

**THE UNIVERSITY OF DANANG  
UNIVERSITY OF SCIENCE AND TECHNOLOGY**

**VÕ MINH CHÍ**

**INVESTIGATION OF THE ELECTRICAL RESISTANCE  
BEHAVIOR OF SELF-SENSING CONCRETE  
UNDER ELASTIC COMPRESSIVE LOADING**

Major: Transport Construction Engineering  
Code: 9580205

**SUMMARY OF DOCTORAL THESIS**

**NĂM 2026**

The work was completed at  
University of Science and Technology - The University of Da Nang

1. Co-supervisor 1:                   **Assoc.Prof.PhD. Nguyen Lan**  
University of Science and Technology  
- The University of Da Nang
2. Co-supervisor 2:                   **PhD. Nguyen Minh Hai**  
University of Science and Technology  
- The University of Da Nang

Reviewer 1:

Reviewer 2:

Reviewer 3:

The thesis is defended in front of Examination Committee at University level  
in: University of Science and Technology - The University of Da Nang, at  
..... on ....., .....

The thesis can be found at:

- National Library of Viet Nam.
- The University of Da Nang – The Center for Learning Information Resources and Communication.
- Learning Resources and Communication Center, University of Science and Technology .

## LIST OF PUBLICATIONS BY THE AUTHOR RELATED TO THE DISSERTATION

### 1. International Publications

- (1) **V. M. Chi**, N. M. Hai, N. Lan, and N. Van Huong, “An empirical model for electrical resistivity of mortar considering the synergistic effects of carbon fillers , current intensity , and environmental factors,” Case Stud. Constr. Mater., vol. 19, no. October, p. e02685, 2023, [doi: 10.1016/j.cscm.2023.e02685](https://doi.org/10.1016/j.cscm.2023.e02685). (**SCIE, Q1**)
- (2) **V. M. Chi**, N. M. Hai, N. Lan, and N. Van Huong, “Stress Self-sensitivity of Carbon Black-filled Mortar under Non Destructive Compression and the Effects of Electric Circuit and Specimen Dimensions,” J. Adv. Concr. Technol., vol. 21, no. 9, pp. 762–776, 2023, [doi: 10.3151/jact.21.762](https://doi.org/10.3151/jact.21.762). (**Q2**)
- (3) **V. M. Chi**, N. Lan, N. M. Hai, and N. Van Huong, “Compression self-sensibility of the concrete using high content carbon black with various measurement conditions,” IOP Conf. Ser. Mater. Sci. Eng., vol. 1289, no. 1, p. 012033, 2023, [doi: 10.1088/1757-899x/1289/1/012033](https://doi.org/10.1088/1757-899x/1289/1/012033). (**International Conference Papers TISDIC 2023, Web of Science**)

### 2. Domestic Publications

- (1) **Võ Minh Chí**, Nguyễn Minh Hải, Nguyễn Lan, Nguyễn Văn Hương, “Research on factors affecting electrical conductive properties and applications of self-sensing concrete”, Journal of Science and Technology of Ho Chi Minh City University of Transport, Volume 13, Issue 2, Pages: 64 - 78, 2024, doi: [https://www.doi.org/10.55228/jtst.13\(2\).64-78](https://www.doi.org/10.55228/jtst.13(2).64-78)
- (2) **Vo Minh Chi**, Nguyen Minh Hai, Nguyen Lan, Pham Van Ngoc, Nguyen Van Huong, Nguyen Duc Hung, “Electrical resistance response of a pair of self-sensing concrete blocks under non-destructive compression,” Transport and Communications Science Journal, Vol. 76, Issue 04 (05/2025), 568-582. [Doi: https://doi.org/10.47869/tcsj.76.4.10](https://doi.org/10.47869/tcsj.76.4.10)

### 3. Utility Model Patent

Title: “*Method for Fabricating Self-Sensing Concrete Specimens and a Traffic Load Weighing System Using Such Concrete Specimens.*” Patent No.: 5110.  
Inventors: Ph.D. Nguyen Minh Hai; M.Sc. Ph.D. Student. **Vo Minh Chi**;;  
Ph.D. Pham Van Ngoc; Assoc. Prof. Ph.D. Nguyen Lan; Assoc. Prof. Ph.D. Nguyen Van Huong, and M.Sc.Mai Thi Thu Thuy.

## INTRODUCTION

### 1. Rationale of thesis

In the context of modern infrastructure development, self-sensing concrete (SSC) has emerged as a promising solution for large-scale sensing applications. The sensing mechanism of SSC is based on the incorporation of electrically conductive fillers into the concrete matrix, resulting in changes in electrical resistance under the influence of mechanical loading and environmental conditions. These changes enable the indirect determination of stress and strain states without the need for externally attached sensors.

Previous studies have primarily focused on the sensing performance of SSC during damage initiation and propagation, whereas investigations into its sensing capability under non-destructive conditions remain limited. Therefore, this dissertation aims to clarify and formulate the electrical resistance behavior of SSC within the low-stress elastic range, thereby facilitating its long-term sensing applications and improving its economic efficiency.

In addition, most existing studies have considered SSC as an individual sensing element. This research extends the investigation to systems comprising multiple SSC units operating simultaneously, providing a basis for the development of large-scale weighing systems. Such systems have potential applications in load monitoring, traffic management, and intelligent logistics, offering a cost-effective alternative to conventional sensing technologies.

These considerations highlight the urgency, scientific significance, and practical value of the selected research topic.

### 2. Research Objectives

The primary objective of this study is to elucidate the electrical resistance behavior of self-sensing concrete (SSC) when functioning as bearing elements in structural components subjected to loads within the elastic compressive range, where the material remains in a non-destructive state. The research outcomes are intended to support the development of a new generation of sensing systems constructed from the concrete material itself, capable of performing continuous real-time load measurement.

The specific objectives of the study are as follows:

- i. To fabricate SSC and investigate the fundamental mechanisms governing its electrical resistance behavior under loading within the elastic compressive range.
- ii. To identify the factors affecting the electrical resistance behavior of SSC, including the type and content of conductive fillers, specimen dimensions, measurement conditions, and environmental factors.
- iii. To investigate the electrical resistance behavior of systems comprising multiple SSC specimens subjected to static loads within the elastic compressive range under both concentric and eccentric compression conditions, thereby providing a basis for the development of large-scale load-weighing systems.

### **3. Research Objects and Scope**

#### **3.1. Research Objects**

SSC using conductive fillers, including carbon black or carbon fibers.

#### **3.2. Research Scope**

SSC incorporating conductive fillers in the form of carbon black or carbon fibers was employed in this study. The research focuses on investigating the electrical resistance behavior of SSC subjected to static loading within the elastic compressive range of the material, while the effects of dynamic and impact loading are beyond the scope of the present work. Furthermore, the study examines the influence of temperature and moisture on the electrical properties of SSC under controlled laboratory conditions, without extending the investigation to field environments involving combined cyclic temperature–moisture exposure.

#### **4. Research Methods.**

The study employs theoretical analysis, experimental methods, and statistical analysis.

