Review Article

Research Progress in Environmental Response of Fiber Concrete and Its Functional Mechanisms

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1. Introduction

Due to the nonlinear relationship between the applied stress and the resistivity of concrete, the self-stress sensing ability of concrete under stress is limited, and the detection of its health is required. The current concrete monitoring technologies are mainly the embedded piezoelectric sensors, surface-mounted strain sensors, etc. [1]. These methods are of low sensitivity, lack real-time nondestructive testing, show poor performance in extreme conditions, complex procedures, time-consuming, high cost, etc. Smart concrete with self-sensing and self-healing capabilities can make up for these defects and significantly improve the durability and safety of the infrastructures, such as high-rise buildings, long-span bridges, dams, tunnels, marine structures, and nuclear power plants [2]. Therefore, there is a vast potential in using smart concretes in the infrastructure structure of health monitoring. In addition, most sensor materials are different from cement-based composites, so the embedded structure of the sensors will harm the structure. The smart component (fiber) in smart FRC is part of the concrete itself. The addition of fibers will not only not hurt the concrete but also increase its strength [3]. To a larger extent, smart FRC can reduce the impact of construction on the environment. It is an essential element of developing a smart urban environment, which can sense and quantify the impact of catastrophic incidents such as earthquakes, tsunamis, storms, or terrorist acts. Stress crack damages, fatigue damages, chemical corrosion damages, material aging, and other unfavorable defects would be caused in the concrete when subjected to the stress field, temperature field, electromagnetic field, and chemical field in the environment alone or combination. It is inevitable for the concrete to experience damage accumulation and resistance attenuation. If real-time monitoring and rectification are not possible, sudden accidents are prone to occur. While
external monitoring consumes many human resources, material resources, and financial resources, it cannot achieve real-time and nondestructive testing. Therefore, it is necessary to develop smart FRC that respond to the environment intelligently.

2. Environmental Response Field and Characteristics

2.1. Response Field. The environmental response fields of smart FRC mainly include stress field, temperature field, electromagnetic field, chemical field, and humidity field. The types and environmental response fields are shown in Figure 1. Among them, the stress field is the main intelligent response field. Smart CFRC, OFRC, GFRC, and NFRC can all have characteristic changes in the stress field that can be easily measured, such as changes in resistivity. This shows its intelligent characteristics under the stress field. The temperature field is also a very important intelligent response field. Smart CFRC, OFRC, and NFRC can show measurable changes in the temperature field, such as changes in the number of light waves, showing their smart characteristics in the temperature field. The characteristics of intelligent response to electromagnetic fields are mainly reflected in smart CFRC. It shows the electrothermal effect and electric effect under electromagnetic field manifested as changes in reflectivity and thermal effect. The intelligent response to chemical fields is mainly reflected in smart GFRC. Chemical substances (Cl−, SO42−, etc.) stimulate the self-healing performance of hollow glass fibers, manifested in filling concrete cracks by the outflow of repair liquid inside the hollow glass fiber. The intelligent response of the humidity field is mainly reflected in the smart NFRC. The humidity field mainly affects the electrical conductivity of the concrete matrix and the field emission effect at the tip of the nanofiber tube, which is manifested as the change of the piezoresistive response sensitivity of the concrete.

2.2. Response Characteristics

2.2.1. Self-Sensing Response. The self-sensing of concrete refers to the fact that, by adding other ingredients, the concretes can have such characteristics as mechanical sensitivity, temperature sensitivity, pressure sensitivity, magnetic sensitivity, thermoelectric effect, and photoelectric effect. When the concrete is under stress, due to the matrix’s deformation and the cracks’ expansion, the insertion and removal of fibers will occur, resulting in the formation and destruction of a conductive network [4]. At the same time, the matrix’s deformation changes the spacing between the fibers, which affects the ability of the electrons to conduct the tunnelling [5]. These two factors work together to make concrete exhibit self-induced stress performance. The self-induction mechanism of the bending damages in smart FRC similar to compression. On the one hand, in the process of bending and cracking, the matrix in the compression zone is compressed, and the matrix in the tension zone is tensile cracked, which reduces the conductive section. On the other hand, the fibers are inserted and pulled out, which will lead to changes in the spacing and contact resistance [6].

Adding fibers to concretes can not only maintain or improve the strength and toughness of the concretes but also enable the concrete to sense stress, temperature, humidity, magnetism, and surrounding ion concentration. When the environmental conditions around the concrete material change, the internal fiber network also changes. It will cause changes in the electrical properties and the number of light waves of the composite material [7]. The typical self-sensing behavior of FRC under compression and tension is shown in Figure 2. Therefore, the strain, stress, temperature, humidity, cracks, magnetic field, etc., of FRC under static and dynamic conditions can be detected by measuring its changing performance. The relationship between loading and resistivity is taken as an example. The self-sensing response characteristic of concrete pressure is shown in Figure 3. It can be seen that the concrete’s piezoresistive characteristic intelligent resistivity response has strong sensitivity.

2.2.2. Self-Healing Response. The self-healing of damages in FRC refers to an intelligent self-repair network system formed by the flowable repair material—repair adhesive in the repair fiber tubes mixed with the concrete matrix. Under the influence of the external environment, once the concrete matrix is cracked or damaged, part of the fiber tube ruptures, and the adhesive in the tube flows out and penetrates the crack to harden, realizing the self-repairment of concrete cracks and damages. According to Edvardsen, continuous hydration of cement can only repair microcracks up to 6 μm wide. In practice, only minor cracks can be repaired. Therefore, it is necessary to add self-healing fibers.

The self-repair process of hollow fiber concrete is shown in Figure 4(a). The self-repair processes are as follows: (1) the smart FRC is subject to environmental changes such as stress, temperature, and electromagnetic fields. (2) Concrete cracks are due to environmental changes, and the cracks pass through the hollow fiber. (3) The healing liquid in the hollow fiber of smart FRC flows out to fill the cracks in the concrete so that the concrete can achieve a dense rerepair effect. Figure 4(b) is a schematic diagram of the main forces acting near the concrete cracks. When the repair fluid’s gravity and the meniscus’s surface tension overcome the capillary resistance, capillarity attraction, and the sealing end negative pressure, the repair fluid will flow out to repair the cracks. The significance of the self-repair of smart FRC is that when the concrete cracks, the hollow fibers near the cracks will break. The outflow of the healing agent reacts with the curing agent or the hydrate inside the concrete, achieving the crack-healing effect, and the strength after healed is better than before. In addition, the damage repair model of FRC can be used to explain the test results of concrete and clarify the indicators for the evaluation of the healing degree. Damage repair models can provide information about damage repair behavior and changing pressures. The static repair period and crack configuration greatly influence the mechanical response of the self-healing system [25].
3. Response Mechanism

The environmental response of smart FRC includes carbon fiber, optical fiber, glass fiber, and nanofiber concrete. Different concretes have different intelligent response fields, and different response fields also have their parameters and response mechanisms. The mechanism map is shown in Figure 5.

