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## Opinion Article

# Research progress on electrical and mechanical properties of self-sensing concrete

## ABSTRACT

In civil construction projects such as roads, Bridges and tunnels, concrete structures work with cracks in the normal use stage, and adverse factors such as load and environment during service will significantly reduce the applicability and durability of the structure, resulting in unexpected accidents. Therefore, the realization of structural health monitoring is of great significance. The appearance of intelligent concrete provides a new way to solve the problem of poor effect of conventional inspection means. Smart concrete is a collection of load-bearing and self-sensing functions and one of the cementing materials, usually in the conventional concrete mixed functional conductive additives made, under the action of external loads, the concrete will produce microscopic deformation will cause changes in the structure's internal conductive network, resulting in a stable and regular electrical performance response, so that the material has self-inductive characteristics. Intelligent concrete is an integrated structural function material which not only has good mechanical properties but also can monitor the health of concrete structures during service, accumulate damage to structures in case of natural disasters, and make early prediction of the remaining life of concrete structures. This paper reviews the development background of smart concrete based on self-sensing, the conductive mechanism and influencing factors with and without external loads, the evolution characteristics of self-sensing, and summarizes and looks forward to the future development of smart concrete.

**Keywords:**Smart concrete; Influencing factors; Mechanical properties; Electrical properties; Force-electrical effects;

# 1.Introduction

Engineering structures slowly age and gradually deteriorate, starting at the material level. Sensing the deterioration of material properties at an early stage enables maintenance before significant damage occurs to the structure, improving its safety, toughness and longevity. Therefore, self-perception of material properties is essential for the development of intelligent structures with digital characteristics [1]. Smart concrete is a new generation of concrete materials, compared with traditional concrete has the ability to sense external load or environment (also known as piezoresistive). 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[2]. 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[3] et al. incorporated carbon fiber with different shapes, aspect ratios and content into concrete/mortar, which could sense external environmental loads and convert them into electrical signals. By collecting resistance signals to judge the internal changes of the structure, a series of related studies are carried out. Since then, the research and related technologies of smart concrete have attracted wide attention from countries all over the world. Smart concrete features include self-sensing, self-healing, self-regulation, self-heating, self-cleaning, electromagnetic shielding/absorption, energy harvesting, light transmission and aircraft interception. This paper mainly introduces the internal self-sensing intelligent concrete research.

Self-induced concrete was first proposed by American researchers, Self-sensing concrete (also known as intrinsically self-sensing concrete, self-monitoring concrete, intrinsically intelligent concrete, piezoresistive or pressure-sensitive concrete) is made by adding functional fillers (carbon nanofibers, carbon black, carbon nanotubes, multi-walled carbon nanotubes, graphite nanofibers, graphene, nickel, steel fibers, and carbon fibers, etc.) to conventional concrete to enhance its perception of strain, stress, cracks, or self-damage The ability to damage while maintaining or even improving mechanical properties [3, 4]. Intrinsic Self-sensing concrete (ISSC) refers to a structural material that can self-monitor without embedding, connecting, or remote sensors. By measuring the resistance of the ISSC, the stress, strain, crack and damage of the ISSC can be monitored in situ. Compared with traditional structural materials that require additional sensors for monitoring or testing, ISSC has the advantages of high sensitivity, good mechanical properties, good natural compatibility, the same life span as concrete, and easy installation and maintenance [5-10]. Traditional concrete, as a structural material, has no sensing capability. The presence of functional fillers in concrete is necessary for the autobiography to be of sufficient size and reproducibility. Functional fillers need to be well dispersed in the concrete matrix through effective treatment techniques to form an extensive conductive network inside the concrete. With the deformation or stress of the concrete material, the conductive network inside the material changes, thus affecting the electrical properties of the material [11, 12]. Thus, strain (or deformation), stress (or external forces), cracks and damage under static and dynamic conditions can be detected by measuring resistance.

Although a lot of research progress has been made, the results are varied. 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, crack or damage, hoping to provide reference for future research.

