Journal of Research in Science and Engineering (JRSE)
ISSN: 1656-1996 Volume-7, Issue-6, June 2025
DOI: 10.53469/jrse.2025.07(06).10

Health Monitoring of Cement-Based Materials via Graphene Conductive Skin

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Abstract: ***As the complexity of building structures increases, traditional monitoring methods face significant challenges. To address this issue, a novel health monitoring technology for cement-based materials is proposed to achieve non-destructive, real-time monitoring of structures. This method is easy to operate, requires minimal maintenance, and is suitable for health monitoring of existing structures. By using conductive skin made from graphene-based conductive carbon ink, and covering the surface of structural components with it, along with the analysis of resistance, strain, and load data, the formation and development of cracks can be effectively monitored. The experimental results show that the crack monitoring sensitivity of a standard 0.5mm-thick conductive skin can reach 206.963Ω/mm, and the resistance variation of the conductive skin can effectively detect crack propagation with excellent monitoring sensitivity.***

Keywords: Structural Health Monitoring, Conductive skin, Cement-based materials, Graphene.

1. Introduction

During service, cement-based materials experience damage accumulation and degradation of mechanical resistance due to external loads and adverse environmental factors. This accelerates the propagation of existing cracks and the formation of new ones, significantly reducing the structural usability and durability, hastening structural aging, and potentially causing sudden failures. Therefore, the application of Structural Health Monitoring (SHM) systems in engineering infrastructure enables continuous and systematic monitoring of structures, allowing assessment of their durability and safety. Such monitoring can significantly enhance structural performance, reduce maintenance costs, extend service life, and improve safety [1].

Existing SHM methods primarily rely on the self-sensing capabilities of cement-based materials with respect to strain, damage, and cracking, and include traditional destructive testing [2], ultrasonic monitoring [3], and conductive concrete monitoring. However, traditional destructive methods and ultrasonic monitoring cannot provide long-term continuous health data [4][5]. Moreover, the conductive materials embedded in conductive concrete alter its mechanical properties, causing porosity and microcracks [6], which lead to reduced compressive strength [7].

SHM systems based on conductive coatings address many of the limitations of current SHM methods and offer more precise monitoring capabilities. Conductive coating-based SHM not only enables crack width prediction [8], but also provides damage indices derived from resistivity changes that are more sensitive than conventional damage indicators [9]. Furthermore, through Electrical Resistance Tomography (ERT) techniques, local variations in the resistivity of the sensing skin can be monitored to identify damage locations [10][11].

To achieve long-term structural health monitoring while maintaining high sensitivity and operational convenience, this study proposes a novel non-destructive health monitoring method for cement-based materials based on graphene carbon ink conductive skins. Key technologies investigated include the SHM system framework, conductive skin design, and targeted analysis of critical experimental parameters. Combined with Internet of Things (IoT) technology, this approach holds promise for expanding applications in structural health monitoring (see Figure 1), promoting accurate, intelligent, real-time, and long-term non-destructive damage detection.

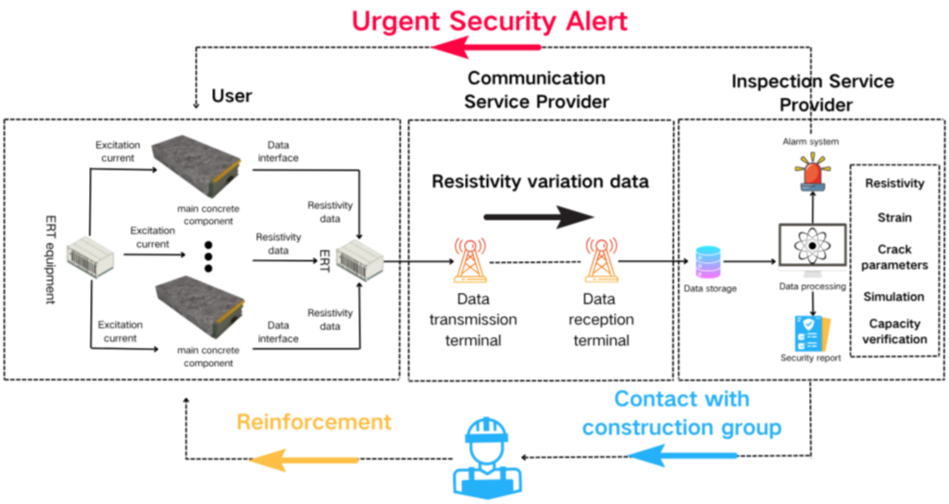

Figure 1: Applications of SHM

2. Experimental Study

2.1 Experimental Setup

As shown in Figure 2, a 300 kN hydraulic testing machine was used in this experiment to apply a uniform load to the flexural member. A Tonghui-2516A-DC resistance meter was employed for real-time monitoring of the resistance of the conductive skin, while strain gauges combined with a dynamic-static strain analysis system were used for real-time strain measurements.