The environmental response effect reflects the intelligent characteristics of smart FRC, which is positively correlated with the sensitivity of environmental changes such as stress, temperature, humidity. The response effect is generally expressed by the FCR of FRC and its variation coefficient, as shown in Table 1.

3.1. Smart CFRC. Many researches on environmental intelligence response to CFR have focused on mixing carbon fiber into concrete randomly [29–36]. The incorporation of carbon fiber gives concrete intelligent characteristics. The following are some examples:

(i) The conductivity of carbon fiber causes concrete to produce a seepage threshold [28, 37–39]

(ii) Changes in electrical properties due to changes in structural health in the form of strain can be monitored by piezoresistive effects [29–31, 40, 41]

(iii) Moisture will affect the piezoresistivity of mixed CFRC below the seepage threshold [42]

CFRC can be made into a sensor of piezoresistive material [43, 44] and can also be used as a smart health material. In addition, there is also the addition of carbon fiber cloth to the concrete as an intelligent response element [45]. Smart CFRC’s environmental intelligent response characteristics include temperature, pressure, and magnetic sensitivity. These characteristics will be affected by the size, shape, content, length, diameter, and other factors of carbon fiber to various degrees [46–50] and other admixtures [51].

3.1.1. Stress Field. The CFRC’s stress field response mechanism is mainly based on concrete pressure sensitivity. On the one hand, when CFRC is subject to stress, the volume resistivity will change with stress changes in size and direction. Using the detector to detect the change of resistance, the change of internal stress and strain of concrete can be roughly judged. Thus, the damage location and damage degree in concrete can be sensed, and the effect of the intelligent response of the stress field can be achieved. On the other hand, the response mechanism is based on the conductive ability of the electron tunnel, which shows that the deformation of the CFRC changes the spaces between the fibers. It will reduce the conductivity of the electron tunnel and increase the resistivity of the concrete. The characteristic of the intelligent response of CFRC is the result of two mechanisms.

For the first mechanism, the intelligent response of strain is based on the basic relationship between the resistance and the length of carbon fiber and its cross-sectional area ratio. The strain under stress can cause elongation and contraction of the carbon fiber cross-sectional area, which increases the integrated resistance of CFRC. When the smart FRC is stressed, particularly when the crack is generated, the strain is uneven along with the carbon fiber distribution. At this
time, the resistance layout caused by the strain is shown in Figure 6(a). \( r(x) \) represents the resistance of the unit length. \( r(x) \) is affected by and varies along with the traction. \( R_s = \int r(x)dx \) considered local strain near concrete cracks and strain effects along with the carbon fiber distribution. The circuit generated by the resistance layout in the FRC is shown in Figure 6(b). Furthermore, the CFRC produces the resistance characteristics at different humidity, and the stress field response characteristics are also generated.

For the second mechanism, there are two conductive mechanisms in CFRC: electronics and electrolysis. Electronic conduction is achieved by the movement of free electrons in carbon fibers, and ions achieve electrolytic conductive in the pore solution. The conductivity of smart CFRC depends mainly on the physical interface between the carbon fibers and the pore solution in the concrete substrate, the fiber, and the substrate. Carbon fibers can reduce the resistivity of cement-based composites, and the effect of the volume fraction of carbon fibers on the conductivity is shown in Figure 7(a). Conductivity in CFRC systems follows the theory of seepage. This theory assumes that the particles or filaments can contact and form clusters only when their volume fraction exceeds a critical value. Conductive phenomena will occur due to the connection of clusters [55]. As shown in Figure 7(b), the current is shown by the three states of concrete. The region 1 base and the fibers are separated, and the current \( I \) will not flow. The carbon fiber bridge portion in region 2 allows \( I \) to pass through the matrix crack. Once the material is compressed and, the crack is closed, the increased resistivity is partially or completely reversible. The conductivity of the intact region 3 occurs due to the cement matrix and conductive fibers.

Meehan et al. [56] prepared carbon fiber cement mortar and found that if an affected area is affected, a cement sander comprising short carbon fibers can effectively sense its impact damage by affecting DC or AC resistance. In the direction of resistance measurement, the length of the region can be 25~203 mm, and the longer the region, the smaller the damage sensitivity will be. In addition, carbon fiber self-sensing concrete can also effectively sense impact damage under impact stress. The response force field and its response effect in different loading modes are shown in Table 2.

### 3.1.2. Temperature Field

The temperature field response mechanism of CFRC is mainly based on temperature sensitivity; the temperature around the surrounding changes in a specific range, and its resistivity will generate regular changes. The ambient temperature changes can cause changes in resistivity. This phenomenon is called resistance-temperature characteristic, also known as the Seebeck effect. At the same time, the internal temperature difference also generates potential differences inside the concrete, which changes the temperature of the CFRC to form a thermoelectric effect. The test of electrical resistivity-temperature characteristics of the concretes showed that the electrical resistivity of the smart CFRC showed an NTC effect at the initial stage. That is to say, the resistivity decreases with the increase in temperature. And then, there is a region where the resistivity of the CFRC barely changes with the change of temperatures. As the temperature increases, smart CFRC shows a PTC effect as a gradual increase in temperature increases [60]. The three effect changes are shown in Figure 8(a). The temperature field intelligent response of CFRC is based on this rule, and the temperature is distributed through its temperature sensitivity to perform temperature adjustment.

