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The Study and Application of Intelligent Self-Monitoring and Self-Repairing Concrete

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Abstract: *Concrete is an indispensable building material in the construction industry, and in recent years, people's attention to smart concrete materials has increased dramatically. Intelligent concrete is a composite of intelligent materials in concrete, and concrete with special functions such as self-perception, self-healing, self-monitoring, and self-adaptation is prepared, which improves the performance of concrete. The self-monitoring of intelligent concrete is manifested in the fact that when the concrete is damaged, the concrete itself will feedback a signal, and the damage degree of the concrete can be characterized through the feedback signal, and then the concrete self-monitoring can be achieved. Self-repair is manifested in the fact that when the internal structure of concrete is damaged, the filled intelligent material can repair the internal damage of the concrete under certain conditions. This paper mainly reviews the current self-monitoring and self-healing properties of smart concrete, expounds its research process and shortcomings, and puts forward the prospect of future research and application of smart concrete.*

Keywords: *Smart concrete, Smart materials, Self-monitoring, Self-healing*

1. Introduction

Concrete is an artificial stone prepared by mixing cementitious materials, granular aggregates, water, as well as a certain amount of admixtures and mineral additives in specific proportions, followed by uniform stirring, dense forming, and curing to harden [1]. Owing to its abundant raw materials, low cost, simple production process, high compressive strength, excellent durability and plasticity, and strong bonding capacity with steel bars, it has been widely favored by the construction industry. In building engineering, concrete is commonly used to fabricate structural components such as foundations, walls, beams, slabs, and columns; in highway and bridge engineering, it also serves as an indispensable raw material for constructing piers and bridge decks.

Although concrete is a highly practical construction material, it has inherent limitations, including high self-weight and distinct brittleness. During the hardening process, cracks are prone to occur due to factors such as water evaporation of concrete and ambient temperature variations. The propagation of cracks not only impairs the aesthetic appearance of structures but also exerts adverse effects on their durability and safety [2]. Consequently, how to monitor and mitigate such cracks has become a novel research topic. With the advancement of science and technology and the in-depth investigations conducted by scholars, smart concrete—a new type of concrete material—has been developed, elevating the performance of concrete materials to an unprecedented level. Smart concrete is a multifunctional material that is modified by incorporating intelligent components into the original concrete mix, thus endowing it with the properties of self-sensing, memory, self-adaptation, and self-healing.

The earliest research on smart concrete can be traced back to the former Soviet Union, where scholars proposed that incorporating carbon as an intelligent material into concrete could produce electrically conductive concrete [2]. In the late 20th century, the concepts of self-sensing concrete and self-healing concrete were put forward by some researchers [3]. In China, Fu Mingfu et al. [4][5] found that the incorporation of nano-SiO_2 and silica fume as mineral additives could enhance the strength and durability of concrete, and pointed out that adding a certain amount of nanomaterials into concrete

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enabled the preparation of concrete with special functions. Cui Di, Li Hongnan et al. [6] demonstrated that Shape Memory Alloys (SMA) are ideal additives for the research on the self-healing performance of smart concrete, and possess high research value for seismic disaster prevention and mitigation in concrete engineering. Li Lei, Li Qingbin et al. [7] applied smart concrete to bridge design, indicating that the additional prestress of SMA tendons embedded in concrete could be controlled by adjusting their temperature, thereby regulating the deformation of concrete bridges and improving their load-bearing capacity. Liu Bingfei, Liu Xiangrui et al. [8] discovered through experiments that SMA fibers can not only repair damaged concrete but also enhance its compressive, flexural, and shear properties when added at an appropriate dosage. Additionally, some scholars have proposed the application of computer artificial neural networks in the preparation of smart concrete, utilizing computer vision technology to achieve accurate monitoring of structural damage in concrete. With the continuous improvement of modern materials and the development of science and technology, the research on smart concrete is moving towards a more intelligent and integrated direction.

