Effects of Fibers on the Properties and Performance of Polymer Composite Concrete

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Abstract. Geopolymer is a new type of chemically-inspired cementitious material that meets the concept of green and sustainable development due to its low energy consumption and low carbon emissions. However, when subjected to bending and tensile stresses, geopolymers exhibit brittle characteristics and require fiber reinforcement to control crack expansion and enhance toughness. Fibers can significantly enhance the performance of geopolymers in various aspects. By summarizing domestic and international papers on fiber-reinforced geopolymer composites (FRGC), this paper summarizes several properties and parameters of fibers that have a greater impact on the performance of Geopolymer concrete (GPC) and analyzes the impact of fibers on the performance of GPC from the perspective of the fiber type, size, admixture, interface with the matrix, and the modulus of elasticity. The influence of fiber on concrete properties is analyzed from five perspectives: fiber type, size, admixture, interface with matrix and elastic modulus. The type of fiber directly affects the performance of the fiber, the size and the amount of mixing, there is an optimal range, beyond or insufficient could lead to a decline in the performance of the GPC, and the ground polymer matrix bonding interface determines the fiber to play the effect of their performance, the modulus of elasticity of the fiber to reflect their mechanical properties, the greater the strength of the GPC toughening enhancement is more pronounced.

Keywords: Fiber-reinforced geopolymer composites; Fiber performance parameters; Reinforced toughening.

1. Introduction

Research on green and sustainable building materials is receiving increasing attention as the population grows and global modernization and construction standards continue to be updated. Statistical trends estimate that global cement production will increase from about 4.3 billion tons in 2015 to about 6.1 billion tons in 2050, and the widespread use of cement brings serious problems of pollution and energy consumption while providing convenience [1].

The high production of ordinary silicate cement (OPC) faces the destruction of limestone reserves, large amounts of carbon dioxide emissions (about 7% of global carbon dioxide emissions) [2], the combustion of cement clinker also consumes a large amount of resources, and the generation of electricity produces one ton of fly ash for every two tons of coal consumed, and it also generates large amounts of solid waste. What's more, OPC is more susceptible to erosion in the general environment, and poor erosion resistance directly affects the durability and service life of structural components. In order to reduce greenhouse gas emissions and energy consumption, it is pivotal to develop an environmentally sustainable and high-performance cementitious material to replace OPC from an environmental point of view. As a result, a new type of inorganic cementitious material, geopolymer concrete (GPC), has received more and more attention and has been rapidly developed. Compared with OPC, the production and preparation of geopolymer can reduce about 80% of CO2 gas emissions and 60% of energy consumption [3]. In addition, many studies have analyzed the properties of geopolymer composites (GPCs) and have shown that they have excellent properties such as excellent surface hardness, high early strength, chemical resistance and high fire resistance.

Researchers have found that GPC suffers from the same problems as ordinary concrete, with the intensive study of GPC in recent years, such as apparent brittleness, poor flexural properties, lack of toughness and resistance. These problems can lead to localized cracking, resulting in premature

rusting of reinforcement in structural components, reducing the strength and durability of the component or structure [4, 5]. This can also indicate that GPC is more difficult to be put into applications, and the current research mainly stays at the material level. Adding fibers is one of the most common methods of toughening concrete in the world today, which can improve the toughness, plasticity and flexural strength of concrete, and this composite material consisting of fibers and concrete is called fiber-reinforced concrete (FRC). Fiber can be in the concrete cracks, change the extension orbit of the crack tip, spread out the large cracks predicted to emerge dispersed into the crack field, increase the crack development of energy consumption, and play a certain role in toughening.