The microscopic mechanism of CFRC intelligent response can be interpreted by the electronic excitation theory. The internal electrons are thermally activated to obtain energy when the temperature rises. More electrons
Figure 5: Environmental response mechanism map of smart FRC.
Table 1: Environmental response effects of FRC.

| Ref. | Concrete types          | Sensitivity factor | Sensitivity coefficient change graph | Results                                                                 | Measurement formula                                                                 |
|------|-------------------------|-------------------|-------------------------------------|--------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| [13] | PP/nano carbon black concrete | FCR/stress (% MPa) | ![Graph](image1.png) | The piezoresistive sensitivity of the composite material has a linear relationship with the amount of fiber added | \[ FCR = \Delta \rho / \rho_0 = \Delta R / R_0, \quad \sigma_f = 100 \Delta R / R_0 (1.27X + 0.01) \] |
| [26] | Carbon nanotube concrete | FCR or \( \lambda \) | ![Graph](image2.png) | Even when the stress limit is reached, the linear fitting effect is also good | \[ \lambda = FCR / \text{stress} = \Delta R / R_0 / \varepsilon \] |
| [27] | Nanocarbon black concrete | FCR               | ![Graph](image3.png) | FCR exhibits reversible behaviors during load cycles and is linear       | \[ FCR = \Delta \rho / \rho_s = \Delta R_s / R_s \approx \Delta R_s / \rho_s (t) - R_s (t_0) / R_s (t_0) \] |
| [28] | Carbon nanofiber smart concrete | Coefficient of variation of sensitivity | ![Graph](image4.png) | When the sensitivity is greater than 500, the pressure sensitivity exerts a good effect. When the amount of CNF is low, a better dispersion effect can meet the sensitivity requirements. | — |

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Figure 6: Electrical behavior of the carbon fiber (a) resistance layout due to straining, (b) Resistance layout due to wetting. (c) Wheatstone bridge ($R_x$ designates the resistance of the carbon fiber and $V_b$ is the measured voltage) [52].

Figure 7: (a) Percolation theory [53]. (b) Electricity flows through concrete in three states: (1) postfiber pullout, (2) fiber bridged cracks, and (3) uncracked [54].

Table 2: Intelligent response fields and effects of different loading methods of CFRC.

| References                        | Discussion                                                                 | Loading methods          | Response effects                                                                 | Principle analysis                                                                 |
|-----------------------------------|---------------------------------------------------------------------------|--------------------------|---------------------------------------------------------------------------------|---------------------------------------------------------------------------------|
| Saiprasad et al. [57]             | The relationship between carbon fiber generic polymer concrete stress state changes and its resistance | Three-point bending loading | The resistance of the samples decreases with the increase in bending stress | The surface distance of the sample is shortened, and the conduction length is reduced. The densification of geological polymerization and the development of the internal microcracks in the matrix have an opposite effect on the resistance with increased compression load. |
| Deng et al. [58]                  | Charge properties of carbon fiber reinforced alkali-activated fly ash/slag mortar | Uniaxial compression     | When the compressive stress increases and the fiber gap is reduced, the resistance is reduced. The reconstruction and destruction of the conductive network reach a balance when the compression stress reaches the critical value. The resistivity amplitude increases sharply in the first few cycles, fluctuating in the subsequent cycle | If the critical value is exceeded, the sample would have cracks and cause damages to the existing conductive network, resulting in a sudden increase in resistance. |
| GürkanYıldırım et al. [59]        | Intelligent self-induction of mixed concrete of carbon fibers and CNT/CB in different ages | Uniaxial compression     | Carbon fiber materials (especially in the early stages of initial curing) contribute most to the sample’s self-inductance. | The carbon-based material itself has electrically conductive properties, and the resistance at uniaxial pressure will change. It has electrically conductive properties to generate changes in resistance under splicing stretching. The ability attributes at a single CNT/CB particles bridged microcracks or attached to PVAF. |
overcome the barrier formed by the matrix, making it easier to form a current path and reduce the resistivity [61]. When the temperature drops, the internal electron energy of smart CFRC will decrease. At this time, electrons cannot overcome the barriers formed by cement, sand, stone, and so on, which will hinder the formation of the current pathway, resulting in large resistivity. The temperature of CFRC can also be monitored and regulated by monitoring the resistivity. Moreover, Figure 8(b) displays the electron excitation overcoming barrier at different temperatures.

Zhuoqiu Li et al. [61] firstly reported that the temperature difference of the Seebeck effect of CFRC has been linearly related to the temperature difference and pointed out that it has a repetitive and stable feature. Then, the influence of carbon fiber content, cement matrix, and curing age on the Seebeck effect was studied. Among them, the carbon fiber content is the main factor affecting the Seebeck effect. As the fiber dosage increases, the thermo-electromotive force reaches the maximum. When the carbon fiber content is 1.0%, the thermo-electromotive force tends to be stable with the extension of curing time, while the cement matrix has little effect on the thermo-electromotive force. At the optimal amount of fiber content, the thermo-electromotive force can reach $18 \mu V/\degree C$, and the temperature self-diagnosis of the concrete structure using the Seebeck effect is studied. Sihai Wen et al. [63] observed that the changes of the temperature differences between the Seebeck voltage and the CFRC are linear and substantially the same during heating and cooling. Chen Bing et al. [64] studied the temperature resistance change of smart CFRC when heated and cooled repeatedly. With the volume of the carbon fiber being 0.8%, the temperature resistance change of the sample is shown in Figure 9. As the number of cycles increases, the temperature resistance curve of the system tends to stabilize and exhibit an excellent NTC/PTC effect. Its transition temperature is around 90\degree C. At the same time, they also studied the temperature resistance characteristics of different fiber volumes and found that this critical temperature value decreased when the fiber volume increased.

3.1.3. Electromagnetic Field. The electromagnetic field response mechanism of CFRC is mainly based on the conductive properties of carbon fibers, which will make the resistivity vary with the changes in the surrounding electric field and the magnetic field, causing the conductive network formed by carbon fibers to act with an external electromagnetic field [65]. When the distributed direction of the carbon fibers is parallel to the incident electric field, as the electrical loss material, the carbon fiber produces a large conductive current, resulting in a strong reflection of the incident electric field. When the two are vertical, the carbon fiber is the loss medium of radar waves at this time. When the two have a certain angle, the reflected electric field produces an electric field component perpendicular to the incident electric field. It determines the electromagnetic field.
distribution according to the size and direction of the reflected electric field. At the same time, the change in the electric field will cause thermal effects and deformation inside the CFRC, generating electrothermal effects and electricity effects. The surrounding electromagnetic field distribution is judged by the concrete’s electromagnetic field intelligent response mechanism, thereby achieving electromagnetic field adjustment around the concrete. It is also possible to determine the application of electromagnetic field according to the rate and amount of thermal effect. Meanwhile, CFRC is good in electromagnetic shielding performance.

Li et al. [66] found that smart CFRC mainly affects the reflection loss ratio of electromagnetic wave shielding and dielectric losses absorbed by electromagnetic waves by analyzing the electromagnetic parameters and conductive mechanism. Both parameters are attributed to the increase in carbon fibers to increase the electrical conductivity. Figure 10 shows the reflection loss mechanism of smart concrete with a filling carbon fiber comparison diagram and reflectivity diagram of different carbon fiber content concrete. In addition, carbon fibers with a diameter of 0.1 µm incorporate into concrete at a volume dosage of 0.34%, its electromagnetic wave shielding effect at the 1~2 GHz band can reach 30 dB. CFRC has electromagnetic shielding property because it absorbs electromagnetic waves. Regardless of the absorption or reflective performance, this material is good in electromagnetic shielding, which provides a reference in the fields like electromagnetic radiation, radar wave interference, nuclear radiation, and others. Studies have shown that carbon fiber’s amount, length, and molding mode greatly influence the shielding effect.

