Damage Detection and Localization by Interpretation of Square Inner Electrical Resistivity Measurements

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ABSTRACT

Early diagnosis of structural damage not only reduces maintenance costs, but also increases the structure reliability, elongates the structure service life, and reduces the operational costs. This is why damage detection is one of the fundamental prerequisites for structural health monitoring (SHM). SHM as a strategy can be defined as the process of identifying damage continually with time, using minimum labor involvement. This is in contrast to visual inspections which fail to assess hidden damage accurately at early stages of occurrence. Accordingly, a variety of damage detection techniques were introduced recently to apply SHM on structural systems. SHM as a procedure includes data collection from sensors, followed by data processing, and finally interpretation of the post-processed data to obtain sufficient information about the structural integrity and reliability. In this paper, it is suggested to use the phenomenon of electrical resistivity measurements variation as an indicator of damage initiation and propagation. An inner electrical resistivity measuring technique (SIERM) using a square configuration of probes is proposed for detecting crack initiation and following its propagation. Cement Based Composites (CBC) blocks, with probes embedded inside, are the test bed for the proposed technique. The specimens were loaded under compression, splitting tension, and flexural loads during the tests. Results indicate that the electrical resistivity sensors have high sensitivity to detect crack locations and to reflect their propagation within the specimens. This is done through the correlation between the SIERM results and loading up to failure.

INTRODUCTION

Damage detection is one of the basic issues for assessment and monitoring of structures. In addition, Structural Health Monitoring (SHM) has received significant

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attention in recent years due to needs for different structures. The timely detection of damage occurrences in these structures can not only enhance the safety and security, but also elongate the product service life and reduce the operational and maintenance cost. SHM must include at least the data collection in addition to data interpretation [1]. Damage detection methods include acoustic emission methods [2,3], magnetic field methods[4], eddy-current techniques [5], thermal methods[6], vibration/frequency response methods[7], lamp wave methods[8,9], impedance-based techniques[10,11],….*etc.* In this paper, the inner electrical resistivity measurement (IERM) is used as a new reliable technique [17] for non-destructive tests (NDT) which can be used as SHM of Cement-Based Composites (CBC). An experimental program is performed to study the relation between damage and Inner electrical resistivity measurements (IERM) during different types of loading (compression, splitting tension and flexural).

Previous Studies to Detect Cracks by Measuring Electrical Resistivity

Lataste *et al* [12] introduced advice that is made of four electrodes spaced at 5 or 10 cm, arranged in a square pattern. The dimensions were chosen such that not to be disturbed by aggregate size, and to characterize the location of main alterations. The investigation depth is taken equivalent to the distance between probes. Two neighboring electrodes (A and B) inject a known electric current intensity. The potential difference created by the passage of the current in the material is measured between the two remaining electrodes (M and N). This is then repeated in a different configuration where the current electrodes are (B and N) and the potential difference electrodes are (A and M). The characterizing electrical properties of the material according to the two configurations of orthogonal directions define the apparent anisotropy which changes due to changing of material properties (e.g. cracks) [12].

This device showed a good sensitivity in detecting cracks but it needs more effort to collect accurate data on surface of structures and also electrical properties changes dramatically with changing surface conditions which may change the resistivity suddenly without crack occurrence. Furthermore, it can not estimate the damage (it can assess cracks only) earlier and continuously for monitoring the structures. The modified sensor, called square inner electrical resistivity measurements (SIERM), was introduced to improve the serviceability and avoid problems of previous devise, and also assess damage during surface life of structure.

