A Review of Research on the Smart Performance of Geopolymer Concrete

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Abstract

To achieve the goals of energy conservation, emission reduction, and sustainable development, geopolymer concrete, as an emerging green building material, has garnered widespread attention. By incorporating conductive materials, its electrical conductivity can be significantly enhanced, thereby transforming it into an innovative smart material. This paper provides a comprehensive review of the current research status, both domestically and internationally, on the smart properties of conductive geopolymer concrete. Specifically, it covers the conduction mechanism, piezoresistivity, thermosensitivity, hygrosensitivity, electromagnetic shielding, and electrothermal characteristics of geopolymer conductive concrete, as well as the research progress in numerical simulation.

Keywords

Geopolyme; Conduction Mechanism; Smartness; Numerical Simulation.

1. Introduction

Geopolymer, as a novel environmentally friendly inorganic cementitious material, has garnered significant attention in the field of building materials in recent years. Since its initial proposition by French scientist Davidovits in 1978, geopolymer has emerged as a crucial candidate for replacing traditional Portland cement due to its unique chemical and physical properties. Geopolymer concrete not only boasts a low carbon dioxide emission profile during its production process but also effectively utilizes industrial solid wastes, thereby offering promising prospects for applications in sustainable development. By incorporating conductive phase materials, the electrical conductivity of geopolymer concrete is significantly enhanced. This not only preserves the inherent durability and robustness of the structural material but also enables intelligent monitoring, autonomous regulation, and even self-repair of internal structural damages through its intrinsic conductive network, thus ensuring the long-term stability and safety of structures. As a new type of smart material, conductive geopolymer concrete has found widespread applications in projects such as structural damage monitoring, thermal insulation and heating in building structures, as well as snow and ice melting on highways and bridges[1].

2. Conduction Mechanism of Conductive Geopolymer Concrete

Conductive geopolymer concrete is a novel type of conductive composite material fabricated by incorporating conductive phase materials or conductive polymers into a geopolymer matrix through physical or chemical compounding processes. These materials can be broadly categorized into two types: one type comprises inherently conductive polymeric materials, while the other type involves uniformly dispersing conductive fillers within an insulating polymeric matrix to form a composite conductive system. The conduction mechanisms in such materials primarily arise from the synergistic effects of percolation theory, effective medium theory, tunneling effect, and electric field emission theory.In conductive geopolymer concrete, the conductive phase materials or polymers create a conductive network within the geopolymer matrix. When the concentration of conductive fillers reaches a certain threshold, known as the percolation threshold, a continuous conductive pathway is formed throughout the material, enabling the flow of electric current. This phenomenon is explained by percolation theory, which describes the transition from an insulating to a conductive state as the filler concentration increases.Effective medium theory, on the other hand, provides a framework for predicting the electrical conductivity of composite materials by considering the properties of the individual components and their interactions within the matrix. It assumes that the composite can be treated as a homogeneous medium with an effective conductivity that depends on the volume fraction, shape, and distribution of the conductive fillers.The tunneling effect plays a significant role in conductive geopolymer concrete, especially at low filler concentrations or when the conductive particles are not in direct contact. In this case, electrons can tunnel through the insulating barrier between adjacent particles, contributing to the overall conductivity of the material. The probability of tunneling depends on the distance between particles, the energy barrier height, and the applied electric field.Lastly, electric field emission theory suggests that under high electric fields, electrons can be emitted from the surface of conductive particles and travel through the insulating matrix to other particles, thereby facilitating electrical conduction. This mechanism becomes more prominent at high voltages or in materials with a high aspect ratio of conductive fillers.Collectively, these theories provide a comprehensive understanding of the conduction mechanisms in conductive geopolymer concrete, guiding the design and optimization of such materials for various applications in smart infrastructure systems.

2.1 Percolation Theory

Percolation theory primarily explains the relationship between resistivity and filler concentration. When the filler concentration is low, the filler particles are merely isolated and dispersed within the matrix, unable to form a continuous conductive network. However, as the filler concentration reaches a certain level, the distance between filler particles shortens, eventually leading to the formation of a continuous conductive network and thus enabling electrical conduction[1-2]. Percolation theory only provides a macroscopic understanding of the conductive phenomena in composite conductive materials, without delving into the microscopic essence of conductivity.Liu Chengcen[3] applied percolation theory to the mechanism of conductive composites and highlighted the discrepancies between theoretical models and actual research systems.

