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Optimization of Electrical Conductivity of Carbon Fiber Reinforced Concrete (CFRC) and Its Application in Structural Health Monitoring

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Abstract: *In order to promote the engineering application of carbon fiber reinforced concrete (CFRC) in the field of structural health monitoring, this study systematically explores the optimization of CFRC conductivity and monitoring applications. Through experiments, the key influencing factors of the conductivity of CFRC were identified, and based on these factors, three optimization methods were proposed: optimizing the carbon fiber content and distribution through ultrasonic stirring and magnetic field induction techniques, improving interface bonding through oxidation/coupling agent treatment, and constructing a synergistic conductive network by adding carbon nanotubes and graphene, all of which achieved a reduction in CFRC resistivity and an improvement in conductivity. In applied research, the CFRC force electric coupling effect is established as the monitoring core principle (external loads cause microstructural changes, which in turn lead to quantitative correlations between resistance and stress, strain, and damage), and a structural health monitoring system is constructed that includes CFRC sensors, data acquisition and transmission, and data analysis and processing (statistical analysis, machine learning algorithms) to achieve real-time perception, accurate judgment, and early warning of structural status. This research results provide theoretical and technical support for the large-scale application of CFRC in engineering structural health monitoring.*

Keywords: *Carbon Fiber Reinforced Concrete (CFRC); Optimization of Conductivity Performance; Structural Health Monitoring*

1. Introduction

With the rapid development of the modern construction industry, the performance requirements for building materials are becoming increasingly stringent. Carbon fiber reinforced concrete (CFRC) has emerged as a new type of composite material, which combines the high strength and high modulus of carbon fiber with the good compressive performance of concrete, demonstrating great potential for application in the field of construction. CFRC not only has excellent mechanical properties, such as significantly improved tensile strength and bending strength, effectively improving the low tensile strength and easy cracking defects of ordinary concrete, but also performs outstandingly in durability and impermeability. It is widely used in many important engineering fields such as bridges, high-rise buildings, and hydraulic structures, providing strong support for improving the safety and reliability of engineering structures.

Ensuring the safety and stability of a building structure is crucial throughout its entire lifecycle. Structural health monitoring, as an effective means, can real-time grasp the working status of structures, timely detect potential damage and hidden dangers, and provide scientific basis for the maintenance, repair, and life prediction of structures. Due to its unique composition and structure, CFRC has certain electrical conductivity, and its resistance will undergo regular changes with the internal stress, strain, and damage state of the structure. This characteristic makes it a research hotspot in the field of structural health monitoring. By optimizing the conductivity of CFRC, the health status of the structure can be monitored more accurately and sensitively, early warning of structural damage can be achieved, and the occurrence of structural safety accidents can be avoided. This is of great significance for ensuring the safety of people's lives and property, reducing engineering maintenance costs, and extending the service life of the structure. This study comprehensively applies experimental research, theoretical analysis, and case analysis methods to deeply reveal the influencing factors and optimization mechanisms of the conductivity performance of CFRC, providing a solid theoretical basis and technical support for its wide application in the field of structural health monitoring.

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2. Basic characteristics and preparation process of CFRC

2.1 Composition and structure of CFRC

Carbon fiber reinforced concrete (CFRC) is a high-performance composite building material composed of a cement matrix, carbon fibers, and additives[1]. The cement matrix provides the foundation strength and stability for the material, and the skeleton formed after hardening can bear and transfer loads, which is the structural foundation of CFRC.

Carbon fiber is the core element for improving the performance of CFRC, with high strength, high modulus, and low density characteristics: high strength can effectively bear tensile force, making up for the tensile shortcomings of ordinary concrete; High modulus can enhance material stiffness, reduce stress deformation, and improve structural stability; Low density reduces self-weight while ensuring strength, making it suitable for weight sensitive engineering scenarios such as large-span bridges and high-rise buildings.

