



# **Advances in Self-Sensing Ultra-High-Performance Concrete: A Comprehensive Review**

**Hui fa Zhang <sup>a\*</sup>**

<sup>a</sup> *School of Civil Engineering and Transportation, North China University of Water Resources and Electric Power, Zhengzhou, Henan 450045, China.*

### **Author's contribution**

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

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## **Abstract**

In the past three decades, ultra-high-performance concrete (UHPC) is undoubtedly been one of the most innovative engineering materials, and its application scenarios have become more and more extensive. Ultra High Performance Concrete (UHPC) has the inherent potential of self-sensing ability because it contains steel fibres or other conductive materials. The paper aims to explore the research status of the self-sensing performance of ultra-high-performance concrete. Self-sensing concrete has attracted extensive attention in engineering and academia, mainly to replace the traditional health monitoring system for the health monitoring of concrete structures. Many studies have examined the electrical and piezoresistive properties of UHPC. With the combination of micro steel fibres, carbon nanotubes, carbon nanofibers or nano graphite sheets, it has opened up great potential for UHPC to effectively sense stress, strain and crack. The research focuses on the self-sensing principle, characteristics and influencing factors of self-sensing ultra-high performance concrete. The results show that in the concrete with 20  $\mu$  m diameter and 0.5% SSSW content, seepage and polarisation disappear, and the resistivity measured by the four electrode DC method

\*Corresponding author: E-mail: 308806194@qq.com;

decreases from  $20.8 \times 10^4 \Omega \cdot \text{cm}$  to  $44 \Omega \cdot \text{cm}$ . Future considerations/Recommendations for self-sensing concrete in the engineering field are summarised. To sum up, the research on the self-sensing performance of UHPC has not only made a breakthrough in theory but also shown great potential in practical application. Future research will further promote its application and development in the field of intelligent building materials.

**Keywords:** *Ultra-high-performance concrete; functional filler; self-sensing; fibre; aggregate; structural health monitoring.*

## 1. Introduction

“Ultra-high-performance concrete (UHPC) is a form of cementitious composite that has been the most innovative product in concrete technology over the last three decades. Ultra-high-performance concrete has been broadly employed for the design of numerous forms of construction owing to its excellent mechanical characteristics and durability, and studies on its behaviour have grown rapidly in the last decades” (Abdal *et al.*, 2023; Bahmani & Mostofinejad, 2022). In the past three decades, ultra-high-performance concrete (UHPC) has undoubtedly been one of the most innovative engineering materials, and its application scenarios have become more and more extensive. Compared with ordinary concrete, ultra-high-performance concrete adds fibres inside and adopts a more compact stacking mode. Traditional approaches to UHPC mixture design, relying on empirical or trial-and-error methods, are both laborious and costly. Moreover, the designed mixtures obtained through such methods may be only feasible but not necessarily optimal. Therefore, developing a universal and scientifically grounded mixture design approach for UHPC becomes imperative to address these challenges effectively (Fan *et al.*, 2024). At present, the compressive strength of UHPC on the market can easily reach more than 150MPa, and the flexural strength and tensile strength can reach 15MPa and 7MPa. In addition, UHPC has higher corrosion resistance and stability than ordinary concrete. The excellent mechanical performance and durability of UHPC make it more widely used in bridge engineering, construction engineering, military engineering and other important fields. In addition, because the internal components of UHPC contain unique components such as steel fibre, it has more application potential, including self-sensing performance and structural health monitoring (SHM), and heating can be achieved in the form of power on. By adding magnetite and other admixtures, it can also have electromagnetic shielding and other characteristics. These characteristics of UHPC

provide the possibility to solve the existing special engineering problems.

