Effect of Carbon Fiber and Graphite Powder on Resistivity of Cement-based Sensor under Compression

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Abstract
Structural health monitoring currently becomes an important part in the maintenance of concrete structures. Thus, using of sensors to monitor the structural behavior is necessary. Cement-based sensors have been developed recently to be embeddable in structures and to be implemented by measuring the change in their resistivity. In this research, the electrical resistivity and compressive strength of the cement-based sensors with the addition of carbon fiber (2% and 4% by volume fraction) and graphite powder (2%, 4%, and 10% by weight of cement) were studied. Three water to binder ratios (w/b) that are 0.3, 0.4 and 0.5 were varied. For 28 days after demolding, the resistivity of the non-load-bearing sensors was monitored to determine the influence of their maturity. At the age of 28 days, their compressive strength was evaluated. Subsequently, the fractional change in resistivity (FCR) of the sensors was measured under a set of compressive loading, which comprised of three cycles of loading; first loading to the strain of 0.0025, then to 0.005 and 0.01. From the test results, it is showed that the carbon fiber was more favorable than the graphite powder. Although the addition of graphite powder could reduce the resistivity, it dropped the compressive strength and highly fluctuated the resistivity results of the cement-based sensors. In term of the piezoresistivity, all of the sensors when loaded provided good responses only when the compressive strain was less than 0.005.

***Keywords**: Cement-based Sensor, Carbon Fiber, Graphite Powder, Piezoresistivity*

1 Introduction

Concrete structures in service carry a variety of loads. Sometimes, the loads carried exceed the designed capacity. Besides, concrete structures always suffer from severe environmental threats. Such conditions impair the structural health and shorten the service life of the structures. A monitoring of the rate and level of the concrete structure deterioration is thus of essential.

Recently, to continuously monitor structural health, various sensors such as strain gages installed in structures have been employed. Based on the concept of piezoresistivity, the electrical resistivity of the gage is increased as a tensile strain at a point where it is placed is increased, and vice versa. Thus, by the change in electrical resistivity, the gages can determine the state of strains and assess the deterioration of structures. However, as most gages are made of metals and requires adhesive for bonding to concrete, they corrode with times and debond very quickly when exposed to severe environment. Additionally, they are relatively expensive and incompatible with concrete [1].

A potential alternative to strain gages is a cement-based sensor primarily made of cementitious matrices reinforced with electrically conductive materials, e.g. cement pastes with carbon fiber [2]. Using of cement-based matrices enhances the sensor in several aspects [3], i.e. providing a good bond to concrete structures, allowing the sensor to be put inside concrete, and solving the strain incompatibility problem. Moreover, it is also economical.

Yet carbon fiber cement-based sensors have some drawbacks. For example, to mix carbon fibers uniformly in a cement paste is difficult. Also, the mostly used chopped carbon fibers often lack of continuity. Those problems result in high variation of outcome. Using graphite powder which is conductive and more easily to be distributed evenly in cementitious matrices may alleviate those obstacles.

Therefore, in this research, the resistivity of cement-based sensors made of carbon fibers at 2% and 4% by volume fraction, graphite powder at 2%, 4%, and 10% by weight of cement, and plain cement paste (as a control mix) was investigated. Not only the effect of additives, the influence of aging, water to cement ratio, and compressive stresses on their resistivity was also evaluated.

2 Theoretical Background

2.1 *Piezoresistivity*

Most strain gages possess a special characteristic namely piezoresistivity-an electrical resistivity of a piezoresistive material is variable and mechanical strain dependent. The piezoresistivity is the most common sensing principle used in sensors and was applied to the cement-based sensors studied herein.

Typically, an electrical resistivity of a matter depends on positions and movement of atoms inside. When the matter is stressed, the strain is occurred causing the change of atoms' position. The resistivity is thus altered as a consequence. Such correlated manner is reversible. Therefore, by monitoring a change in resistivity, strains in structural elements can be determined.

Cement paste also is piezoresistive and is used as the main component of a cement-based sensor. It normally has resistivity so high that its sensitivity is low. Nonetheless, its resistivity can be reduced by adding conductive constituents such as carbon fibers and graphite powder.

2.2 *Resistivity*

A property that determines a geometry-independent electrical resistance of a matter is called resistivity (ρ). It mainly depends on the type and microstructure of materials. Therefore, in composites like cementitious materials, ingredients and proportion become of highly influential on resistivity. Also, it is affected by environmental factors such as temperature and relative humidity.

