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Compression self-sensibility of the concrete using high content carbon black with various measurement conditions

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Abstract. Self-sensing concrete (SSC) is a smart material created by dispersing a conductive filler into the concrete. This helps to increase the resistivity variation of concrete when the microstructure of the material changes under the effect of load. Thus, the stress, strain or damage of the concrete can be sensed by resistivity measurements of the concrete itself. This study aims to clarify the effects of parameters related to the measurement method on the self-sensibility of SSC. SSC specimens were prepared using carbon black with 7% volumetric content. A series of compression tests were conducted to investigate the relationship between the resistivity variation and the applied load of different test specimens in terms of excitation voltage, electrode distance and specimen size. The results show that the excitation voltage need to be large enough to generate a current of suitable stability when measuring the self-sensibility of SSC. The resistivity of all specimens decreased with increasing compressive load on the SSC specimen. The larger the specimen size and the smaller the electrode distance, the more pronounced the resistivity variation.

1. Introduction

Nowadays, the concrete material technology has made great advances. In addition to technologies for improving the basic properties of the concrete such as the mechanical strength, the workability, the light weight, the durability, etc., there are many projects have developed a novel concrete with smart features. Several types of smart concrete studied in recent years can be mentioned as Self-Compacting Concrete [1], Self-Curing Concrete [2], Self-Healing Concrete [3], and Self-Sensing Concrete [4], etc. Among them, Self-sensing Concrete (SSC) is a material that is attracting great attention from researchers in the context of acceleration of digital transformation in the construction industry.

SSC was invented in the early years of the 21st century. Self-sensibility of concrete is defined as the ability for self-sensing stress and strain states present in the concrete itself. The principle for forming the concrete self-sensibility is to provide an appropriate amount of conductive material into the concrete mixture to increase the conductivity of the concrete. At that time, the resistivity of concrete is changed when the microstructure of concrete is changed under the loads. That is, particles of the conductive material inside the concrete is closer under the compressive load, and further apart under the tensile load, causing the resistivity of the concrete to change. Based on the continuous measurement of this variation of resistivity, the change of stress or strain of the concrete under the effect of various loads on the structure can be indirectly predict. Therefore, SSC is considered a potential material for application in intelligent monitoring systems for the civil structures and traffic infrastructure in the context of the industrial revolution 4.0 spreading around the world.

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There are many studies related to SSC in recent years. Some types of conductive filler used to create the SSC include steel, copper, zinc, carbon, and graphene etc., in the form of a fine powder, nanotubes, or short fibres that form a conductive network inside the concrete. Studies show that the self-sensibility of SSC depends on the type, the shape, the size, and the content of these conductive fillers inside the concrete matrix [5-7]. While conductive fillers in the form of fibers or nanotubes create an electrical network within the concrete, achieving even dispersion throughout the concrete matrix to minimize measurement errors is problematic. Finely powdered fillers have become widely used because of their even dispersion in the concrete matrix, but high concentrations are required to ensure electrical conductivity. Therefore, carbon black has emerged as a potential material for self-sensing concrete due to its low cost and resistance to rusting in harsh environments. In addition, the mixture composition of the base concrete affects the dispersion of conductive fillers in the concrete, thus also significantly affecting the self-sensibility of the SSC [5]. Meanwhile, several studies have focused on investigating the relationship between the resistivity variation and the strain or the stress of SSC under the effect of different types of loads such as compression, tension, bending, or dynamic and static loads [8-10]. These studies show the wide application potential of SSC in smart infrastructure system.

On the other hand, a prerequisite when measuring the resistivity of the SSC under load is to provide an excitation electrical current passing through the SSC. Therefore, the charged particles inside the SSC are not only subjected to the mechanical impact of the load, but also to the complex effect of the electromagnetic forces generated inside the material. That is, under the same mechanical load, different excitation amperage passing through the specimen maybe give different measurement results in the resistivity variation of SSC. Also, the amperage passing through the specimen depends on the measurement conditions such as the excitation voltage, the electrode distance, and the size of the SSC specimen. However, previous studies were conducted with the condition when the amperage of excitation current and the size of specimens is a certain value. Therefore, investigating the influence of these parameters is crucial for accurate measurements under different excitation current conditions.