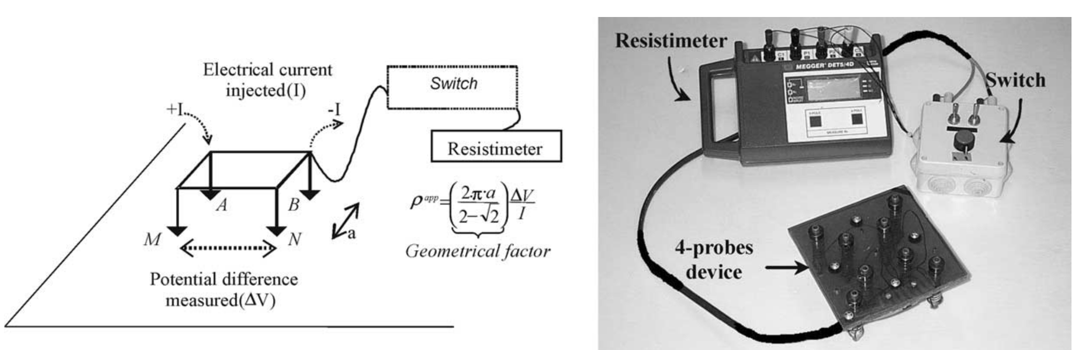


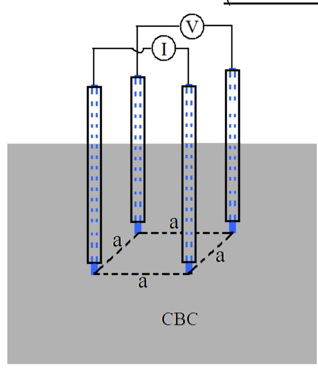
Figure 1. Four probe square array principle and photo [12].

Square Inner Electrical Resistivity Measurements (SIERM) Technique (The Proposed approach)

The Set-Up consists of four probes that are placed inside the cement based composites (CBC) specimen during casting and separated by an equal distance (a). The probe is made from a material that has good electrical conductivity and the tip of probe is allowed to be contact with CBC material while the remaining part is covered with an insulation material. Thus, the connection between the CBC and the probe is just at the tip of the probe. The current and voltage are measured at the tips of probes (see Fig. 2).

The probes are arranged at the four corners of a square where the two current (or voltage) probes are not in diagonals. Thus, the current is driven between the two adjacent corner points of the square member but not in diagonals and the voltage drop across the other probes is measured. The later configuration is adapted in analogy to the technique used by latste [12] for surface electrical resistivity measurements. The (SIERM) technique may be more suitable especially in the case of having steel reinforcement as in reinforced concrete structure. The new equations of the calculated electrical resistivity were derived by Anndif [14] as per methodology explained in the references [15] and [16].

(SIERM) configuration



$$\rho = \left(\frac{4\pi a}{2-\sqrt{2}}\right)\frac{V}{I}$$

Note: ρ is the electrical resistivity, a is the spacing between probes, V is the voltage and I is the electrical current

Figure 2. (SIERM) Technique and Corresponding Equations for Measuring Electrical Resistivity.

EXPERIMENTAL DETAILS

Experimental Program and Materials Used

The experimental program is conducted to test the applicability of detecting damage during different kinds of loading. The experimental program uses mortar as the test bed for CBC. The used cement is CEM I N42.5; natural sand is used as a fine aggregate, with specific gravity of 2.684. The used superplastizer is type F (ASTM). The Proportions of mixture by weight (sand: cement: water) are presented in table (1).

Table 1. Portions of Mixture, (w/c), and Result of Flow Table Test.

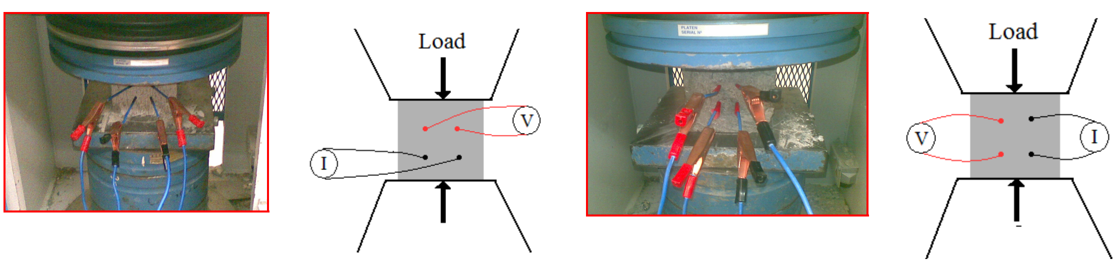
Mixture	(w/c) ratio	Proportions of mixture by weight (sand : cement)	Result of flow table test
M1	0.45	2	93%
M2	0.5	2	108.3%
M3	0.6	2	142.1%

Three groups of specimens were cast using different water to cement ratios. The first specimens group is cubic samples (100mm x 100mm x 100mm). The second group is produces prisms samples (75mm x 75mm x 260mm) and the third group cylindrical samples, diameter =75 mm x 150mm. The four probes for measuring electrical resistivity are fixed at four square corners (spacing between probes 25 mm) directly after casting. The probe is made from isolated copper wire but the isolation is removed at the tip of the probe (length of removed isolation (5mm)) to allow the electrical contact between the probe and the CBC to measure electrical resistivity. For electrical resistivity measurements, digital earth resistance tester model f-366 has been used. This model fully satisfies JIS C1304 requirements.