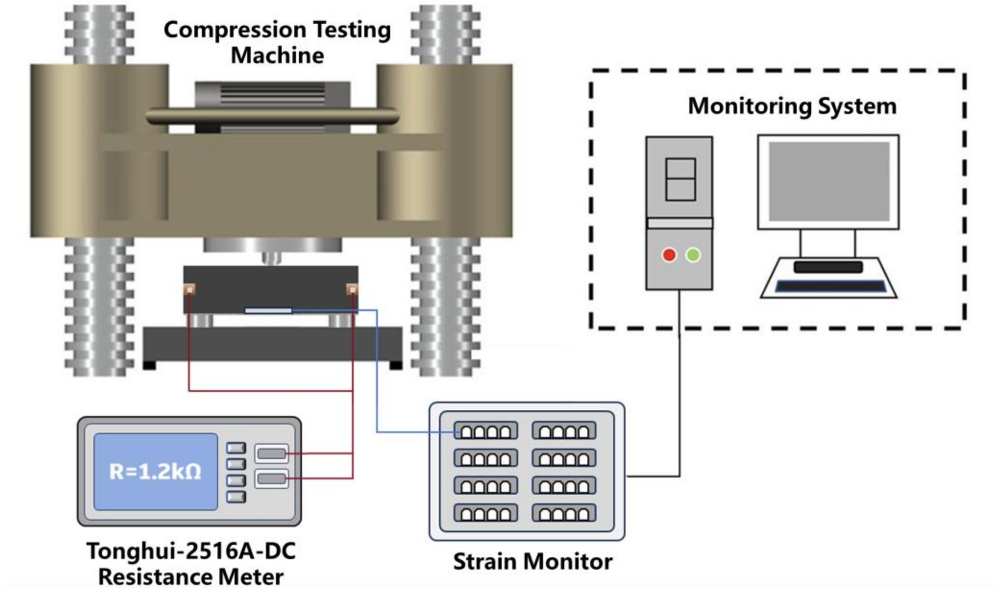

Figure 2: Experimental apparatus

Table 1: Experimental Parameters

Sample ID	Dimensions (mm)	Cement (kg/m³)	Water (kg/m³)	Sand (kg/m³)	Aggregate (kg/m³)	Conductive Skin Thickness (mm)
PPC-1-1	400*100*100	300	150	1575	/	0.5
PPC-1-2	400*100*100	300	150	1575	/	1.0
PPC-1-3	400*100*100	300	150	1575	/	1.5
B-04-01	1450*150*100	450	183	600	1192	0.5
B-04-02	1450*150*100	450	183	600	1192	0.5
B-04-03	1450*150*100	450	183	600	1192	0.5

2.2 Technical Approach

This experiment monitors the health of cement-based materials using graphene-based conductive skin. The conductive skin was applied via screen printing, connected to a DC resistance measurement system with conductive copper foil and tape. A strain gauge at mid-span was linked to a strain monitoring system. A three-point bending test was conducted, during which crack width and resistance changes were recorded. Data were then analyzed to produce results and conclusions.

2.3 Experimental Parameters

The main research variable in this experiment is the thickness of the conductive skin. The test specimens are divided into six groups. Among them, three groups are cement mortar specimens mixed with 1% polypropylene fibers by volume, each coated with conductive skins of different thicknesses. The other three groups are C30-grade reinforced concrete beams with varying reinforcement ratios: B-04-01, B-04-02, and B-04-03 represent under-reinforced, properly reinforced, and over-reinforced beams, respectively. Detailed specimen codes and corresponding parameters are shown in the Table 1.

3. Test Data Analysis and Processing

3.1 Data Analysis

Through multiple groups of experiments, data on resistance variation, strain, and concentrated load were analyzed to determine overall trends, and relevant curves were plotted.