3.2. Smart OFRC

3.2.1. Stress Field. The stress field response mechanism of smart OFRC is mainly based on the stress sensitivity of optical fiber. When the OFRC is subject to stress, the optical wave amount in the optical fibers will show real-time changes, including the intensity, phase, wavelength, frequency, polarization state, or the like. According to the change of light waves, the internal stress and strain can be generally inferred, and the damage inside the concrete is determined to achieve the effect of the intelligent response of the OFRC stress field [57, 67–69]. The optical fibers consist of three parts, as shown in Figure 11(c). The fiber core and cladding are made of a dielectric material. The refractive index of the cladding material is smaller than the refractive index of the core, which can reduce the loss of light transmitted in the core. The coating protects the optical fiber from physical damage [70].

When cracks occur in the OFRC under the influence of the stress field, the fiber will be partially deformed, such as tension, compression, and shear. The optical fibers suffer losses under separate or integrated effects of stretching, shear, lateral extrusion, and surface unevenness. Thereby, the detection signal of the OTDR/BOTDR will attenuate, and the change reflects in Figure 11(a). According to the detected optical wave signal, the stress change of OFRC can be judged, and concrete can be adjusted to achieve monitoring in real-time [73].

Figure 11(b) indicates the physical principle of smart OFRC when performing stress detection. When the concrete is under the action of the stress field, the reflected signal will produce a wavelength shift, which will be monitored as a function of the measured signal. When the broadband light transmits through optical fiber, the light will pass through at a smaller attenuation. In contrast, the narrowband light is transmitted through optical fiber, reflecting in the Prague grating portion [74]. Prague wavelength is shown as follows:

$$\lambda_b = 2n_{ef}/\Lambda, \quad (1)$$

where $\lambda_b$ is the wavelength of the Prague or the reflected light, $n_{ef}$ is an effective refractive index of the fiber core, and $\Lambda$ is the optical fiber period. As described above, if the optical fiber is subject to external stress, $\lambda_b$ changes, and the strain can be known by measuring the minute change of the wavelength. $\lambda_b$ is related to strain and temperature.

$$\frac{\Delta\lambda_b}{\lambda_b} = \left[ (\alpha_f + \xi_f)\Delta T + (1 - \rho_e)e \right]. \quad (2)$$

where $e$ is strain, $\Delta T$ is temperature change, $\alpha_f$ is the thermal expansion coefficient, $\xi_f$ is a thermosetting coefficient, and $\rho_e$ is the strain optical coefficient of the fiber.

Lau et al. [75] embedded the optical fiber into concrete, measuring the accurate strain of different locations, and provided structurally delayed or microcrack failure information. It is found that the fiber-optic concrete monitoring is detected earlier than the strain gauge, indicating that it is more sensitive to the crack and physical conditions of concrete, as shown in Figure 12. Lee et al. [76] used the fiber sensor to measure the crack tip of the concrete structure. The three-point bending test verified the recognition effect of optical fiber on concrete cracks. It is found that, with the concrete deflection increases, the correlation curves between light intensity attenuation and beam deflection have a strong rise, which means that optical fibers are susceptible to tensile and shear strain. There is a slope mutation in the curve, indicating that the concrete produces a microcrack, and with the increase of deflection, new cracks are generated. This phenomenon shows that the optical fiber has a good effect on the generation of cracks in the concrete structure, and the effect of recognition is very significant.

3.2.2. Temperature Field. The smart OFRC temperature field response mechanism is similar to the stress field. The effect of light transmission is susceptible to temperature in fibers, and temperature changes can cause changes in optical waves and power. If the change in the amount of optical wave can be measured, the temperature change can be known. The relationship between Prague wavelength and temperature is shown in formulas (1) and (2).

The following is another explanation of the thermometer response mechanism of smart OFRC: optical fiber will show the effects like the stretch, shear, extrusion, and other effects
Figure 10: (a) Schematic diagram of reflection loss mechanism between plain concrete and smart concrete filled with spiral carbon fiber [66] (b) reflectivity of concrete with different carbon fiber content [66].

Figure 11: (a) Typical reflection chart of OTDR [71]. (b) Physical principle of stress detection of smart OFRC [72]. (c) Schematic diagram of optical fiber [70].

Figure 12: (a) Schematic diagram of the OFRC system for strain measurement [75]. (b) Comparison of strain measured by OFRC concrete sensor and strain gauge. [75].
under temperature influence, that is, temperature stress. Bending sensing mechanism and three types of misplaced possibilities can be found in Figures 13(a) and 13(b). The temperature stress causes the loss of radiation and absorption of light and changes the space state of optical fiber. It causes mode coupling in optical fibers, where some of the guided wave modes transform into radiation modes, as shown in Figure 13(c). The light propagating at an angle less than the critical angle in the fiber may have an increased incidence angle at the interface between the fiber core and the cladding as the fibers’ bending. At this time, one part of the light is transmitted into the cladding, causing a decrease in the output intensity and the occurrence of microbending loss. It can cause attenuation of the OTDR detection power, measure the fiber optic power output directly, and calculate the loss amount. The power loss and temperature change have a certain relationship with crack width, stress, and sliding distance [71, 77]. Depending on the amount of power loss, the temperature loss can be judged, and then the deformation type and deformation size generated by the temperature can be judged.

Zou et al. [78] prepared smart OFRC to sense the temperature changes and hydration processes in the early hydration process. The schematic diagram is shown in Figure 14(a). As shown in Figures 14(b) and 14(c), the peak temperature of plain concrete is higher than OFRC and decreases faster. It is mainly because the thermocouple’s sensing behaviors in the concrete and its measurement results are easily affected by the service environment. While the OFRC can provide many small temperature field responses, its intelligence is stable and reliable. The characteristics of optical fiber temperature intelligent response in large volume concrete were studied. A large amount of heat is released during the curing of large volume concrete, resulting in internal thermal stress and thermal crack. Therefore, the optical fiber can be embedded to monitor the temperature inside the concrete and provide a basis for controlling the cooling rate in the curing process.