The resistivity, which is a resistance of the flow of electrical current through a given area within a given unit distance, of a material can be determined with the equation (1) as follows,

$$\rho = R\frac{A}{l} \tag{1}$$

where ρ is resistivity (Ω-m),
R is resistance (Ω),
A is cross sectional area (m^2),
l is length between points measured (m).

2.3 *Fractional change in resistivity, FCR*

Based on the concept of piezoresistivity, strain taken place in a sensor following the deformation of structures can be computed from a fractional change in resistivity (*FCR*) as shown in equation (2),

$$FCR = \frac{\rho_t - \rho_0}{\rho_0} = \frac{\Delta\rho}{\rho_0} \tag{2}$$

where FCR is fractional change in resistivity,
ρ_t is resistivity at time t,
ρ_0 is initial resistivity,
$\Delta\rho$ is change in resistivity.

2.4 *Gage factor, GF*

Effectiveness of a sensor can be determined from a value of gage factor (*GF*), which is a ratio of a fractional change in resistivity (*FCR*) to strain (ε) occurred as in equation (3),

$$GF = \frac{\Delta\rho / \rho_0}{\varepsilon} = \frac{FCR}{\varepsilon} \tag{3}$$

3 Experimental

3.1 *Preparation of cement-based sensors*

Cement-based sensors investigated in this study were made of cement pastes as a main matrix. The pastes were prepared from portland cement type I blended with silica fume 15% by wt. of cement and from water at the water to binder ratio (w/b) of 0.3, 0.4, and 0.5. To reduce resistivity, the sensors were modified with the addition of chopped carbon fibers (length of 3 mm) at 2% and 4% by volume fraction and graphite powder at 2%, 4%, and 10% by wt. of cement. The summary of mix proportions aforementioned was tabulated in Table 1. The properties of the carbon fiber and graphite powder were shown in Table 2 and 3, respectively. In addition, the flow of all mixes was controlled by adding type F superplasticizer. The cement-based sensors were molded to a cubical shape with a dimension of 5×5×4.7 mm^3. Each of them contains four pieces of copper, each of which is 10-mm wide, 70 mm long, and 0.03 mm thick, embedded in the center and aligned at a 10-mm apart as shown in Figure 1. An identical cube specimen without the copper plates was also formed to determine the compressive strength. Three replicates were prepared for each of the tests described in the next section.

After mixing all ingredients as proportionate in Table 1 with a mortar mixer, the pastes were poured in the cubical molds defined above and were consolidated with a vibrating table. The molds were covered with plastic sheets to prevent moisture loss for 24 hours. Subsequently, the plastic covered sensors were cured in a chamber at the temperature of 30°C until the time of testing.

Table 1: Mix proportions and designations used in the study

Name	Matrix	CF[a]	GP[b]	SF[c]
CON	Cement Paste[d]	-	-	15
CF2%		2	-	15
CF4%		4	-	15
GP2%		-	2	15
GP4%		-	4	15
GP10%		-	10	15

[a] CF = Carbon Fiber (% by volume)
[b] GP = Graphite Powder (% by weight of cement)
[c] SF = Silica Fume (%by weight of cement)
[d] Cement Paste with w/b = 0.3, 0.4, and 0.5

Table 2: Properties of Carbon Fiber

Item/Type	Chopped carbon fiber
Tensile Strength (MPa)	51.9
Breaking Strength (MPa)	4.9
Splitting Modulus of Elasticity in Compression (GPa)	40.5
Anti-permeability (1.2MP in filter Height) (mm)	39.0
Contractibility Rate (×10^{-6})$^{10^{-6}}$	350
Impact Resistance (times)	58

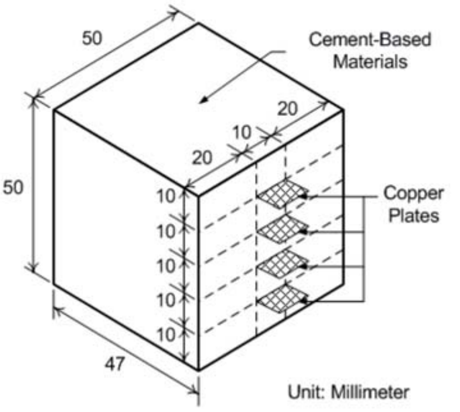

Figure 1: Sample of the cement-based sensor.