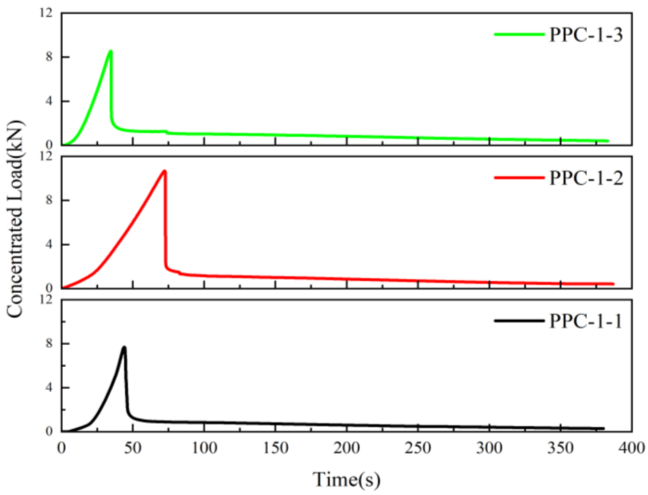

Figure 3: Concentrated Load Variation Curve

As illustrated in Figure 3, analysis of the concentrated load variation curves for the three specimen groups indicates that during the three-point bending process, the concentrated load of the cement mortar specimens gradually increases over time until it reaches a peak. At this point, cracks begin to appear on the specimen surface and propagate progressively as loading continues. When crack propagation reaches a critical state, the specimen fails suddenly, resulting in a sharp decrease in its load-bearing capacity. The load then stabilizes.

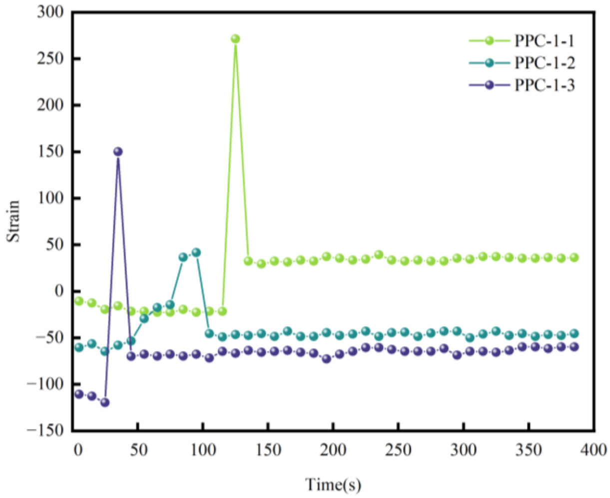

Figure 4: Strain Variation Curve

As shown in Figure 4, the strain curves of the three cement mortar specimens reveal that strain remains relatively stable during the initial loading phase. With increased load, micro-defects within the specimen (such as pores and microcracks) begin to propagate under tensile stress, leading to a rise in strain. Once the strain reaches its peak, visible cracks form and ultimately cause failure. After failure, strain decreases as the load is removed, but due to incomplete crack closure, strain stabilizes at a value higher than the initial level.

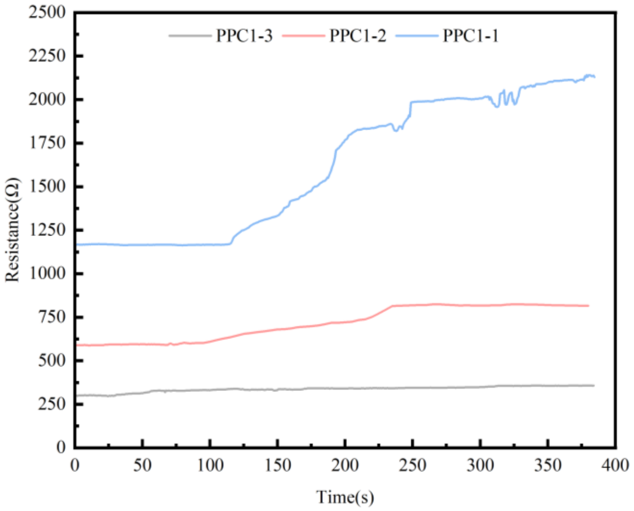

Figure 5: Resistance Variation Curve

The resistance variation curves for the three cement mortar specimens, presented in Figure 5, show a consistent pattern throughout the three-point bending tests. Prior to the appearance of microcracks, the resistance remains essentially stable. As the specimen approaches a critical failure state, microcracks begin to develop. Due to the ductility of the conductive skin, resistance increases only slightly at this stage. Once strain increases sharply, cracks start to form in the conductive skin, leading to a significant rise in resistance. After the specimen fails, as cracks continue to propagate, resistance keeps increasing until it eventually stabilizes.