#### **5. Scientific and Practical Significance of the Dissertation**

The novelty and scientific significance of this dissertation can be summarized as follows:

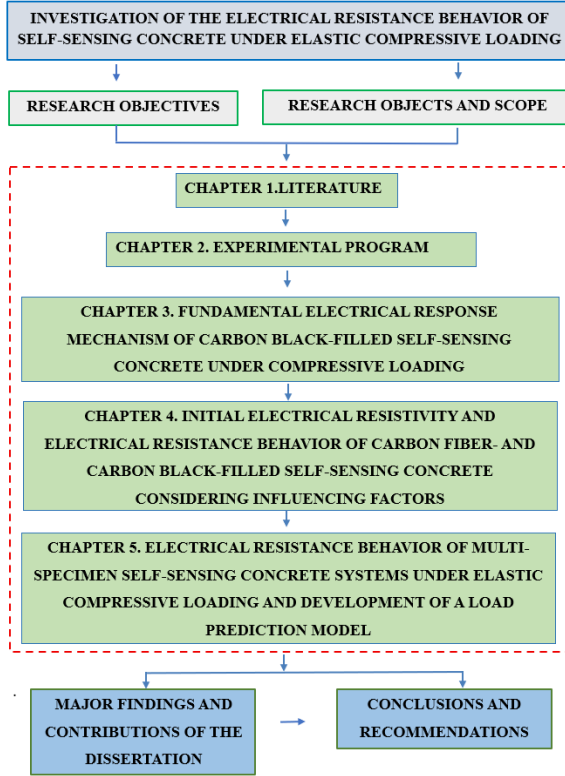
- First, the study clarifies the linear electrical resistivity response range of self-sensing concrete within the elastic compressive stress domain.
- Second, an electrical resistivity model is developed by simultaneously considering the effects of multiple influencing factors, rather than examining them individually as commonly reported in previous studies.
- Third, the electrical resistance behavior is investigated not only at the individual specimen level but also in systems comprising multiple SSC units, representing a novel research approach that has not been previously explored.

The practical contributions of the dissertation are summarized as follows:

- (1) Demonstrating the feasibility of using SSC as a compressive load-sensing device.
- (2) Providing an important scientific basis for the development of next-generation weighing systems utilizing SSC materials at a reasonable cost, thereby diversifying sensing technologies and enhancing their application potential in intelligent transportation infrastructure.

#### **6. Structure of the Dissertation**

The structure of the dissertation is summarized in the following diagram



## CHAPTER 1. LITERATURE

The literature review was developed based on a systematic survey and synthesis of studies related to self-sensing concrete (SSC). Specifically, the review was organized into three main categories: (i) the effects of material composition and fabrication methods on the self-sensing properties of concrete; (ii) the effects of experimental conditions, including electrode configuration, excitation current, specimen geometry and dimensions, loading conditions, and environmental factors; and (iii) the applications of self-sensing concrete in civil infrastructure, particularly for structural health monitoring and traffic management.

Based on the literature review, several important research gaps were identified, providing the foundation and direction for this dissertation, as follows:

- **Issue 1:** To clarify the electrical resistivity behavior mechanism of SSC under compressive loading within the elastic range.
- **Issue 2:** To investigate the factors affecting the initial electrical resistivity of SSC under unloaded conditions.

- **Issue 3:** To clarify and develop a predictive model for the electrical resistance behavior of SSC by considering the combined effects of environmental factors and measurement conditions.
- **Issue 4:** To investigate the sensing behavior of systems consisting of multiple SSC specimens under compressive loading within the elastic range.

## CHAPTER 2. EXPERIMENTAL PROGRAM

### 2.1. General overview

The experimental program of this dissertation was designed following a progression from fundamental research to practical applications. The study began with the investigation of the characteristics of self-sensing concrete (SSC) at the individual specimen level and subsequently advanced to evaluating the load-identification capability of multi-specimen systems. The research was organized into three interconnected stages to clarify the self-sensing mechanism, identify the influencing factors, and assess the application potential of the material. The overall experimental program is illustrated in Figure 2.1.

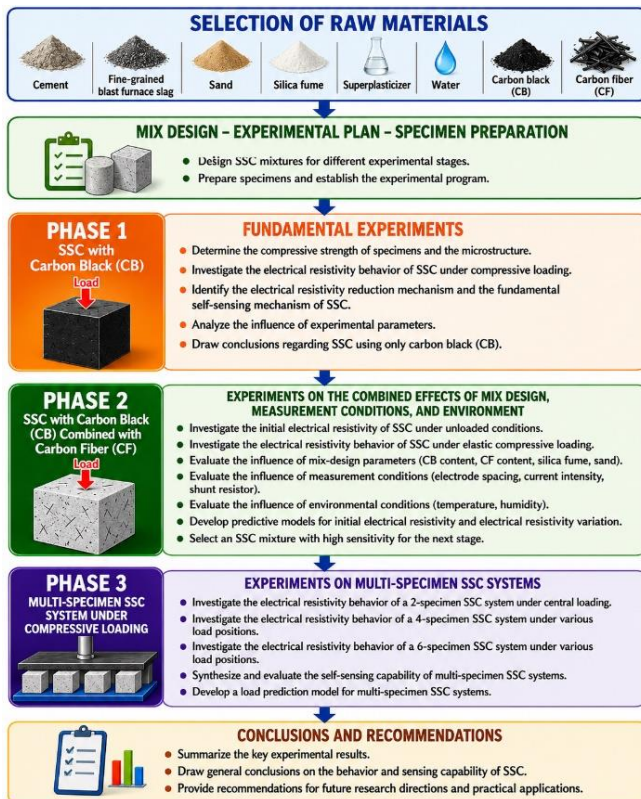


Figure 2.1. Schematic Diagram of the Experimental Program

## 2.2. SSC mixing procedure and specimen curing

The SSC mixing procedure (Figure 2.2) was developed based on previous studies and incorporates both wet-mixing and dry-mixing approaches suitable for conductive fillers, as follows:

- For CB specimens, carbon black was first dispersed in water to form a suspension, ensuring adequate dispersion of the particles. The suspension was then mixed with the dry materials in a stepwise manner, and the workability of the mixture was finally adjusted using a superplasticizer.
- For CF specimens, carbon fibers were dry-mixed with the other solid constituents to prevent fiber agglomeration and floating. Water and superplasticizer were subsequently added to obtain a homogeneous mixture.
- For CB+CF specimens, the two mixing procedures were combined. Carbon black was first dispersed as a suspension, while carbon fibers were dry-mixed with the solid materials. The components were then mixed sequentially to ensure uniform dispersion of the conductive fillers and the formation of a stable conductive network within the SSC matrix.



**Figure 2.2. SSC mixing procedure.**

The specimens were cured after casting in accordance with Vietnamese Standard TCVN 3105:2022, as shown in Figure 2.3.



**Figure 2.3. SSC specimen curing**

## 2.3. Experimental methods

The experiment for determining the initial electrical resistivity of SSC specimens under unloaded conditions was conducted as illustrated in Figure 2.4.

The electrical resistivity was measured using a direct current (DC) electrical measurement system, consisting of a power supply and a shunt resistor to regulate the current intensity. The voltage and current were recorded and subsequently used to calculate the electrical resistivity of the material.

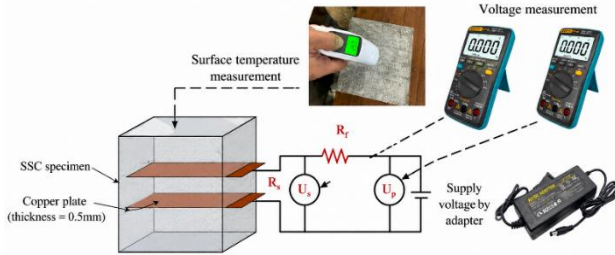


**Figure 2.4. Schematic diagram for measuring the initial electrical resistivity of SSC specimens**

The experiment investigating the electrical resistance behavior of independently operating SSC specimens under compressive loading within the elastic range was conducted as illustrated in Figure 2.5.