In recent years, various types of fibers have been widely used in the reinforcement and toughening of concrete, and there is no lack of fiber research on geopolymer-based concrete. At present, many types of fibers can be used for concrete reinforcement, and the various aspects of the performance parameters of the fibers are also complex and diverse, and many scholars have studied the effects of different properties of the fibers or changes in the parameters on the concrete. The performance of fibers is largely derived from the material properties of the fibers, that is, the types of fibers. Zhao et al. studied on the influence of different fiber types on the bending properties of GPC, and concluded that the reinforcing effect of the end-hooked steel fibers (SF), basalt fibers (BF), and short polyethylene fibers (SPPF) is from high to low in descending order, and that the reinforcing effect of the above types of fibers is reduced to a minimum if they are combined with long polypropylene fibers (LPPF) would show better results [6]. The size and amount of fibers in a certain range can have a greater enhancement on the performance of concrete, Yang et al. investigated the effect of different sizes of polypropylene fibers on concrete beams, using two kinds of polypropylene fine fibers and one type of polypropylene coarse fibers, and found that the performance of only the coarse fibers was enhanced by 8.67%, and that of the three types of fibers blended was enhanced by 17.07% when compared to ordinary reinforced concrete beams [7]. The adhesion of the interface between fibers and geopolymer matrix bond is very important for the overall performance of GPC and also directly determines whether the fibers can perform optimally, Hafizuddin et al. found that the interfacial bond between matrix and fibers depends on the nature of contact area on the surface of the material such as hydrophobicity or hydrophilicity, as well as surface softness or roughness [8]. Chen et al. found that modification of the fiber surface could change the GPC properties, the compressive and flexural strength of GPC specimens of PVA fibers modified by SiO2 hydrophobicity decreased, and the compressive and flexural strength of EGC specimens of PE fibers modified by SiO2 hydrophilicity was improved [9].

At present, many scholars have more in-depth research on the influence of different performance indicators of fibers on geopolymer, but mainly for a single property change on the impact of geopolymer concrete [10], the lack of integration of articles. Therefore, this paper discusses the effects of fibers on the properties of geopolymer concrete from five aspects: type of fiber, size, admixture, bonding interface with concrete matrix and elastic modulus.

2. Effects of fiber type on GPC performance

The changes in the properties of geopolymer composites are more related to the nature of the incorporated fibers themselves. After cracking of geopolymer concrete, the fibers bear tensile stresses inside the concrete, thus limiting the further cracking of the concrete, and thus increasing the tensile properties and toughness of geopolymer composites. In other words, different fiber blending on the performance of geopolymer concrete also has the same characteristics. It could improve the cracking resistance of concrete, but also improve the toughness of the concrete, so as not to produce brittle damage under the action of external loads. The same synergistic effect is also observed for different types of hybrid fibers. The different hybrid fibers form a reticulated structure, which improves the properties of concrete to a certain extent. Therefore, many researchers in China have used fibers to improve concrete and make significant contributions to the development of concrete.

Although different types of fibers have common points in reinforcing geopolymer, they also have different characteristics in terms of surface properties and mechanical properties. Different surface properties directly affect the bond strength between fibers and geopolymer. For example, steel fibers usually have nice good bonding ability and can effectively bond with geopolymers to provide high bond strength, while polypropylene fibers have relatively low bond strength with some geopolymers (e.g., polymer adhesives) due to their low surface energy and chemical stability. Different mechanical properties have different reinforcing effects. For example, steel fibers increase the tensile strength and toughness of geopolymers, glass fibers improve the impact resistance of geopolymers, and carbon fibers provide higher strength and stiffness.

3. Effects of fiber size on GPC performance

Fiber incorporation can effectively improve the properties of GPC such as crack resistance and toughness, and different sizes of fibers affect the mechanical properties of GPC. We generally use the aspect ratio to describe the morphology and geometric characteristics of the fiber, which is the ratio between the length and the diameter of the fiber. It means that a higher fiber aspect ratio means that the fiber is longer and finer.

When the fiber length is longer, its enhancement of the crack resistance of concrete is more obvious, and the fluidity of concrete is significantly reduced, affecting the concrete and anisotropy. When the fiber length is shorter, the effect on the performance of concrete is not obvious enough. Most researchers found that long and fine fibers enhance the best. Finer fibers have a greater performance enhancement on concrete than coarser fibers, and the finer fibers can absorb more energy when the cross-section breaks, thus delaying the breakage of concrete to a greater extent. The strength and toughness of concrete increases with fiber length and fiber number.

