Current Research Status of Mechanical and Electrical Properties of Geopolymer Concrete

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Abstract

In order to accelerate the development of new productive forces and achieve sustainable development, using land polymers instead of cement as cementitious materials has become a current research hotspot. Adding other materials to geopolymers can enhance their conductivity and make them a new type of intelligent material. This article combines the current research status at home and abroad to introduce the research status of geopolymer concrete from three aspects: mechanical properties, electrical conductivity, and numerical simulation.

Keywords

Geopolymer; Mechanical Properties; Electrical Performance; Numerical Simulation.

1. Introduction

During the 14th Five Year Plan period, China's ecological civilization construction has entered a strategic direction with carbon reduction as the focus. At the same time, in order to accelerate the development of new quality productive forces, it is necessary to solidly promote high-quality development. In China's engineering construction, cement is an essential material, and the calcination of one ton of cement clinker will produce 0.95 tons of carbon dioxide, affecting the ecological environment. Therefore, reducing the use of cement and developing new types of cementitious materials have significant implications for achieving carbon peak and carbon neutrality.

Geopolymer is a new type of inorganic cementitious material that is activated by alkaline activators, rich in minerals such as silicon and aluminum, and has a three-dimensional network structure in space. Geopolymer cementitious material is a good green cementitious material that conforms to the concept of sustainable development. It has a wide range of raw material sources and can effectively utilize solid waste.

At present, the research and application of intelligent concrete has become a hot research topic of concern for many scholars [1]. Conductive geopolymer, as a new type of intelligent material, can play an important role in structural damage monitoring, building structure insulation and heating, snow and ice removal of highways and bridges, and other projects.

2. Research on the Mechanical Properties of Polymer Composite Materials in Engineering Sites

In 1972, French scientist Davidovits published the first patent on geopolymers in 1975 using kaolin and quartz as substrates in the laboratory, thus pioneering modern research on geopolymers.

In the 1980s, Davidovits continued to conduct detailed research on the internal structure of geopolymer materials [2], believing that it was a new type of inorganic silica alumina cementitious

material with a three-dimensional network like bonding structure similar to organic polymer space, prepared by mixing active low calcium silica alumina materials with alkaline activators under curing conditions below 150 ℃. Since then, geopolymers have begun to enter the field of research in building materials.

In the early 21st century, Chinese scholars began to study geopolymers. Sha Jianfang et al. from Southeast University [3] prepared geopolymer cement using metakaolin and fly ash as raw materials through alkali excitation, and studied the effect of different fly ash contents on mechanical properties. The results showed that at a dosage of 30% fly ash, the compressive strength and flexural strength of geopolymer cement were both improved. However, the proportion of alkali activator in the geopolymer cement prepared by this method is not clearly specified. The appropriate alkali activator and its proportion are the key to preparing high-performance geopolymers. Therefore, Fu Xinghua et al. [4] used high-temperature calcined clay as a cementitious material to prepare geopolymers, and studied the effects of water glass modulus, calcination temperature, alkali content, and other factors on the properties of the cementitious material. The results showed that when the modulus of the alkali activator was 1.3 and the alkali content was 6-8%, the geopolymer specimens showed the best performance, with high compressive strength, superior acid resistance, sulfate resistance, seawater erosion resistance, and high temperature resistance.

To verify the acid resistance, sulfate resistance, seawater erosion resistance, and high temperature resistance of geopolymers, a series of studies have been conducted by foreign scholars. Foreign scholar M Olivia conducted a wet dry cycle test and compared it with ordinary concrete (using a 3.5% NaCl solution). The test results showed that after the wet dry cycle, the mass loss rate of fly ash geopolymer concrete specimens can be basically ignored, and the mechanical properties are also relatively small, while the mass loss of ordinary concrete is relatively large [5]. Meanwhile, April and Roy Alvin J [6] used fly ash as a cementitious material to prepare fly ash geopolymers, which were then soaked in a 5% concentration sulfate solution for 28 days. The results showed that the prepared geopolymers had strong acid resistance and significantly improved unconfined compressive strength. Grorge Mathew and Benny Joseph [7] analyzed and studied the microstructure of fly ash based polymers under high temperature conditions. They used various analysis methods such as FTIR, XRD, TGA, and SEM to analyze the microstructure of geopolymer mortar and paste specimens under conditions of 200-800 degrees Celsius, and compared the quality loss characteristics of geopolymer mortar and ordinary Portland cement mortar under high temperature environment.