Although the dosage of additives is relatively small, their function is crucial. Dispersants can improve the dispersibility of carbon fibers in the matrix, avoid agglomeration, and fully exert the reinforcing effect; Water reducing agents can reduce the amount of mixing water and improve the strength and durability of concrete while ensuring its workability; Early strength agents can accelerate cement hydration, shorten the early strength formation period of CFRC, and improve construction efficiency.

At the micro level, CFRC exhibits an ordered and complex structure, with carbon fibers uniformly dispersed in the matrix and forming a good interfacial bond. This interface is the key to stress transmission, ensuring that the two are subjected to coordinated forces - when external forces act, carbon fibers bear the tensile force and transmit the stress to the matrix through the interface, improving the overall strength and toughness of the material; If the interface bonding is poor, it is easy to cause debonding and stress transmission failure, greatly reducing performance. In addition, factors such as raw material characteristics and preparation processes can affect the microstructure, which in turn affects the macroscopic properties of CFRC.

2.2 Preparation process of CFRC

In the preparation of CFRC, the selection of raw materials is the basis for ensuring performance. Cement should prioritize the use of high-strength grades and stable quality products. The former can meet the early and late stage strength requirements of the project, while the latter can reduce CFRC performance fluctuations; The selection of aggregates should take into account particle size, gradation, and texture. Reasonable gradation and appropriate particle size can improve compactness, and clean and hard aggregates can reduce impurity interference; The selection of carbon fiber should be based on its mechanical properties, length, diameter, and surface characteristics. Excellent mechanical properties can enhance the strengthening effect, and the suitable length and diameter should meet the engineering requirements. Good surface characteristics can optimize the interface bonding with the matrix.

The stirring process directly affects the dispersibility of carbon fibers, and mechanical stirring and ultrasonic stirring are commonly used. Mechanical stirring achieves raw material mixing through high-speed rotation of blades, but it is difficult to solve the problem of carbon fiber agglomeration; Ultrasonic stirring utilizes cavitation and mechanical vibration to eliminate agglomeration and improve dispersion uniformity. The mixing time and speed need to be precisely controlled - too short a time can result in insufficient mixing, while too long can easily damage the carbon fiber; Excessive speed can cause segregation, while excessive speed can reduce efficiency. The optimal parameters need to be determined through experiments.

The forming process determines the structure and performance of CFRC, vibration forming improves compactness through vibration foaming, pressure forming is suitable for high-strength demand scenarios, and pouring forming is suitable for complex large volume components. The molding pressure, vibration frequency, and time need to be adjusted as needed: insufficient pressure results in low density and compactness, while excessive pressure can easily damage the mold and structure; The vibration parameters should be combined with the characteristics of the mixture and the size of the components to avoid insufficient vibration or excessive damage to the structure.

The maintenance process affects the hydration and strength development of cement, and temperature, humidity, and time need to be controlled: suitable temperature accelerates hydration, insufficient humidity leads to incomplete hydration, and too short maintenance time affects strong durability performance. Usually, wet environments are used for curing, and curing under standard conditions (temperature 20 ± 2 ℃, relative humidity ≥ 95%) can achieve the best performance of CFRC.

2.3 Basic performance of CFRC

The mechanical properties of CFRC are the core basis for its engineering applications, covering compressive, tensile, flexural strength, and toughness. The compressive strength is improved compared to ordinary concrete, as carbon fiber can suppress the generation and propagation of internal microcracks and enhance compactness; Research has shown that when the carbon fiber content is within a reasonable range, the compressive strength increases with the increase of content. However, if the content exceeds the limit, the carbon fiber tends to aggregate and instead reduces the strength.