The effect of fiber length-to-diameter ratio on the toughness of fiber-reinforced geopolymer is more complex. Within a certain range, an appropriate increase in fiber L/D ratio can increase the toughness of geopolymer, the fiber with a large L/D ratio occupies a large specific surface area in the fracture cross-section of the concrete, the larger the fiber specific surface area, the more the fiber can absorb the fracture energy when the concrete is fractured, and the greater the enhancement of the concrete properties. However, when the fibers are too thin and long, it is easy to have fiber fracture, resulting in a decrease in the overall toughness of the ground polymer.

4. Effects of fiber dosage on GPC performance

The effect of fiber admixture on the performance of GPC is very significant, a certain amount of fiber admixture can improve the crack resistance of GPC and increase toughness, but with the increase of fiber admixture, the performance of concrete is not necessarily better.

Increasing the fiber dosage can effectively prevent crack propagation, enhance the damage tolerance of the material, and significantly improve the strength and stiffness of the fiber geopolymer. Fibers, as reinforcing materials, can be uniformly distributed in the geopolymer matrix and assume the role of resisting external loads. With the increase of fiber admixture, the compressive strength of fiber-reinforced concrete is basically unchanged, and the tensile strength and toughness are significantly improved. The increase in fiber dosage can also increase the number of fibers and distribution area, and elevate improve the toughness and energy absorption capacity of fiber geopolymer. Fibers can effectively disperse stresses when loaded, and absorb and dissipate energy to prevent crack expansion.

However, there is an optimum parameter for fiber admixture, and when the volume rate of the optimum fiber admixture is exceeded, the performance of concrete tends to decrease. Fiber is a rigid material, and its addition reduces the plasticity and deformability of the ground polymer. Especially at high fiber dosage, the plasticity of the material is significantly reduced, which makes the molding and deformation of the material limited and may lead to an increased risk of brittle fracture.

5. Effects of fiber-concrete bonding interface on GPC performance

The fiber-GPC bonding interface is the contact surface and interaction region between the fibers and the concrete matrix. At this interface, physical and chemical interactions occur between the fibers and the geopolymer, which affect the enhancement of concrete properties by the fibers. Bond strength is the strength of the adhesion and interaction between the fibers and the concrete matrix. Excellent bond strength ensures a strong connection between the fibers and the geopolymer matrix, enabling the fibers to effectively transfer stresses and serve to enhance the properties of concrete. Insufficient interfacial bond strength will result in slippage between the fibers and the concrete, affecting the concrete properties. The interfacial bond between the matrix and the fibers depends on the nature of the surface contact area of the material, such as hydrophobicity or hydrophilicity, and the softness or roughness of the surface. The nature and quality of the fiber-GPC bond interface directly affects the mechanical properties, durability and overall performance of fiber-reinforced concrete.

The interaction and bond strength between the fibers and the concrete matrix can enhance the tensile strength and ductility of concrete. A well-bonded fiber-geopolymer interface prevents the fibers from detaching or breaking in the concrete, thus improving the tensile properties of the concrete.

The bonding interface between fibers and concrete matrix is related to the durability of concrete. A well-bonded fiber-geopolymer interface can resist fiber shedding and matrix damage caused by environmental and oxidative effects. In addition, excellent interfacial properties also help to reduce cracking and bursting of concrete and improve the durability of concrete

Better interface can improve the impact and crack resistance of concrete: As fiber-reinforced concrete is subjected to external impact or load, the fibers can play a role in absorbing energy and dispersing stress, thus reducing cracks and fracture of concrete. A good fiber and geopolymer bonding interface can effectively fix the fibers in the concrete, enhance its resistance to loads, and enhance the impact and crack resistance of concrete.

Bonding interface improves the fatigue performance of concrete: The fatigue performance of fiber-reinforced concrete depends on the strength of the bond between the fibers and the concrete matrix and the arrangement of the fibers. A well-defined fiber-geopolymer bonding interface can keep the position of the fibers stable and prevent fiber displacement and fracture, thus maintaining the strength and durability of the concrete over multiple load cycles

In summary, the nature and quality of the fiber-geopolymer bonding interface has a significant impact on the performance of fiber-reinforced concrete, and together they contribute to the overall performance and durability of the concrete.