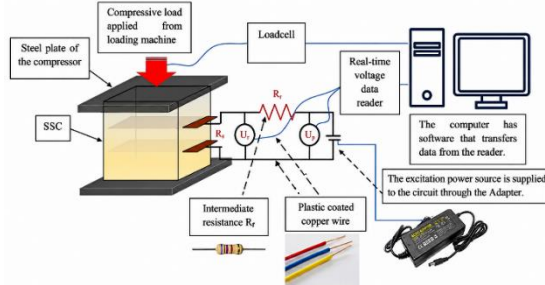


**Figure 2.5. Electrical circuit diagram for the compression test**

The experiment investigating the electrical resistance behavior of a multi-support SSC system under compressive loading was conducted as illustrated in Figure 2.6.

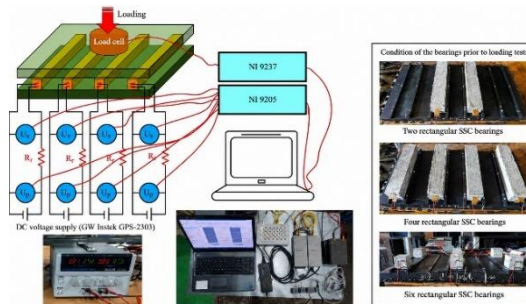
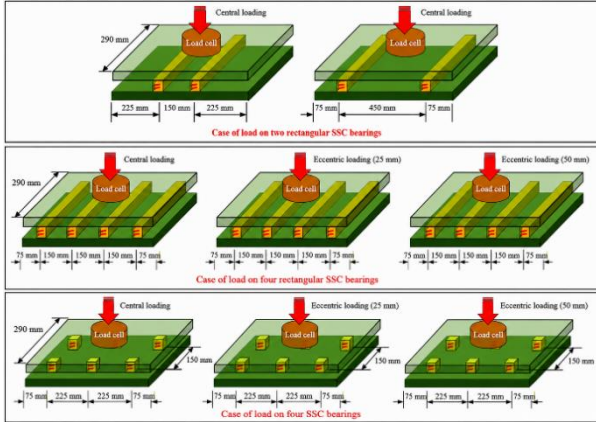


**Figure 2.6. Electrical circuit diagram for the bearing system under compressive loading**

A scaled weighing system was designed for the experimental program, in which SSC bearings were used as sensing elements and installed beneath a rigid weighing platform. This configuration enabled the applied load to be transferred directly into compressive forces while minimizing the influence of bending moments. The model was employed to investigate the electrical resistance behavior of a multi-bearing SSC system under non-destructive compressive loading, as illustrated in Figure 2.7.



(a) Models of the load-bearing weighing system at different positions



(b) Scaled weighing system installed in the compression testing machine

**Figure 2.7. Scaled weighing system model in the laboratory**

In addition, several other experimental investigations were conducted, including: (i) compressive strength testing of SSC; (ii) porosity measurement of SSC; (iii) determination of the moisture content of concrete specimens; (iv) measurement of specimen temperature; and (v) microstructural analysis using scanning electron microscopy (SEM).

## 2.4. Conclusions of Chapter 2

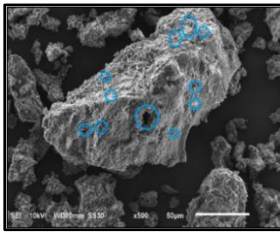
Chapter 2 established the experimental framework of the study, covering material selection, mix design, experimental methods, and specimen preparation procedures. The three experimental stages were organized in a progressive and

interconnected manner, enabling the clarification of the electrical conduction mechanism of SSC and the identification of an optimal mix design for application-oriented investigations. This chapter provides a solid foundation for the analyses and discussions presented in the subsequent chapters of the dissertation.

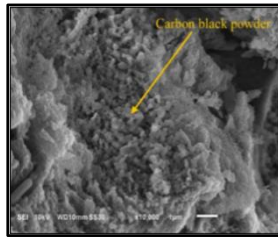
### CHAPTER 3. FUNDAMENTAL ELECTRICAL RESPONSE MECHANISM OF CARBON BLACK-FILLED SELF-SENSING CONCRETE UNDER COMPRESSIVE LOADING

#### 3.1. Compressive strength of ssc specimens and SEM

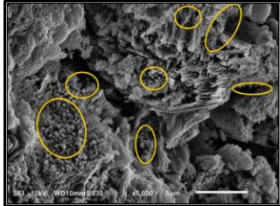
The SSC-CB7 specimens achieved compressive strengths of 20, 25, and 34 MPa at 3, 7, and 28 days, respectively, compared with the target strength of 30 MPa.



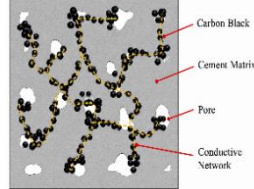
(a) pores in concrete



(b) Carbon black in concrete



(c) The dispersion of carbon black  
in concrete



(d) Images of carbon black dispersion  
in concrete

**Figure 3.1. SEM image of SSC CB7 specimen**

SEM observations revealed that pores were concentrated around regions containing carbon black, which was distributed as randomly agglomerated clusters within the concrete matrix. These clusters were interconnected, forming conductive networks throughout the SSC. The microstructural analysis results (Figure 3.1) provide a basis for clarifying the mechanism of electrical resistivity variation of the material under compressive stress, as discussed in the following sections.

#### 3.2. Relationship between electrical resistivity and compressive stress, and the fundamental mechanism of SSC resistivity behavior

The experimental results showed that, when a supply voltage of 12 V was applied, the relationship between the electrical resistivity variation of SSC and the compressive stress was not clearly observed. When the excitation voltage

was increased to 24 V, the current flowing through the specimen became more stable, enabling the electrical resistivity of SSC to be clearly recorded as decreasing with increasing compressive stress. The relationships between electrical resistivity and compressive stress under different supply voltages are presented in Figure 3.2.

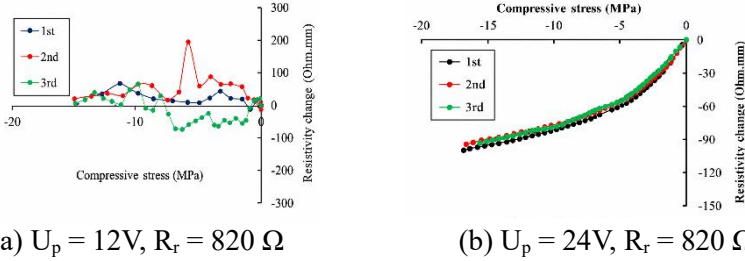


**Figure 3.2. Relationship between electrical resistivity variation and compressive stress**

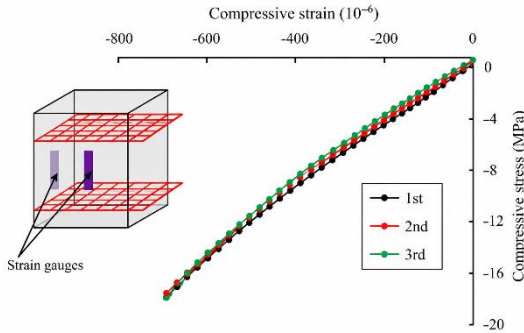


**Figure 3.3. Relationship between compressive stress and strain of specimen W150L40**

When the compressive stress was less than or equal to 6 MPa (corresponding to approximately one-fifth of the compressive strength of SSC), the relationship between compressive stress and electrical resistivity was nearly linear. As shown in Figure 3.3, the relationship between compressive stress and strain remained almost linear until the stress approached approximately one-half of the actual compressive strength of the concrete. Therefore, it can be inferred that microcracks had not yet formed in the concrete when the applied compressive stress was approximately one-fifth of its compressive strength.