Therefore, this study aims to clarify the effect of measurement conditions on the relationship between the resistivity variation and the compressive load on SSC. SSC specimens were made by adding 7% by volume carbon black powder to the concrete mixture. The concentration of carbon black at 7% was determined by referring to previous studies [11]. The effectiveness of carbon black in enhancing the self-sensing properties of concrete has been demonstrated in previous studies [5, 6, 11]. Parameters including excitation voltage, the value of intermediate resistance, the distance between two electrodes, and the size of the test specimen were changed to clarify these effects on the measurement results.

2. Raw materials and specimen preparation

Raw materials for casting SSC include cement, fine sand, blast furnace slag, carbon black, mineral additives, water, and superplasticizers. The basic properties of these raw materials are shown in Table 1. The grade of concrete is designed with a target compressive strength equivalent to that of normal concrete of 30MPa. The composition for $1m^3$ of concrete is shown in Table 2. Blast furnace slag and mineral admixtures are used as binders to partially replace Portland cement, while carbon black is used to partially replace fine sand in the concrete mixture design. Large aggregates with a wide range of particles can affect the homogeneity of the concrete matrix and interfere with the movement of the conductive particles when the load is applied. Therefore, this study did not use large aggregates when designing the SSC concrete mixture. The high fineness of carbon black significantly reduces the workability of the concrete mixture. To improve workability, GGBS and superplasticizers were used. The GGBS provided by Hoa Phat Dung Quoc Steel., JSC improves the workability of the concrete mixture due to its smooth surface [12]. Moreover, GGBS enhances the paste coating around fine aggregate particles, reducing internal friction between particles, thereby improving the workability of the concrete mixture [13]. This aids in the even dispersion of carbon black in the concrete mixture. Additionally, mineral additives were used to accelerate the strength development rate of SSC specimens by reacting with $Ca(OH)_2$ to form a secondary C-S-H gel [14], which is consistent with the 28-day experimental plan.

Table 1. Raw materials of SSC.

Material	Manufacturer (product code)	Specifications
Cement	Nghi Son, Vietnam (PC50)	Specific content = 3.11 g/cm^3, Unit mass = 1.155 g/cm^3
Blast furnace slag	Hòa Phat, Vietnam (S95)	Specific content = 2.91 g/cm^3, Unit mass = 0.988 g/cm^3
Mineral Additives	Lotus, Vietnam (SP2)	Specific content =2.15 g/cm^3; SIO_2>=93%
Fine sand	Phong Đien, Vietnam	Fineness modul = 1.58, Specific content = 2.65 g/cm^3, Unit mass = 1.427 g/cm^3
Carbon black	OCI, Korea (N330)	Specific content = 1.63 g/cm^3, Unit mass = 0.394 g/cm^3
Superplasticizer	Lotus, Vietnam (R301M)	Specific content = 1.06 g/cm^3

Table 2. Mixture proportion for 1m^3 SSC (Unit: kg).

Cement	Mineral additives	Blast furnace slag	Fine sand	Carbon black	Superplasticizer	Water
525	60	315	644	70,5	9	400

