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Research Progress on Electrical Properties of Self-sensing Concrete

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

In order to effectively avoid the different degrees of impact and damage to the existing buildings and structures, it is particularly important to strengthen the health detection of such structures and facilities, which is also an important research field in the development of green building discipline. Smart concrete is both structural and functional, and has the potential of self-monitoring of concrete structures. This paper reviews the basic concepts of self-sensing concrete, including the research progress of self-sensing concrete materials, and summarizes the classification of different conductive phase materials and their conductive properties. Secondly, the basic mechanical properties and electrical properties of self-sensing concrete are discussed. The factors affecting the perceptual performance of self-sensing concrete considered by different scholars are summarized. It is concluded that few scholars have studied the mechano-electric interaction evaluation mechanism that takes the electrical parameters into account the stress, strain, crack or damage of concrete, and evaluates mechanical properties and crack propagation length through the change of electrical signals. Finally, the importance of self-sensing performance of intelligent concrete is emphasized, and the prospect of future research is put forward.

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1.INTRODUCTION

Building materials such as nuclear power plants, dams, residential buildings, roads and tunnels are exposed to heavy loads and harsh environments, leading to problems such as ageing and cracking. In such environments, the health of structures must be monitored and maintained accordingly [1]. Sensing the state of cement-based materials during the design and use stages allows for early warning and timely maintenance before structural damage occurs. improving its safety, toughness and longevity. Therefore, self-perception of material properties is essential for the development of intelligent structures with digital characteristics [2]. Smart concrete compared with traditional concrete has the ability to sense external load. The concept of smart concrete and structure was first introduced in the 1960s, when Soviet researchers proposed conductive concrete mixed with conductive material - nano carbon black [3]. In the late 1980s, some Japanese civil scholars began to investigate and study intelligent building materials that "have a certain perception and control ability due to changes in the external environment". After that, Professor Yanagida of the University of Tokyo incorporated glass fiber and carbon fiber into concrete in 1992 and proposed self-testing concrete. In the early 1990s, Chung [4] et al. incorporated carbon fiber with different shapes, aspect ratios and content into concrete/mortar, the device is capable of detecting the external environmental load and transforming it into an electrical signal. By collecting resistance signals to judge the internal changes of the structure, a series of related studies are carried out. Since then, the related technologies of smart concrete have attracted wide attention from countries all over the world. Smart concrete features include self-sensing, self-regulation, self-heating, self-cleaning, electromagnetic absorption. This study mainly introduces the internal self-sensing intelligent concrete research.

Smart concrete was first proposed by American scholars, it is made by adding functional fillers (carbon nanofibers, multi-walled carbon nanotubes, graphite nanofibers, graphene, nickel, steel fibers) to enhance the perceptual performance of traditional concrete [4,5]. Intrinsic self-sensing concrete is a kind of concrete material with self-monitoring ability. It achieves real-time perception of external strains, stresses and cracks by adding functional fillers, for instance, carbon nanofibers, carbon black, etc. This concrete enables active monitoring of its condition in the structure, thereby improving safety and durability. Compared with intelligent sensing materials such as optical fiber and piezoelectric sensors, it has the advantages of low cost, good durability, and no mechanical degradation due to embedded sensors,it has the same life as concrete and is easy to maintain and install [6-11]. Traditional concrete, as a structural material, has no conductive capability. Conductive fillers need to have sufficient size and quantity to bond the conductive path, in addition, to avoid the agglomeration phenomenon of conductive fillers in the collective, resulting in a decline in mechanical properties, conductive network incoherence and other phenomena, the dispersion of conductive fillers is also particularly important. With the deformation or stress of the concrete material, the conductive network inside the material changes, Thus, the sensing properties of cement-based materials are affected [12, 13], strain, stress, and cracks under static and dynamic conditions can be detected by changes in resistance.

This review aims to evaluate the conductive mechanism, types and influencing factors of smart concrete based on self-sensing, as well as the research results of electrical signals on stress, strain or crack, aiming to offer guidance for many new functions of concrete such as self-monitoring and self-diagnosis in the future.