## 2. Self-sensing concrete composition

As a functional composite material, self-sensing concrete usually consists of two major parts: the base material and the functional filler. Matrix materials that act as binders and provide structural functions enable cement-based composites, including cement slurry (Portland cement only), cement mortars (Portland cement and fine aggregate), concrete (Portland cement and fine and coarse aggregate), in addition to Portland cement-based composites, Sulphoaluminate cement, geopolymer cement, and asphalt concrete are also used as matrix materials for sensing concrete. The mechanical properties (such as ultimate stress and strain, Young's modulus and Poisson's ratio) and sensing properties (such as sensitivity, repeatability, compatibility and durability) of the sensing concrete are highly dependent on the type and mix of the base material.

Functional fillers play an important role in providing sensing capabilities and enhancing structural performance. From carbon to metal, single to hybrid, fiber to particle, macro to nano functional fillers should have electrical conductivity and chemical stability. Recent developments in nanomaterials have stimulated the use of functional fillers at the nanoscale. Particularly promising functional fillers are nanocarbon, including carbon nanotubes, carbon nanofibers, carbon nanoblacks, and multilayer graphene, due to their excellent mechanical, thermal, and electrical properties. Table 1 summarizes typical functional fillers for self-sensing concrete.

## 3. Self-sensing conductive mechanism of concrete

Self-sensing concrete is the addition of conductive or semiconductor fillers to traditional concrete to improve the conductivity of concrete. Under the action of load (external force or deformation) or environment (temperature, humidity, etc.), the internal conductive network of the composite material changes [13, 14]. Thus, its electrical performance parameters (including resistance, capacitance, inductance, impedance, etc.) will undergo stable and regular changes. That is, the composite material has a sensitive and stable coupling relationship between force (deformation)

-electricity, heat-electricity and humidity-electricity, and has the ability to sense stress, strain [15], damage (including cracks and fatigue, etc.), temperature and humidity[16][17]. The addition of conductive or semiconductor fillers generally should not be harmful to the mechanics and durability of concrete, and the ideal filler can significantly improve the mechanics and durability of concrete. The existing researches mainly focus on the force-electric self-sensing properties of concrete.

The resistivity of traditional concrete materials is generally 106 Ω·cm~109Ω·cm, which is closely related to factors such as curing age and water content. Since the hydration of cement in concrete generates various ions such as Ca2+, Na+, K+, OH−, etc., and the concrete contains a large number of pores, some of which are filled by water, the resistivity of concrete is mainly determined by the ionic conductance of its internal pore solution[18, 19]. When the resistance of concrete is measured, the positive and negative ions in the hole solution move and gather on the surface of the hole due to the external electric field, which causes the resistance value to increase with the test time. Therefore, ionic conductivity will affect the stability of concrete resistance measurement.

The addition of conductive or semiconductor fillers helps to short-circuit the ionic conductance path, thus giving the concrete a stable resistance[20, 21]. The resistivity of concrete varies with the amount of conductive or semiconductor filler, that is, the seepage phenomenon. When the content of conductive or semiconductor filler is low, the resistance of the composite material does not change much, and the resistance of the composite material is dominated by ionic conduction. When the conductive or semiconductor filler reaches a certain value, the resistance of the composite material will change significantly, that is, seepage occurs, and the resistance of the composite material is dominated by ion conductance, tunnel conductance and contact conductance. When the amount of conductive or semiconductor filler continues to increase to a certain value, the resistance of the composite becomes stable, and the resistance of the composite is dominated by contact conductance. In general, self-sensing concrete needs to have a low resistivity, that is, a stable resistance, while having a high sensing sensitivity, that is, a high resistivity change rate, but these two aspects are contradictory. Therefore, the self-sensing concrete filler content range should be near the seepage threshold according to the load.

## 4. Factors affecting the sensing performance of self-sensing concrete

### 4.1Functional Filler Concentration

Le et al.[5] studied the effect of functional filler content on FCR and SSC of intelligent ultra-high performance concrete (S-UHPC). The results show that the higher the content of functional fillers, that is, the shorter the distance between functional fillers, the lower the FCR is because the initial resistance of S-UHPCs containing functional fillers is lower than the threshold content of functional fillers. Garcia-Macias et al. [22] 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. [23] 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. Lee et al. [42] showed that S-UHPCs containing 2 vol% steel fibers and multi-walled carbon nanotubes (MWCNTs) with 0.5% functional filler added to cement produced lower FCR than S-UHPCs containing only 2 vol% steel fibers. Because the content of functional fillers, including MWCNTs and fibers, will exceed the permeability threshold, Han[24] et al. studied the influence of the concentration of carbon nanotubes on the sensing properties of composites. They observed that the change in the amplitude of the resistance of all three composites increased as the concentration of carbon nanotubes increased.