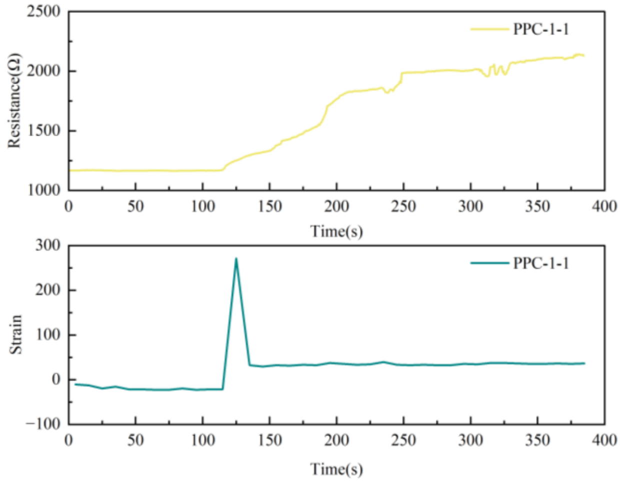

Figure 6: Resistance and Strain Variation of PPC-1-1

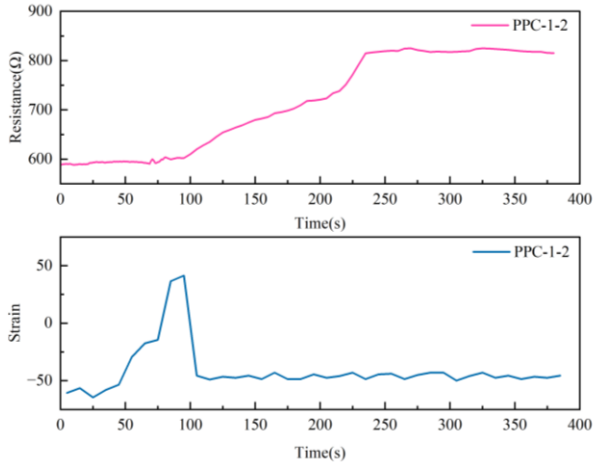

Figure 7: Resistance and Strain Variation of PPC-1-2

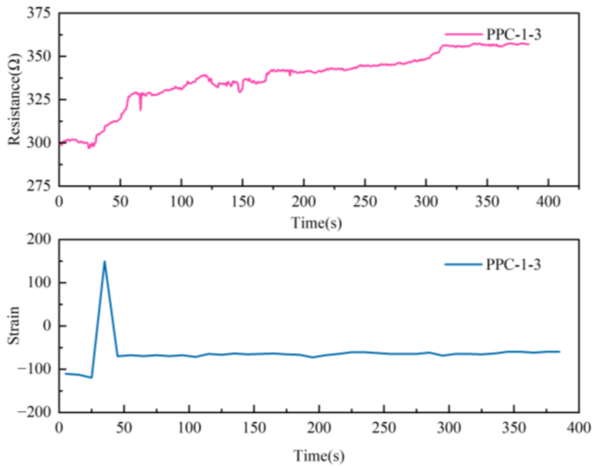

Figure 8: Resistance and Strain Variation of PPC-1-3

Analysis of Figures 6, 7, and 8 shows that the changes in resistance and strain during loading can be divided into three stages:

Stage I: Sudden Resistance Change and Crack Initiation

As the test proceeds, resistance increases markedly at points where strain surges. This indicates that internal microcracks have reached a critical threshold and begun to develop unstably. Stress distribution becomes uneven due to stress concentration at crack tips, causing local strain to rise rapidly and initiating crack coalescence.

Stage II: Crack Propagation and Load-Bearing Failure

The cracked regions lose continuity and no longer carry external loads. As cracking continues, the conductive coating continues to rupture, resulting in further resistance increases. Meanwhile, strain in the crack zones drops sharply due to material failure.

Stage III: Full Crack Penetration

Once a macro-crack fully penetrates the specimen, the conductive coating ruptures entirely (see Figure 9), and resistance stabilizes. The separation of mortar on both sides of the crack leads to strain release, which approaches zero in the cracked region.