2. Self-Monitoring Technology for Smart Concrete

2.1 Principles of Self-Monitoring Technology

Concrete is a massive brittle material that is highly susceptible to damage under load impacts and natural disasters, which may lead to casualties and property losses. Therefore, it is imperative to conduct structural health monitoring of concrete. Early concrete monitoring methods were primarily manual inspections, which are simple to operate but cannot achieve real-time monitoring due to environmental constraints. In addition, the accuracy of manual inspections cannot be guaranteed owing to the reliance on inspectors' experience, thereby compromising the reliability of test results. Subsequently, some scholars proposed the use of acoustic emission technology to detect concrete damage. Based on the principle that concrete emits acoustic waves when undergoing deformation and fracture, the location and time of crack propagation in concrete can be determined by counting the acoustic waves collected via acoustic emission receivers [9]. Other scholars suggested using sensors to assess the degree of concrete damage. Leveraging the principle that waves reflect different levels of energy under varying conditions, stress waves attenuate more rapidly in damaged concrete; thus, the degree of concrete damage can be analyzed based on the received sensor data [10][11]. Although sensor-based methods and acoustic emission technology can theoretically and experimentally detect concrete damage, their practical engineering applications are limited by stringent operational conditions and high costs, which hinder their widespread adoption in smart concrete-related projects. Traditional monitoring techniques are labor-intensive, material-consuming, and costly, whereas the self-monitoring technology of smart concrete provides a more convenient and reliable alternative. The mechanism of concrete self-monitoring technology is as follows: when damaged, smart concrete spontaneously emits damage signals. By analyzing these feedback signals and combining them with engineering technical deduction, the safety and reliability of structural components can be accurately evaluated, thereby reducing the probability of accidents.

In current research on the self-monitoring performance of smart concrete, a commonly adopted approach is to incorporate a certain amount of smart materials (e.g., carbon black, carbon fibers, steel fibers, optical fibers, etc.) into concrete to prepare self-monitoring smart concrete. Based on the characteristic that the electrical resistivity of concrete changes when it sustains damage, the degree of damage can be characterized by measuring the variation in electrical resistivity when an electric current is applied to the smart concrete, thus realizing self-monitoring of concrete. Common methods for measuring the electrical resistivity of concrete include the two-electrode method and the four-electrode method [9].

(1) The two-electrode method involves applying an electric current between two electrodes and measuring the potential difference between them to obtain the electrical resistance of the tested concrete, as illustrated in Figure 1. This method features simple operation but has a drawback: it cannot eliminate the interference of contact resistance, which adversely affects the accuracy of measurement results [12][13][14].

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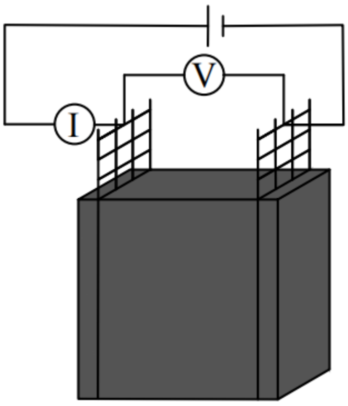

Figure 1: Two-electrode test setup.[15]

(2) The electrodes of the four-electrode method are linearly arranged with equal spacing between adjacent probes. The outer electrodes are used to apply electric current, while the inner electrodes are responsible for measuring voltage, as illustrated in Figure 2. As a widely adopted method for measuring the electrical resistivity of concrete, the four-electrode method can effectively eliminate the interference of contact resistance between concrete and electrodes, thereby rendering the test results more accurate and reliable.

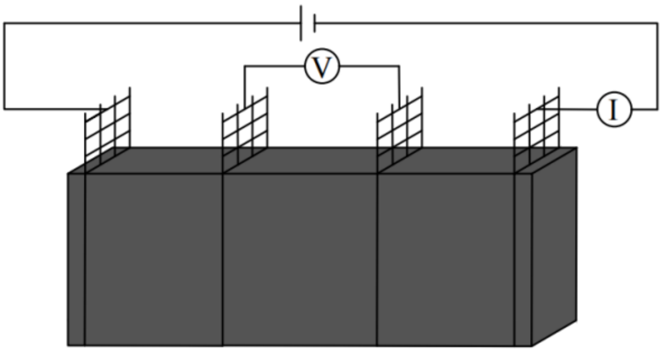

Figure 2: Application of four-electrode method in resistivity in smart concrete.[15]

2.2 Research Progress on Self-Monitoring Technology

Guan Xinchun et al. [16] uniformly incorporated chopped carbon fibers into concrete. A comparison with plain concrete revealed that the carbon fiber-reinforced concrete exhibited higher tensile strength, larger ultimate tensile strain, as well as temperature and pressure self-sensing properties. Liu Genjin et al. [17] investigated the correlation between crack propagation on the tensile side of smart concrete beams under bending load and the corresponding variations in electrical resistivity of the beams. They also compared the effects of different combinations and dosages of carbon black, steel fibers, and carbon fibers on self-monitoring sensitivity. The results indicated that an appropriate amount of carbon black contributed to enhancing the sensitivity of the monitoring system, and the smart concrete with hybrid incorporation of steel fibers and carbon fibers at a specific ratio demonstrated the optimal crack detection performance.