Tests Procedure

Compressive Strength Test

This test is used on cubes samples (100 x 100 x 100mm). During applying the compression load (strength test), the electrical resistivity is measured at different levels of loading up till failure. The electrical resistivity is measured using two (SIERM) configurations, first where the current and voltage are measured in the direction perpendicular to the loading direction and second where the current and voltage are measured in direction parallel to loading direction. See figure (3).

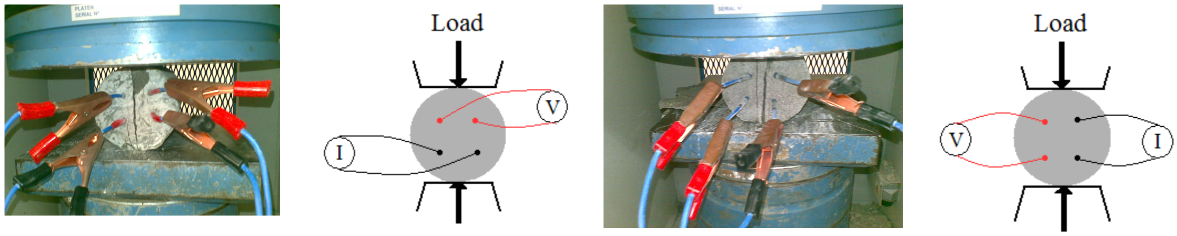


First configuration	Second configuration

Figure 3. Configurations of proposed technique to measure inner electrical resistivity during compression loading.

Splitting Tensile Strength

This test is used on cylindrical samples (diameter 75mm x 150mm). During applied Splitting tensile load, the electrical resistivity is measured at different levels of loading up to failure. The electrical resistivity is measured using two (SIERM) configurations, first where the current and voltage are measured in direction (perpendicular to loading direction) and second, where the current and voltage are measured in direction (parallel to loading direction) as shown in Figure (4).



First configuration	Second configuration

Figure 4. Configurations of proposed technique to measure inner electrical resistivity splitting tensile loading.

Flexural Strength

This test is used on prisms (beam samples) (75 x 75 x 260mm). During applied flexural load, the electrical resistivity is measured at different levels of loading up till failure at two locations. The first location was in the center mid span of beam, and the second location is 80mm apart from the center. The electrical resistivity is measured using two (SIERM) configurations, First, where the current and voltage are measured in direction (perpendicular to loading direction), and second, where the current and voltage are measured in a direction parallel to loading direction. This is applied at each location as before in the other kinds of strength tests as shown in Figure (5).

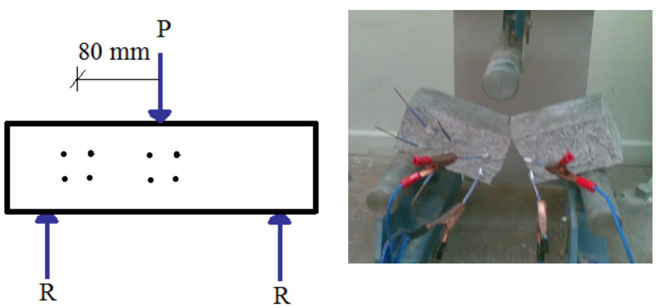


Figure 5. Illustration of two positions of measuring electrical resistivity using SIERM technique.

RESULTS AND DISCUSSION

Damage Detection during Compression Loading by Using SIERM Technique

On measuring electrical resistivity using (SIERM) technique, the cubic specimens (100 x 100 x 100mm) are casted with different water to cement ratio (0.45, 0.5and 0.6) and tested at age 28 days . The results of both the (H-resistivity) and (V-resistivity) configurations until failure are presented in Figure6.