3.3. Smart GFRC

3.3.1. Stress Field. The stress field response mechanism of smart GFRC is based on the stress sensitivity of hollow glass fibers. When the smart GFRC is stressed, the glass fibers in the concrete sense the stress and break. At the same time, the repair fluid flows to the crack to expand and indurate, realizing the self-healing of concrete cracks [79]. The basic self-healing principle is as follows: (i) cement as the matrix material, adding porous glass fiber web. (ii) In the hydration process of cement, the glass fiber releases the polymerization initiator and polymerizes with monomers to form the polymer. (iii) The remaining moisture is involved in the hydration of cement. The surface of the net forms a large number of organic and inorganic substances, which incorporate with each other. Finally, it is a composite material similar to an animal skeletal structure with excellent strength and ductility. If damages occur during the use of the material, glass fibers will release the polymer and repair damage [80].

The mechanism of the intelligent response of the smart GFRC stress field will be listed in the following part. When concrete is subject to external force, the resistivity of concrete changes regularly. Therefore, concrete deformation, cracks, and damage can be monitored by measuring the resistance [82]. Scholars used fiber-reinforced composites to detect the surface cracks of the bridge in the concrete, and the stress intelligent response phase is carbonaceous-glass fiber [81]. It can be seen from Figure 15 that the concrete resistance changes linearly with the crack width. The damage can be detected by determining the relationship between the damage degree and the change of concrete conductivity. In addition, they successfully adopt intelligent response carbonaceous-glass fibers to memorize the crack width.

Sugita et al. [83] embedded carbon and glass fiber into the concrete and served as an enhancement and intelligent response phase. They found that the resistance characteristics of concrete change with load, and the permanent residual resistance was observed after removing the load, which depends on the maximum load applied. In this case, Ding et al. [84] obtained the resistivity relaxation law of exponential decay. Therefore, monitoring resistance change during and after loading is an effective method to predict the concrete fracture. Muto et al. [85] pointed out that intelligent response carbon-glass fiber-reinforced polymer fibers can be used as an early warning for risk and monitor high strain values of concrete structural disasters. The test proves that the internal pressure of the glass fiber affects the quality of the concrete structure crack from healing. When the pressure increases to 0.23 MPa, the fiber tube breaks, wherein the repair liquid flows rapidly to the crack damage, and 95% of the crack can be bonded.

3.3.2. Chemical Field. Smart GFRC faces different challenges in different chemical environments. When the concrete is used in marine environment with high Cl− concentration, Cl− has a great influence on the durability of the concrete [85, 86]. Cl− also diffuses along the existing cracks, becoming an intermediate catalyst that destroys concrete and shortens concrete life [87]. When the smart GFRC is in a sulfate environment, sulfate will make the interface between fiber and matrix degummed and damaged prematurely, causing a potential risk for concrete performance and structure [88].

Smart GFRC also has different intelligent response mechanisms in different chemical environments. The intelligent response mechanism of Cl− in GFRC is that when there are chloride ions around the concrete, it will penetrate the interior of the concrete. Moreover, Cl− will cause hollow glass fibers to rupture so that the liquid inside the fibers flows out and repair the cracks, resulting in intelligent self-healing. The sulfate intelligent response mechanism of GFRC is that when there is sulfate around the concrete, the sulfate diffuses into the bonding interface and stimulates the cracked glass
Vinyl ester + carbon particles
Glass fiber
Vinyl ester
resin

Figure 15: (a) Intelligent response to fiberglass [81]. (b) The resistance of intelligent fiberglass concrete varies with the crack width [81].
fiber so that the repair fluid flows out and fixes the cracking concrete interface.

3.4. Smart NFRC

3.4.1. Types and Functions. Smart nanofibers include CNF, Ni-NF, CNT, GNP, NCB, and one or more of their mixtures, and their morphologies are shown in Figure 16.

In general, CNT, GNP, CB, and Ni-NF are in nanoscale, while CF is in micron scale. The Ni-NF is made of nickel-plated CNT. The volume fraction of CNT and nickel are 5.6% and 94.4%, respectively. After nickel plating, two crossed CNT are connected to improve the conductivity. The diameter of CNT is 20–30 nm, the length is 10–30 um, and the surface area is more than 200 m²/g. There are many connection points between CNTs, which help to improve the conductivity. The diameter of GNP is about 5 mm, the thickness is 50–100 nm, and the surface area is about 13 m²/g. The surface area of CB is about 30–50 m²/g, and the average particle size is about 20–100 nm.

3.4.2. Field Response Mechanism. The field response of smart NFRC can be divided into six types according to fiber types. (i) The stress field, humidity field, and temperature field response of smart CNFC. (ii) The stress field and temperature field response of smart Ni-NFC. (iii–iv) The stress field response of smart CNTC and smart GNP. (v) The stress field and electromagnetic field intelligent response of smart NCBC. (vi) The intelligent response of stress field and temperature field of two or more kinds of mixture concrete.

(1) Smart CNFC. The resistance of smart CNFC has two sources: inherent resistance and contact resistance. The mechanism of the intelligent response of its stress field is as follows. When CNF smart concrete is deformed under external load, the length and diameter of the CNF will change, resulting in a change in its inherent resistance. Compared with the inherent resistance, contact resistance is more important in affecting the change of concrete resistance. Under the external load, the thickness of the matrix between adjacent CNT changes, which will reduce the gap in the contact region of the electrical tunnelling and make the resistance of the concrete conductive network change obviously [93, 95]. Figure 17(a) shows the conductive network. According to the change of resistance, the intelligent response of the stress field is realized.

The research of Han et al. shows that the stress field intelligent response sensitivity of CNFC is greatly affected by water content, as shown in Figure 17(b) [93]. There are two factors affecting the water content: one is the conductivity of the substrate, and the other is the field emission effect of the nanofiber tip [96–98]. The adsorption of water molecules can enhance the nanofiber tip’s conductivity and field emission effect. When the water content increases to 3.3%, the conductivity of the concrete will be filled with the increasing tunnel gap (the contact resistance decreases). Besides, as the field emission effect of the nanofiber tip increases, the conductivity of the concrete increases. When the concrete is deformed under the compression load, the electron tunnelling barrier is reduced, and the tunnelling effect is easy to occur. At this time, CNF shows lower resistance and higher stress field sensitivity. In addition, CNT can enhance the thermoelectric properties of concrete [99]. Bhattacharjee et al. [94] found that when the CNT content is 0.07 wt.% and 0.49 wt.%, respectively, the dielectric constant and pyroelectric coefficient increase as the temperature increases, as shown in Figures 17(c) and 17(d), which will also cause the change of resistance.