Wang Haifeng et al. [18] proposed a type of Z-shaped smart aggregate. Leveraging the temperature-resistance characteristic of carbon fibers, they conducted tests on smart concrete specimens via a constant-rate temperature adjustment method. The findings showed that the smart concrete embedded with Z-shaped smart aggregates could predict its own damage and failure more accurately, thereby improving the safety performance of concrete structures. Cai Chenning et al. [19] integrated graphene conductive ink onto the concrete surface through manual coating, endowing the concrete with self-sensing functionality. By adopting the method of reconstructing conductivity variation images after identifying concrete damage via electrical impedance tomography (EIT), the location and size of concrete damage were detected, achieving effective and accurate monitoring of concrete damage and providing a novel technical solution for concrete damage monitoring.

Austin Downed et al. [20] pointed out that cement-based smart sensors could be applied to structural health monitoring (SHM). Utilizing the strain-sensing and damage-sensitive characteristics of conductive cement composites, damage in structures could be detected, located, and quantified under a computationally efficient resistance network model, enabling real-time distributed SHM of smart concrete structures. K. S. C. Kuang and T. W. K. Goh [21] developed an integrated embedded device for concrete crack sensing and healing. This device was capable of detecting and locating cracks; by connecting it to sensors via a simple resistance circuit, it could accurately identify the location of cracked areas in concrete beams. Tests on the assembled device demonstrated its successful performance in detecting, locating, and healing cracks in reinforced concrete beams.

Some scholars have also proposed applying the principles of computer artificial neural networks and machine learning to the preparation of smart concrete, utilizing computer vision technology to address issues such as damage detection of concrete structures [22]. Han Xiaojian and Zhao Zhicheng [23] proposed an algorithm for crack detection and quantitative analysis that combines deep learning and traditional image processing technologies. Based on a fully convolutional neural network (FCN)-based crack segmentation algorithm, they processed images to create a crack segmentation dataset, which could effectively measure the length, width, and direction of concrete cracks. By improving the edge gradient, the algorithm realized the localization and automatic acquisition of the maximum width of cracks. Yue Qingrui, Liu Xiaogang et al. [24] indicated that the safety diagnosis of structures in service is inevitably moving towards intelligence. Constructing an intelligent diagnosis system for the service safety of engineering structures and realizing the intelligent evaluation and prediction of structural service performance have become the key research focuses of current intelligent diagnosis studies.

2.3 Insufficiency of Self-monitoring Technology

The self-monitoring technology of smart concrete primarily relies on the electrical conductivity of concrete to characterize its damage indicators. The realization of self-monitoring functionality requires the processing and analysis of large volumes of monitoring data. However, concrete is subjected to long-term exposure to the external environment and is thus highly susceptible to the impacts of temperature, humidity, chemical substances, and other factors, which may lead to inaccurate feedback data and compromise the reliability of monitoring results. Furthermore, projects employing concrete are generally large-volume structures, and the incorporation of intelligent admixtures into concrete will prolong its curing period, thereby impeding the construction schedule. In current research on the self-monitoring performance of smart concrete, feedback signals can only be captured when the concrete has sustained damage to a certain extent, and minor internal damage cannot be detected. Consequently, this technology fails to accurately predict the timing of structural failure of concrete.

3. Self-healing Technology for Smart Concrete

3.1 The Principle of Self-Healing Technology

The self-healing technology of concrete involves incorporating healing-functional admixtures into concrete. When concrete sustains damage, these intelligent admixtures react spontaneously to repair the damaged areas, thereby achieving the goal of self-healing. Self-healing concrete can be categorized into two major types: The first type imitates the regeneration and repair mechanism of animal bone tissue after injury, which entails compounding healing binders with concrete materials. When the material matrix is damaged and cracked, microcracks emerge within the concrete, and the healing binders then automatically bond these cracks through chemical reactions. This process inhibits crack propagation, repairs the concrete, enhances concrete strength, and improves the overall structural safety and durability [25].