Table 3: Properties of Graphite Powder

Item/Type	Chopped carbon fiber
Atomic Number	6
Molecular Weight (g/mol.)	12.01
Apparent Density (g/cm^3)	2.0-2.25
RTECS Number	FF5250100
Melting Point (°C)	~3650°C
Boiling Point (°C) (Sublimes)	4200°C
Surface Area (m^3/g)	7.2
Thermal Conductivity @230°C (cal/s-cm-°C)	0.38
IMIS Code	1366

3.2 *Testing Methods*

The testing program was divided into two phases, i.e. 1) the testing of the sensors in normal condition (the state of no strain) at the age of the sensors of 3, 7,14, and 28 days and 2) the testing of the sensors under compressive stresses (the range of compressive strain was no more than 0.01) at the age of 28 days.

In both phases, the resistivity of the sensors was measured by using a LCR meter (Agilent 4263B). The four copper plates in the sensors were connected to the probes of the meter. The measurement was carried out following a four probe method as shown in Figure 2. The sensor received a DC electrical current (frequency of 100 kHz) via the two outer terminals while the potential was monitored from the two inner terminals. Based on the Ohm's law, the resistance of the sensor can be obtained from the proportion between the measured potential and the applied current.

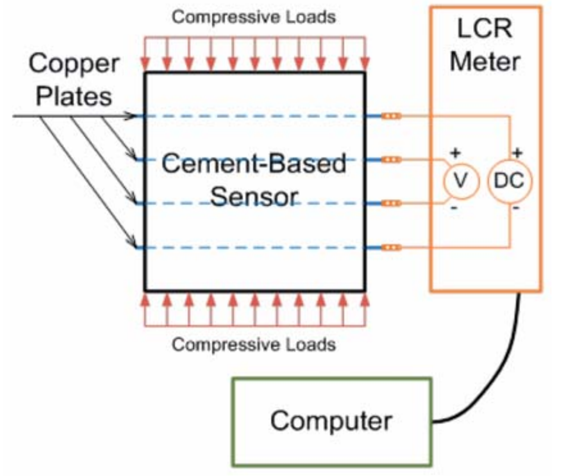

Figure 2: Schematic diagram of the connection between the sensor and the LCR meter following the four probe method.

Before the second phase testing was begun, the ultimate compressive strength of the sensors (specimens without copper plates) was determined at the age of 28 days using a universal testing machine (Instron FastTrack Testing System, Series 8800).

Since the good characteristic of sensors is to response quickly and clearly to the strain, the cement-based sensors were tested under compression in the second phase. The efficiency was determined from how they react to the strain in the term of resistance. The measurement was taken at every 1 second while the compression was displacement controlled at the rate of 0.15 mm/min. During the test, the sensors were loaded to a given strain (i.e. 0.0025 in the first round, 0.005 in the second round, and 0.01 in the final round) and then unloaded prior to start the next round. Moreover, at each round, the test was repeated three times.

4 Results and Discussion

4.1 *Resistivity of cement-based sensors at the age of 3, 7, 14, and 28 days*

Test results on the resistivity of the sensors at the age of 3, 7, 14, and 28 days were presented in Figure 3. It was clearly showed that the resistivity increases with the age of the sensors. Since the hydration process was progressed, the pore water was decreased and the dense hydration products were increased exponentially

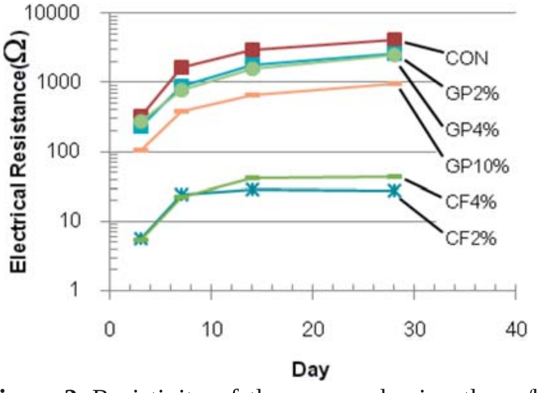

Figure 3: Resistivity of the sensors having the w/b ratio of 0.3.

within the age of 28 days. As a result, the resistivity was raised significantly at the initial period and then steady after 28 days.