Based on the above analyses, the fundamental mechanism governing the electrical resistivity behavior of SSC can be explained as illustrated in Figure 3.4, which consists of three main stages:

**Stage 1:** Under compressive loading, the carbon black particles move closer to one another, while the pores within the concrete matrix contract.

**Stage 2:** Because pore contraction occurs rapidly during the initial stage and gradually stabilizes once the compressive stress reaches a certain threshold, the pore-closing effect becomes less significant in Stage 2. Consequently, the decrease in electrical resistivity slows down, and the relationship between electrical resistivity and compressive stress becomes nonlinear (when the stress reaches approximately one-fifth of the compressive strength).

**Stage 3:** At higher compressive stress levels, the variation in the electrical resistivity of SSC becomes slower or unstable due to the initiation and propagation of microcracks within the concrete matrix.

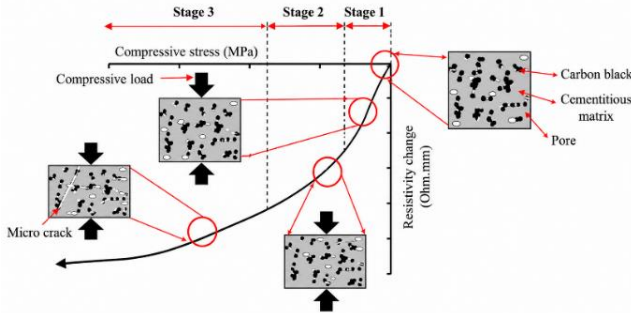


**Figure 3.4. Mechanism of the relationship between electrical resistivity variation and compressive stress of SSC specimens**

### 3.3. Analysis of the influence of experimental parameters

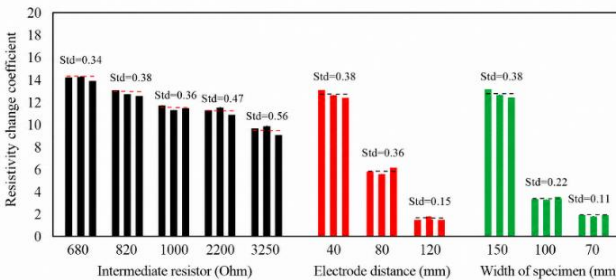


**Figure 3.5. Influence of experimental parameters on the resistivity variation coefficient of SSC**

Based on the electrical resistivity–compressive stress relationships obtained from SSC specimens with varying specimen dimensions, electrode spacings, and shunt resistances, linear regression analysis was performed to determine the resistivity variation coefficient, as shown in Figure 3.5. The results demonstrate that these parameters significantly affect the electric current passing through the specimens, which consequently alters the electrical resistivity response of SSC under compressive loading.

### 3.4. Conclusions of chapter 3

Main conclusions are as follows:

- (1) The electrical resistivity of SSC decreases significantly with increasing compressive stress under the applied excitation current.
- (2) In the low-stress range ( $< 6$  MPa,  $\sim 1/5$  strength), the resistivity–stress relationship is nearly linear due to the absence of microcracks, indicating good potential for stable and durable sensing applications.
- (3) Factors such as electrode spacing, specimen size, and series resistance influence the current passing through the specimen, thereby significantly affecting the electrical resistivity and sensing sensitivity of SSC.

## **CHAPTER 4. INITIAL ELECTRICAL RESISTIVITY AND ELECTRICAL RESISTANCE BEHAVIOR OF CARBON FIBER- AND CARBON BLACK-FILLED SELF-SENSING CONCRETE CONSIDERING INFLUENCING FACTORS**

### **4.1. Compressive Strength, Porosity and SEM**

The 28-day compressive strengths of the N-, CB2-, CF2-, and CB1CF1-specimens are 56.8, 53.0, 58.4, and 57.6 MPa, respectively, all satisfying the design requirement of 50 MPa. Porosity results, determined in accordance with TCVN 3112:2022, indicate that CF2 has lower porosity and higher compressive strength than the other specimens.

Additionally, SEM observations of SSC specimens (Figure 4.1) reveal agglomeration of carbon black particles, with small pores forming around these clusters. In contrast, carbon fibers are relatively uniformly distributed within the concrete, with minimal evidence of agglomeration. Moreover, the interface between carbon fibers and the surrounding cementitious matrix shows no significant voids, indicating strong interfacial bonding.

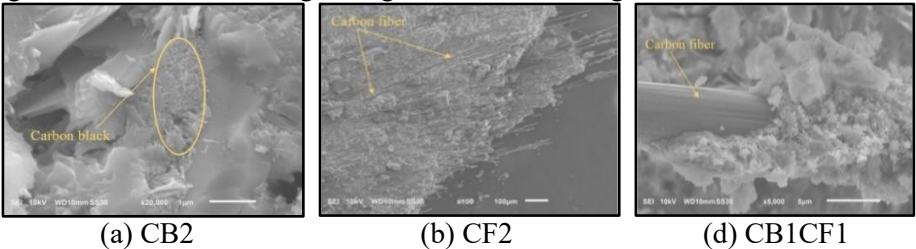


**Figure 4.1. SEM images of specimens with carbon fibers and carbon black**

### **4.2. Initial electrical resistivity of SSC under unloaded conditions**

#### **4.2.1. Effect of material composition and current intensity**

The experimental results indicate that specimens having the same material composition and produced from the same batch still exhibited different electrical resistivity values, as shown in Figure 4.2. These differences may be attributed to the inherent heterogeneity of the material microstructure, the non-uniform distribution of conductive constituents, and minor variations introduced during specimen preparation and curing processes. Therefore, producing SSC specimens with a completely homogeneous structure and identical electrical resistivity values remains a significant challenge in practice.

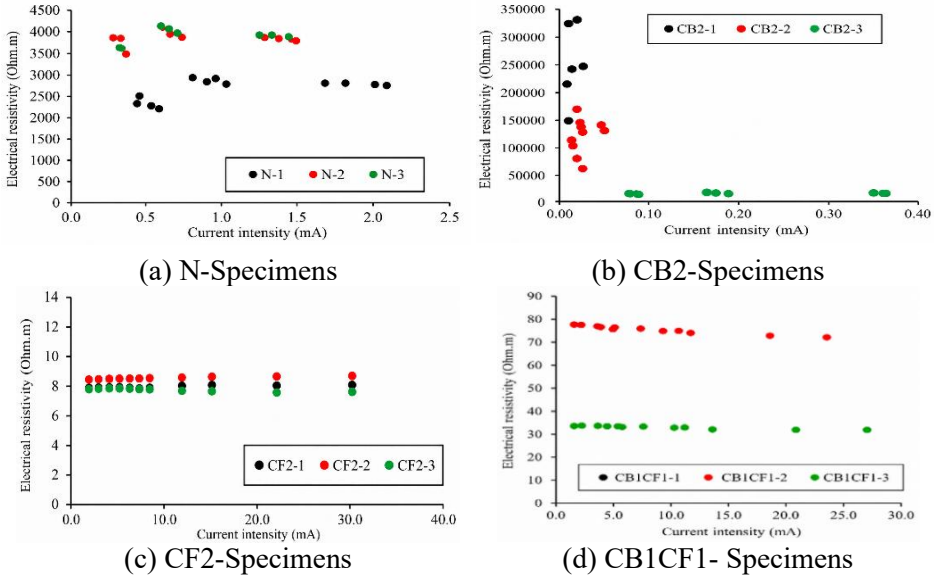


**Figure 4.2. Relationship between current intensity and electrical resistivity**  
**4.2.2. Effect of temperature and moisture**

The electrical resistivity of SSC is highly sensitive to temperature. As shown in Figure 4.3, the effect of temperature on electrical resistivity increases with the enhancement of the material's insulating properties.