In 1993, Chen and Chuang first realised the combination of self-sensing ability and cementitious composites by adding carbon fibre to concrete for nondestructive flow detection. Since then, the self-sensing performance of concrete has gradually attracted the attention of academic and engineering fields, and the research on monitoring stress, strain, cracking, deflection and other properties of ultra-high performance concrete is also increasing. The self-awareness of concrete comes from the internal conductive filler. The common conductive filler is mainly divided into metal materials and carbon materials. Metal materials include steel fibre, nickel powder, magnetite, etc. Carbon nanotubes (CNT), carbon black (CB), and carbon fibre (CF) are commonly used carbon materials.

UHPC has the potential to make self-sensing concrete due to its high-quality conductive filler steel fibre inside. In general, for typical UHPC, its compressive strength can reach 150MPa and above, tensile strength can reach 7MPa, and fracture energy can reach 40000 J/m<sup>2</sup>. In addition, compared with ordinary concrete, UHPC has a more excellent tensile strain, and even the ultimate tensile strain is equivalent to that of steel, which provides a strong support for the realisation of UHPC tensile self-awareness. No matter in terms of compression resistance, compression resistance, or any other property, UHPC is undoubtedly an ideal material to realise SHM function. In addition, it also has high self-transmission ability. In this paper, the first research results of UHPC composites in self-sensing properties are reviewed, and the future applications and challenges are discussed.

## 2. Self-sensing Principle of UHPC

Generally, for any concrete or cement-based composite with self-sensing ability, the sensing performance comes from the change of the internal conductive network (Chung, 1998). At

present, the most common measured sensing signal is resistance or resistivity. In order to quantify the sensitivity, the resistance or resistivity change rate is usually used to measure. For example, the stress sensitivity can be quantified as FCR. The higher the value, the better the sensitivity. For self-sensing concrete, the content of conductive filler inside is very important. Too much conductive filler will not make the self-sensing performance of the structure better, because excessive conductive filler will cause the initial conductive network to be too stable, so it is unable to make a timely response when the external load changes or the structure is damaged. Therefore, in the process of studying the self-sensing performance of UHPC, it is necessary to pay attention to the selection of functional fillers and the control of dosage (Wen & Chung, 2000).

For UHPC, because the internal fibre filler has a longer structure than the aggregate, it is very easy to cause agglomeration during mixing, which is not conducive to the formation of a conductive network. Therefore, the dispersion of the UHPC mixture is crucial to the sensing ability. However, due to the extremely low water content and binder of UHPC, the dispersion problem is aggravated. For metal fibre or metal aggregate, adjusting the dispersion of fibre is mainly through adjusting the fibre content. At present, the most common method for carbon-containing materials,

such as carbon fibres and carbon nanotubes, is to first place the fibres in polycarboxylate superplasticiser, improve the compatibility between carbon fibres and cement matrix through surface modification, so as to promote their dispersion, and then use ultrasonic dispersion treatment. Ultrasonic treatment can destroy the aggregates of carbon fibres and disperse them into the cement paste (Lee et al., 2018). In addition, carbon fibres can be dispersed into the cement matrix through high-speed mechanical mixing. The efficiency of mechanical mixing depends on the mixing speed, mixing time and the design of the mixer.

At present, the core mechanism and theoretical basis of UHPC self-sensing performance are mainly divided into four aspects, namely, seepage theory, piezoresistive effect and piezoelectric effect. Generally speaking, "the conductive phenomenon of conductive composites is caused by the combination of the direct contact of conductive fillers and the tunnelling effect between gaps. However, there is a different conductive threshold between the content of conductive filler and the conductivity of concrete. Conductive filler helps to short-circuit the ionic conductive path and make UHPC have stable resistivity. The resistivity of concrete will change with the content of conductive filler, and the effect of seepage and tunneling" (Heidarian et al., 2022). As shown in Fig 1, when "the