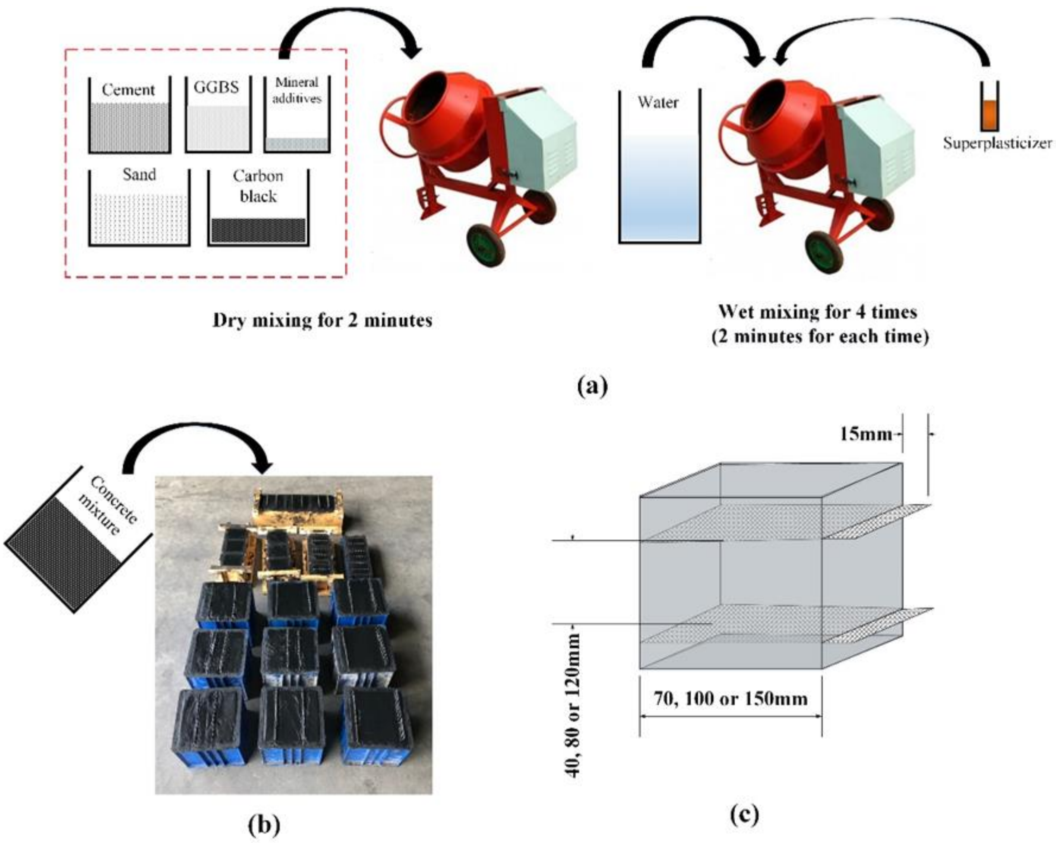


Figure 1. Specimen preparation: (a) Steps for mixing the SSC, (b) SSC specimen after casting, (c) Parameters of specimen dimension.

The raw materials (except water and superplasticizers) are put into a 50L concrete mixer, and dry mixed for 2 minutes. Next, water was added and wet mixed for about 2 min. Finally, superplasticizer was added to the mix to correct the proper ductility of the concrete for about 2 min. These steps are shown in Figure 1(a). After the concrete mixture was fully casted into the prepared formwork, two electrodes were added to the concrete specimens as shown in Figure 1(b). Galvanized wire mesh with a 1.4 cm grid cell was used for the two electrodes of the test specimen. The specimen was moulded after 2 days of casting and cured in water continuously for the next 26 days. Then, the specimens were allowed to dry naturally for 3 days before conducting the tests to measure the resistivity of SSC.

There are four parameters, that were changed in the experiment including (i) the size of specimen, (ii) the distance between two electrodes, (iii) the excitation voltage, and (iv) the value of intermediate resistance. There are three types of cube specimen sizes with sides of 70, 100, and 150mm, and 3 types of electrode distance of 40, 80, and 120mm as shown in Figure 1(c). In addition, for testing on the specimens with 150mm-side and with 40mm- distance of electrodes, the parameters for excitation voltage (12 or 24V) and intermediate resistance value (680, 820, 1000, 2200, or 3250 Ohm) were changed. This aims to change the excitation amperage passing through the SSC specimen during the test, thereby helping to investigate the effect of the excitation amperage on the resistivity variation of SSC under the action of the compressive load.

3. Test method

3.1. Principle of the measurement method of SSC resistivity

After placed into the compressive loading tester, the SSC specimen is connected to an electrical circuit as shown in the diagram of Figure 2. The specimen is seen as a resistance (R_s) and is connected in the circuit through 2 electrodes made of galvanized mesh. R_s is connected in series with an intermediate resistance with a constant value (R_r). By measuring the total voltage (U_p) of the circuit and the voltage (U_s) between the two electrodes of R_s, the resistance and the resistivity between the two electrodes of the SSC specimen can be calculated by the method shown below.