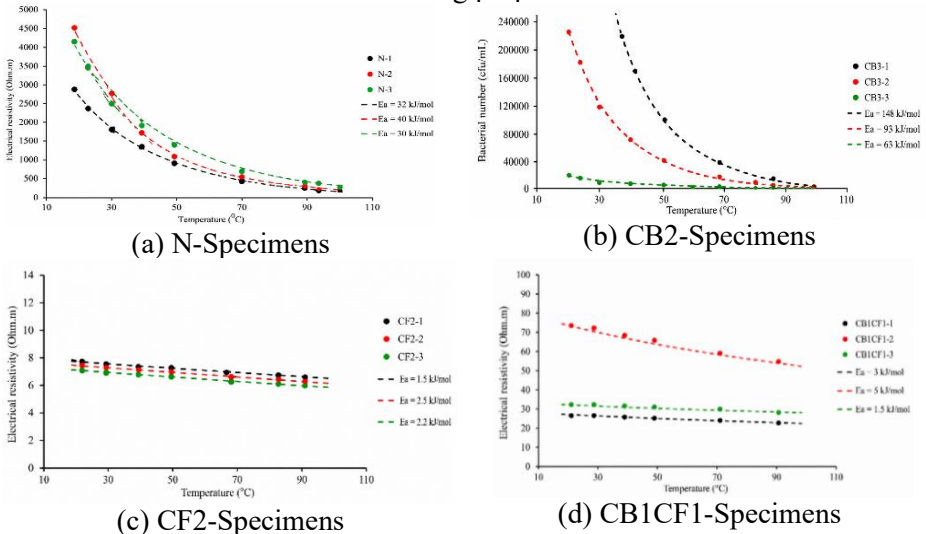


**Figure 4.3. Relationship between temperature and electrical resistivity of the specimen**

In addition, moisture also affects the electrical resistivity of SSC. As moisture increases, the resistivity of N and CB2 specimens decreases, with the rate of reduction diminishing as the material approaches saturation. In contrast, specimens containing carbon fibers (CF2- and CB1CF1-) exhibit the opposite trend, with resistivity remaining stable or slightly increasing as moisture rises. Figure 4.4 highlights the significant influence of moisture on SSC resistivity, which varies depending on the material composition.

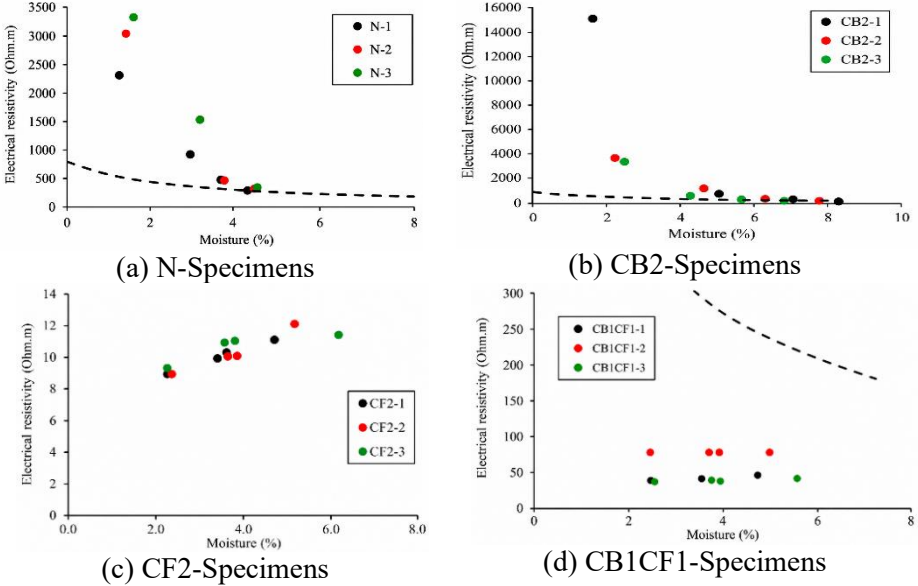


**Figure 4.4. Relationship between moisture and electrical resistivity**

#### 4.2.3. Development of a predictive model for the initial electrical resistivity of SSC considering the combined effects of material composition and environmental factors

Previous studies indicate that the electrical resistivity of concrete under unloaded conditions is influenced by factors such as material composition, temperature, and moisture; however, no empirical model has simultaneously accounted for these effects. Based on the Arrhenius equation, this study develops a predictive model for the initial electrical resistivity incorporating the combined influence of these factors. The results are expressed in the following formulation:

$$\rho_s = \rho_{s(0)} e^{1.2\alpha(T-T_0) + 0.9\beta(W-W_0)} \quad (4.10)$$

The proposed model is validated against the data of Joanna et al., showing not only strong agreement with the experimental results of this study but also a reliable assessment of the temperature effect on the electrical resistivity of cementitious materials under varying moisture conditions, as illustrated in Figure 4.5.

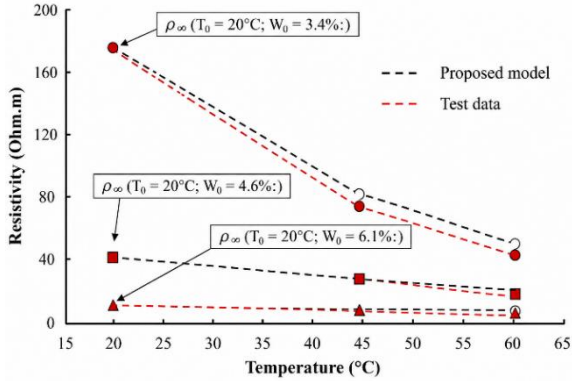


**Figure 4.5. Correlation between the proposed model and reference data**

**4.3. Electrical Resistance Behavior and Predictive Modeling of the Resistivity Variation Coefficient of Self-Sensing Concrete under Elastic Compressive Loading**

Four specimens, CF2-1, CF2-2, CB1CF1-1, and CB1CF1-2, were tested under compressive loading within the elastic range under different temperature and moisture conditions. The results showed that the electrical resistance decreased linearly with increasing compressive load, as illustrated in Figure 4.6, demonstrating the effective operation of the self-sensing mechanism under loading.

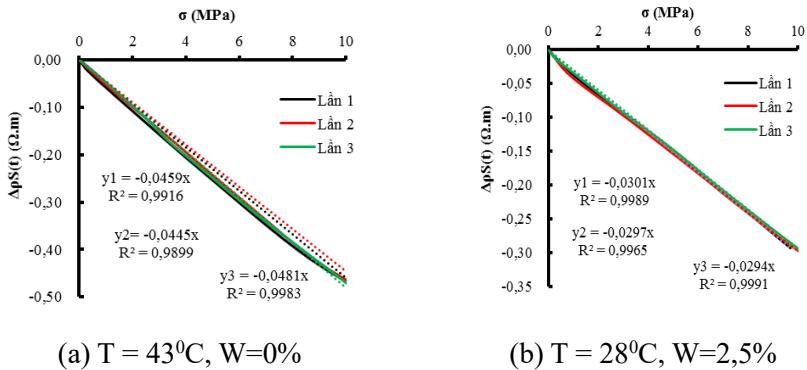


**Figure 4.6. Electrical resistivity behavior under compressive stress of specimen CF2-1 at different temperature and moisture levels**

Linear regression analysis indicated that the slope of the regression line represents the resistivity variation coefficient,  $K$ , of the specimen under compressive loading while accounting for the effects of temperature and moisture. The values of  $K$  differed only slightly among the tested cases, suggesting that the initial resistivity may be the primary factor governing the coefficient  $K$  during loading.