The self-healing mechanism of microbial smart concrete is as follows: The microorganisms involved in self-healing, after being combined with carrier materials, remain in a dormant state in the highly alkaline internal environment of concrete. When cracks appear in concrete, oxygen and water penetrate into the concrete as catalysts, activating the aerobic microorganisms. The CO_2 produced during the metabolic process of the activated aerobic microorganisms reacts with the free calcium ions in the concrete to regenerate calcium carbonate, which fills the cracks and thus realizes the self-healing

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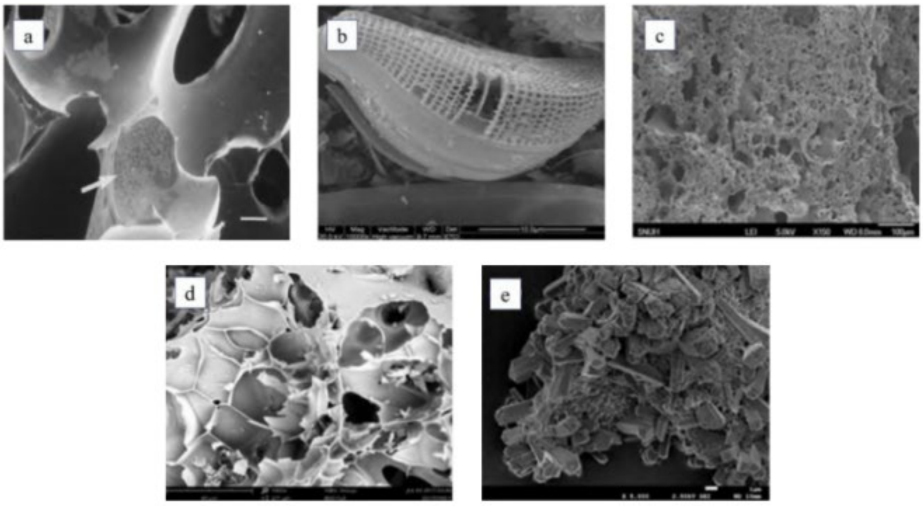
of concrete [26][27].

In the research progress of microbial smart concrete, scholars have mainly focused on the carrier materials of microorganisms, which are primarily divided into porous materials, encapsulated materials, and nanomaterials. Porous materials were the first to be used as protective carriers for microorganisms in self-healing concrete, featuring low density and high porosity. Commonly used porous materials include polyurethane, expanded clay, expanded perlite, and zeolite, as illustrated in Figure 3. Encapsulated materials, also known as enclosed materials, can effectively prevent microorganisms from being damaged by the internal environment of concrete and enhance the repair efficiency; they mainly include microcapsules, hydrogels, and inorganic cementitious materials. Nanomaterials utilize the interaction between nanoparticles and microbial biofilms, serving as effective protective carriers for microorganisms [33].



(a)Polyurethane[28]; (b)Diatomaceous earth[29]; (c)Expanded clay[30]; (d)Expanded perlite[31]; (e)Zeolite[32]

Figure 3: Microstructure of different porous carriers.[27]

At present, most scholars employ Shape Memory Alloys (SMA) as the intelligent admixture for self-healing concrete. Studies have demonstrated that SMA exhibits prominent characteristics including large recoverable deformation, high driving force during initial recovery, high sensitivity to resistance strain, and excellent fatigue resistance. Moreover, it possesses the shape memory effect under specific conditions, enabling it to revert to its original shape upon stimulation by temperature changes or external forces. Therefore, SMA is an ideal admixture for preparing self-healing smart concrete. As an admixture, SMA has gained extensive attention in research pertaining to the self-healing performance and structural safety of smart concrete. With the continuous improvement of requirements for the safety and durability of structures, research on the application of SMA in the self-healing field of smart concrete has been driven toward further advancement.

Some scholars have also applied concrete self-healing technology to asphalt concrete pavements. Although asphalt pavements are prone to cracking, asphalt itself has certain viscoelastic properties, and asphalt concrete exhibits favorable temperature sensitivity. When the temperature reaches the critical threshold, damaged asphalt concrete can achieve self-healing. The primary methods for raising the temperature of asphalt concrete include electromagnetic induction heating, microwave heating, and infrared heating.