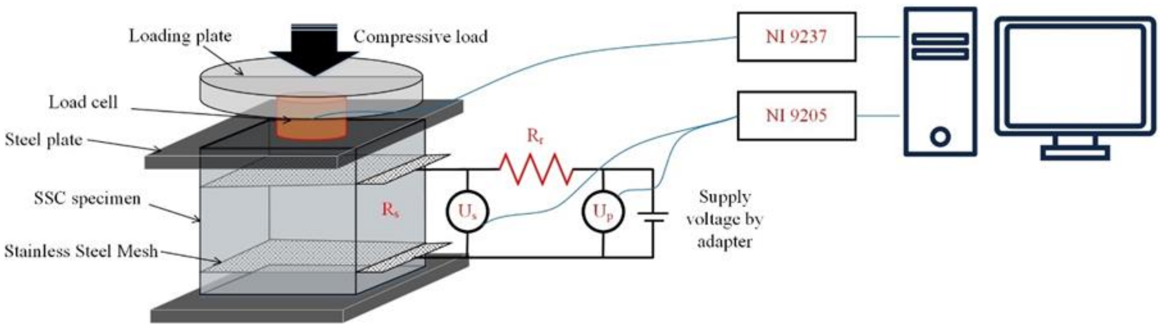


Figure 2. Diagram of instrumentation in the compression test.

Since the circuit is connected in series, the following equation is established.

$$I(t) = I_s(t) = I_r(t) = \frac{U_s(t)}{R_s(t)} = \frac{U_r(t)}{R_r} = \frac{U_p(t) - U_s(t)}{R_r} \quad (1)$$

In which, $I_s(t)$ and $I_r(t)$ are the amperage of the electric current passing through the SSC specimen (R_s), and the intermediate resistance (R_r) at a certain time (t), respectively. From Equation (1), the resistance (R_s) and resistivity (ρ_s) of the SSC specimen can be calculated according to Equations (2) and (3).

$$R_s(t) = R_r \frac{U_s(t)}{U_p(t) - U_s(t)} \quad (2)$$

$$\rho_s(t) = R_s(t)\frac{A}{L} = R_r\frac{A.U_s(t)}{L.(U_p(t)-U_s(t))} \quad (3)$$

In which, A and L are the cross-section and the distance between two-electrode of the SSC specimen, respectively.

Thus, at a certain time (t) with the applied compressive load P on the specimen, the resistivity value ($\rho_s(t)$) can be calculated according to equation (3). When the compressive load is changed, the resistivity variation ($\Delta\rho_s(t)$) of the SSC specimen compared to the initial resistivity (ρ_{s0}) at the time when the compressive load equals zero, can be determined as follows.

$$\Delta\rho_s(t) = \rho_s(t) - \rho_{s0} \quad (4)$$

Thus, the resistivity variation of the SSC specimen at a certain time (t) with any compressive load can be calculated based on the measured values in Figure 2 and applying equations (1) – (4).

3.2. Measurement devices

First, the SSC specimen is placed in a compression loading tester (with a maximum load of 2000kN). The load cell is placed between the SSC specimen and the steel plate of the loading tester to continuously measure the load applied to the specimen during the test. Load cell is connected to the NI-9237 data logger (Manufacturer: National Instruments), that allows measurements in both static and dynamic tests with a reading frequency of 12.8 MHz.

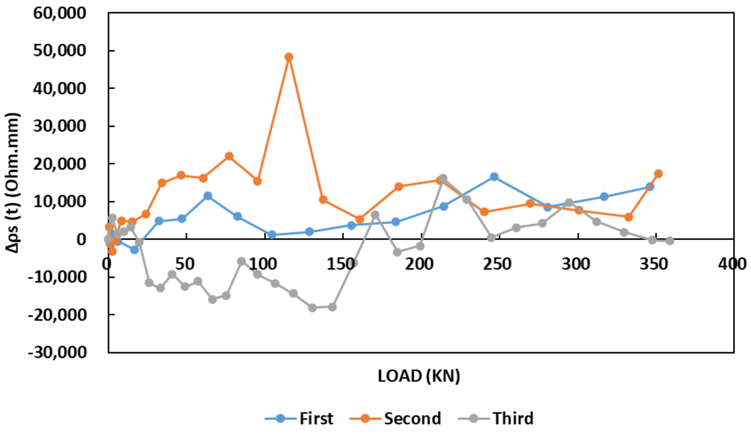
Before the loading test, the SSC specimen is connected to the circuit shown in Figure 2 with the principle as explained in Section 3.1. The adapters (type 12V and type 24V) are used as a device to convert voltage from a domestic power source (220V) to supply voltage for the experiment. Using the adapters has two main purposes: (i) to help stabilize the excitation voltage, (ii) to actively change the amperage according to the experimental purpose. In addition, the NI-9205 data logger is used as a continuous measuring device for U_s, U_p voltage during the experiment. The signals from the NI-9237 and NI-9205 data loggers are converted to data on the computer through the NI Signal Express-2015 software, which makes it easy to observe the variation of the measurement values during the experiment.