To verify the reliability of Equation (4.10), the calculated resistivity values were compared with the experimental results. The comparison revealed a strong correlation between the calculated and measured values (Figure 4.7), confirming the suitability of the proposed equation. Regression analysis further showed that this relationship is best described by a second-order exponential function (Figure 4.8).

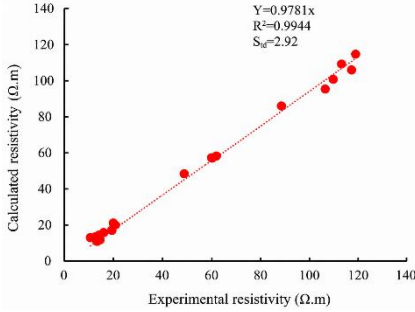


**Figure 4.7. Correlation between experimental and calculated electrical resistivity**

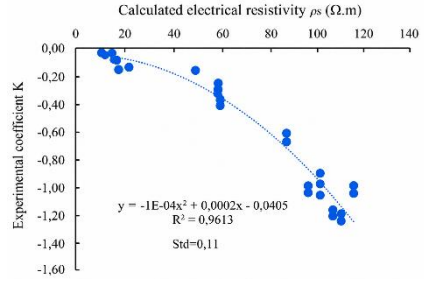


**Figure 4.8. Relationship between experimental coefficient K and calculated electrical resistivity**

The correlation between the resistivity variation coefficient KKK and the calculated resistivity, accounting for the combined effects of temperature and moisture, is expressed by the following equation:

$$y = -10^{-4}\rho_s^2 + 0,0002\rho_s - 0,0405 \quad (4.11)$$

From Equation (4.11), the predictive model for the resistivity variation coefficient KKK under compressive loading, considering the simultaneous influence of factors such as mixture composition, temperature, and moisture, is expressed in Equation (4.12):

$$K = -10^{-4}\rho_{s0(0)}^2 e^{2,4\alpha(T-T_0)+1,8\beta(W-W_0)} + 0,0002\rho_{s0(0)} e^{1,2\alpha(T-T_0)+0,9\beta(W-W_0)} - 0,0405$$

#### 4.4. Conclusion of Chapter 4

The conclusions drawn from this chapter are as follows:

- (1) Temperature and moisture affect the initial resistivity of SSC specimens under unloaded conditions. These effects vary not only among specimens with different material compositions but also among specimens with the same material composition.
- (2) An equation for predicting the initial resistivity of self-sensing concrete (SSC) in the absence of applied load was developed by considering the combined effects of material composition and environmental factors. The proposed equation is presented in Equation (4.10).
- (3) The electrical resistance behavior of SSC specimens under compressive loading within the elastic range exhibited a linear decreasing relationship, regardless of differences in mix composition, temperature, and moisture.
- (4) An equation for determining the resistivity variation coefficient,  $K$ , under compressive loading within the elastic range was established by considering

the simultaneous effects of mix composition, temperature, and moisture. This equation can be used to predict the load applied to SSC specimens and is presented in Equation (4.12).

## CHAPTER 5. ELECTRICAL RESISTANCE BEHAVIOR OF MULTI-SPECIMEN SELF-SENSING CONCRETE SYSTEMS UNDER ELASTIC COMPRESSIVE LOADING AND DEVELOPMENT OF A LOAD PREDICTION MODEL

### 5.1. Electrical resistance behavior of self-sensing concrete (ssc) support systems under elastic compressive loading

#### 5.1.1. Electrical resistance behavior of a two-ssc-support system ( $50 \times 50 \times 250$ mm) under centric compression

Before evaluating the electrical resistance behavior under loading, the SSC support specimens were tested under unloaded conditions. The results showed only very small fluctuations in resistance with no clear trend, indicating that the electrical resistance of the supports remained stable when subjected to the excitation voltage. This stability ensures the reliability of the measurements and provides a sound baseline for analyzing the resistance behavior under compressive loading in the subsequent stages.

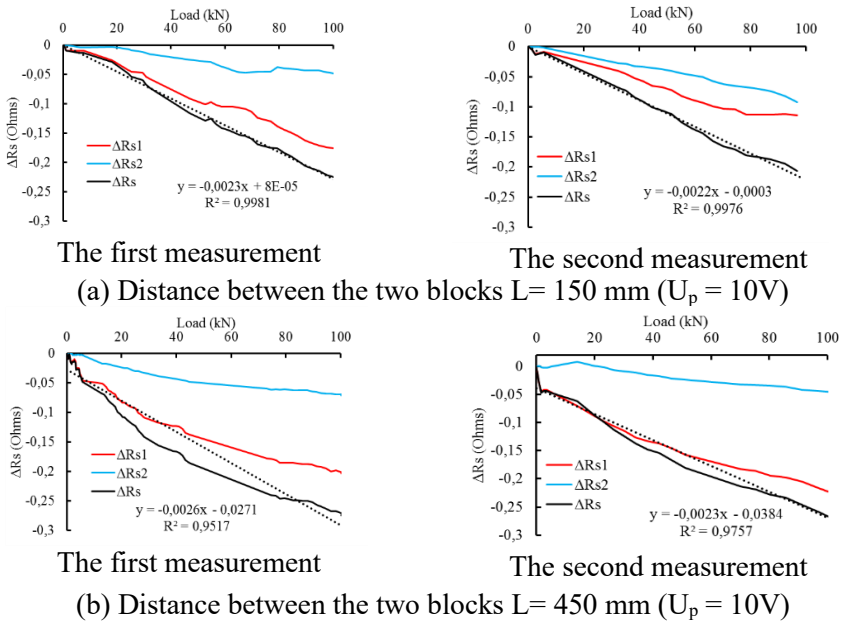


**Figure 5.1. Electrical resistance behavior of a two-ssc-support system under elastic compressive loading**

Under centric compressive loading, the combined resistance response of the two supports was relatively consistent in both test runs. Although the resistance response of each individual support exhibited a complex variation pattern, the

overall response of the system maintained a stable linear relationship with the applied load (Figure 5.1a). However, as shown in Figure 5.1(b), the response became nonlinear. This behavior may be attributed to the increased spacing between the two supports ( $L = 450$  mm), which introduced the influence of eccentric loading effects.

Based on the above findings, the supply voltage ( $U_p$ ) was further varied in four additional cases, namely 6 V, 12 V, 15 V, and 18 V, in order to modify the electric current passing through the concrete specimens, which is a factor that may influence their electrical resistance behavior. The results showed that although the resistance response of individual supports could fluctuate, the combined resistance response of the support system remained nearly linear and stable in all cases.

The slope of the regression line relating the total resistance change of the support system to the applied load was defined as the resistivity variation coefficient. This parameter was used to convert the resistance changes of the SSC supports in the weighing system into the corresponding applied load on the weighing platform. The results indicated that, for a given resistance variation, the actual load could deviate by approximately  $\pm 10\%$  from the mean predicted value, as illustrated in Figure 5.2.