From figure (6), it can be seen that the electrical resistivity measurements of both the first configuration and the second are reduced during loading. Also, the reduction of electrical resistivity measurements for the first configuration is more than the reduction of electrical resistivity for the second configuration for the same specimen and water to cement ratio and at 28 days of age. The shown reduction of electrical resistivity that took place may be due to pore network conductivity which may have increased due to confinement stress. This may also be attributed to the pattern of failure which may have increased the conductivity where the probes are.

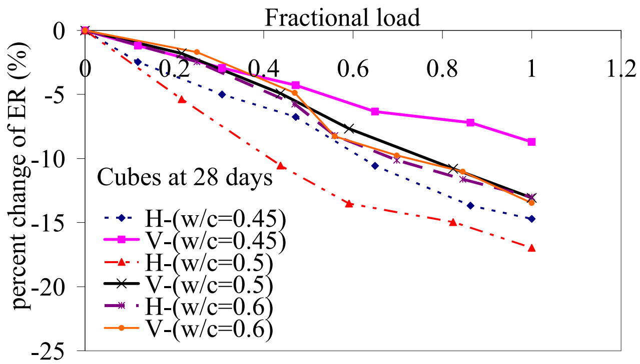


Figure 6. Relationship between percent of change of Electrical Resistivity (ER) (SIERM) and compression load up to failure at 28 days age.

For more analysis, the Decimal Logarithmic of Electrical Resistivity Anisotropy [DLRA (Log (H (resistivity)/V (resistivity))] is calculated for different water to cement ratio specimens at the age 28 days and presented in Figure (7). The (DLRA) measures the changing of anisotropy of electrical properties for the specimens. This means that, this parameter can be used to assess the cracks (widening of cracks). From Figures (7), it can be shown that the change of (DLRA) during compression loading is very small because the electrical resistivity for both configurations is reduced during loading. Consequently, the isotropy of CBC material does not change. In this case, the DLRA does not change although considerable damage exists. In other loading configurations, the change will be more obvious as shown in the next sections.

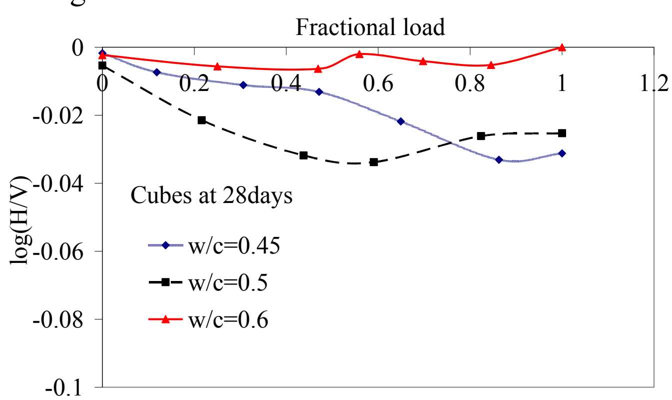


*Figure 7. Relationship between **DLRA (**log (H/V)) and compression load for different (w/c) specimens at 28 days age.*

Damage Detection during Splitting Tensile Loading by Using SIERM Technique

By measuring the electrical resistivity using (SIERM) technique for the cylindrical specimens (diameter = 75mm x 260mm) are cast with different water to cement ratios (0.45, 0.5and 0.6) and tested at 28 days age. The results of both configurations on measuring the electrical resistivity by using the (SIERM) technique against loading are presented in figure (8). From figure (8), it can be seen that the electrical resistivity of the first configuration is increased but for the second configuration, the reduction occurs during loading for the same specimen and water to cement ratio that is clear from the percent of change of electrical resistivity.

The increase in electrical resistivity for the first configuration took place due to crack appearance between the two current probes (and also between the two voltage probes). This caused the reduction in the conductivity. Also, the reduction of electrical resistivity for the second configuration is due to crack but it is not between the two current probes (parallel to current direction between two current probes) which caused the increasing in the conductivity [13].