2.2 Effective Medium Theory

Effective medium theory posits that conductive phase materials form a conductive network by either coming into contact with each other within the matrix or being spaced closely enough to create channels for electron transport. It further elucidates that the conductive percolation threshold of the composite system is related to the types of geopolymer and conductive fillers. Through theoretical calculations, the content of conductive fillers required to reach the percolation threshold can be predicted. Compared to percolation theory, effective medium theory is more applicable when the volume fraction of filler particles is small[4]. Nevertheless, in certain scenarios, percolation theory and effective medium theory can be combined to provide a more comprehensive understanding and prediction of the conductive properties of composite materials. Wang Chengcheng[5] mentioned that Mclachlan's Generalized Effective Medium (GEM) equation integrates both theories.

2.3 Tunneling Effect Theory

In scenarios where conductive fillers do not establish direct contact with one another, electrons or ions can still be transmitted between them through a quantum mechanical phenomenon known as the "tunneling effect." This phenomenon typically manifests when the distance between conductive fillers is exceedingly small, often on the nanometer scale. The current density associated with the tunneling effect can be mathematically expressed as follows:

$$\mathrm{j}(\varepsilon) = \mathrm{j}_0 \exp\left[-\frac{\pi x w \left(\frac{|\varepsilon|}{\varepsilon_0} \right)^2}{2} \right] \tag{1}$$

Among them:

$\mathrm{j}(\varepsilon)$ is the gap voltage of ε ;The tunnel current when the gap equivalent conductivity is j_0 ;

w is the gap width;

$|\varepsilon|$ represents the gap electric field intensity;

ε_0 is a constant related to the material;

x and others are other parameters related to the material properties and experimental conditions.

2.4 Electric Field Emission Theory

Van Beek proposed the electric field emission theory, which suggests that when conductive phase particles are distributed within a non-conductive geopolymer matrix with small gaps between them and do not come into direct contact, a significant electric field emission phenomenon can be triggered under the influence of a sufficiently strong externally applied electric field. This strong electric field effect between the conductive phase particles facilitates the transmission of electric current[6].

The current density associated with the electric field emission theory can be expressed as:

$$\mathrm{j} = AE^{\mathrm{n}} \exp\left(-\frac{B}{E} \right) \tag{2}$$

E is the current intensity;

A is the tunnel frequency;

n and B are other parameters related to the material properties and experimental conditions.

3. Smartness of Geopolymer Concrete

3.1 Pressure-sensitivity

The piezoresistive property is a significant functional characteristic of conductive geopolymer concrete. When external loads are applied to geopolymer concrete, the internal conductive network structure undergoes alterations. As the load increases, the distance between conductive particles gradually decreases, leading to more unobstructed conductive pathways and a reduction in resistivity. This, in turn, indirectly reflects the changes occurring within the concrete's internal structure. Consequently, conductive geopolymer concrete can function as a highly sensitive pressure-sensing device, capable of real-time monitoring and feedback on the pressure states experienced by the structure.

Ding Yong[7]conducted piezoresistive tests under uniaxial compression by incorporating graphite and steel slag into polymers. The results demonstrated that, during uniaxial compression, the resistance of geopolymer concrete containing graphite and slag increased with strain, exhibiting a consistent monotonic behavior throughout the process, suggesting its potential as a sensing material. Ma Bin[8] investigated fiber-modified geopolymers and discovered that the piezoresistive property of geopolymers initially increased and then decreased with an increase in carbon fiber content, reaching its optimal performance when the volume fraction of carbon fibers reached 0.4%. In contrast, basalt fibers had an inhibitory effect on the piezoresistive property of geopolymers. Öztürk Oğuzhan[9] applied loads to geopolymer beams reinforced with carbon nanotubes and carbon black under normal temperature curing conditions to study the piezoresistive self-sensing capabilities of the composite materials. They found that the geopolymer beams reinforced with carbon nanotubes exhibited higher sensitivity in responding to stress.