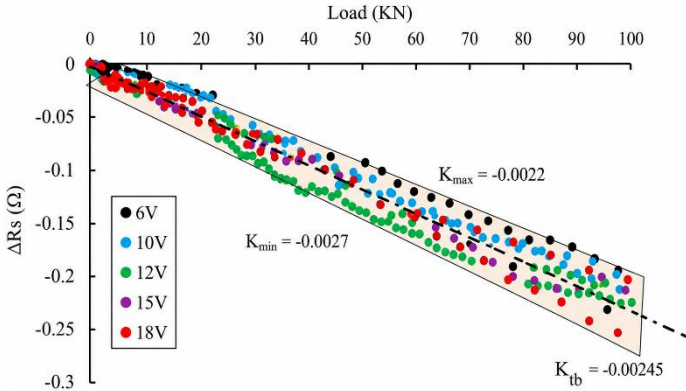


**Figure 5.2. Measured relationship between resistance variation and compressive load under different excitation voltages**

#### **5.1.2. Electrical resistance behavior of a four-ssc-support system ( $50 \times 50 \times 250$ mm) under elastic compressive loading**

The electrical resistance behavior of the four-SSC-support system was investigated under centric compression and eccentric compression with eccentricities of 25 mm and 50 mm. Although the resistance responses of the individual supports differed and did not follow a consistent trend, the overall resistance of the system still exhibited a linear decrease with increasing applied load, as illustrated in Figure 5.3.

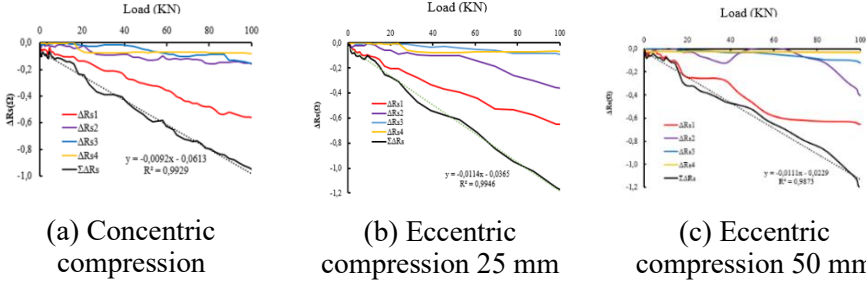


**Figure 5.3. Electrical resistivity behavior of a system consisting of 4 blocks (50×50×250 mm) subjected to compressive loading at different positions**

The experimental results of the weighing system under different load application positions showed that, for a given resistance variation, the corresponding load could deviate by approximately  $\pm 14.4\%$  from the mean predicted value, as illustrated in Figure 5.4. This deviation mainly arises from differences in load distribution among the supports and the inherent heterogeneity of the SSC material. Nevertheless, the relationship between resistance variation and applied load remained clearly observable, indicating that the proposed weighing system is capable of detecting and estimating loads with an acceptable level of reliability.

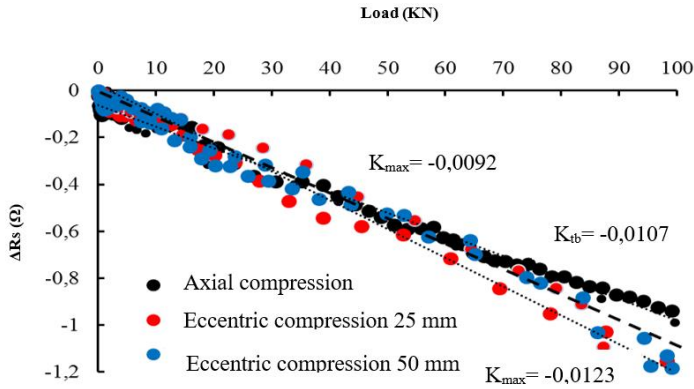


**Figure 5.4. Aggregated data of the total resistance variation of a system consisting of four SSC (50×50×250 mm) under compressive loading at different loading positions**

**5.1.3. Electrical resistivity behavior of a six-ssc-support system (50 × 50 × 50 mm) under compressive loading at different loading positions**

Tests conducted on a six-SSC-support system (50 × 50 × 50 mm) subjected to compressive loading within the elastic range at different loading positions showed that the resistance responses of the individual supports were non-uniform and did not follow a consistent trend. However, the combined electrical resistance response exhibited a generally linear decreasing trend with increasing load, as illustrated in Figure 5.5. The resistivity variation coefficient was found

to vary with the load application position, resulting in a load prediction error of approximately  $\pm 10.8\%$  relative to the mean predicted value, as shown in Figure 5.6.

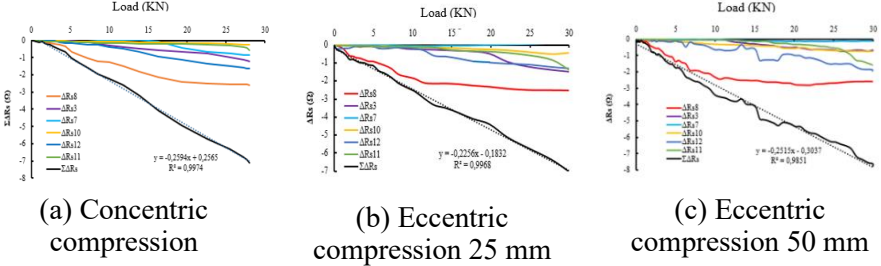


**Figure 5.5. Electrical resistivity variation behavior of a system consisting of six SSC blocks ( $50 \times 50 \times 50$  mm) subjected to compressive loading at different positions**

These results demonstrate that a multi-support SSC system is capable of reflecting load variations through its combined resistance signal. Furthermore, the proposed model maintains an acceptable level of accuracy even when the applied load is unevenly distributed among the supports.

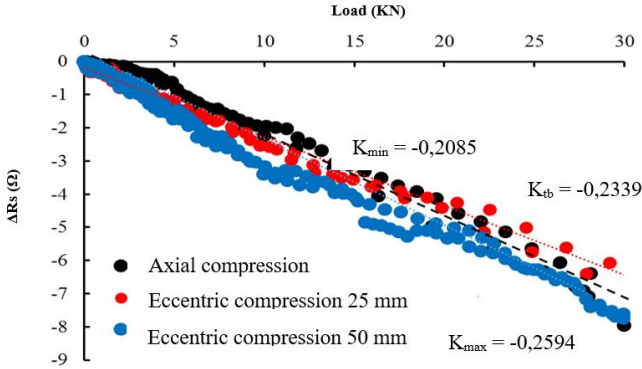


**Figure 5.6. Compiled data of the total electrical resistance variation of a system consisting of six SSC blocks ( $50 \times 50 \times 50$  mm) under compressive loading at different loading positions**

## 5.2. Load prediction model for a multi-SSC pad system

The load prediction model for the laboratory-scale weighing system is established as follows: the applied load ( $P$ ) on the weighing platform is transferred to a system consisting of multiple concrete blocks at different loading positions.

$$P = A \cdot \frac{a}{L} \left( \frac{\Delta R_1}{K_1} + \frac{\Delta R_2}{K_2} + \dots + \frac{\Delta R_n}{K_n} \right) \quad (5.4)$$

Where  $P$  (kN) is the load of the object to be determined;  $\Delta R_1, \Delta R_2, \dots, \Delta R_n$  ( $\Omega$ ) are the resistance changes relative to the initial resistance of SSC specimens from specimen 1 to specimen  $n$ , respectively;  $K_1, K_2, \dots, K_n$  are the resistivity variation coefficients of SSC specimens from 1 to  $n$ , determined according to

Equation (4.12);  $A$  ( $\text{m}^2$ ) is the load-bearing area of each pad;  $a$  ( $\text{m}^2$ ) is the contact area between the electrode and the concrete of each pad; and  $L$  (m) is the distance between the two electrodes of each block.