Its tensile and bending strength have been significantly improved. Carbon fiber has high tensile strength and modulus, which can effectively bear tension and prevent cracking. Experiments have shown that adding an appropriate amount of carbon fiber can increase the tensile strength of concrete by 30% - 50% and the bending strength by 50% -100%. For example, in bridge engineering, CFRC bridge decks have enhanced bending performance, can bear larger loads, and improve bridge safety and service life. In terms of toughness, CFRC has significantly improved compared to ordinary concrete: under external forces, the interface between carbon fiber and matrix can absorb and dissipate energy, and delay crack propagation; Under impact loads, it can withstand greater impact forces without sudden damage, making it suitable for scenarios with high safety requirements such as high-rise building frames and seismic structures. Durability is a key consideration in the application of CFRC engineering, including impermeability, frost resistance, and chemical resistance. The impermeability is significantly improved due to the anti-cracking effect of carbon fiber, which can reduce the infiltration channels of water and harmful media, and is suitable for anti-seepage of hydraulic structures such as dams and water tanks. Good frost resistance, carbon fiber reinforced internal structure in freeze-thaw cycles. After multiple cycles, its quality loss and strength reduction are much smaller than ordinary concrete, making it suitable for engineering in cold regions. Excellent resistance to chemical erosion, due to the strong chemical stability of carbon fiber, it can protect cement stone from erosion and is suitable for harsh environments such as chemical construction and marine engineering. It can work stably for a long time and reduce maintenance costs.

3. Conductivity and influencing factors of CFRC

3.1 Conductivity principle of CFRC

The conductivity of carbon fiber reinforced concrete (CFRC) lies in its unique microstructure: carbon fibers are uniformly dispersed as a conductive phase in the cement matrix, and their carbon atom arrangement structure endows excellent electron transfer ability. When the carbon fiber content and distribution reach specific conditions, they overlap with each other to form a conductive path, providing a channel for electron movement and making CFRC conductive.

The conductive mechanism of CFRC includes two types: electronic conductivity and ion conductivity. Electronic conductivity is dominated by electron transfer between carbon fibers, and under the action of an external electric field, free electrons in carbon fibers move in a directional manner to form an electric current, especially when the carbon fiber content is high and a continuous conductive network is formed; Ionic conductivity relies on the movement of ions (such as Ca^{2+}, Na^{+}) in the pore solution of cement matrix, but due to the slow movement speed of ions and the constraints of pore structure and solution concentration, the conductivity efficiency is much lower than that of electronic conductivity.

The percolation theory model is the core theory for studying the conductivity of CFRC: when the carbon fiber content reaches the percolation threshold, a connected conductive network is formed inside CFRC, resulting in a sudden change in conductivity and a sharp decrease in resistivity. When the dosage is below the threshold, carbon fibers are dispersed and isolated, with few conductive pathways and high electrical resistivity; When approaching the threshold, carbon fibers gradually overlap, conductive pathways increase, and electrical resistivity decreases; After exceeding the threshold, the conductive network is fully connected, the conductivity is significantly enhanced, and the resistivity remains at a low level. Related studies have verified the applicability of the model through a combination of experiments and numerical simulations, and found that the resistivity drops sharply when the carbon fiber content reaches a specific value, which is consistent with theoretical predictions.

ISSN 2616-5767 Vol.8, Issue 5: 32-39, DOI: 10.25236/AJETS.2025.080505

3.2 Factors affecting the conductivity of CFRC

The carbon fiber content has a significant impact on the conductivity of CFRC. Within a reasonable range, increasing the doping amount increases the number of internal conductive pathways, enhances conductivity, and reduces resistivity. When the dosage is low, the carbon fiber is sparsely dispersed, making it difficult to form an effective conductive network; As the dosage increases, the probability of carbon fiber overlap increases and the electrical resistivity significantly decreases; After the dosage exceeds the threshold, aggregation intensifies, resulting in a decrease in performance improvement, and in severe cases, a slight decrease. Research has shown that increasing the dosage from 0.5% to 1.5% results in a decrease of more than an order of magnitude in resistivity, and when it continues to increase to 2.5%, the decrease is significantly reduced.

The length of carbon fiber needs to be adapted. Longer fibers are prone to overlap and form continuous conductive pathways, while shorter fibers have weaker effects; However, excessively long fibers are prone to uneven dispersion and aggregation, which is actually detrimental to conductivity. By comparing 5mm, 10mm, and 15mm fibers, it was found that 10mm fibers can ensure dispersibility while achieving better conductivity in CFRC.