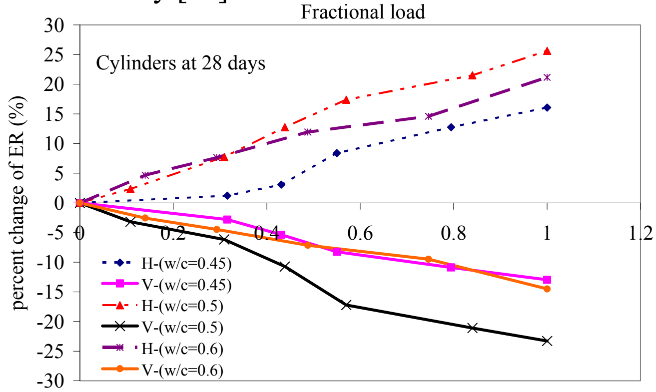


Figure 8. Relationship between percent of change of the Electrical Resistivity and Splitting tensile load up to failure after 28 days age.

Furthermore, the Decimal Logarithmic of Electrical Resistivity An isotropy (DLRA (Log (H/V)) is calculated for different water to cement ratio specimens at age (28 days) and presented in Figure (9). The (DLRA) measures the change in the anisotropy of electrical properties of a specimen. This means, it can be used to assess the cracks (widening of cracks). From Figure (9), it can be shown that, the (DLRA) increased during splitting tensile loading because the electrical resistivity for the first configuration is high but for the second is small. Also, the (DLRA) increased during splitting tensile loading due to increase in the crack widening [12].

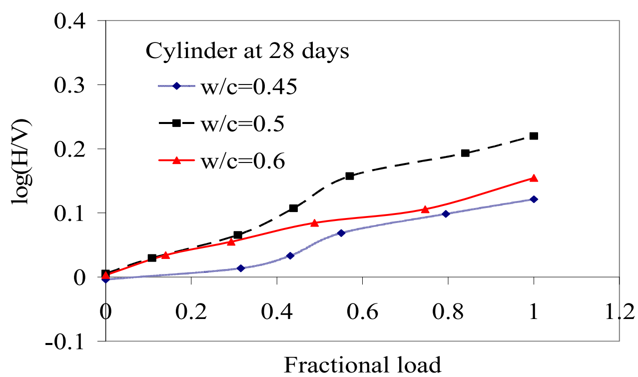


*Figure 9. Relationship between **DLRA** (log (H/V)) and splitting tensile load for different (w/c) specimens at 28days age.*

Damage Detection during Flexural Loading by Using SIERM Technique

In first configuration, the current and voltage were measured horizontal (perpendicular to loading direction (H-resistivity)) and In the Second one, the current and voltage were measured vertical (parallel to loading direction(V-resistivity)). The results of both configurations for measuring electrical resistivity by using (SIERM) technique for sensor at center and at 80 mm from away center against the load until failure after 28 days are presented in Figures (10a & b) respectively.

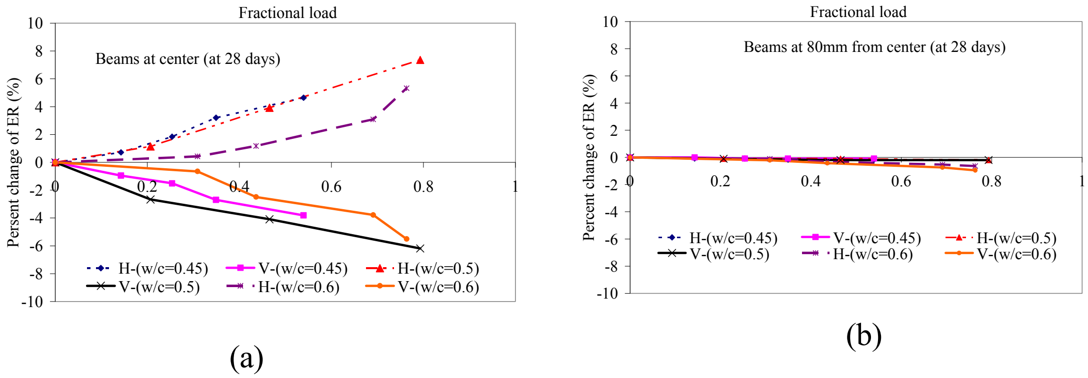


Figure 10. Relationship between percent of change of the Electrical Resistivity and flexural load after 28 days age. a). for the first sensor (at center) after 28 days. b). for the second sensor (at 80 mm from center) at 28 days.