3.2 Research Progress on Self-Healing Technology

Sun L et al. [34] conducted a study on the effect of unbonded length on the self-healing performance of SMA beams. The results showed that a longer unbonded length corresponds to a better crack healing effect. Kuang Yachuan et al. [35] investigated the electrothermal actuation rate of shape memory alloy (SMA) smart concrete. To enhance the electrothermal actuation rate, they proposed a novel heating method that involves winding enameled wire around the SMA surface followed by coating with thermal insulation adhesive. Experiments and finite element analysis were performed on SMA concrete specimens, and the findings indicated that this novel heating method could significantly improve the heating rate of SMA, while the thermal insulation adhesive effectively reduced heat transfer to the concrete.

Zhang Yanan et al. [36] incorporated shape memory alloy (SMA) materials into concrete to develop an SMA-driven smart concrete material. Theoretical and experimental investigations on the relationship between the electrical resistivity of SMA materials and concrete cracks revealed an approximately linear correlation between SMA resistance variation and concrete crack development. The constrained recovery force of SMA was found to undergo three stages: thermal expansion, phase transformation recovery, and post-full-phase-transformation thermal expansion. The study concluded that SMA materials can only achieve limited repair of concrete cracks. S. Malagisi et al. [37] proposed an effective procedure for crack repair of reinforced concrete beams equipped with SMA actuators. A nonlinear nonlocal damage-plasticity model for concrete was established and applied to simulate the construction stage of beams, providing a finite element program foundation for solving highly nonlinear problems.

Kuang Yachuan and Ou Jianping [38] developed a smart concrete beam by utilizing the shape memory effect of SMA and its characteristic of exerting large forces on constrained components during heating. Experimental results demonstrated that increasing the initial pre-strain of SMA wires could significantly enhance the self-recovery capability of SMA concrete beams. Li Shuangbei et al. [39] explored the crack repair effect of shape memory alloy (SMA) on reinforced concrete beams and conducted recovery performance tests on SMA wires. The results verified that increasing the diameter and number of SMA wires, as well as raising the initial strain, could all enhance the crack repair effect of SMA wires on beams; notably, increasing the SMA wire diameter was a more effective measure to improve the crack control rate of concrete beams.

Chuan Y K, Ping J O et al. [40] developed a smart concrete beam by leveraging the shape memory effect of SMA and its ability to exert large forces on constrained components during heating-induced transformation. The results showed that under the premise of increasing the initial pre-strain of SMA wires, electrical heating of SMA wires could significantly improve the self-healing performance of concrete.

Dong Sufen, Song Zexuan et al. [41] investigated the self-healing efficiency of asphalt concrete via thermally induced technology. They found that utilizing the temperature sensitivity of asphalt concrete and realizing the staged flow and diffusion of asphalt at crack interfaces are the key factors for its self-healing property. Li Bin [42] carried out experiments on the temperature and healing distribution characteristics of steel fiber-reinforced asphalt concrete under electromagnetic induction heating. The results indicated that asphalt concrete exhibits distinct self-healing behavior under electromagnetic induction heating, and the healing efficiency increases with the number of heating cycles. Wang Haopeng [43] designed a conductive asphalt concrete capable of self-healing via microwave heating. By incorporating conductive materials into asphalt concrete, the insulator asphalt was converted into a conductor. Experiments showed that conductive asphalt concrete can absorb more heat under the same heating conditions, and its healing efficiency is far higher than that of plain asphalt concrete.

To reduce the impact on the long-term activity of biomineralizing microorganisms during the preparation of microbial smart concrete, Meng Yongdong, Xue Yu et al. [26] selected expanded perlite and ceramsite as microbial carriers, with cement paste and metakaolin slurry as coating materials. Splitting tensile tests demonstrated that the microbial smart concrete prepared using this approach not only effectively ensured the long-term activity of microorganisms but also improved the crack repair effect of concrete.

Wang et al. [44] applied melamine-based microcapsules as microbial carriers in self-healing concrete. Experiments showed that the activity of microorganisms in microcapsules would not be damaged by the high pH environment inside concrete, and microbial spores remained in an inert state within the microcapsules. When cracks appeared in concrete, the microcapsules would rupture and activate the enclosed microbial spores to repair the cracks. The maximum healed crack width of the repaired concrete reached 0.97 mm, demonstrating excellent repair performance. Su et al. [45] integrated microorganisms (Bacillus megaterium), nutrients, and low-alkalinity carriers into a single unit via extrusion, using low-alkalinity sulphoaluminate cement as the carrier matrix. This method not only protected microorganisms from the high-alkalinity environment caused by cement hydration but also effectively reduced the negative impacts of nutrients on concrete properties.