The monotonic loading method was applied to all specimens. The maximum load for each specimen was calculated before conducting the test so that the specimen is only subjected to a stress of about 15MPa, which is equivalent to 1/2 of the compressive strength of SSC. Testing with low maximum stress allows repeated tests on the same SSC specimen, thereby helping to verify the reproducibility of the results between measured times.

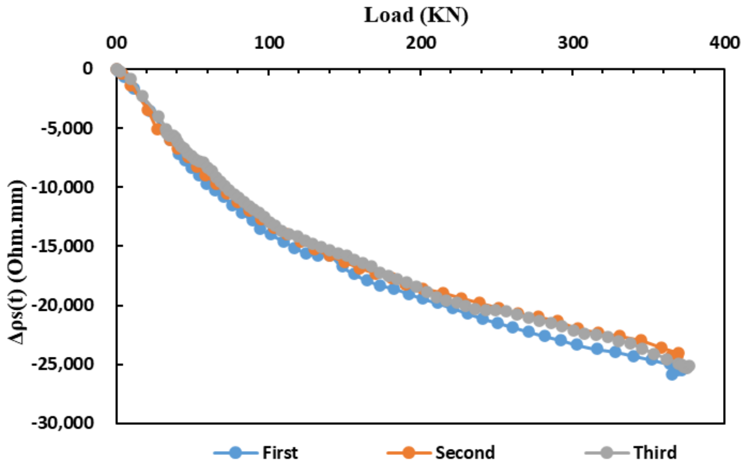
4. Results and discussions

4.1. Relationship between the applied load and the resistivity variation of SSC specimens

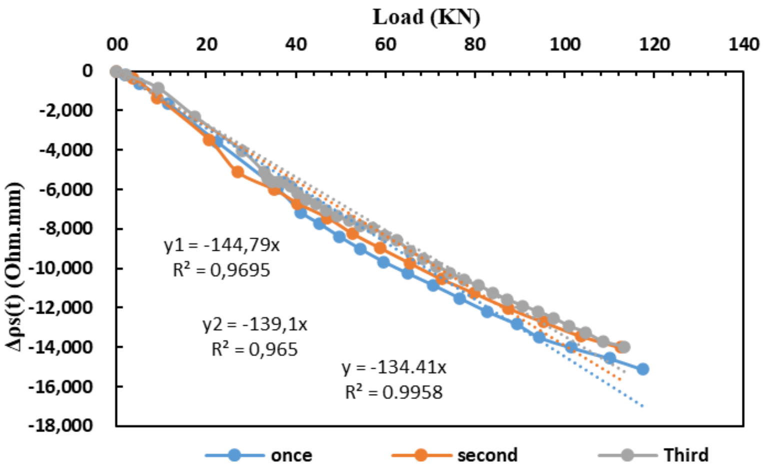
Several specimens have been used to investigate the compressive strength of SSC. The results show that the 28-days compressive strength of SSC is 34Mpa, which is satisfactory compared with the design target of the compressive strength. Accordingly, the maximum load on the SSC specimens during the loading test is calculated so that the stress generated is only 1/2 the strength of the test specimen. In the loading test to investigate the resistivity variation under the compressive load, each specimen is connected according to the circuit diagram as shown in Figure 2 with each type of intermediate resistance (680, 820, 1000, 2200 or 3250 Ohm) and each type of excitation voltage by 12 or 24V Adapter to determine the relationship between the resistivity variation and the load for each case. Figure 3 shows an example of compressive load – resistivity variation relationship of W150-40-specimen (150mm-side length and 40mm-distance between two electrodes). Note that, for each case, the experiments were repeated three times to determine the reproducibility of the experiment.