In recent years, scholars such as Sindhunata have conducted in-depth research on the various components of geopolymer cementitious material systems, their roles and effects, and explored the reaction mechanisms of geopolymers [8]. Long Tao et al. [9] prepared fly ash geopolymer concrete and analyzed the experimental results, which showed that geopolymer concrete using recycled aggregates had higher strength than ordinary concrete. From a microscopic perspective, geopolymer concrete can effectively fill the pores between recycled aggregates. Liu Leping et al. [10] prepared geopolymers using slag as raw material and solid water glass as alkali activator, and conducted in-depth research on the setting time and compressive strength of geopolymers at different water cement ratios. The experimental results show that an increase in water cement ratio will delay the setting time of geopolymers and reduce their compressive strength.

3. Conductivity of Polymer Composite Materials in Engineering Sites

3.1 Conductivity Principle

Ordinary concrete has high insulation resistance and generally does not have electrical conductivity. By adding a certain amount of conductive material during the preparation of concrete, the internal structure of the specimen can be changed to achieve good electrical conductivity. The conductivity mechanism of conductive composite materials can be mainly divided into three types: ion conductivity, tunneling effect, and particle conductivity [11]. See Figure 1 below.

During the preparation process of conductive concrete, a large number of ions, such as Ca2+, K+, Na+, OH -, SO42- ions, are released internally due to hydration. By applying an external electric field, the internal ions undergo directional movement to achieve conductivity, which is called ion conduction [12].

The conductive materials added to concrete mainly transmit electrical energy through tunneling effect. Some of the conductive materials overlap and come into contact with each other during the curing process of the specimens, forming a conductive network inside. These conductive materials have a significant effect on improving the conductivity of concrete.

Another part of the conductive materials did not form effective overlap inside during the dispersion and doping process, but the distance between particles was very close. Under the continuous action of an external electric field, electrons could obtain sufficient energy to penetrate the membrane between the conductive materials and form a conductive network through the directional movement of electrons [13].
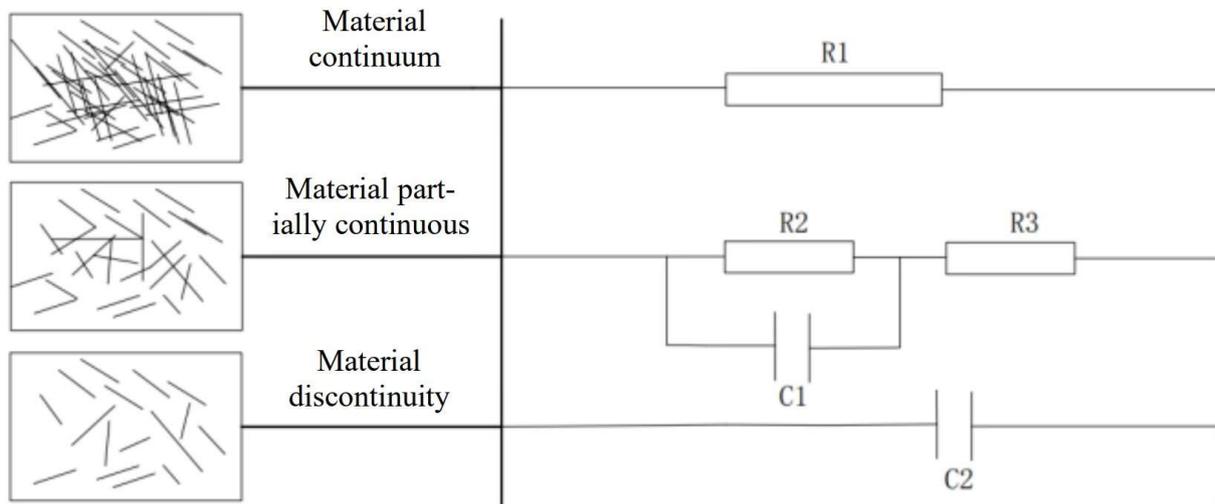