2. SELF-SENSING CONCRETE STRUCTURE

Self-sensing concrete usually consists of two major parts: the base material and the functional filler. Base materials used as binders include cement slurry, cement mortar, concrete, geopolymer cement and asphalt concrete. The other part is conductive fillers, functional fillers play a key role in providing sensing capabilities. From carbon to metal, single to hybrid, fiber to particle, macro to nano functional fillers should have electrical conductivity and chemical stability. In addition, at the micro level, nano-scale functional fillers are also widely used because of their good electrical and mechanical properties, including nano carbon black, nano carbon fiber, and carbon nanotubes. Table 1 Table 1 lists some conductive fillers under different classifications.

Table 1. ISSC list of conductive fillers under different classifications [7]

Type		Common functional packing
Standard	**species**	
Material composition	Carbon-based material	Carbon fiber, carbon nanofibers, carbon black, carbon nanotubes, graphite powder, nano titanium dioxide
	Metal/Metal oxide	Steel fiber, nickel powder, nano titanium dioxide, Fe_2O_3, ZnO、MnO_2
Fill size	Macroscopic scale	Steel fiber, steel slag, stainless steel microfilament
	nanoscale	Carbon nanotubes, carbon nanofibers, graphene, nano-titanium dioxide, iron oxide, zinc oxide, Fe_2O_3, ZnO
Packing shape	2D	Graphene, multilayer graphene
	one-dimensional	Carbon fiber, carbon nanofiber, carbon nanotube, steel fiber
	zero-dimensional	Carbon black, steel slag, nickel powder, graphite powder
conductivity	conductor	Steel fiber, Carbon fiber, Carbon nanofibers, Carbon black, Ultra-fine stainless steel wire, Carbon nanotubes
	semiconductor	Nano-TiO2, flyash、Fe_2O_3, ZnO, MnO_2, steel slag
	insulator	Polyvinyl alcohol fiber（PVAF）

Researchers Han [7] et al. believe that the filler is distributed in the concrete matrix, and the concrete matrix between the filler will also form a conductive channel, so the self-sensing performance of concrete is jointly affected by the matrix and the filler. Some researchers have also found that at the microscopic level, in addition to the interface between the matrix and the filler, there is also the interface between the filler and the filler. The multiple effects of these interfaces affect the distribution of the conductive network of the self-sensing concrete, which in turn affects its sensing performance.

3. SELF-SENSING CONCRETE CONDUCTION PRINCIPLE OF CONCRETE

In order to make concrete conductive, conductive fillers are usually added to traditional concrete to reduce the resistance of concrete and achieve the effect of electrification. After adding conductive filler, the conductive network inside the composite material will change [14,15]. In practical engineering, under the influence of external load or external environment, electrical parameters will change with the compression and bending of materials caused by force action.

Self-sensing concrete is the addition of conductive or semiconductor fillers to traditional concrete to improve the electrical conductivity of concrete is influenced by external forces or deformations, as well as environmental factors such as temperature and humidity, which cause changes in the internal conductive network of the composite material. Consequently, its electrical performance parameters, including resistance and capacitance, undergo stable and predictable variations. In other words, the composite material has a corresponding contrast relationship between force and electricity, which can make the material have the ability to sense stress and strain [16], temperature and humidity [17,18]. The addition of conductive or semiconductor fillers generally should not be harmful to the mechanics and durability of concrete, and the ideal filler can improve the mechanics of concrete. The existing researches mainly focus on the force-electric self-sensing properties of concrete.

Cement-based materials have extremely high resistivity, almost as an insulator. The change of resistivity is closely related to the moisture content, the curing method, and the concentration of conductive filler. The cement undergoes a hydration reaction that dissolves cement particles and releases calcium and silicon ions into the surrounding water, the resistivity of concrete is mainly determined by the ionic conductance of its internal pore solution [19,20]. When measuring concrete resistance, due to the polarization effect, the positive and negative ions in the pore solution of concrete move to the positive and negative electrodes respectively and gather together under the action of external electric field, resulting in increased or irregular resistance. Therefore, ionic conductivity will affect the stability of concrete resistance measurement.