(a)



(b)



(c)

Figure 3. Compressive load – resistivity variation relationships: (a) W150-40-specimen with the excitation voltage 12V and the intermediate resistance 820 Ohm, (b) W150-40-specimen with the excitation voltage 24V and the intermediate resistance 820 Ohm, (c) Relationship of Figure 3(b) in the load range less than 120 kN (equivalent to stress less than 6Mpa)

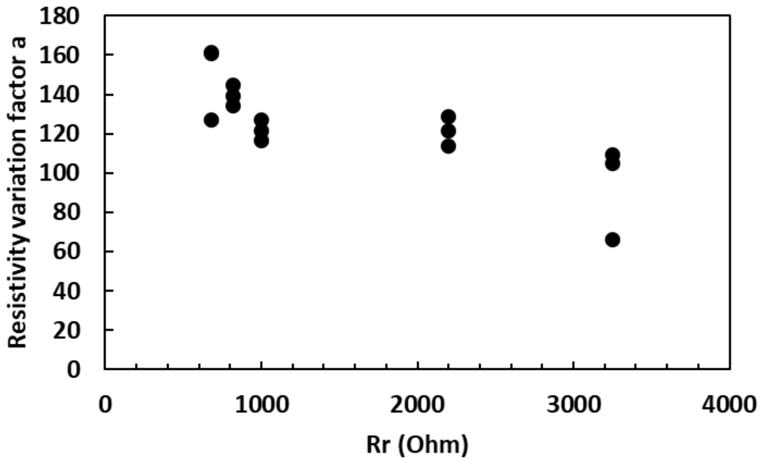
Figure 3(a) shows an example of the relationship between the load and the resistivity variation for 3 repeated measurements of the case using 12V-adapter and 820 Ohm-intermediate resistance. While Figure 3(b) shows the relationship between the load and the resistivity variation of the same specimen in the case of using the 24V-adapter, 820 Ohm-intermediate resistance. The relationship between the load and the resistivity variation is unstable and non-reproducible for the results in Figure 3(a). This is because the excitation voltage of 12 V is not enough to generate a stable amperage to allow accurate measurement of the resistivity of the SSC specimen. In contrast, the results for the 3 measured-times in Figure 3(b) show high reproducibility, and the resistivity variation decreases nonlinearly with increasing compressive load. That is, under a certain value of excitation voltage, the resistivity of the SSC specimen decreases with the effect of a compressive load. This is because the conductive particles get closer under compressive load, increasing the material's ability to conduct electricity. Thus, an excitation voltage of 24V is suitable and will be used in measurements to investigate the effect of other experimental parameters in the study.

In Figure 3(b), the relationship between the load and the resistivity variation is nonlinear. The cause of the nonlinear behavior is that micro-cracks have appeared inside the concrete matrix during compressive loading. These cracks create air voids that affect the conductivity of the SSC specimen, increasing the resistivity of the SSC specimen. This effect is opposite to the effect of reducing the resistivity of SSC under compressive load. This leads the nonlinear relationship between the load and the resistivity variation of SSC specimen. However, the relationship in the load range less than 120 kN, corresponding to the stress appearing on the SSC specimen less than 6 MPa is almost linear. This linear relationship is shown in Figure 3(c) and the dotted line represents the regression line for the data. The slope (a) and correlation coefficient (R) of the data for the regression line have also been shown in the figure. In all 3 measurements, the correlation coefficient of the measured data for the regression line is greater than 0.95. This shows a high correlation in the linear relationship between the load and the resistivity of specimen. On the other hand, the slope of the regression line is the value representing the degree of resistivity variation corresponding to a certain value of applied compressive load. For example, a slope of -144 means that the resistivity of the material decreases by 144 Ohm.mm when the compressive load varies every 1kN. Therefore, it can be understood that the higher the absolute value of the slope, the higher the self-sensing of the SSC. Here, we define a as the absolute value of the slope in the load – resistivity variation relationship, referred to as the "Factor of resistivity variation" under the effect of the compressive load. Based on this value, the self-sensibility of SSC is discussed in the following sections of the paper.