Dispersion is a key influencing factor. Uniform dispersion can form a uniform conductive path, improving stability; Uneven dispersion and aggregation can cause interruption of conductive pathways and increase in electrical resistivity. Dispersion can be improved by adding dispersants (reducing surface energy) and optimizing stirring processes (such as ultrasound and high-speed stirring).

The performance of cement matrix is also affected. The variety (chemical composition, mineral composition causing differences in the electrical properties of the slurry), strength grade (high-strength cement stone dense, low porosity, hindering ion conduction), and pore structure (high porosity, large pore size conducive to ion conduction) all play a role; The interface bonding between the matrix and fibers is crucial. Good bonding ensures electronic transmission and enhances conductivity, while poor bonding hinders transmission and reduces performance.

3.3 Testing methods and evaluation indicators for conductivity performance

The commonly used methods for testing the conductivity of CFRC are the DC four electrode method and the AC impedance spectroscopy method. The DC four electrode method uses two pairs of electrodes (with a constant current applied to the current electrode and a potential difference measured by the voltage electrode) to calculate the resistivity according to Ohm's law (formula ρ=νI· I/S, where ρ is the resistivity, V is the potential difference, I is the current, L is the distance between the voltage electrodes, and S is the cross-sectional area of the specimen). Its advantages include high measurement accuracy, elimination of contact resistance effects, and adaptability to various specimen shapes. However, the testing is complex, requires specialized equipment, and time-consuming.

The impedance spectroscopy method is used to test the impedance characteristics of components under different frequency AC signals. By combining Randles circuit, Warburg impedance and other equivalent circuit models to fit data, the conductivity mechanism can be analyzed, and parameters such as resistance and capacitance can be obtained. It can detect subtle changes in microstructure (such as interface state and pore structure), which is of great significance for studying the correlation between performance and structure. However, it requires professional instruments and analysis software, high cost, and high technical requirements for operators.

The core indicators for evaluating the conductivity performance of CFRC include resistivity, conductivity, and resistance change rate. The resistivity reflects the material's ability to obstruct current, and the lower the value, the better the conductivity, which needs to meet engineering requirements (such as low resistivity in structural health monitoring to improve monitoring sensitivity); Conductivity is the reciprocal of resistivity, which more intuitively reflects conductivity and is also commonly used as an evaluation index. The resistance change rate refers to the relative change in resistance of a material under external factors such as stress and temperature, reflecting the sensitivity of resistance to external factors. In structural health monitoring, the stress and damage status of the structure can be grasped in real time. The larger the change rate, the more conducive it is to early detection of structural hazards.

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4. Optimization strategy for CFRC conductivity performance

4.1 Optimizing the dosage and distribution of carbon fiber

The carbon fiber content plays a decisive role in the conductivity of CFRC. Multiple studies have shown through experiments that when the doping amount is low, it is difficult to form an effective conductive network inside CFRC, resulting in poor conductivity; As the dosage increases, there are more opportunities for carbon fiber overlap, and conductive pathways gradually form and connect. The conductivity is significantly enhanced, and the resistivity is significantly reduced; However, when the dosage exceeds the threshold, carbon fibers tend to aggregate, hindering the formation of conductive pathways and reducing or even decreasing the degree of performance improvement. A certain study tested CFRC specimens with dosages of 0.5%, 1.0%, 1.5%, 2.0%, and 2.5%, and found that when the dosage increased from 0.5% to 1.5%, the resistivity rapidly decreased and the conductivity improved; When the dosage continues to increase to 2.5%, the decrease in resistivity decreases, and some specimens experience fluctuations in conductivity due to carbon fiber aggregation.