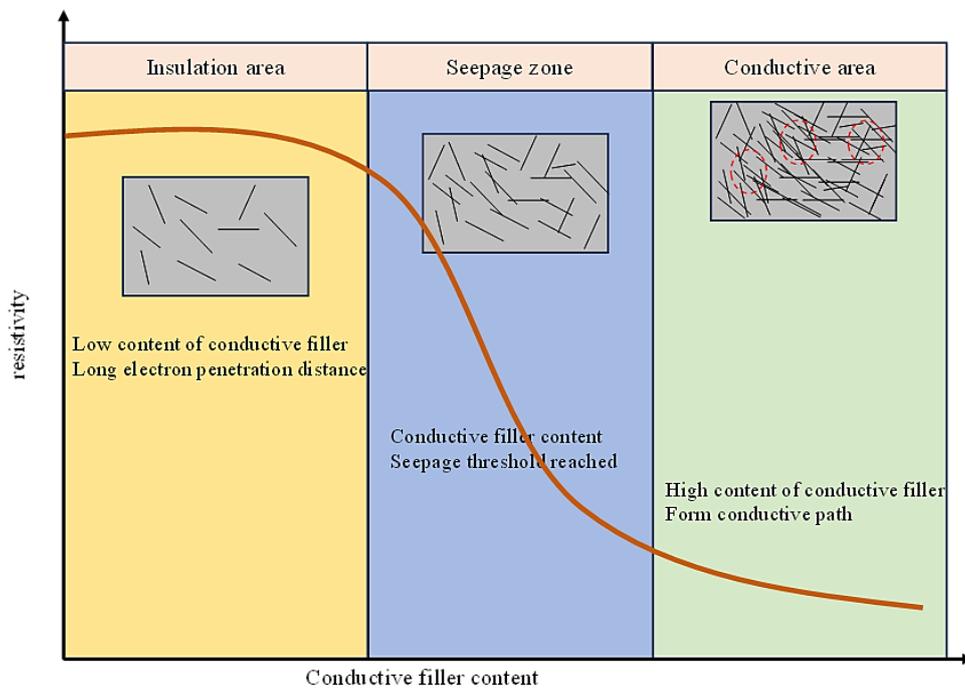


Fig. 1. Schematic diagram of concrete seepage principle

content of conductive or semiconductor fillers is low, the resistance of conductive concrete changes slightly, and its resistance is mainly dominated by long-distance electron tunneling; When the content of conductive filler reaches a certain value, that is, the percolation threshold, the resistance of conductive concrete will decrease significantly, that is, the percolation phenomenon occurs. At this time, the resistance of the composite material is mainly affected by tunnel conduction and contact conduction. When the content of conductive filler or semiconductor filler continues to increase to a certain value, the conductive filler will appear to have partial aggregation. At this time, the resistance of the composite tends to be stable, mainly in contact conduction" (Li et al., 2024). The resistivity changes little with the increase of conductive filler content, indicating that the percolation threshold has been exceeded. Since the self-induction concrete needs to have low resistivity, i.e. stable resistivity, and high induction sensitivity, i.e. high resistivity change rate, the content range of self-induction concrete filler should be designed near the seepage threshold.

### 3. Factors Affecting UHPC Self-perception

Under the background of the high cost of traditional structural health monitoring system and the inability to achieve structural life-cycle monitoring, Dong et al. (2016), For the first time, short cut ultra-fine stainless steel wire (SSSW) is used as a cementitious composite material mixed with cement, silica fume, fly ash and silica fume, which successfully endows the concrete with the ability of conductivity and self-induction. Through in-depth study of the electrical conductivity of SSW reinforced concrete and its response to external loads, the electrical conductivity mechanism was explained in detail by means of electrochemical impedance spectroscopy and intrinsic conductivity analysis. The results show that in the concrete with 20  $\mu$  m diameter and 0.5% SSSW content, seepage and polarisation disappear, and the resistivity measured by the four electrode DC method decreases from  $20.8 \times 10^4 \Omega \cdot \text{cm}$  to  $44 \Omega \cdot \text{cm}$ . In addition, the code coefficients of 8  $\mu$  m diameter SSW reinforced concrete under cyclic compression, monotonic compression, and bending loads can reach 22.5, 94.9 and 43.6, respectively. Kim et al. (2018) studied the mechanical and electrical self-induced responses of strain-hardened steel fibre reinforced concrete and ultra-high performance fibre reinforced concrete under tensile conditions