(2) Smart Ni-NFC. The response mechanism of smart Ni-NFC can be listed as follows: when the concrete is stressed, the resistivity is in line with the stress. According to the change of resistivity, the stress of Ni-NFC can be inferred, realizing the intelligent response. Han et al. [100, 102] prepared smart Ni-NFC with Portland cement filled with Ni-NF and found good consistency between the fractional change of resistivity and the compressive force, as shown in Figure 18(a). Moreover, the scaling coefficient of smart Ni-NFC can reach 1929.5, which shows high sensitivity to stress. The fractional change resistivity of concrete with 22% volume of Ni-NF goes up to 80% under compression, so the force (displacement) can be measured intelligently according to the change of stress (strain). Zhang et al. [101] observed that the concrete with Ni-NF has stable electrical conductivity, as shown in Figure 18(b). The heating rate increases with an increase in the input voltage. When the input voltage is 20 V, the concrete can achieve a temperature increment of about 50°C within 30 seconds.

(3) Smart CNTC. The undermentioned is the intelligent response mechanism of smart CNTC. When concrete is stressed, the resistance changes significantly, and its resistance response to stress is reversible and sensitive [102]. According to the change in resistance, the stress of CNTC can be inferred, and an intelligent response can be achieved [103]. The addition of CNT results in forming a strong three-dimensional conductive network, and the contact resistance at the CNT connection is quite complicated. The contact resistance depends on the CNT’s physical characteristics and dispersion in the medium, the tunnel gap at the contact point, and the conductive properties of the matrix [104]. On the one hand, many CNTs increase concrete conductivity and loading capacity. On the other hand, when there is no mechanical contact between CNT, the conductivity is achieved by the “tunnelling effect,” which depends on the separation distance between CNT. When CNT’s concentration reaches the percolation threshold, the contact conductivity will dominate the nanocomposites’ conductivity [105]. Although the tunnelling conductivity has little effect on the total conductivity of the nanocomposites, there is an essential contribution to the compression resistance of the composite. When applying compression or tension, the concrete will deform, and the CNTs will move, resulting in the decrease or increase of the tunnelling distance. Furthermore, the tunnelling conductivity of the concrete will become stronger or weaker, as shown in Figure 19. This
Figure 16: SEM photos of (a) CNF [89]; (b) Ni-NF [90]; (c) CNT [89, 91]; (d) GNP [89]; (e) NCB [89]; (f) CNT/NCB [92].

Figure 17: Continued.
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Figure 17: (a) Diagram of the conductive network in smart CNFC [93]. (b) Comparison of CNFC parameters with different water contents [93]. (c) Relationship of dielectric constants ($\varepsilon'$) of CNFC with temperature [94]. (d) Relationship of pyroelectric coefficient of CNFC with temperature [94].

Figure 18: (a) Relationship between compressive force and resistivity of smart Ni-NFC [100]. (b) Temperature-time curve of smart Ni-NFC during heating with different input voltages [101].

Figure 19: Schematic for the effect of tunnelling on the resistance: (a) initial condition, (b) during compression loading, and (c) during tensile loading [26].
change in smart CNTC conductivity makes it a potential candidate for strain sensing and shows high pieces of compressive resistance, thus exhibiting the characteristics of intelligent response.

Figure 20 shows the resistance change in self-sensing CNTC under repeated compression load and impulsive load. As shown in Figure 20(a), the resistance change $\Delta R$ reaches $1500 \Omega$ when the repeated compression load is up to 6 MPa. The resistance of concrete decreases after loading and increases after unloading, indicating the response of resistance to compressive stress $\sigma$ is regular under repeated compressive load. As shown in Figure 20(b), the impulsive load also causes the regular change of smart CNTC resistance. Therefore, the resistance response of smart CNTC to stress is reversible and sensitive, which means that it has excellent self-sensing ability. Materazzi et al. [107] studied the dynamic response of prismatic smart CNTC specimens. It is found that the input sinusoidal compression load will have sinusoidal output resistance, and the input and output frequencies are almost the same. It shows a very close correlation between the measured resistance and strain, and the load frequency can be inferred from the change of resistance.

(4) Smart GNPC. The intelligent response mechanism of smart GNPC can be listed as follows. When concrete is stressed, its resistivity will change obviously, and its resistance is sensitive to the stress response. According to resistivity change, the stress of smart GNPC can be inferred, and thus the intelligent response can be realized [108–110]. Wu et al. [108] found that graphene nanofibers can form a stable conductive network, resulting in a considerable change in the resistivity of the composite. The curve of Figure 21(a) shows a good linear relationship between RCR and strain in the strain range of about 10%. RCR shows an approximate exponential growth trend with a further increase in the strain. Figure 21(b) shows that when the strain is less than 4%, the composite is in the elastic deformation stage, and the GFs of the sample are 71, 47, and 34, respectively, which is much larger than that of the traditional strain gauge. The 0.8 wt.% sample has higher resistivity and is more sensitive to strain change. In addition, Mohamed et al. [111] found that GNP dispersed in concrete can form a strong barrier to reduce the movement of corrosive chemicals and enhance the resistance to corrosive elements.

(5) Smart NCBC. Smart NCBC intelligent response mechanism is illustrated in the following part. When concrete is subject to stress and electromagnetic field, the resistivity and electromagnetic shielding effect will change significantly. According to the change in resistivity and electromagnetic shielding effect, it can be inferred that the size of the stress and electromagnetic fields of smart NCBC, in turn, can achieve intelligent response [113–115]. It is found that the resistance change rate of concrete with 15% NCB can reach 80% under monotonic compression. Adding 4% NCB is beneficial for enhancing the mechanical properties, and adding 7%–10%’s NCB is more conducive to realizing the stress field’s intelligent response [116]. Dai et al. [112] tested the EM wave absorption effect of concrete filled with NCB, as shown in Figure 22(a). The results show that the concrete with the frequency range of 8–26.5 GHz is good in electromagnetic wave absorption. When the concrete contains 2.5 wt.% NCB, the minimum reflectivity reaches 220.30 dB, and the frequency bandwidth with reflectivity less than 210 dB is 14.9–26.5 GHz. Figure 22(b) shows that the minimum loss of concrete containing 0.5 wt.%, 3.0 wt.% NCB is 3.6 and 9.6, and the maximum loss factors are 8.7 and 26.7. It shows that filling NCB can change the loss factor of concrete materials. According to the change in the resistivity or loss factor of smart NCBC, the stress and electric field can be determined. Thus, an intelligent response achieves.