6. Effects of elastic modulus of fibers on GPC performance

The modulus of elasticity of a fiber is a measure of how much the fiber deforms after being subjected to a force, specifically the ratio between stress and strain per unit area. Modulus of elasticity is measured in pascals (Pa) or megapascals (MPa). In practice, MPa is commonly used as the unit of modulus of elasticity. The modulus of elasticity can reflect the stiffness and deformation characteristics of the fiber, and is an important parameter to measure the fiber's ability to resist bending and tensile deformation. The modulus of elasticity of fibers depends on the material and structure of fibers. Common fiber materials such as glass fibers, carbon fibers, and polymer fibers, have different moduli of elasticity. It is important to note that the modulus of elasticity of a fiber is an idealized parameter, assuming that the fiber is able to fully recover to a stress-free state after being stressed. However, in practice, fibers may undergo a certain degree of plastic deformation and fatigue damage, which may result in a change in the modulus of elasticity of the fibers. Therefore, factors such as durability and fatigue life of fibers also need to be considered in engineering design and practical applications.

The elastic modulus of fibers influences the performance and properties of GPC geopolymers, and suitable fiber materials and designing the ratio of fibers to geopolymers can optimize the mechanical properties, shape stability, and energy absorption capacity of GPCs. Higher modulus of elasticity of

fibers can effectively enhance the stiffness and strength of geopolymer. When fibers have a high modulus of elasticity, they are better able to carry loads and resist deformation, thus improving the mechanical properties of geopolymers. The modulus of elasticity of fibers also determines the deformation behavior of geopolymer when subjected to force, and a higher modulus of elasticity of fibers can make geopolymer more rigid when subjected to force and reduce the degree of deformation and creep. For the interfacial bonding properties between fibers and geopolymer, lower fiber elastic modulus may lead to stress concentration between fibers and geopolymer as well as interfacial shear failure, which reduces the strength of interfacial bonding and adhesion.

7. Conclusion

The addition of fibers affects the performance of GPC in many ways. Fibers can improve the tensile strength of GPC, bear and disperse stress, prevent cracks from arising and expanding, and increase the toughness and ductility of GPC. It forms bridges in concrete, absorbs energy and delays the development of cracks, improves the deformation capacity, crack resistance, durability, and fatigue properties of concrete, controls the width and length of cracks, prevents cracks from expanding, and improves the life of the material.

The type of fiber decisively influences the mechanical properties of the fiber and the nature of the fiber surface, but also directly related to the modulus of elasticity of the fiber. Different kinds of fibers produce different degrees of enhancement of the toughening effect on the ground polymer concrete. Brittle fibers can improve the strength of the concrete but are difficult to improve the ductility of the concrete. Good toughness of the hydrophobic fibers can better improve the toughness of the concrete, but the bond interface with the matrix is prone to slip.

For fiber size, fibers with a larger L/D ratio such as slender fibers, tend to improve the performance of geopolymer concrete better. Fibers with a larger L/D ratio occupy a larger specific surface area in the fracture cross-section of the concrete and therefore absorb more energy, thus improving the performance of the concrete. However, if the fibers are too thin and long, the fibers are prone to fracture, which leads to a decrease in the overall toughness of the geopolymer.

Based on the fiber can make the ground polymer concrete enhanced toughness characteristics, the appropriate increase in fiber mixing can significantly improve the strength and stiffness of fiber ground polymer, effectively prevent crack propagation, and enhance the damage tolerance of the material. However, too high fiber dosage may lead to reduced fluidity of the concrete, and the local agglomeration of fibers in the concrete, increasing the difficulty of concrete casting while reducing the mechanical properties of the concrete.

The bond interface between the fibers and the geopolymer concrete is critical to the overall strength of the fiber concrete. Good bond strength ensures a strong connection between the fibers and the geopolymer matrix, allowing the fibers to effectively transfer stresses and serve to enhance the properties of the concrete. Insufficient interfacial bond strength can lead to slippage between the fibers and the EGC and reduce the performance of the EGC. Overall, the nature and quality of the fiber-GPC bond interface directly affects the mechanical properties, durability and overall performance of fiber-reinforced GPC.

The higher elastic modulus of fibers can effectively enhance the stiffness and strength of GPC. When fibers have a high modulus of elasticity, they are better able to carry loads and resist deformation, thus improving the mechanical properties of the ground polymer. The modulus of elasticity of fibers also determines the deformation behavior of geopolymers when subjected to forces.

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