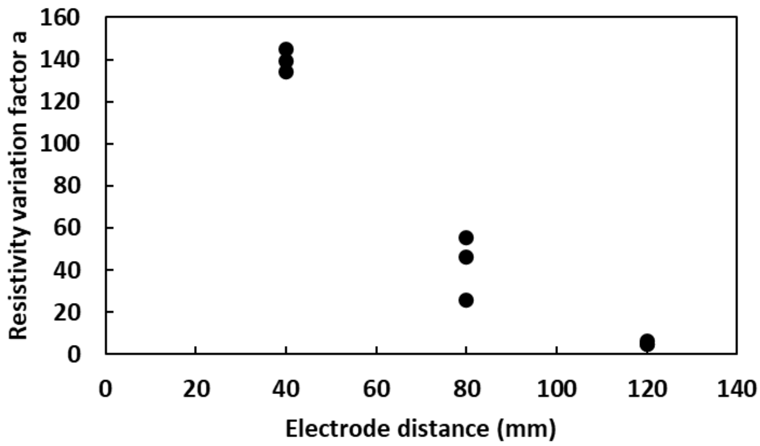
4.2. Effect of experimental parameters on the self-sensibility of SSC

Figure 4 shows the relationship between the factor of resistivity variation and the experimental parameters such as the value of the intermediate resistance (Figure 4(a)), the distance between two electrodes (Figure 4(b)), and the cross-section of the SSC specimen (Figure 4(c)). Note that, since the excitation amperage when using the total voltage of 24 V in Figure 2 is $I(t)=24/(R_s(t)+R_r)$, so changing the intermediate resistance in the circuit indirectly changes the excitation amperage passing through the SSC. The excitation amperage decreases with increasing R_r value in the circuit. Figure 4(a) shows that the factor (a) decreases with increasing value of the intermediate resistance R_r. That is, the smaller the excitation amperage, the lower the resistivity variation of the SSC under the same load.

On the other hand, Figures 4(b) and 4(c) also show a clear effect of electrode distance and SSC specimen cross-section on the resistivity variation of SSC. These effects can also be explained through the excitation amperage as follows. The relationship between the resistance and the resistivity is $R_s(t)=\rho_s(t)$ L/A. In which, A and L are the cross-section and distance of two electrodes of the SSC specimen respectively. Basically, the resistivity of a material at a certain time (t) is constant, thereby the electrode distance (L) is directly proportional, and the cross-section (A) is inversely proportional to the resistance $R_s(t)$ of the SSC. Thus, the larger the electrode distance L and the smaller the cross-section of the SSC specimen, the larger the resistance value $R_s(t)$ of the SSC. This leads the smaller amperage of the



(a)



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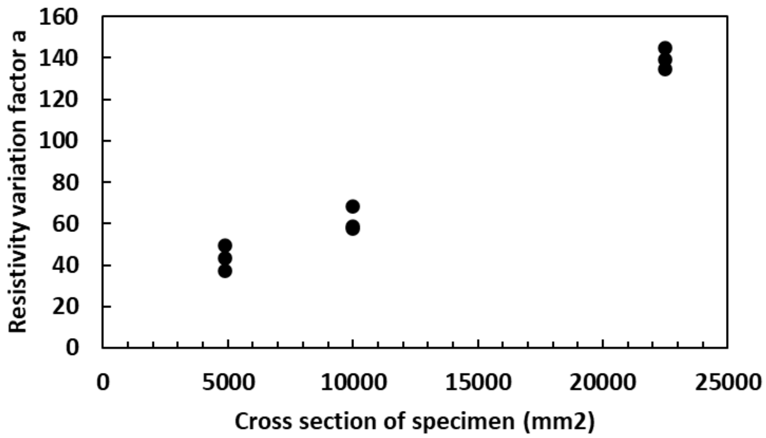

(c)

Figure 4. Effect of experimental parameters on the self-sensibility of SSC: (a) Relationship between the factor of resistivity variation and the value of intermediate resistance, (b) Relationship between the factor of resistivity variation and the distance between two electrodes of SSC specimen, (c) Relationship between the factor of resistivity variation and the cross-section of SSC specimen

excitation current, and the smaller of the factor (a) of resistivity variation. In summary, it can be concluded that, under the same compressive load, the resistivity of the SSC decreases more strongly with increasing the excitation amperage, and vice versa. This phenomenon has not been discussed in any previous studies and can be explained as follows. The excitation current breaks the bond between the electron and the ion of the electric conductor, forming heat-generating electron currents [15]. At that time, the higher the amperage of the excitation current, the higher the number of these electrons, the higher the heat, so the resistivity of the SSC decreases. Therefore, the higher the excitation amperage, the higher the factor of resistivity variation. This phenomenon is like the effect of amperage on the resistivity of semiconductor materials or insulating materials [16].

