinforced ground polymer concrete started late, and the research results are still in the initial stage. In addition, the mineral composition of different regions varies greatly, and a great deal of research work is still needed.

(1) The distribution of fibres has been mostly experimented with disordered dispersion or laminar dispersion (e.g., fibre felt). Still, there are fewer studies on the effect of fibre distribution (e.g., regular distribution of fibres or the number or thickness of layers of fibre felt) on GPC.

(2) The interdoping of fibres may bring positive synergistic effects. Most of the current studies deal with the effect of the GPC of single-doped fibres, but there are few studies on the effect of fibre intermixing on the GPC, and relevant studies are urgently needed.

(3) The actual engineering environment is complex and variable, and the engineering structure is difficult to work in a single environment. However, most of the current studies only focus on the single performance of fibre-reinforced GPCs under the action

of a single environment. In contrast, the performance changes under the act of multiple factors which are rarely studied and further research needs to be performed.

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