Various innovative methods have been applied to optimize the distribution of carbon fibers. Ultrasonic stirring technology utilizes high-frequency ultrasonic vibration and cavitation effects to effectively break down the agglomeration of carbon fibers, allowing them to be uniformly dispersed in the cement matrix. The CFRC specimens treated with this technology have a more uniform distribution of carbon fibers, significantly improving the stability and consistency of electrical conductivity. The magnetic field induction method applies an external magnetic field during preparation to orient carbon fibers along the direction of the magnetic field, forming an ordered conductive network. A study has shown that applying a specific strength and direction of magnetic field reduces the resistivity of CFRC by about 30% and significantly improves its conductivity. In addition, adding dispersants during stirring can reduce the surface energy of carbon fibers, decrease their mutual attraction and agglomeration tendency, and further promote the uniform distribution of carbon fibers.

4.2 Improving the interface bonding between carbon fiber and matrix

The interface bonding between carbon fiber and matrix has a crucial impact on the conductivity of CFRC. Good interface bonding can ensure smooth electron transfer between carbon fibers and cement matrix, enhancing the conductivity of CFRC; If the interface bonding is poor, electronic transmission will be hindered, leading to a decrease in conductivity. Surface treatment is a commonly used and effective method to improve interface bonding. Oxidation treatment introduces oxygen-containing functional groups such as hydroxyl and carboxyl groups on the surface of carbon fibers, increasing the roughness and activity of the carbon fiber surface, thereby improving the mechanical interlocking and chemical bonding between carbon fibers and cement matrix. Research has shown that the interface bonding strength of carbon fiber reinforced CFRC treated with oxidation has increased by about 20%, and the electrical conductivity has also been correspondingly improved.

The use of coupling agents is also an important means to improve interfacial bonding. Coupling agent molecules have two different chemical groups. One end can react chemically with the groups on the surface of carbon fibers, while the other end can interact with the components in the cement matrix, forming a bridge between carbon fibers and cement matrix and enhancing their interfacial bonding. For example, after treating carbon fibers with silane coupling agents, the interfacial bonding strength of CFRC is significantly improved, and the conductivity is significantly improved. Experimental data shows that the resistivity of CFRC specimens with added silane coupling agent is reduced by about 15% compared to untreated specimens.

In practical applications, multiple methods for improving interface integration can be used in conjunction to achieve better results. For example, first oxidizing carbon fibers and then treating them with coupling agents can further enhance the interfacial bonding between carbon fibers and cement matrix, thereby more effectively improving the conductivity of CFRC. A study compared the effects of a single treatment method and a synergistic treatment method on the conductivity of CFRC specimens. The results showed that the synergistic treatment of CFRC specimens resulted in a greater improvement in conductivity and a more significant decrease in resistivity compared to a single treatment method.

4.3 Adding auxiliary conductive materials

Carbon nanotubes have excellent electrical properties, and their unique tubular structure gives them

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extremely high electrical conductivity and carrier mobility. Adding carbon nanotubes to CFRC can synergistically interact with carbon fibers to form a more complex and efficient conductive network. The high aspect ratio of carbon nanotubes enables them to span larger distances within CFRC, connecting more carbon fibers and increasing the number and connectivity of conductive pathways. Research has shown that when a small amount (0.1% -0.5%) of carbon nanotubes are added to CFRC, the resistivity of CFRC can be reduced by 20% -40%, and the conductivity can be significantly improved.

Graphene, as a new type of two-dimensional carbon material, has excellent conductivity and mechanical properties. Its atoms are tightly arranged in a hexagonal shape, allowing electrons to move freely and have extremely low resistance. Introducing graphene into CFRC can form a two-dimensional conductive network in the cement matrix, interweaving with the three-dimensional conductive network of carbon fibers, further improving the conductivity of CFRC. A study has found through experiments that the conductivity of CFRC specimens with added graphene has been uniformly improved in different directions, with a decrease in resistivity of about 35%. Moreover, the stability of conductivity is better during long-term use.