Moreover, it was noticed that the carbon fiber and graphite powder cement-based sensors have lower resistance than the plain cement paste. At the age of 28 days, the resistance of the plain cement paste was dropped from 5000 ohm to 1000-2000 ohm in graphite powder sensors and 10-30 ohm in carbon fiber sensors due to the remarkable electrical conductivity of both graphite powder and carbon fiber.

When comparing the sensors containing 2% and 4% carbon fibers, it was found that the resistivity of both sensors are fairly similar. Although the conductivity is typically increased with the amount of carbon fiber added, this correlation may be no longer exist when the carbon fiber exceeds a certain amount due to the percolation effect [4].

4.2 *Influence of w/b ratio on resistivity of cement-based sensors*

Porosity and pore solution in cement pastes have influenced directly on the variation of electrical resistance [5]. Pore solution adsorbed inside highly porous pastes can cause the reduction of resistance. Therefore, the higher the w/b ratio, the lower the resistance of all cement-based sensors as can be seen in Figure 4, 5 and 6 for the plain cement paste, the graphite powder, and the carbon fiber sensors, respectively.

When the w/b ratio is 0.3, the hydration during the first 28 days had a significant effect on the resistance. In the same manner but very less extent, the 0.4 and 0.5 w/b ratio sensors were also affected.

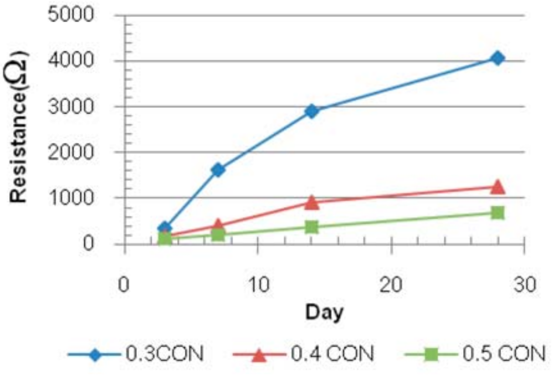

Figure 4: Resistivity of the sensors made of plain cement paste having the w/b ratio of 0.3, 0.4, and 0.5.

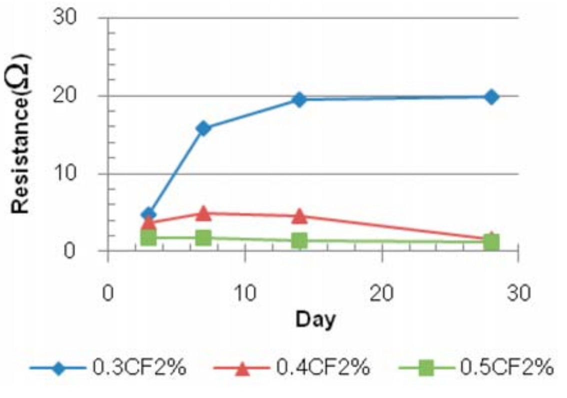

Figure 5: Resistivity of the sensors made of 2% carbon fiber cement paste having the w/b ratio of 0.3, 0.4, and 0.5.

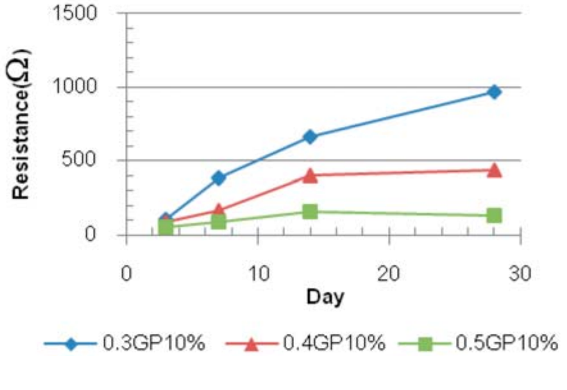

Figure 6: Resistivity of the sensors made of 10% graphite powder cement paste having the w/b ratio of 0.3, 0.4, and 0.5.

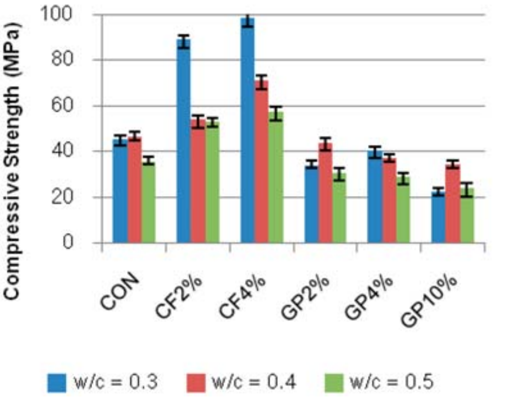

Figure 7: Compressive strength of the sensors made of different mixes.