3.2 Temperature Sensitivity

Temperature sensitivity refers to the characteristic where the resistivity of a material undergoes significant changes in response to variations in the external temperature. The conduction mechanism in conductive geopolymer concrete is such that as the temperature rises, the thermal motion of ions or electrons within the concrete intensifies. This leads to more unobstructed conductive pathways, resulting in a decrease in resistivity and an increase in electrical conductivity. Conversely, when the temperature drops, the resistivity increases, and the electrical conductivity decreases.Therefore, in the field of intelligent buildings, the temperature sensitivity of conductive geopolymer concrete can be utilized to fabricate temperature sensors or thermal control systems, enabling real-time monitoring and regulation of the internal temperature of buildings.

Emugeetu[10] studied the relationship between the compressive strength, elastic modulus, peak strain, and ambient temperature of polymer-modified concrete with different proportions of polyacrylate emulsion added. The results indicated that the temperature sensitivity of geopolymer concrete showed a significant positive correlation with the polymer-to-cement ratio.Liu Libing[11] employed an electrostatic self-assembly method to deposit carbon nanotubes onto basalt fibers. During the melt-mixing process with poly(arylene ether nitrile), strong shear forces were applied, and the resistance and acoustic emission were measured in real-time. The findings revealed that basalt fiber-reinforced geopolymer composites exhibited a low percolation threshold, high electrical conductivity, and high mechanical properties, along with damage self-sensing and temperature-sensitive characteristics.

3.3 Humidity Sensitivity

The humidity sensitivity of geopolymer concrete is primarily based on the characteristic that its resistivity changes with humidity. When the concrete is in a moist state, the number of mobile ions increases, leading to a decrease in the concrete's resistivity. This change in resistivity can be monitored through an external circuit, enabling real-time monitoring and early warning of the internal humidity of the concrete.

Lorena Biondi[12] utilized electrochemical impedance spectroscopy and equivalent circuit models to understand and optimize the electrical response of low-calcium fly ash-based geopolymer sensors to water content and temperature. Their study demonstrated the feasibility of using geopolymers for humidity sensing, which can be applied to monitor the health condition of concrete structures.Jia Gao[13] investigated a new type of conductive geopolymer based on fly ash and modified with carbon fibers. They studied various factors affecting the resistivity and found that short-cut carbon fibers enhanced the electrical conductivity and mechanical properties of the geopolymer concrete, as well as its sensitivity to temperature, pressure, and humidity.

3.4 Electromagnetic Shielding

The electromagnetic shielding principle of geopolymer concrete primarily relies on the addition of conductive fillers into geopolymer concrete. These conductive fillers form a conductive network within the geopolymer matrix. When a magnetic field passes through, the conductive fillers can generate induced currents, thereby achieving a shielding effect on the magnetic field.

Liu Wanshuang[14] formulated a geopolymer composite material by combining aluminosilicate minerals, alkalis, water, and organosilicon-modified conductive fillers. They found that the prepared geopolymer composite material exhibited excellent electromagnetic shielding performance.Dimuthu Wanasinghe[15] systematically investigated the influence of fiber morphological parameters on the electromagnetic shielding effectiveness of the material through four ratio schemes involving the incorporation of carbon fibers of three different lengths. The experimental results indicated that the shielding effectiveness of the material was significantly positively correlated with the fiber length and dosage. Among them, the 12 mm carbon fibers achieved the best shielding level at an optimal dosage of 0.7%. Nguyen Van Vu[16] studied the effect of carbon mesh on the geomagnetic shielding of geopolymer composite materials. The research results showed that the carbon mesh not only enhanced the mechanical properties of the geopolymer composite materials but also reduced the electromagnetic field.İlker Tekin[17] examined the impact of geopolymer composite materials reinforced with polypropylene fibers, steel fibers, carbon fibers, and ZnO powder on electromagnetic shielding effects. The experimental results demonstrated that the synergistic effect of carbon fibers and a 10% ZnO dosage could achieve the optimal electromagnetic shielding performance.