4.3. Reproducibility of the self-sensibility of SSC under the compressive load

The reproducibility of the relationship between the load and the resistivity variation can be considered by the uniformity of the results from 3 measured times on the same specimen with the same measurement conditions. This consideration is conducted to investigate the error degree in the measurement method using the SSC. To apply SSC in actual application, this error should be reduced to an acceptable level. The results in Figure 3 and 4 shows that there is still a certain deviation in the results of 3 measured times when the experimental conditions are the same. Therefore, Figure 5 shows the relationship between the error in 3 measured times and the factor of resistivity variation of the SSC specimens. Here, the error in 3 measured-times is calculated as the percentage of the standard deviation (SD) of the factor of resistivity variation in 3 measured-times divided by their average value (a_{ave}). Figure 5 shows that the error in the measurement ranges from 0.3 - 15%. In addition, the larger the factor a, the degree of error in the measurement tends to decrease. That is, the reproducibility of the measurement is higher when the excitation amperage is higher. However, this trend is not obvious and needs to be further clarified based on a lager experimental database in the future.

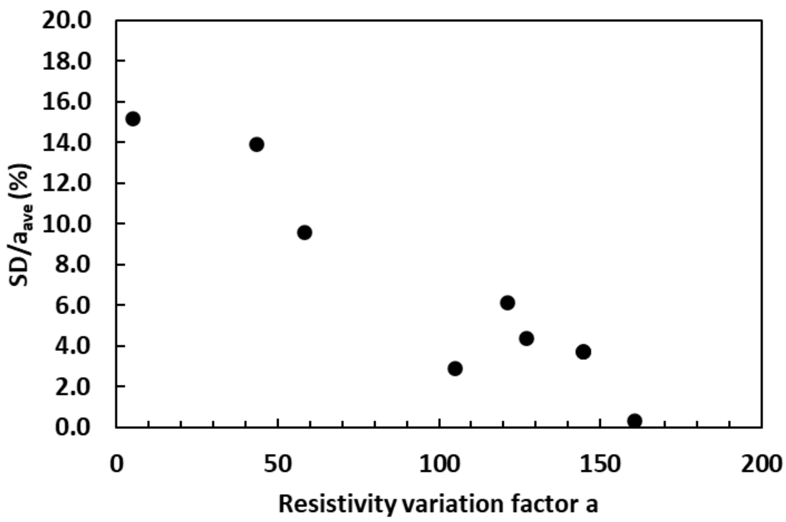

Figure 5. Relationship between the factor of resistivity variation and the error in 3 measured times.

5. Conclusions

This study was conducted to clarify the effect of various measurement conditions on the relationship between the resistivity variation of SSC and the compressive load. SSC specimen was made by adding 7% by volume carbon black to the concrete mixture. The experimental parameters are the excitation voltage, the intermediate resistance, the distance between two electrodes, and the size of the test specimen. The obtained conclusions are as follows.

(1) In a condition of the excitation current with a certain amperage, the resistivity of the SSC decreases markedly with increasing the compressive load. This is because, the conductive particles (in this case, that is carbon black) inside the concrete get closer under the action of compressive load, reducing the resistivity of the material.

(2) The excitation amperage of the circuit used in measurement clearly affects the resistivity variation of SSC under the same compressive load. This can be explained by the fact that the excitation amperage also affects the electrons current of the conductive material inside the SSC.

(3) The size and distance between two electrodes of the SSC specimen affect the electrical resistance of the specimen, thereby also the amperage passing through the specimen during the test. Therefore, the smaller the electrode distance and the larger the specimen cross-section lead the higher the resistivity variation under the same compressive load.

(4) In the scope of the study, the larger the factor of resistivity variation, the higher the reproducibility of the measurement. However, this trend needs to be further clarified based on a lager database in the future.

CRediT author statement

Vo Minh Chi: Conceptualization, Methodology, Investigation, Original draft preparation. **Nguyen Lan:** Supervision, Conceptualization, Resources, Writing-Reviewing and Editing. **Nguyen Minh Hai:** Project administration, Supervision, Conceptualization, Methodology, Original draft preparation. **Nguyen Van Huong:** Resources, Methodology, Writing-Reviewing and Editing

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