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3.3 Shortcomings of Self-healing Technology

The smart materials adopted in self-healing smart concrete are predominantly chemical materials. Most of these chemical materials exert adverse impacts on the environment. Conversely, the healing agents may also be affected by ambient factors such as temperature, humidity, and chemical substances, leading to performance degradation or even failure. In practical applications, the supply and distribution of healing agents may be constrained by the internal structure and permeability of concrete, which prevents the agents from reaching cracked regions effectively and thus undermines the healing effect. Physical materials, such as shape memory alloys (SMA) and hollow glass fibers, entail high material and construction costs when applied in practical engineering projects. They are also vulnerable to environmental influences, failing to exert their intrinsic effectiveness. Furthermore, current research on the actuation methods for SMA wires is limited to electrical heating, which requires an excessively high current during operation and poses certain potential safety hazards in experimental processes. Further investigations are needed on the anchoring methods between SMA and concrete, as the existing approaches may sometimes impair the prestress of concrete and reduce its overall strength.

Research on the self-healing of asphalt concrete mainly focuses on laboratory-scale studies, such as modifying the types of admixtures and optimizing the heating methods of concrete. There is a lack of research on the healing performance of asphalt concrete during heating and cooling cycles, as well as studies on minimizing energy consumption during the induction process, which will become key research directions for asphalt concrete in the future.

Microbial self-healing smart concrete relies on the synergistic interaction between microorganisms and their loaded carriers during application. However, the carrier materials reported in current research exhibit relatively poor physical properties and high costs, making them difficult to be scaled up for engineering applications. In addition, the incorporation of carrier materials may sometimes compromise the mechanical properties of concrete. For example, the addition of microcapsules has a significant negative impact on concrete strength; Hou Fuxing et al. [27] demonstrated through research that adding microcapsules accounting for 3%–5% of the cement mass reduces the compressive strength of concrete by 33%–47%. Moreover, the current carrier materials have poor compatibility with the cement matrix, which impairs the activity of microorganisms encapsulated in the carriers and further compromises the self-healing performance of microbial self-healing smart concrete.

4. Prospects of Smart Concrete

Since its development, smart concrete has seen advances in both concept and technology, yet the technology remains incompletely mature. In the experimental research phase, the close integration of self-monitoring, self-regulation, and self-healing functionalities has not been fully achieved. In practical applications, more research is required to verify its long-term performance, safety, and reliability. With the advancement of science and technology, future smart concrete will become more intelligent, and its integration with computer technology will bring revolutionary changes to concrete structures and materials science.

By embedding various multifunctional sensors (e.g., strain gauges, temperature sensors, humidity sensors, etc.) into smart concrete to collect real-time data on concrete structures, the collected data can be input into artificial neural networks to train models for identifying the location and degree of concrete damage. This enables more accurate damage detection, facilitating timely maintenance and reinforcement. Artificial neural networks can also learn from data to identify when the self-healing mechanism needs to be activated, optimally regulate the release and distribution of healing agents, and thereby make the self-healing process more precise, efficient, and energy-saving.

The environmental impact can be reduced by adopting renewable materials and low-carbon production technologies. Furthermore, future smart concrete can extend the service life of structures through its self-healing functionality, reducing resource waste and waste generation. Beyond the traditional civil engineering field, smart concrete will also find applications in aerospace, marine engineering, intelligent transportation, and other sectors. Currently, Dong Sufen et al. [46] have proposed the use of smart concrete for constructing intelligent multifunctional pavements. Pavements built with such intelligent multifunctional concrete are more environmentally friendly, adaptable, reliable, and durable, which enhances the safety and efficiency of traffic