were studied. The results show that the copper mesh significantly reduces the polarisation of the electrode when embedded, and the high resistance of UHPC significantly improves the reduction of resistivity of concrete under tensile state. Nguyen et al. 2020), based on the experimental study, the tensile self-sensing and fracture energy of UHPC were emphatically studied. It was found that within the range of 0-2%, the strain-sensing ability of UHPC gradually increased with the increase of fibre content, and 2% was the best fibre content for strain-sensing ability. Cholker et al. (2021), A new method for health monitoring of concrete structures based on the change of electrical resistance is proposed. The volume ratio of carbon fibre is set at 0-2%. The test results show that the percolation threshold of carbon fibre is about 1.5%. The health monitoring technology of intelligent concrete structures based on electrical resistance can be successfully applied to the health monitoring of intelligent concrete structures. You et al. (2017), "The electrical and self-sensing properties of ultra-high performance fibre reinforced concrete with and without carbon nanotubes were investigated. The effects of steel fibre content, orientation and pore water content on the electrical and piezoresistive properties of UHPC without carbon nanotubes were evaluated for the first time". The test structure showed that the better the orientation of the steel fibre, the higher the content of pore water, and the higher the conductivity of UHPC. In addition, a single steel fibre can not give the piezoresistive effect of UHPC. The introduction of carbon nanotubes combined with steel fibres significantly improved the conductivity of UHPC. Carbon nanotubes can significantly increase the pre-cracking self-sensing ability of UHPC in tension. Lee et al. (2024), The amount of conductive materials is set as the main variable of the test, such as steel fibre (0%, 1%, and 2%) and multi-walled carbon nanotubes (0.1wt% and 0.5wt%). The experimental results show that the synergistic interaction between steel fibre and carbon nanotubes is necessary for concrete composites to have self-sensing ability. In addition, the specimens with 2% steel fibre and 0.5wt% multi-walled carbon nanotubes have a higher gauge factor. The higher the gauge factor, the better the self-sensing performance of concrete, and the FCR changes significantly before and after cracking.

In ultra-high-performance concrete, a single steel fibre cannot form an effective conductive network. It usually needs to form a synergistic effect with

other conductive directions. Aggregate is an excellent synergistic item. At present, the commonly used aggregates include steel slag, magnetite and copper slag. Le et al. (2020), The self-sensing characteristics of ultra-high performance intelligent concrete containing steel slag aggregate and steel fibre under compression were studied. The influence of steel slag particle size (0.39, 2 and 5mm) and steel fibre content (1% and 2% volume fraction) on the piezoresistive effect of UHPC was explored. The results showed that when the steel slag aggregate particle size was too large, the steel fibre would be unevenly distributed, which would reduce the piezoresistive response.

When the steel fibre content is high enough (volume ratio reaches 3%), the fibre orientation has little effect on the conductivity of ultra-high performance fibre reinforced concrete (Huang et al., 2021). However, when the fibre content is low, the fibre orientation will have a significant impact on the conductivity, and good fibre orientation can make the conductivity higher. The influence of fibre orientation on the piezoresistive properties of UHPC is mainly due to the large diameter of the steel fibre. The test shows that the fractional change of resistivity (FCR) of steel fibre with only 3% volume fraction does not change significantly under cyclic compression load, which may be due to the large diameter of steel fibre, insufficient pore water or the dense microstructure of UHPC interfering with the connection between steel fibres (Yildirim et al., 2019). Wang et al. (2021), It was found that

UHPC with high aspect ratio and aligned fibres showed better conductive orientation, piezoresistance and mechanical properties.