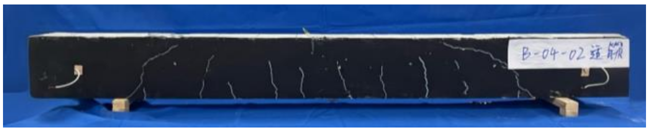

Figure 9: Crack Development in B-04-02

In summary, resistance, strain, and concentrated load exhibit a clear correlation during the loading process. Changes in resistance effectively reflect the entire crack evolution process—from initiation and propagation to final failure. Specifically, resistance begins to increase during crack initiation, continues to rise throughout crack propagation, and eventually stabilizes after complete failure.

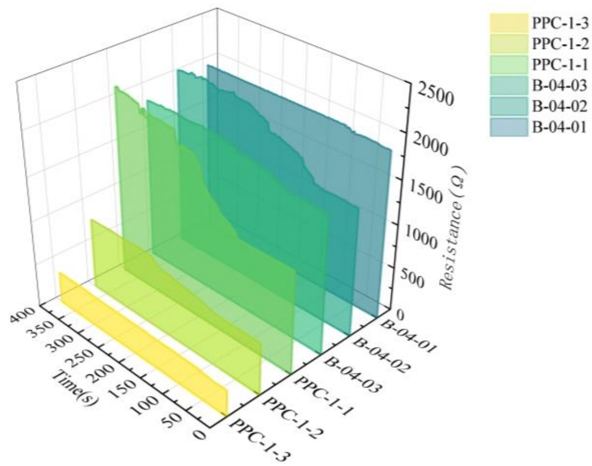

Figure 10: Resistance Variation Trend of Conductive Skin

As shown in Figure 10, both cement mortar specimens and reinforced concrete beam specimens display similar resistance trends, confirming the effectiveness of conductive skin resistance measurements for structural damage monitoring.

3.2 Sensitivity Analysis

During the analysis of experimental data, the relationship between resistance variation and crack propagation is a key factor for evaluating the performance of conductive skin in monitoring. While a trend can be observed indicating their correlation, in order to more precisely quantify this relationship and establish a mathematical model of resistance response to crack width, this study performed a linear fit between the resistance variation and crack width growth. The mathematical expression obtained through fitting not only quantitatively describes the relationship between resistance and crack expansion but also allows the calculation of crack sensitivity, which is used to assess the ability of the conductive skin to detect fine cracks. Furthermore, this fitted relationship can be used to predict crack development, enabling resistance measurement results to be employed to infer crack width, thereby facilitating quantitative evaluation of structural damage and providing theoretical support for the optimization of intelligent monitoring systems.
The sensitivity calculation formula is:

$$S = \frac{\Delta R/R}{w} \tag{1}$$

S—Sensitivity (Ω/mm)
R—Resistance value (Ω)
R_0—Initial resistance value (Ω)
w—Crack width (mm)
$\Delta R = R - R_0$

Based on the formula above, the sensitivity of resistance after stabilization for the three test groups is calculated as follows:

Table 2: Sensitivity of Conductive Skin Resistance to Crack Width

Specimen	PPC-1-1	PPC-1-2	PPC-1-3
Sensitivity (Ω/mm)	206.963	46.129	11.909

The sensitivity analysis results indicate that the sensitivity of the conductive skin to crack propagation decreases with an increase in the skin's thickness. In other words, thicker conductive skins are less sensitive to crack development, whereas thinner conductive skins offer higher monitoring sensitivity for crack propagation.

Additionally, through the fitting analysis of crack width growth and resistance variation, the results exhibit a nearly linear relationship (as shown in Figure 11). This linear relationship verifies the conductive skin's ability to detect crack propagation, showing that its response is relatively stable. This further demonstrates that resistance measurement can be used for real-time monitoring of crack development, providing a reliable basis for structural damage assessment.