(6) Smart Hybrid Concrete. Many scholars have studied the intelligent response characteristics of the smart hybrid concrete and found that the intelligent response has a coupling effect [117–121]. It is related to the distribution and contact of the mixed fiber in the concrete and is affected by the type of mixed fibers, and the content and proportion of fibers, ambient temperature, and water content [121–126]. Dong et al. [13] prepared CB/PP smart concrete. It was found that the compressive resistance of 0.4 wt.% CB/PP fiber increased by three times under cyclic compression but is not related to the loading rate. The bending stress sensing efficiency is significantly lower than that of compression stress sensing, but it increases with the increase of PP fiber. It is attributed to more contact points: the conductive PP fiber is more likely to form contact points than the conductive CB nanoparticles, as shown in Figure 23. The same is true for other types of fibers [127].

Ding et al. [92] prepared CNT/NCB smart concrete and evaluated the self-sensing properties of smart nanofibers under monotonic and cyclic loading by measuring resistivity fraction. It is found that the piezoresistive coefficient has high stability and repeatability under cyclic loading in the elastic range. Therefore, smart NFRC is suitable for embedded concrete to make smart buildings and calibrate structural monitoring in practical application. Wu et al. [108] prepared CNF/RGO smart concrete and found that CNF can significantly improve the dispersion of RGO and help form a stable conductive network. The results show that the composite is highly sensitive to mechanical strain and resistivity, and its regularity coefficient is 34–71. In the range of 0–4% strain, the piezoresistive properties of the composites have excellent linearity and repeatability, which can well monitor the strain and cracks on the concrete surface. G. Kim et al. [128, 129] discussed the thermoelectric properties of CNT/CF smart concrete. They verified that adding CF to CNT concrete can reduce the damage of conductive path caused by thermal expansion, and its intelligence is shown in Figure 24. Therefore, the mixed nanofiber can improve concrete intelligence and give the concrete the characteristics of the dual intelligent response of stress field and temperature field.
Figure 20: Relationships between compressive stress and resistance for the self-sensing CNTC: (a) under repeated compressive loading; (b) under impulsive loading [106].

Figure 21: (a) The correlation of the RCR and strain. (b) The correlation of RCR and strain within a 4% strain range [108].

Figure 22: (a) Absorption performance and (b) loss factors of smart NCBC with different contents of NCB [112].
Figure 23: Schematic diagram of CB, PP fibers, and potential contact points in smart concrete. [13].

Figure 24: Schematics of the intelligent hybrid fiber concrete (CNT/CF). [128].
| Fields          | Types | Parameters                                                                 | Applications                                                                 | References                  | Disadvantages                                                                                                                                 |
|----------------|-------|-----------------------------------------------------------------------------|--------------------------------------------------------------------------------|-----------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| Stress fields  |       | (1) Stretching, bending, compression, and cutting                           | Alireza Sassani et al. [130]                                                  | Smart CFRC:                 | (1) The coarse aggregate has a significant effect on conductive properties                                                                 |
| Smart CFRC     | Resistivity | (2) Online detection of material internal conditions under loading                | Feng Xingguo et al. [131]                                                      | (2) The resistivity is not stable                                                                         |
|                |       | (3) Real-time monitoring of external fatigue damage                         | Jacopo Donnini et al. [132]                                                   | (3) The extraction and evaluation methods of resistivity change signals are immature |
|                |       | (4) Early fault warnings and life cycle health monitoring                   |                                                                              | (4) The self-monitoring system of health status has not been established [142]                                                             |
| Smart GNPC     | Resistivity | (1) Stretching, bending, compression, and cutting                           | Raphael Fulham-Lebrasseur et al. [133]                                         |                             |
|                |       | (2) Online detection of the concrete internal condition under loading       | Jianwei Li et al. [134]                                                        |                                                                                             |
|                |       | (3) Improvement of microstructure in the concrete                           | Dong et al. [13]                                                              | (5) Carbon fibers are higher in price                                                                                                    |
| Smart NCBC     | Resistivity | (1) Structural health work status online monitoring                         | Heydar Dehghanpour et al. [135]                                                |                                                                                             |
|                |       | (2) Removal of snow and ice on the airport runway                           |                                                                              |                                                                                             |
| Smart CNFC     | Resistivity | (3) Being used as a concrete voltage restriction sensor                     | Austin Downey et al. [136]                                                     | Smart OFRC:                                                                     | (1) The embedded fiber will be damaged by mechanical vibration.                                                                 |
|                |       | (1) Online structural health work status monitoring                         |                                                                              | (2) The preparation technology is immature.                                                                                          |
| Smart Ni-NFC   | Resistivity | (2) Online detection of the concrete internal condition under loading       | Han Baoguo et al. [102]                                                        | (3) The shear strength of the optical fiber is poor                                                               |
|                |       | Online detection of the material’s internal condition under loading         |                                                                              | (4) Chemical durability of optical fiber in the high alkalinity environment is poor                                    |
| Smart CNTC     | Resistivity | (1) Health monitoring and structure evaluation based on vibration            | Rajani Kant Rao et al. [26]                                                    |                                                                                             |
|                |       | (2) Improvement of microstructure in the concrete                           |                                                                              |                                                                                             |
| Smart OFRC     | Light amounts | (1) Smart OFRC stress field sensor.                                         | Tang Yongsheng et al. [137]                                                     | (5) The signal detection and data processing systems are complicated |
|                |       | (2) Distributed measurement strain.                                         |                                                                              |                                                                                             |
| Smart OFRC     | Self-healing and resistivity | (1) Stress damage of concrete self-healing                                   | SuZhihao et al. [138]                                                          |                                                                                             |
|                |       | (2) Online detection material internal condition under loading              |                                                                              |                                                                                             |
Comparison of Environmental Response FRC

The comparison of environmentally intelligent response FRC includes field response analysis, application, advantages, and disadvantages, as shown in Table 3.