Different loading forms will lead to changes in the internal stress distribution and electrical properties of UHPC, which will affect its self-perception ability. Under compression load, the self-sensing performance of UHPC mainly depends on the relationship between its internal electrical response and stress. During the whole compression process, the resistivity of the structure first decreases, then stabilises, and finally increases. Under tensile load, the self-perception of UHPC can also show a unique behaviour. Bekzhanova et al. (2021), It is found that there is a nonlinear relationship between the resistance change and the tensile strain of UHPC during the tensile process. Different from compression loading, the resistivity of UHPC under tensile loading may increase with the increase of strain, which is mainly due to the different forms of crack formation and propagation in the tensile process compared with the compression process, resulting in different forms of interruption of the conductive path. See Fig. 2 for resistivity change curves under different loading modes. Wanget al., (n.d.) Based on the study of the self-sensing properties of carbon fibre reinforced UHPC, the changes of conductivity under three different loading levels were studied. The results show that different loading forms have a significant impact on the self-sensing properties of UHPC, which provides new information for the preparation of UHPC with carbon fibre.

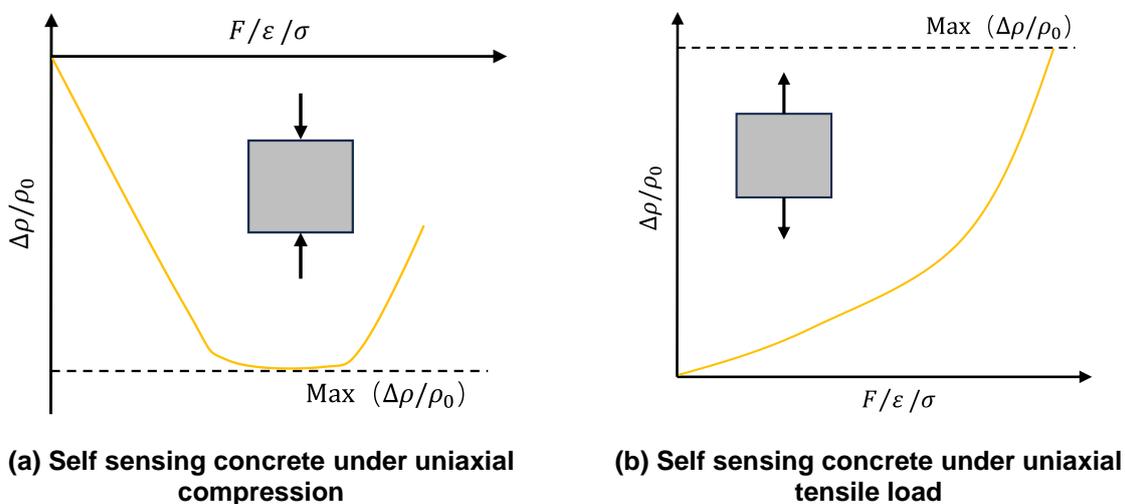


Fig. 2. Self sensing concrete under different loading forms

#### 4. Conclusion and Prospect

This review briefly summarises the research status of self-sensing performance of ultra-high performance concrete, focusing on its mechanism and influencing factors. As a high-performance building material, the research on self-sensing performance of ultra-high performance concrete (UHPC) has made significant progress. By adding conductive aggregates such as carbon fibres, carbon nanotubes and steel fibres to UHPC, its self-perception ability can be significantly improved. These conductive aggregates can not only enhance the conductivity of UHPC, but also make it perceive strain and damage through the change of resistivity when subjected to external force. In addition, the self-sensing sensitivity of UHPC can be further improved by optimising the type, content and distribution of conductive aggregate.

To sum up, the research on the self-sensing performance of UHPC has not only made a breakthrough in theory, but also shown great potential in practical application. Future research will further promote its application and development in the field of intelligent building materials.

#### 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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