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References

[1] XUE G P. Brief Discussion on the Technical Application of Concrete in Water Conservancy and Hydropower Engineering [J]. SiChuan Building Materials,2010, 36(04), 32 - 35.
[2] Ding X F, Wu X, Zhang X M, et al. Reviews on research progress of strength theories for materials [J/OL]. Journal of Railway Science and Engineering, 2024, 3(06), 1-34.
[3] He Z Q. Basic Study on State Monitoring and Self-ensing of Gangue-cemented Backfilling Body during Bearing Failure [D]. China University of Mining and Technology, 2023.
[4] Qu E X, Niu X T, Zhou J Q, et al. Research Progress and Applications of Self-diagnosis and Self-healing Functions in Smart Concrete [J]. Development Guide to Building Materials, 2022, 20(04), 12 - 14.
[5] Fu M F, Xiong J G,Song G Q. Research and Applications of Nanomaterials in Concret [C]. Nanchang University, 2004.
[6] Cui D, Li H N, Song G B. Progress on Study and Application of Shape Memory Alloy in Civil Engineering [J]. Journal of Disaster Prevention and Mitigation Engineering, 2005, (01), 86 - 94.
[7] Li L, Li Q B, Zhang F. Design and Experiment of a Smart Concrete Bridge with Embedded Shape Memory Alloy Bundles [J]. Engineering Mechanics, 2010, 27(03), 45 - 54.
[8] Liu B F, Liu R X, Lan T, et al. Laboratory Analysis of Shape Memory Alloy Smart Concrete Materials [J]. China Concrete and Cement Products, 2014, (04), 47 - 51.
[9] Liu G J. Effect of hybrid fiber and nano carbon black on the self-sensing ability of crack for smart concrete [D]. Dalian University of Technology, 2021.
[10] Xiao M. Study on Loading-electrical-magnetically Coupling Law of Gangue-based Functionally Cemented Body [D]. China University of Mining and Technology, 2022.
[11] Liang K. Experimental Study on Electric Conductivity Characteristics and Influential Factors of Concrete [D]. Southwest Jiaotong University, 2018
[12] LATASTE J-F. Electrical resistivity for the evaluation of reinforced concrete structures, In: Non-destructive evaluation of reinforced concrete structures [M]. Sawston: Woodhead Publishing, 2010, 243 - 275.
[13] AZARSA P,GUPTA R.Advanced cementitious materials :Mechanical behavior,durability,and volume stability [J]. Advances in Materials Science and Engineering, 2017,2017: 1 - 30.
[14] GONZALEZ J, et al. A new method forin-situ measurement of electrical resistivity45 Fel iu S.Andrade Cofreinforced concrete [J]. Materials Structures, 1996,296: 362 - 365.
[15] HAN B,GUAN X,OU J.Electrode design,measuring method and data acquisition system of carbon fiber cement paste piezoresistive sensors [J]. Sensors&Acutuators A Physical,2007,135(2): 260 - 369
[16] Guan X C, Ou J P, Han B G et al. State of art of carbon fiber reinforced concrete [J]. Journal of Harbin University of C. E. and Architecture, 2002(06), 55 - 59.
[17] Liu G J, Ding Y N, Song S D. Effect of steel fiber-nano carbon black/concrete smart layer on crack self-monitoring performance [J]. Acta Materiae Compositae Sinica, 2021, 38(07), 2348 - 2358.
[18] Wang H F, Yan H D. Study on Smart Aggregate of Concrete and Its Temperature and Mechanical Properties [J]. Journal of Basic Science and Engineering, 2018, 26(03):,631 - 639..
[19] Cai C N, Yan G, Chen S L et al. Damage detection for smart concrete structure by using electrical impedance tomography [J]. China Measurement and Test, 2022, 48(11), 8 - 14.
[20] DOWNEY A ,D'ALESSANDRO A ,BAQUERA M , et al. Damage detection, localization and quantification in conductive smart concrete structures using a resistor mesh model [J]. Engineering Structures, 2017, 148: 924 - 935.
[21] KUANG K ,GOH T . Crack sensing and healing in concrete beams based on wire-crack sensors and healing tube [J]. Construction and Building Materials, 2017, 132: 395 - 411.
[22] Shen J K. Research On Crack Detection Algorithm Of Concrete Structure Based On Computer Vision [D]. Institute of Engineering Mechanics, China Earthquake Administration, 2019.
[23] Han X J, Zhao Z C. Structural surface crack detection method based on computer vision technology [J]. Journal of Building Structures, 2018, 39(S1), 418 - 427.
[24] Yue Q R, Liu X G, Chen H B. Research and application progress of intelligent diagnosis for structural service safety [J]. Journal of Building Structures, 2022, 43(10), 41 - 49.
[25] Shi M ,XU G ,ZHAO J , et al.The study on bond-slip constitutive model of shape memory alloy fiber-reinforced concrete [J]. Construction and Building Materials,2024,18: 135395.
[26] Meng Y D, Xue Y, He Z Q, et al. Experimental study on mineralized microbial immobilization and self-healing of hydraulic concrete [J]. Journal of Hydroelectric Engineering, 2024, 43(06), 1 - 10.
[27] Hou F X, Bai Y M, Shen D, et al. Research Progress of Carrier Materials in Microbial Self-healing Concrete [J/OL]. Materials Reports. 2024, 07(23), 1 - 35.
[28] BANG S S ,GALINAT K J ,RAMAKRISNAN V. Calcite precipitation induced by

polyurethane-immobilized Bacillus pasteurii [J]. Enzyme and Microbial Technology, 2001, 28(4): 404 - 409.