3.5 Electrothermal Properties

The electrothermal characteristics of geopolymer concrete refer to the phenomenon where a certain proportion of conductive phase materials are incorporated into geopolymer concrete. When an external power source is connected, an electric current passes through the conductive network within the geopolymer concrete. According to Joule's law, the conductive phase materials and the surrounding medium generate a significant amount of heat. As a result, geopolymer concrete with electrothermal properties is widely applied in various fields, such as road snow and ice melting, building heating, industrial heating, and precise temperature control.

Zhang Yajun[18-19] systematically investigated the electrothermal behavior of geopolymer concrete under the influence of different conductive phase materials or applied electric fields. The results revealed that, at low voltages, carbon fibers, graphite, and their composite systems can all form stable conductive networks. Higher voltages lead to larger peak currents and a decrease in electrical conductivity. An increase in the graphite content enhances the thermal conductivity of the material. Moreover, the effects of rapid geopolymer setting under high voltages and slow setting under low voltages on the pore structure are significantly different. Jabbar M S[20] conducted research on the multi-scale design of geopolymer matrices with ultra-high graphite content. The study found that when the graphite content is 90% and the water content is 57 ml, the material exhibits high compressive strength and stable electrothermal properties. Additionally, the deterioration of the electrothermal performance of graphite/geopolymer composites can be addressed through washing.

4. Numerical Simulation of Geopolymer Concrete

In recent years, with the rise of numerical simulation software technology, many scholars have conducted systematic research on the smart properties of geopolymer concrete using numerical simulation tools. Wang Dongyang[21] utilized ANSYS finite element software to analyze the temperature field of metakaolin-based rolled geopolymer concrete and obtained its temperature field distribution. The research results indicated that the data derived from finite element simulation were in good agreement with the experimental results. Therefore, the ANSYS finite element analysis method can accurately simulate the transient temperature field of geopolymer concrete. Domenico F[22] investigated the temperature distribution and thermal properties of geopolymer concrete with or without fiber incorporation during transient charging and discharging cycles using the finite element method (FEM). The study demonstrated that the incorporation of fibers into geopolymer concrete could enhance its heat storage capacity.Wang Kai[23] conducted a numerical study on the chloride ion penetration behavior of saturated geopolymer concrete under an applied electric field. The research findings revealed that the average chloride ion penetration depth obtained from numerical simulation was consistent with the experimental values. Yu Sheng[24] employed COMSOL simulation software to perform thermal simulations to verify the thermal insulation performance of a geopolymer-based foam concrete roof insulation system. The results indicated that the geopolymer-based foam concrete roof insulation system exhibited excellent thermal insulation performance, and the thermal conductivity derived from numerical simulation was in good agreement with the experimental results.

Currently, there is a wealth of research on freeze-thaw numerical simulation in the field of concrete. However, exploration into the smart properties of geopolymer concrete remains relatively scarce. The potential and significance of this area warrant in-depth investigation and research by numerous scholars.

5. Conclusion

To promote sustainable development and enhance the quality of life, geopolymer concrete, as a novel green building material, stands out due to its widely available raw materials and its ability to effectively utilize industrial waste, thereby reducing environmental pollution. By incorporating conductive phase materials, the smart properties of geopolymer concrete can be significantly enhanced. This not only allows it to be used as a traditional building material but also enables it to serve as an integral part of structural health monitoring systems, facilitating real-time monitoring of structural conditions and damage, thus ensuring structural safety. Geopolymer concrete holds great promise as a multifunctional, environmentally friendly, and cost-effective new type of building material.

Furthermore, despite being a cutting-edge building material, geopolymer concrete currently lacks unified and standardized operational guidelines in its production process, which to some extent restricts its widespread promotion and application in various engineering fields. Additionally, the research on the smart properties of conductive geopolymer concrete faces challenges in terms of the stability of electrical conductivity, material selection and dispersibility, long-term performance, as well as construction and application aspects. Consequently, more time and effort need to be invested in in-depth research to fully leverage the performance advantages of geopolymer concrete.

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