The wrapping of conductive materials facilitates the ion conduction pathway [21,22]. The resistivity of concrete varies with the amount of conductive filler. The resistivity of self-sensing concrete is usually divided into three regions by the content of conductive filler. When the content of conductive filler is low, the ionic conductivity is the main one, and the sensitivity is low. When the filler content is high, the contact conductivity is the main; When the filler content just reaches the threshold value of seepage, the ion and contact conduction work together.

4. FACTORS AFFECTING THE SENSING PERFORMANCE OF SELF-SENSING CONCRETE

4.1 Functional Filler Content

Garcia-Macias et al. [23] studied the sensitivity of smart beams with different carbon nanotube content, and the content of the doped filler was close to the threshold of penetration and the piezoresistivity coefficient was higher. Sun et al. [24] showed that the resistivity of the gellar composite with low content of nano-graphite sheets (NGPs) was difficult to stabilize. The resistivity of NGPs filled gelling conforming material decreases with the increase of NGPs content. Han et al. [25] showed that the resistivity of composites with carbon nanotube content of 1.0% was higher than that of composites with carbon nanotube content of 0.5%. Ge et al. [26] show that the content of carbon fiber will change the resistance of concrete. He believes that with the increase of carbon fiber, the resistance of composite material gradually decreases, and the content of carbon fiber exists an optimal point, at which time the stress-strain sensitivity of carbon fiber reinforced cement-based material reaches a peak.

In summary, the above scholars studied the influence of different packing concentrations on the self-sensing performance of concrete, indicating that appropriate packing concentrations can improve the sensing performance of smart concrete.

4.2 Moisture

The moisture level in self-sensing concrete is influenced by various factors, including surrounding humidity, curing conditions, and the concrete's structure. Its change will cause the change of the conductivity of the functional filler and the concrete matrix, and thus change the sensing performance of the self-inducted concrete.

Wang et al. [21] believe that carbon fiber cement-based materials have two effects of positive and negative pressure sensitivity, which is caused by the change of water content inside the material. There are two kinds of changes in the resistance of fiber cement-based materials under macroscopic pressure, one depends on the contact of conductive filler, and the other depends on the tunneling effect of quantum mechanical particle movement. When the former or the latter effect is dominant, it shows positive and negative pressure sensitivity.

Jia et al. [27] found the effect of moisture content on the electrical conductivity and pressure sensitivity of waste slag mortar. It is concluded that the influence of moisture content on the conductivity and pressure sensitivity of waste slag mortar is gradually weakened with the enhancement of the conductivity and the extension of the age. In addition, when the temperature is constant, the resistivity of the specimen will gradually increase under the conditions of saturation - surface dry - air dry - absolute dry, but the increase range will gradually decrease, which leads to the gradual decrease of pressure sensitivity.

Li et al. [28] found through the experiment that the pressure sensitivity of the specimen was significantly reduced compared with that of the test specimen just taken out of the water tank and tested after drying in the drying box. It shows that the moisture content has a great influence on the change of resistance. Li et al. [29] show that the higher the moisture content, the greater the impact on the electrical properties of carbon black-filled cement-based composite concrete (CBCC), the resistance of the specimen with the highest moisture content varied by up to 4.5% throughout the measurement period. The sensitivity of these composites rises with higher water content. Han et al. [30] noted that the piezoresistive sensitivity of the composites increases first and then decreases with the increase of moisture content.

Demirciliog˘lu et al. find that the evolution of resistance under different water content and saturation. In the case of initial water content of 5.2%, when the water content dropped to 4.8%, the resistance dropped to the lowest; when the water content was lower than the optimal value, that is, when the exposure time was more than 1 hour, the water as electrolyte in micropores decreased and the resistance increased.