[29] Yu J W ,DE N B ,W V . Diatomaceous earth as a protective vehicle for bacteria applied for self-healing concrete. [J]. Journal of industrial microbiology & biotechnology, 2012, 39(4): 567 - 577.

[30] Han S ,CHOI K E ,PARK W , et al. Effectiveness of expanded clay as a bacteria carrier for self-healing concrete [J]. Applied Biological Chemistry, 2019, 62(1):1 - 5.

[31] LU J, Guan H J, Chen J, et al. Sugar-coated expanded perlite as a bacterial carrier for crack-healing concrete applications [J]. Construction and Building Materials, 2020, 232: 117222.

[32] ZENG Z ,GREA E ,J. G M , et al. Synthesis and cation exchange capacity of zeolite W from ultra-fine natural zeolite waste [J]. Environmental Technology & Innovation, 2021, (prepublish): 101595.

[33] Wang J Y, DE BELIE N, VERSTRAETE W. Diatomaceous earth as a protective vehicle for bacteria applied for self-healing concrete [J]. Journal of industrial microbiology and biotechnology, 2012, 39(4): 567 - 577.

[34] Sun L, LIANG D , CAO O, et al. Analysis on Factors Affecting the Self - Repair Capability of SMA Wire Concrete Beam [J]. Mathematical Problems in Engineering ,2013(1): 469 - 481.

[35] Kuang Y C, Wang S H, Peng Z W, et al. Research and analysis of electrothermally actuated heating rates of smart concrete beam embedded with Shape Memory Alloy [J]. Journal of Railway Science and Engineering. 2023, 20(05), 1858 - 1870.

[36] Zhang Y N, Li J C, Wang Q F, et al. Mechanism and Experimental Study on Crack Monitoring and Repair of Shape Memory Alloy Intelligent Concrete [J]. Chinese Journal of Solid Mechanics, 2020, 41(02), 170 - 181.

[37] MALAGISI S ,MARFIA S ,SACCO E , et al. Modeling of smart concrete beams with shape memory alloy actuators [J]. Engineering Structures, 2014, 75: 63 - 72.

[38] Kuang Y C, Ou J P. Research on the Deformation Characteristics of Smart Concrete Beam Embedded with Shape Memory Alloy Wire [J]. China Railway Science, 2008, (04), 41 -46.

[39] Li S B, Mo C M, Liang G Q. Recovery performance of shape memory alloy and its application in repairing cracks of concrete beams [J]. Concrete, 2015,(04), 68 - 73.

[40] CHUAN Y K ,PING J O . Experiment and Analysis of Smart Concrete Beam Strengthened Using Shape Memory Alloy Wires [J]. Key Engineering Materials, 2008,(400-402): 371 - 377.

[41] Dong S F, Song Z X, Zhang W H, et al. Research Progress on Heat-induced Self-healing Asphalt Concrete: a Kind of Sustainable Pavement Material [J/OL]. Materials Reports, 2024, 03-05, 1-23.

[42] Li B. Induction Heating and Healing Properties of Asphalt Concrete [D]. Wuhan University of Technology, 2018.

[43] Wang H P. Design and Evaluation of Conductive Asphalt Concrete for Self-Healing [D]. Southeast University, 2016.

[44] WANG J Y, SOENS H, VERSTRAETE W, et al. Self-healing concrete by use of micro encapsulatedbacterial spores [J]. Cement and concrete research, 2014, 56, 139 - 152.

[45] Su Y, Zhang T, Qian C. Application potential of Bacillus megaterium encapsulated by low alkaline sulphoaluminate cement in self-healing concrete [J]. Construction and Building Materials, 2021, 273: 121740.

[46] Su F D, Wei H Z, Xin Y W, et al. New-generation pavement empowered by smart and multifunctional concretes: A review [J]. Construction and Building Materials, 2023.