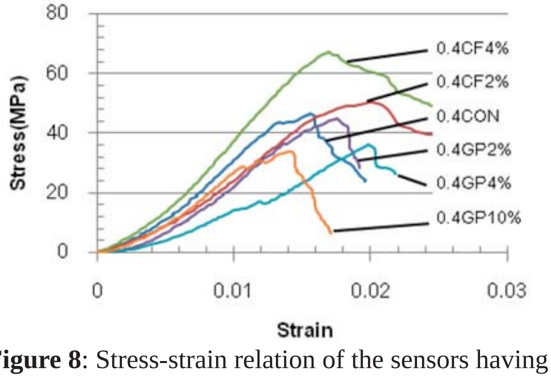

Figure 8: Stress-strain relation of the sensors having the w/b ratio of 0.4 under compression test.

It was probably because of the great amount of free water presented in pores. Although the free water is decreasing as evaporated and consumed in hydration, it occurs very slowly. That causes the variation of the resistance relatively low during the age of 28 days.

4.3 *Compressive strength*

From the compression test on the cube specimens identical to the cement-based sensors but have no copper plates, the compressive strength results of all mixes were plotted as shown in Figure 7 and the stress-strain curves of the 0.4 w/b ratio sensors were depicted as shown in Figure 8. It was found that the 0.5 w/b ratio sensors had the lowest compressive strength as they held lots of free water, which later turned to capillary pores.

The addition of graphite powder resulted in the decrease of compressive strength. The glossy surfaces and weak bond of graphite particles could

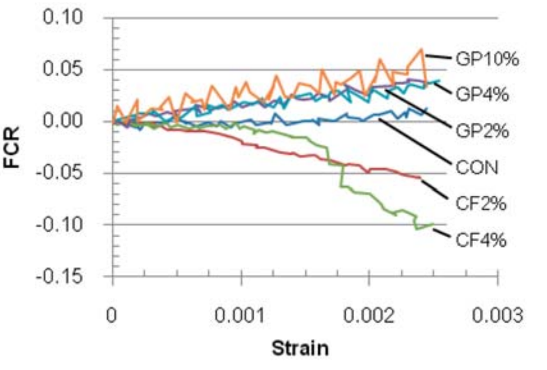

Figure 9: Relation of the FCR of the sensors (w/b ratio = 0.3) and compressive strain in the range of 0.0025.

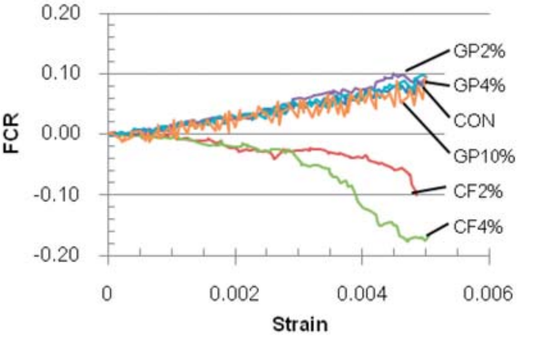

Figure 10: Relation of the FCR of the sensors (w/b ratio = 0.3) and compressive strain in the range of 0.005.

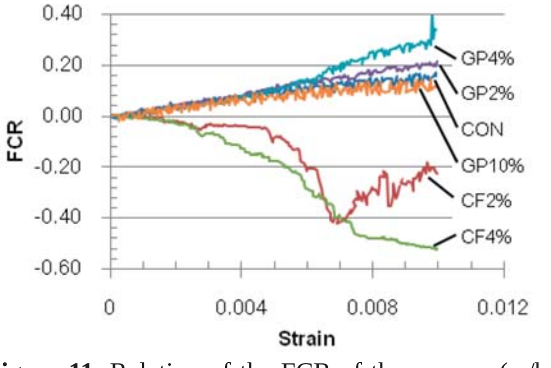

Figure 11: Relation of the FCR of the sensors (w/b ratio = 0.3) and compressive strain in the range of 0.01.

be a reason of strength drop [6]. However, the carbon fiber improves compressive strength as its benefit on mechanical properties is generally known [7]. Moreover, the above mentioned influences of water, graphite powder, and carbon fiber on the compressive strength were directly proportionate to the amount added.