To validate the proposed method, the load calculated using Equation (5.4) was determined for systems consisting of four blocks ( $50 \times 50 \times 250$  mm) and six blocks ( $50 \times 50 \times 50$  mm) under different loading positions, and then compared with the corresponding experimental loads. The results show a strong correlation between the two, indicating that the load prediction method based on the resistivity variation coefficient achieves relatively good accuracy, as illustrated in Figures 5.7 and 5.8.

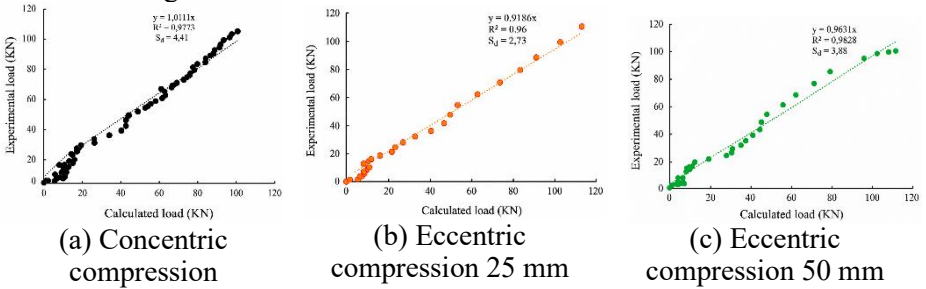


**Figure 5.7. Correlation between experimental load and calculated load for a system consisting of four blocks ( $50 \times 50 \times 250$  mm)**

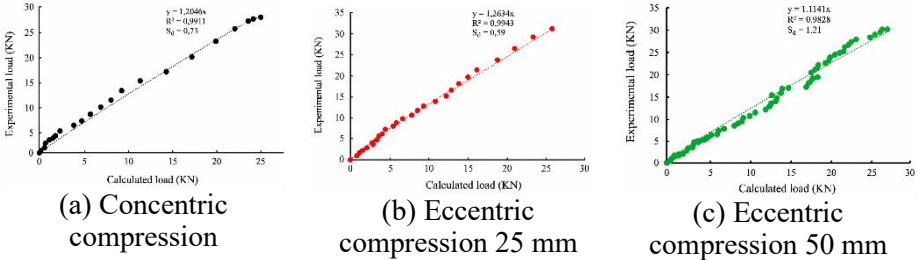


**Figure 5.8. Correlation between experimental load and calculated load for a system consisting of four blocks ( $50 \times 50 \times 50$  mm)**

### 5.3. Conclusions of Chapter 5

The main conclusions drawn from this chapter are as follows:

- (1) In the experimental models, although the electrical resistance responses of individual supports within the system may differ under compressive loads applied at different positions, the overall electrical resistance response of the entire system remains linear and stable across repeated measurements. The degree of linearity decreases as the spacing between supports increases due to the influence of eccentric loading.
- (2) The resistivity variation coefficient,  $K$ , of the system exhibits an error of approximately 10%. Therefore, further studies are required to reduce this deviation and improve the accuracy of large-scale weighing systems.

- (3) Equation (5.4) can predict the load applied to a multi-support system with relatively good accuracy compared to the experimental results, even when the supports have different dimensions and are subjected to loads at different positions.

## **CONCLUSIONS AND RECOMMENDATIONS**

### **1. The main achievements of the dissertation are as follows**

This study systematically investigated the electrical resistance behavior of self-sensing concrete (SSC) under compressive loading and evaluated its potential application in load-measuring systems. The main findings of the dissertation can be summarized as follows:

- (1) The study clarified the fundamental mechanism governing the electrical resistivity behavior of SSC under compressive loading. Experimental results showed that within the elastic compressive stress range, corresponding to approximately one-fifth of the compressive strength of the material, when no microcracks are formed and the pore structure is gradually compacted, the relationship between resistivity variation and compressive stress exhibits a clear linear trend. This finding indicates that SSC can operate stably within the elastic compression range, maintaining the stability of the electrical signal and improving measurement repeatability when used as a sensing material.
- (2) The study analyzed the effects of environmental factors and material composition on the initial resistivity of SSC under unloaded conditions. Experimental results demonstrated that the initial resistivity is significantly affected by temperature, relative humidity, and mix composition. Based on these findings, an empirical model was developed to predict the initial resistivity of SSC, enabling the correction of resistivity values under different measurement conditions. This model provides a basis for reducing errors when comparing resistance values during practical load-monitoring applications.
- (3) The study developed a model describing the resistivity behavior of SSC specimens subjected to compressive loading within the elastic range while simultaneously considering the effects of material composition, temperature, and environmental humidity. From this model, the resistivity variation coefficient,  $K$ , was determined, making it possible to establish a quantitative relationship between the applied load and the electrical resistance signal obtained from SSC specimens.
- (4) The study extended the analysis from a single SSC specimen to a system consisting of multiple SSC specimens in order to simulate the configuration of practical load-sensing systems. Experimental results showed that the proposed load prediction method for multi-support SSC systems exhibited relatively good agreement with the measured loads. Specifically, the error associated with the resistivity variation coefficient,  $K$ , was approximately 10%, demonstrating the potential applicability of SSC systems in load-measuring devices. Based on these findings, a load prediction equation for

multi-support SSC systems was proposed, enabling the determination of loads acting on support systems with different dimensions and load positions.

The results of this research contribute to a better understanding of the sensing mechanism of SSC under elastic compressive loading. Furthermore, the proposed resistivity prediction model and load determination method for multi-support SSC systems provide an important scientific foundation for the development of large-area sensing devices utilizing concrete itself as the sensing material. Such systems are particularly promising for future intelligent transportation monitoring and smart freight management applications.

## **2. Recommendations for future research**

Although this study has clarified several fundamental mechanisms and proposed predictive models for the electrical resistance behavior of self-sensing concrete (SSC) under compressive loading, several issues still require further investigation to strengthen the scientific foundation and enhance the applicability of this material in structural sensing and intelligent transportation systems.

First, further research is needed to investigate the long-term effects of environmental factors on the electrical properties of SSC. Under practical service conditions, concrete structures are often exposed simultaneously to various environmental influences, including temperature fluctuations, humidity variations, wet–dry cycles, carbonation, and the ingress of aggressive ions. These factors may alter the pore structure and conductive network within the material, thereby affecting its electrical resistivity and the long-term stability of sensing signals. Therefore, long-term studies should be conducted to evaluate the degradation of electrical conductivity and sensing sensitivity, as well as to determine the effective service life of SSC when used in structural sensing systems.

Second, the experiments in this study were primarily conducted under static compressive loading, whereas transportation infrastructures and civil engineering structures in practice are commonly subjected to dynamic loads, cyclic loads, and vibrations induced by traffic. Therefore, future research should focus on the electromechanical behavior of SSC under dynamic and cyclic loading conditions, including assessments of signal stability, measurement repeatability, and variations in sensing sensitivity with increasing load cycles. Such investigations would provide a more comprehensive evaluation of the suitability of SSC for traffic load monitoring and structural health monitoring applications.

Third, to advance the development of sensing technologies for intelligent transportation systems, priority should be given to the design and optimization of specific sensing configurations employing SSC supports installed beneath pavement structures. This research direction would facilitate the practical implementation of SSC-based sensing systems in transportation infrastructure and improve their measurement performance and reliability.

Finally, future studies should also address the economic and sustainability

aspects of SSC. The incorporation of conductive materials such as carbon fibers or nanomaterials may significantly increase the production cost of concrete. Therefore, further research is needed to optimize material costs, evaluate the life-cycle performance of SSC, and conduct economic feasibility analyses of SSC-based sensing systems. Such efforts would contribute to the development of cost-effective and sustainable smart monitoring solutions with broad practical applicability.