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.

### 4.2Moisture

The moisture content inside the self-sensing concrete depends on many factors such as ambient humidity, curing regime and concrete 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 and Zhao [20] studied the sensing behavior of carbon fiber cement-based composites with different water contents under compression. The results show that the relative resistance of the composites changes with the change of water content. With the increase of water content, the relative change of resistance during loading increases, and the relative change of resistance during unloading decreases, showing irregular perception characteristics. However, when the moisture content decreases after drying, the relative change of resistance decreases monotonously during loading and increases monotonously during unloading, showing regular sensing characteristics.

Li[25] and Jia[26] respectively observed the sensing properties of concrete mixed with steel slag, magnetic fly ash and steel slag and magnetic fly ash under the conditions of water saturation, surface drying, air drying and absolute drying. The sensitivity of these composites increases with the increase of water content. Han[27] et al. observed that with the increase of the water content of the composite material, the electrical conductivity and sensitivity of the cement slurry mixed with carbon fiber and carbon black were enhanced. In addition, Han et al. compared the resistance response to compressive stress of MWNT/ cement composites with different water contents (0.1, 1.3, 3.3, 5.7, 7.6, and 9.9%) under repeated compressive loading with an amplitude of 6 MPa. The piezoresistive sensitivity of MWNT/ cement composites first increases and then decreases with the increase of water content.

Li et al.[28] show that the higher the moisture content, the greater the increase of the resistance with the measurement time, that is, the greater the impact on the electrical properties of carbon black-filled cement-based composite concrete (CBCC), and the relative fraction of the resistance of the specimen with the highest moisture content during the whole measurement time changes up to 4.5%

Demirciliog˘lu et al. studied 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. [29] determined the influence of water content on strain sensitivity and crack sensitivity, and conducted compression and split tensile tests on steel fiber reinforced smart cement composite samples for 30-60-120-210-330min at 90℃. The results show that there is a strong linear relationship between compressive strain and %R, and the correlation coefficient is 0.97. 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. Enhanced role of fiber-fiber and matrix-fiber contacts in electron transport. Tensile strain breaks these contacts, leading to an increase in strain coefficient in 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 and sensing properties of self-inducted concrete are closely related to temperature, and the increase or decrease of temperature will lead to the expansion or contraction of self-inducted concrete, thus changing the distance between adjacent functional fillers.

Mao et al. [30] tested the electrical conductivity and sensing properties of carbon fiber cement slurry at different temperatures (11.5, 29.5, 34.0, 42.5 and 57.5 °C). They observed that the resistivity and sensitivity of the composite decreased with increasing temperature. Jia[31] studied the perceived behavior of concrete with only steel slag and steel slag mixed with magnetic fly ash at -20, 5, 25 and 50□. He found that this concrete has a high perceptual sensitivity at high temperatures [29]. 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. [29] studied the effect of temperature on the resistance, strain sensitivity and crack sensitivity of steel fiber reinforced smart cement composite, and the research results showed that the resistance was 351Ω at room temperature. As the temperature rises to 200□, the resistance fluctuates and the general trend is slightly increased. Similarly, Demirciliogˇlu[31] 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-aggregate and cement-brass fiber, resulting in a sudden increase in resistance. Li [28] 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 resistivity of the composite material decreased linearly with the temperature, and with the further increase of the temperature, the resistivity of the composite material turned to increase. Similarly, Wang et al. [32] showed that in the initial heating stage, the resistivity of the carbon fiber mortar specimen changed little, and as the temperature continued to rise, the resistivity decreased with the increase of temperature. After the temperature continues to rise beyond a certain value, the resistivity increases with the temperature.

Dehghanpour et al. [33] tested the resistivity of a cylinder sample with a diameter of 10 cm and a length of 20 cm at -10℃ to room temperature. According to the results of the study of the temperature-resistance relationship, when the temperature rises from 10 ° C to about 15 ° C, the resistivity decreases and then becomes fixed with the increase of temperature.

## 5Conclusion and prospect

Self-sensing concrete has been systematically studied by many scholars, using electrical signal changes to evaluate mechanical properties and establish a mechanoelectric interaction evaluation 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.

## Referance

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