4.4 *Fractional change in resistivity of cement-based sensors under compression*

The electrical resistance results of the sensors (w/b ratio of 0.3) when subjected to compression until the strain reached 0.0025 in the first round, 0.005 in the second, and 0.01 in the final round, were analyzed and converted to the fractional change in resistivity *FCR* as demonstrated in Figure 9, 10, and 11, respectively. From those Figures, it was observed that the *FCR* of plain cement paste and graphite powder sensors descended with compressive strains in contrast to that of carbon fiber sensors.

Having the *FCR* decreased when the compressive strain was increased, the carbon fiber sensors exhibited the piezoresistive characteristic. It was a consequence of the paste contraction in which the distributed fibers had concurrently touched each others. The resistivity was thus decreased. The more the volume of carbon fiber, the higher the chance of fiber touching and the higher the rate of *FCR* drop.

As noticed in the section 4.2, the pore solution highly influences the electrical resistance of the cement-based sensors. When the sensors were compressed, it is conceivable that the pores were contracted, the pore network was discontinued, and the water-filled pores were emptied. All those conditions led to the increase of the *FCR* in the plain cement paste sensors. Likewise the graphite powder sensors increased the *FCR* with compressive strain. It is however noted that the effect was insignificant.

Among all the cement-based sensors tested at three ranges of compressive strain (i.e. 0.0025, 0.005, and 0.01), it is found that the response of the 2% carbon fiber sensor within the 0.0025 strain was the best. When the strain was below 0.0025, it responded linearly with a gage factor of 20. In contrast, the other sensors had highly nonlinear responses and highly fluctuated signals.

5 Conclusions

Based on the experimental results in this research, the influence of carbon fiber and graphite powder on the resistivity of cement-based sensors with the w/b ratio of 0.3, 0.4, and 0.5, with the age of 3, 7, 14, and 28 days, and with the compression test to the compressive strain of 0.01 can be summarized as follows.

The resistivity was increased with the age of the sensors. It had vast impact when the sensors had low w/b ratio of 0.3. Contrary to that, the effect was much less for the sensors with high w/b ratio like 0.4 and 0.5. They had low resistivity initially and had lots of free water available. Their variation of the resistivity was thus relatively little during the early age of 28 days.

Using either carbon fiber or graphite powder can reduce the resistivity in cement-based sensors. For the strength point of view, they responded differently. The carbon fiber increased the compressive strength but the graphite powder decreased.

Among all the mixes investigated here, the 2% carbon fiber cement-based sensor provided the best response in association with the principle of piezoresistivity. It had a linear relationship between the *FCR* and compressive strain up to 0.0025 and yielded the gage factor of about 20.

Acknowledgments

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References

[1] D. Huston, *Structural Sensing, Health Monitoring and Performance Evaluation*, United States of America: CRC Press (Taylor & Francis Group). 2011.

[2] D.D.L. Chung, "Cement Reinforced with Short Carbon Fibers: A Multifunctional Material," *Compos. Part B-Eng*, vol. 31, pp. 511-26, 2000.

[3] F. Azhari and N. Banthia, "Structural Health Monitoring using Piezoresistive Cementitious Composites," 2nd International Conference on Sustainable Construction Materials and Technologies, Università Politecnica delle Marche, Ancona, Italy, June 28-30, 2010.

[4] P. Xie, P. Gu, and J.J. Beaudoin, "Electrical Percolation Phenomena in Cement Composites Containing Conductive Fibres," *J.Mater.Sci*., vol. 31(15), pp. 4093-7. 1996.

[5] M. C. Andrade, F. Bolzoni, and J. Fullea, "Analysis of the Relation between Water and Resistivity Isotherms in Concrete," *Materials and Corrosion*, vol. 62(2), pp. 130-8, 2011.

[6] T. Nishikawa, M. Takatsu, and M. Daimon, "Fracture-Behavior of Hardened Cement Paste Incorporating Mineral Additions," *Cement and Concrete Research*, vol. 25(6), pp. 1218-24, 1995.

[7] W.J. McCarter, G. Starrs, T.M. Chrisp, and P.F.G. Banfill, "Activation Energy and Conduction in Carbon Fibre Reinforced Cement Matrices," *J.Mater.Sci*., vol. 42(6), pp.2200-3, 2007.