When adding auxiliary conductive materials, it is necessary to comprehensively consider factors such as compatibility, dispersibility, and addition amount with the original components of CFRC. Poor compatibility may lead to adverse reactions between materials, affecting the performance of CFRC; Poor dispersibility can cause the auxiliary conductive material to aggregate in CFRC, which cannot fully utilize its role in enhancing conductivity; Too much or too little addition is difficult to achieve the optimal conductivity improvement effect. For example, when adding carbon nanotubes, it is necessary to choose appropriate dispersants and dispersion processes to ensure uniform dispersion of carbon nanotubes in CFRC; Meanwhile, the optimal amount of addition is determined through experiments to achieve maximum improvement in conductivity performance.

5. Application principle of CFRC in structural health monitoring

5.1 Overview of structural health monitoring

Structural health monitoring focuses on non-destructive monitoring of the physical and mechanical properties of the structure, aiming to real-time grasp the overall behavior of the structure, accurately diagnose the location and degree of damage, and scientifically evaluate the service status, reliability, durability, and bearing capacity of the structure [2]. In modern engineering, structures such as bridges, high-rise buildings, and large water conservancy facilities are often affected by natural environments (temperature changes, humidity, wind loads, earthquakes) and human factors (traffic loads, mechanical vibrations, changes in usage functions) for a long time, which can lead to performance degradation and damage, and in severe cases, threaten structural safety [3]. Structural health monitoring can capture abnormal structural changes in real time, warn of safety hazards in advance, avoid catastrophic damage, and ensure the safety of life and property.

In practical applications, there are various methods for structural health monitoring technology. Non-destructive testing technology is an important category: ultrasonic testing utilizes the characteristics of reflection, refraction, and scattering of ultrasonic waves when encountering defects within a structure, and detects internal defects by analyzing changes in the received signal; Infrared thermal imaging detection is based on the correlation between the surface temperature distribution of an object and its internal structural state, using an infrared thermal imager to capture the surface temperature field and identify internal damage. Sensor based monitoring technology is widely used: strain gauge sensors accurately measure structural strain and analyze stress states through strain values at different positions; The accelerometer measures vibration acceleration and combines the frequency, amplitude, and other characteristics of the vibration signal to determine the structural dynamic characteristics and health status. In addition, modal analysis based methods identify damage by monitoring changes in modal parameters such as natural frequency and modal shape. Local structural damage can reduce stiffness and cause changes in natural frequency, which can be used to infer the occurrence of damage.

5.2 Principles of CFRC for structural health monitoring

The core principle of CFRC for structural health monitoring is based on its unique force electric coupling effect. When CFRC structures are subjected to external loads, stress and strain are generated internally. Under stress, the microstructure inside CFRC will change, and the interface between carbon fibers and cement matrix will exhibit phenomena such as micro slip and micro cracking, resulting in

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changes in the length, quantity, and contact state of the conductive path, which in turn causes changes in resistance. When the structure is subjected to tensile stress, the interface between carbon fibers and cement matrix may separate, the conductive path may become longer, and the resistance may increase; Under compressive stress, the contact between carbon fibers and cement matrix may become tighter, with an increase in conductive pathways and a decrease in resistance. By monitoring the resistance changes of CFRC, the stress and strain states inside the structure can be inferred.

As structural damage progresses, the resistance changes of CFRC will exhibit more significant characteristics. In the early stages of structural damage, tiny cracks begin to appear, which can cut off some conductive pathways and gradually increase resistance. As the damage intensifies, cracks continue to expand and connect, more conductive pathways are destroyed, resistance further increases, and the rate of resistance change also accelerates. When the structure approaches destruction, the conductive network inside the CFRC will suffer severe damage, and the resistance will increase sharply. For example, in some experimental studies, CFRC beams are loaded step by step, and when the load is small, the resistance change is relatively slow; When the load approaches the ultimate bearing capacity of the beam, the resistance rapidly increases, and the resistance change curve shows a clear inflection point, which is closely related to the development process of structural damage. Therefore, by establishing a quantitative relationship between the resistance change of CFRC and the structural stress, strain, and damage degree, CFRC can be used as a self-sensing material to achieve real-time monitoring of the structural health status.