Teomete et al. [31] determined the influence of water content on strain and crack sensitivity, the linear relation between compressive strain and resistivity reaches 0.9. Specimens placed at 90°C for 60 minutes showed the greatest strain coefficient during compression tests. The resistance is minimized when the water content is 9%. During the compression test, the resistance is minimized by increasing the fiber-fiber and fiber-matrix contacts. By reducing the moisture content, the gauge coefficient of the splitting tensile test is increased. With the decrease of water content, the amount of electrolyte water decreases. The importance of fiber-fiber and matrix-fiber interactions in electron transport is heightened. When tensile strain occurs, these contacts are disrupted, resulting in a higher strain coefficient during the splitting tensile test.

The splitting tensile test results of the crack sensitivities and water content relationship also show that the decrease of water content increases the fiber-fiber and fiber-matrix contact. Crack propagation breaks these contacts, resulting in a sharp increase in resistance, which leads to an increase in crack sensitivity.

4.3 TEMPERATURE

The conductivity properties of self-inducted concrete are closely related to temperature, and the increase or decrease of temperature will result in a change in the volume of the self-inducted concrete, thereby changing the distance between adjacent functional fillers.

According to Mao 's [32] research, they believe that, as the temperature of the composite increases, the sensitivity decreases accordingly. Temperature also has a significant effect on the conductivity of concrete. Typically, an increase in temperature leads to an increase in electrical conductivity, as higher temperatures can increase the rate of electron or ion migration. Teomete et al. [31] showed that temperature had an effect on the resistance of steel fiber reinforced cement-based composites. At 200 degrees, the resistance increased rapidly due to the damage between cement slurry, aggregate and steel fiber. Similarly, Demirciliog˘lu [33] et al show that there is a linear relationship between temperature and material resistance during the initial heating stage, that is, between 25℃ and 50℃. Between 50℃ and 115℃, regardless of temperature, shows a stable resistance, when the temperature reaches more than 150℃ due to the different elongation of the aggregate and brass fiber relative to the cement slurry, resulting in tensile strain damage at the interface of cement slurry, cement-brass fiber and cement-aggregate, resulting in a sudden increase in resistance. Li [29] et al. took the resistivity of the sample at 0℃ as the reference resistivity to study the effect of temperature on the resistivity of cement-based composites filled with carbon black. From -10℃ to about 50℃, the composite's resistivity decreased linearly with temperature, but beyond that, it started to increase. Similarly, Wang et al. [34] showed that in the initial heating stage, the resistivity of the carbon fiber mortar specimen changed little, As the temperature rises, resistivity decreases, but beyond a certain point, it begins to increase with temperature.

Dehghanpour et al. [35] tested the resistance of the cube test block at different temperatures. The experiment shows that the resistance increases at the temperature of room temperature to 200 degrees Celsius, and the resistance increases rapidly after the temperature of 243 degrees Celsius.

5. CONCLUSION AND PROSPECT

Self-sensing concrete has been systematically studied by many scholars, using electrical signal changes to evaluate mechanical properties and establish a mechanoelectrical interaction mechanism. Due to the brittle nature of concrete structures, cracks will cause structural bearing capacity reduction, and even cause safety problems. How to apply intelligent concrete to actual working conditions, there are still many problems to be solved in the future. It can be developed for new structural facilities and green building related codes and standards. The potential of the future development of self-sensing concrete is summarized as follows:

- Self-sensing concrete can be combined with self-healing technology, self-sensing concrete automatically releases the repair material when cracks appear again, extending the service life of the material and reducing maintenance costs
- The application of self-sensing concrete in green buildings will help to achieve efficient use of resources and reduce the energy consumption and carbon footprint of buildings.
- Self-sensing concrete can be combined with ultra-highperformance concrete to produce functional concrete with both high

strength and structural health monitoring ability.

- In smart city construction, Self-sensing concrete also has a certain application space in roads, parking lots and other facilities to optimize traffic management and resource allocation through sensing data.
- In the future, a self-sensing concrete dynamoelectric model can be developed, which can take electrical parameters into account in the formulas of tensile and compressive constitutive.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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