| Fields        | Types | Parameters                  | Applications                                                                 | References                                      | Disadvantages                                                   |
|---------------|-------|-----------------------------|-----------------------------------------------------------------------------|-------------------------------------------------|-----------------------------------------------------------------|
| Temperature   | Smart CFRC | Resistivity and temperature | Heating roads such as airports, carrying the snow and ice                   | S. M. Sajed Sadati et al. [135]                 | Smart OFRC: (1) The matching properties of fibers and matrix, the bonding quality of healing liquid, and the cracking mechanism of cracks have greater impacts on the repair effect |
|               | Smart Ni-NFC | Resistivity | (1) Real-time monitoring of the external fatigue damage (2) Temperature change online monitoring | Han Baoguo et al. [102]                        | (2) The fibrous pressure on the self-healing crack is largely affected. |
|               | Smart CNFC | Resistivity | Real-time monitoring of the external fatigue damage                          | G.M. Kim et al. [140]                          | (3) The buried glass fiber will increase the construction complexity |
|               | Smart OFRC | Light amounts, power        | (1) Concrete thermometer sensor (2) Distributed measurement strain (3) Self-healing of temperature damage of concrete | Zou Xiaotian et al. [78]                       |                                                                  |
| Humidity      | Smart CFRC | Resistivity | (1) Online detection of concrete internal conditions under different humidity (2) Monitoring of damages caused by humidity changes | Wen Sihai et al. [42]                         | Smart NFRC: (1) It is easy to produce a weak area of destruction |
|               | Smart CNFC | Resistivity |                                                                      | Zhou Zhiliang et al. [98]                      | (2) It is necessary to study the performance stability under the coupling effect of environmental factors during long-term use |
| Electromagnetic field | Smart CFRC | Resistivity and electromagnetic shielding | Electromagnetic shield of concrete.                                         | Doo-Yeol Yoo et al. (2020) [141]               | (3) Loading system, temperature, humidity and other environmental factors greatly influence smart NFRC |
|               | Smart NCBC |                                             |                                                                      | Dai Yan Wen et al. [112]                       |                                                                  |
|               | Smart CNFC |                                             |                                                                      | Linwei Li et al. [66]                          |                                                                  |
| Chemical field | Smart OFRC | Self-healing | (1) Self-healing of environmental changes (2) Used as marine engineering concrete | Peng Jianxin et al. [87]                       |                                                                  |
|               |                                             |                                                                          | Zhou, Yingwu et al. [88]                        |                                                                  |

4. Comparison of Environmental Response FRC

The comparison of environmentally intelligent response FRC includes field response analysis, application, advantages, and disadvantages, as shown in Table 3.

5. Conclusions and Prospects

This paper investigates FRC’s environmental intelligent response characteristics extensively and deeply. The initial work includes the induction of the environmental response field and the research summary on the self-sensing and self-healing response characteristics. After that, the intelligent response mechanisms of smart CFRC, smart OFRC, smart GFRC, and smart NFRC were discussed, including stress field, temperature field, humidity field, electromagnetic field, and chemical field. Smart FRC’s intelligent response mechanism parameters in different environmental fields are highlighted. Finally, the field response characteristics of smart FRC are compared and analyzed. Based on this review, the following conclusions can be drawn.

(i) The deformation of FRC is due to the changes in the environment, and the changes in the fiber spaces will affect the conductivity of the electronic tunnels. It will promote the formation and destruction of conductive networks and form intelligent self-sensing characteristics. When the concrete is damaged, the gravity of the repair liquid and the tension of the meniscus surface overcome the resistance, causing fiber breakage. At this time, the repair fluid flows out, penetrates the crack, hardens at the cracks, and realizes intelligent self-healing.
(ii) The stress-sensitive property of smart CFRC is the key to its stress field intelligent response. The response performance includes the change of conductive ability in the microelectron tunnel and the change of macrovolume resistivity under the stress field. The temperature sensitivity of smart CFRC is the key to intelligent response temperature field. Its macroscopic characteristics are mainly the Seebeck effect and thermoelectric effect, and its microscopic mechanism is electron excitation theory. The conductivity of carbon fiber is the key to the intelligent response of electromagnetic field. The carbon fibers in different directions interact with electromagnetic fields to make the reflected electric fields and lose dissipation while generating electrothermal and electricity effects.

(iii) The stress sensitivity of smart OFRC is the key to generating the stress field’s intelligent response. The response is as follows: the optical fiber causes microbending losses, which changes the light wave parameters at the response position. The transmission of light is easily affected by temperature, which is the key to the intelligent response of smart OFRC in the temperature field. The change of temperature causes temperature stress and power loss in concrete, and the macroscopic characteristic is the change of light wave quantity and power.

(iv) The stress sensitivity of smart GFRC is the key to generating the stress field’s intelligent response. The response is that if the glass fiber pipe is broken, the repair fluid flows to the crack to expand and to harden, and the macroscopic characteristic is the change of resistivity. The response mechanism of the chemical field is mainly about ion excitation. \( \text{Cl}^- \) and \( \text{SO}_4^{2-} \) diffusion in a specific environment destroys the fiber surface wall materials, and the repair solution flows out to repair the cracks.

(v) The inherent resistance and the contact resistance of smart CNFC will change in the stress field, and the macroscopic characteristic is the change in resistivity. In the humidity field, the resistivity is affected by the matrix’s conductivity and the nanotube tip’s field emission effect. When smart Ni-NFC is under stress, the relationship between resistivity fraction and stress/strain and the heating rate is consistent, which is the key to its intelligent response. The reversibility and sensitivity of smart CNTC resistance to the stress response is the key to its intelligent response. The contact resistance changes the resistivity, which realizes by the conductivity of CNT in contact and the “tunnelling effect” in noncontact. The sensitivity of smart GNPC resistance to the stress response focuses on its intelligent response in the stress field. When smart NCBC is in the stress or electromagnetic field, its macroscopic resistivity and electromagnetic shielding effect will change significantly. Smart hybrid concrete has the characteristics of field coupling [143].

### Nomenclature

- **FRC**: Fiber reinforced concrete
- **CFRC**: Carbon fiber reinforced concrete
- **OFRC**: Optical fiber reinforced concrete
- **GFRC**: Glass fiber reinforced concrete
- **NFRC**: Nanofiber reinforced concrete
- **CNFC**: Carbon nanofiber concrete
- **Ni-NFC**: Nickel nanofiber concrete
- **CNTC**: Carbon nanotube concrete
- **GNPC**: Graphite nanoparticle concrete
- **NCBC**: Nanocarbon black concrete
- **FCR**: Fractional changes of resistivity
- **PVAF**: Polyvinyl alcohol fiber
- **NTC**: Negative temperature coefficient
- **PTC**: Positive temperature coefficient
- **CFRP**: Carbon fiber reinforced plastics
- **OTDR**: Optical time domain reflectometer
- **BOTDR**: Brillouin optical time domain reflectometer
- **CNF**: Carbon nanofibers
- **Ni-NF**: Nickel nanofibers
- **CNT**: Carbon nanotube
- **GPN**: Graphite nanoparticle
- **NCB**: Nanocarbon black
- **RCR**: Resistance change rate
- **PP fiber**: Polypropylene fiber
- **RGO**: Reduced graphene oxide

### Data Availability

No data were used to support this study.

### Conflicts of Interest

The authors declare that they have no conflicts of interest.

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