5.3 Composition of structural health monitoring system based on CFRC

The core of the structural health monitoring system based on CFRC consists of three parts: sensors, data acquisition and transmission, and data analysis and processing. CFRC sensors can sense stress, strain, and damage changes in real time and convert them into resistance signals by making CFRC materials into specific shapes such as sheets or strips, and placing them at key structural locations (such as beam bottoms and column sides); By optimizing the design (adjusting the carbon fiber content and distribution, improving interface bonding), the sensitivity and stability of the sensor can be enhanced.

The data acquisition and transmission part is responsible for the acquisition, amplification, and transmission of resistance signals: the data acquisition equipment uses high-precision resistance measuring instruments to convert resistance values into digital signals, requiring high precision, high stability, and anti-interference capabilities; The signal amplification device is used to amplify weak resistance signals for subsequent processing; The transmission methods are divided into wired (such as cable, stable and strong anti-interference) and wireless (such as Bluetooth and Wi Fi, easy to install and highly flexible), which need to be selected based on structural characteristics and monitoring requirements.

Data analysis and processing are the core of the system, which determines the structural health status through algorithm analysis of data. Statistical analysis methods are based on historical data to establish the range and pattern of resistance changes under normal conditions, while monitoring data beyond the range is judged as abnormal; Machine learning algorithms (such as support vector machine SVM) establish a mapping relationship between the state and resistance changes by training CFRC resistance data with known structural states, achieving intelligent diagnosis. The analysis results are presented in charts to show stress, strain, and damage trends. In case of abnormalities, timely warnings are issued to guide relevant personnel to take measures.

6. Conclusion

This study focuses on the optimization of the electrical conductivity of carbon fiber reinforced concrete (CFRC) and its application in structural health monitoring, and has achieved important results.

In terms of factors affecting the conductivity of CFRC, a large number of experiments have shown that the carbon fiber content, length, distribution state, and cement matrix properties all have significant effects: the conductivity is enhanced when the content increases within a reasonable range, and the improvement amplitude decreases due to agglomeration after exceeding the threshold; Longer carbon fibers are prone to forming conductive pathways, while longer fibers can cause dispersion problems; Uniform distribution of carbon fibers can enhance conductivity stability; The variety, strength grade, pore structure, and interface bonding with carbon fibers of the cement matrix also have an impact on its electrical conductivity.

ISSN 2616-5767 Vol.8, Issue 5: 32-39, DOI: 10.25236/AJETS.2025.080505

Based on the above factors, effective optimization methods are proposed: when optimizing the carbon fiber content and distribution, the optimal content range under different engineering requirements is clarified, and uniform dispersion and directional arrangement of carbon fibers are achieved through techniques such as ultrasonic stirring and magnetic field induction, significantly improving the conductivity performance; In terms of improving interface bonding, surface treatment methods such as oxidation treatment and coupling agent treatment are used to enhance the interface bonding force between carbon fiber and cement matrix, thereby improving the conductivity performance; Adding auxiliary conductive materials such as carbon nanotubes and graphene to synergistically construct a more efficient conductive network with carbon fibers, further reducing the resistivity of CFRC and improving its conductivity.

In the research on the application principles of structural health monitoring, it is clear that the force electric coupling effect of CFRC is the core principle: when the CFRC structure is subjected to external loads, internal microstructural changes cause changes in resistance, and there is a quantitative relationship between resistance changes and structural stress, strain, and damage degree. The CFRC structural health monitoring system constructed based on this consists of CFRC sensors, data acquisition and transmission, and data analysis and processing parts. The CFRC sensors sense changes in the structural state in real time and convert them into resistance signals. The data acquisition and transmission part ensures accurate signal transmission, while the data analysis and processing part uses statistical analysis methods, machine learning algorithms, and other methods to process data, achieving accurate judgment and early warning of the structural health status.

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