Figure 1. Conductivity Mechanism Model of Conductive Composite Materials

The conductivity of tunnel conduction σ_C can be expressed as:

$$\sigma_C = \sigma_R \, exp(\frac{-K_1}{T+K_0}) \tag{1}$$

Among them:

σ_R — The conductivity of the conductive particles;

T — External temperature value (℃);

K0, K1 — are constants related to the thickness and properties of the material between conductive particles.

The conductive conductivity σ_c of composite material particles can be expressed as:

$$\sigma_C = \frac{6\sigma_R r}{l}(\frac{3l}{d} - 2)(V_R - \frac{4d}{3l}) \tag{2}$$

$D -$ *particle size of conductive particles;*

$V_R -$ *volume fraction of conductive particles*;

$l -$ *characteristic length of the dispersion degree between particles*;

$r -$ *represents the contact radius between conductive particles*.

3.2 Research Status of Conductivity and Application of Geopolymer Composite Materials

In recent years, scholars have made significant progress in the continuous research of geopolymers, which has promoted the innovative application and development of geopolymers in the field of smart materials. By comparing with traditional cement-based materials, it has been found that geopolymers doped with conductive materials have better conductivity [14]. P. Payakaniti et al. [15] studied the conductivity of carbon fiber fly ash based polymers using three methods: I-V curve measurement, cyclic voltammetry, and electrochemical impedance spectroscopy. They found that when the carbon fiber content was higher than the threshold, the conductivity of the sample depended on the carbon fiber content.

It can be seen that due to the low electrical resistivity of geopolymer itself, it is an ideal matrix material for preparing conductive concrete. The excellent conductivity of geopolymers has led researchers to explore their pressure-sensitive and electromagnetic shielding properties.

S. Vaidya et al. [16] believe that conductive geopolymers can be used for health monitoring of building structures. By incorporating carbon fiber into geopolymers and ordinary Portland cement concrete (OPC concrete), and comparing their changes in conductivity, it was found that carbon fiber geopolymers have better performance in conducting current than carbon fiber OPC concrete. However, no experimental research has been conducted on the piezoresistive properties used for structural health monitoring.

Liu Weisen et al. [17] measured the conductivity of alkali excited conductive mortar and cement mortar using four electrode voltammetry, and found that the electrical resistivity of carbon fiber geopolymer was one order of magnitude lower than that of carbon fiber cement, and the reproducibility of pressure-sensitive performance was better. V. V. Nguyen et al. [18] studied the effect of carbon mesh on the electromagnetic shielding of polymers in metakaolin bases. The experimental results showed that carbon mesh not only improved the mechanical properties of geopolymer composite materials, but also reduced the electromagnetic field strength. Liu Wanshuang et al. [19] prepared polymer composites by modifying conductive fillers with organosilicon, alkaline solutions, and aluminosilicate materials. The experimental results show that the electromagnetic shielding function of the geopolymer composite material is excellent.

Previously, carbon fiber has been the main conductive material in geopolymers due to its excellent mechanical properties and electrical conductivity. However, researchers have explored various other types of conductive materials and applied them to geopolymers.