From figure (10a) it can be seen that the electrical resistivity of the first sensor (at center) for the first configuration is increased, but for the second configuration is reduced during loading for the same specimen and water to cement ratio at 28 days. This is clear from the percent change of electrical resistivity.

The increase of electrical resistivity for the first configuration took place due to the crack between the two current probes (and also between the two voltage probes). This caused the reduction in the conductivity and also the reduction of electrical resistivity for the second configuration due to crack presence.

From Figure (10b), it can be seen that the electrical resistivity of the second sensor (at 80mm from center) for both the first configuration and the second configuration show very small reduction during loading for the same specimen and water to cement ratio and at 28 days. This is clear from the percent of change of the electrical resistivity. The small reduction of electrical resistivity that took place may be due to pore network conductivity which increased due to confinement stress.

The (DLRA) measures the changing of anisotropy of electrical properties for specimen. That means, it can be used to assess the cracks (widening of cracks). For more analysis, the decimal logarithmic of electrical resistivity an isotropy (DLRA (Log (H/V)) is calculated for different water cement ratio specimens at age 28 days and presented in figure (11).

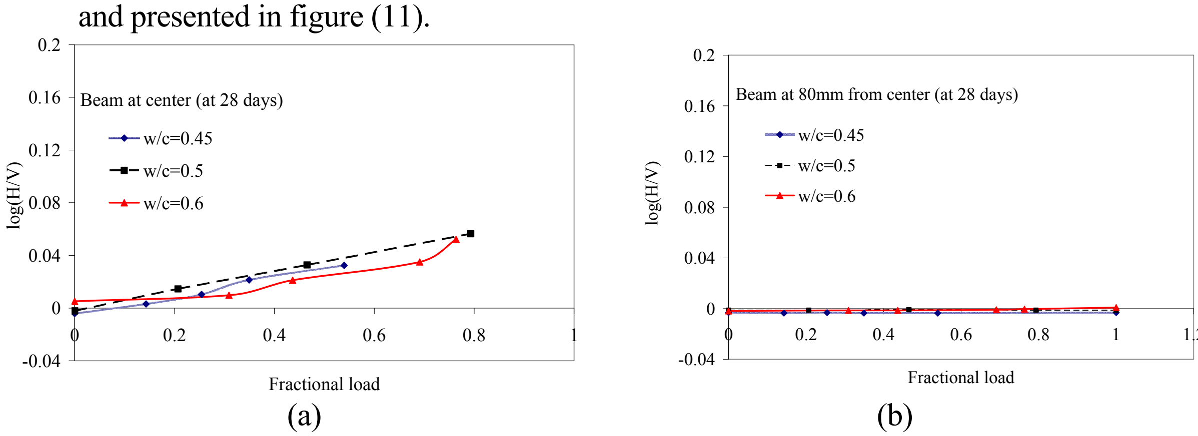


Figure 11. Relationship between DLRA (log (H/V)) and flexural load for specimens with different (w/c) at 28 days age: a). For first sensor (at center). b). For second sensor (at 80mm from center).

From Figure (11a), it can be shown that the DLRA is increased during flexural loading because the electrical resistivity for the first configuration is high but for the second is small. Also the (DLRA) is increased during flexural loading due to increase of the crack widening at middle of span. From figure (11b), it can be shown that the change of (DLRA) during flexural loading is very small and also the reduction of electrical resistivity for both configurations is very small for that the (DLRA) is almost constant. Furthermore there are no cracks appear at 80 mm from center.

CONCLUSIONS

The Inner electrical resistivity measurement was sensitive to damages during loading. The measurements give good indication of crack initiation and propagation during loading. The advantage of this measurement type is the fact that it can help us to get information of structures without the need to do traditional assessment method. It means structure health mentoring.

Despite the Decimal Logarithmic Resistivity Anisotropy (DLRA) is not affected during the increase compression damage (loading) but the electrical resistivity is strongly affected and it is reduced. The (DLRA) is affected during split tensile damage (measured as loading) because the anisotropy of electrical properties increased due to cracks. Also, the (DLRA) is highly affected during flexural damage (loading) for the sensor at middle of span due to crack whereas it is not affected in the other sensor at 80mm from middle of span due to no crack initiation.

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