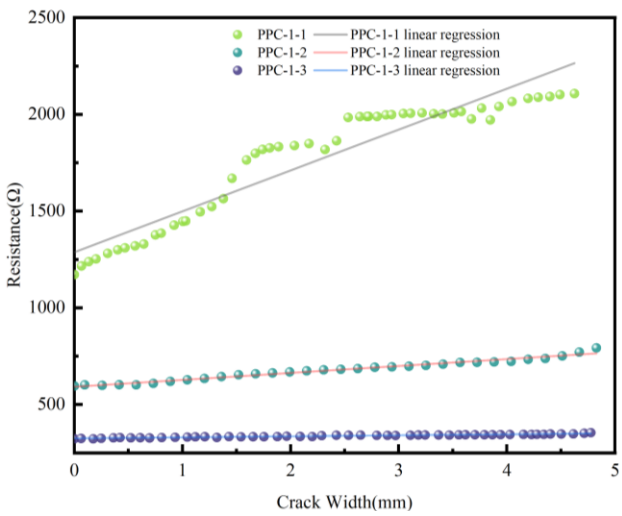

Figure 11: Resistance-Crack Variation Fitting Graph

In the figure, the horizontal axis represents the change in crack width, while the vertical axis represents the change in resistance. The data points are approximately distributed along a straight line, with a high goodness of fit, indicating that the linear fitting is reasonable and that the relationship between resistance and crack width is stable. Using the mathematical relationship derived from the fitting, crack width ww can be directly calculated from resistance measurements, enabling non-destructive crack monitoring. The slope kk of the linear fit can serve as an indicator of the monitoring performance of the conductive skin, helping to optimize material formulation and improve the precision of structural health monitoring. A larger slope kk indicates higher sensitivity of resistance to crack expansion, while a small slope may suggest weaker monitoring performance of the conductive skin.

In this study, the PCP-1-1 group exhibited the largest slope kk, and calculations showed that the resistance of this group was significantly more sensitive to cracks compared to the other two groups. Specifically, the sensitivity of PCP-1-1 was 3 times and 18 times higher than that of PCP-1-2 and PCP-1-3, respectively, demonstrating the significant effect of coating thickness on sensitivity.

In engineering applications, this sensitivity linear relationship can be used for long-term monitoring and also allows the selection of a suitable conductive coating thickness based on specific requirements. This would help determine when cracks reach critical widths, providing early warnings to prevent structural failure and enhance safety.

Through the sensitivity analysis, the study has validated the linear relationship between resistance variation and crack width. The fitting results indicate that resistance changes can accurately reflect the crack expansion process, and the slope kk as a sensitivity indicator effectively evaluates the monitoring ability of the conductive skin for cracks. The thickness of the conductive skin has a significant impact on sensitivity, with thinner coatings showing higher crack monitoring sensitivity. Overall, the linear relationship between resistance and crack width provides a solid theoretical foundation for structural health monitoring and crack quantification.

4. Conclusion

This paper primarily investigates a structural health monitoring system based on conductive skin. Through improvements to traditional conductive concrete monitoring systems using internally mixed conductive materials, conductive skin is created using graphene conductive carbon ink. The system was designed and implemented by analyzing changes in resistance, strain, and concentrated load. Cement mortar specimens mixed with polypropylene fibers and concrete beam specimens with different reinforcement ratios were monitored, and data on concentrated load, strain, and resistance variation during the loading and failure process were collected. Using this data, the sensitivity of conductive skin resistance variation to crack width was calculated, and the following conclusions were drawn from the analysis of multi-dimensional data:

The experimental results show that as the concentrated load on the specimen increases, cracks develop and eventually cause failure. Strain and resistance change with crack development. Specifically, strain decreases after failure, while resistance continues to rise until it stabilizes. The relationship between conductive skin resistance and crack development shows that microcracks lead to an increase in resistance, which is positively correlated with crack propagation. Therefore, resistance changes can be used to monitor the health status of structural components.

The experiment also studied the impact of conductive coating thickness on monitoring sensitivity. The results show that the sensitivity of resistance variation to crack width decreases with increasing coating thickness. The 0.5mm thin coating exhibited the best crack monitoring sensitivity, reaching 206.963Ω/mm.

Fund

This research was supported by the National College Student Innovation and Entrepreneurship Training Program of China under Grant No. 202410183264, titled *"Research on Health Monitoring Method for Cement-Based Materials Based on Graphene Conductive Carbon Ink Skin and Four-Electrode Method"*. It was also supported by the horizontal research project of Jishu Research Institute (Jilin Province, China) Information Technology Consulting and Design Co., Ltd., titled *"Construction and Application System Development of Structural Strength Evaluation Model for Intelligent Three-Dimensional Logistics Warehouse"* under Grant No. 2691715.

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