J. L Rovis [20] proposed a model for the reaction mechanism of geopolymers and pointed out that alkali activators play a catalytic role in the polymerization reaction. After the reaction, they exist in large quantities inside the material, resulting in a higher ion concentration of geopolymers than cement-based materials and better conductivity. As a result, Mizerov á C [21] found that an increase in carbon nanotube content enhances the conductivity of the composite material. When the content exceeds 0.15%, CNTs are prone to aggregation and are unevenly dispersed in the matrix, resulting in a slight decrease in the compressive strength of the sample. To solve the problem of CNTs aggregation, Lu Hui [22] used two methods: mechanical stirring and adding carbon nanotube water dispersant to achieve uniform dissolution of carbon nanotubes. Research has found that specimens doped with carbon nanotubes have better pressure sensitivity than graphite specimens. And when the two are mixed, carbon nanotubes play a major role and exhibit good pressure sensitivity. P. When Rovnanik et al. [23-24] studied the piezoresistive effect of graphite modified fly ash based conductive geopolymers, they pointed out that the conductivity and pressure-sensitive properties of alkali activated slag mortar were superior to those of cement mortar. O. Zturk et al. [25] applied loads to polymer beams of carbon nanotubes and carbon black to study the pressure-sensitive self sensing

function of composite materials, and found that polymer beams of carbon nanotubes were more sensitive to stress.

4. Numerical Simulation of Polymer Composite Materials in Four Regions

In the past five years, with the rise of various numerical simulation software, researchers have explored the properties of polymer composites under more complex conditions through this tool. Zhu [26] used ABAQUS finite element software to numerically simulate the mechanical properties of geopolymer mixing pile composite foundation under different area replacement rates. The results showed that the settlement deformation, pile top stress, surface pile-soil stress, and pile-soil stress ratio obtained from the numerical simulation were in good agreement with the model test values, and the rules were consistent. To verify the performance characteristics of geopolymer materials under dynamic loads, Chen [27] revealed the dynamic failure process and mechanical characteristics of the plate through experimental and numerical studies of the response under loads, and derived empirical formulas to predict the dynamic stamping resistance of reinforced GPC plates. Yin [28] used particle flow numerical simulation software (PFC3D5.0) to simulate the entire process of three-point bending failure of alkali slag red mud geopolymer (AS-RG). The results showed that adding an appropriate amount of polypropylene fibers can effectively improve the flexural strength of AS-RG, and with the increase of fiber length, the material's resistance to instability and damage will improve. The fiber length first strengthens and then weakens with the increase of water cement ratio, and finally decreases. Wang [29] conducted numerical simulations of geopolymer solidified aeolian sand using particle flow software PFC3D. The results showed that for geopolymer solidified aeolian sand, an increase in viscosity made the sample denser and improved the shear strength of the solidified soil sample; The increase in viscosity gradually dominates the shear stress between particles, and the soil transitions from brittle failure with multiple cracks to shear failure with obvious shear bands.

At present, there are many studies on numerical simulation of concrete, but there is very little research on numerical simulation of geopolymer concrete, including numerical simulation of conductive geopolymer composite materials, which urgently needs to be explored by scholars.

5. Conclusion

It is particularly important to address the issue of harmonious coexistence between humans and nature in order to ensure the sustainable development of our country's economy. Geopolymer, as a new type of green building material, has attracted widespread attention. Its raw materials come from a wide range of sources, most of which are industrial waste. Adding conductive materials to enhance its conductivity can effectively achieve a win-win situation of economic and ecological benefits. With the continuous advancement of scientific research and technology, conductive geopolymers are expected to become a new type of material for modern architecture and infrastructure construction.

Meanwhile, as an emerging material, geopolymer concrete lacks unified standardized specifications in production due to its diverse raw material characteristics and varying proportions of alkali activators, which to some extent limits its application in practical engineering. In addition, there is relatively little research on the application of its conductivity. Therefore, further exploration of the mechanical and electrical properties of geopolymer materials is of great significance for whether they can be widely applied in engineering practice.

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