EFECTUL PIEZOREZISTIV AL BETONULUI CU NANOFIBRE DE CARBON EXPUS LA DIFERITE CONDIȚII DE MEDIU
PIEZORESISTIVE EFFECT OF CARBON NANOFIBER CONCRETE EXPOSED TO DIFFERENT ENVIRONMENTAL CONDITIONS

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The addition of well-dispersed carbon nanofiber (CNF) can improve the mechanical and electrical property of concrete and the produced concrete (CNFC) shows a good piezoresistive effect, which is very useful for structural health monitoring. In order to confirm the feasibility of long-term application in real structures, the piezoresistive effects of CNFC samples were measured before and after different environment exposure test including freezing and thawing cycles, chloride penetration and drying under different relative humidity conditions. The results show that the electrical property of CNFC did not change obviously after 200 cycles of freezing and thawing, the resistivity of CNFC was increased by the addition of chloride during the mixing process possibly due to the accelerated cement hydration, and the resistivity of CNFC was increased and the polarization time was decreased with the decreasing relative humidity of exposure surroundings. However, the same or similar piezoresistive effects were found for all the concrete samples before and after different exposure treatment. Therefore, it is suggested that such CNFC can be used for the long-term monitoring of real structures.

Keywords: *carbon nanofiber, piezoresistive effect, structural health monitoring, different environment exposure*

1. Introduction

Concrete is the most widely used construction material and has experienced the developing stages of normal strength concrete, high strength concrete and high performance concrete. On the other hand, carbon fibers have many advantageous mechanical and electrical properties such as high strength, high conductivity and are attractive for producing fiber-reinforced concrete. Chen and Chung [1] pointed out that, by using short carbon fiber together with chemical admixtures, the compressive and flexural strength of concrete were found to increase evidently and the electrical resistivity decreased by up to 83%. In Chen and Chung's research [1–3], carbon fiber reinforced cement composites were found to be a new class of strain sensor based on the concept of short electrically conducting fiber pull-out that accompanies slight and reversible crack opening. The electrical conductivity of the fibers enables the DC electrical resistivity of the composites to change in response to strain, thereby allowing piezoresistive sensing [4-7]. Due to their nanosize, concrete with nanoparticles is superior to normal concrete. Several studies showed that the addition of small amount of carbon nanotube (CNT) has significant improvement on the mechanical and electrical properties of cement-based composites [8-10].

CNT and carbon nanofibers (CNF) are very similar. CNF consist of grapheme layers arranged as stacks of cones, cups or plates to create a cylindrical nanostructure. CNT consist of grapheme layers wrapped into perfect cylinders. CNF are easier to construct than CNT and the former is much cheaper than the latter. It was reported that concrete with carbon nanofibers (CNF) exhibited suitable properties necessary for strain monitoring and electromagnetic interference (EMI) shielding [11-17]. And based on experiments of reinforced concrete (RC) columns under a reversed cyclic loading, it is found that the CNF concrete can be developed as a real-time health monitoring system for the structure's overall integrity [18]. For potential applications in real structures, it is very important to fully understand the sensing ability of CNF concrete under different service conditions. For cement-based materials with carbon fibers and carbon nanotubes, it is reported that the piezoresistive response is dependent on loading rate [19-20]. There is little literature about the influences of

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environmental conditions on the sensing performances of CNF concretes. In this paper, the piezoresistive effects of CNF concretes were tested before and after different environment exposure test including freezing and thawing cycles, chloride penetration and drying under different relative humidity conditions.

2. Experimental

2.1 Raw materials

PR-19-XT-LHT-OX carbon fibers produced by Pyrograf Products company were used in this study. The cement used is ordinary Portland cement with the strength grade of 42.5 according to Chinese standard GB 175-2007[21]. A Class II fly ash was used with a water requirement ratio of 97% according to Chinese Standard GB1596-2005[22]. Crushed granite gravel was used as coarse aggregate, which had a maximum particle diameter of 25-mm and crushed index of 4.8%. River sand was used as fine aggregate with a fineness modulus of 2.82. A commercially available, polycarboxylate-based, high-range water-reducing agent (SP) was used to improve the workability of fresh concrete. Two series of concrete were designed to represent two strength grades (C40 and C60) as shown in Table 1.

2.2 Test method

The four electrodes submerged prism samples were prepared for each concrete mixture. The size of the prism was 100×100×300mm. The electrode were made from stainless steel mesh as shown in Figure 1 and Figure 2. Before the pouring of concrete samples, four stainless steel mesh electrodes were installed stably to the moulds to ensure the correct position of electrodes in samples. The opening of steel mesh is large enough for fresh concrete flowing freely from one side to another side to guarantee the continuity and homogeneity of hardened concrete prisms. The piezoresistive effect test was conducted as described in Ref [17].

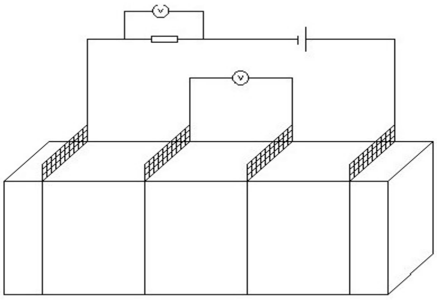


Fig.1 - Four electrode diagram.

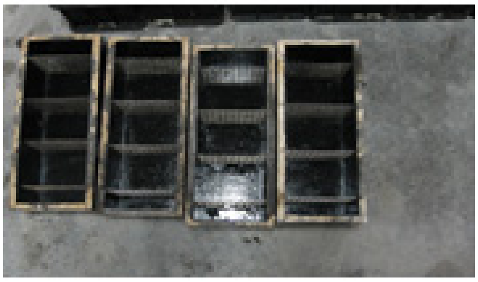


Fig.2 - The mould for four electrode specimen.

2.3 Environmental conditions

Three different relative humanity (32.8%, 52.9%, 75.3%) conditions were built by three sealed vessels containing individual saturated solutions of $MgCl_2$, $Mg(NO_3)_2$ and NaCl respectively and the temperature was kept at

Table1

Concrete mixing proportion

Weight Denotations	Cement kg/m^3	Water kg/m^3	Fly ash kg/m^3	Sand kg/m^3	Pebble kg/m^3	CNF kg/m^3	Water-Reducing Admixture
C40	424	190.8	106	789.2	889.9	0	0.8%
CNFC40-8	424	190.8	106	789.2	889.9	2.867	1.24%
CNFC40-10	424	190.8	106	789.2	889.9	3.553	1.70%
CNFC40-12	424	190.8	106	789.2	889.9	4.267	2.07%
CNFC40-15	424	190.8	106	789.2	889.9	5.333	2.61%
CNFC40-18	424	190.8	106	789.2	889.9	6.400	3.43%
C60	480	186	120	781.2	882.8	0	0.8%
CNFC60-8	480	186	120	781.2	882.8	3.216	1.8%
CNFC60-10	480	186	120	781.2	882.8	4.020	1.93%
CNFC60-12	480	186	120	781.2	882.8	4.824	2.04%
CNFC60-15	480	186	120	781.2	882.8	6.03	2.83%

22±1℃. Before the specimens were taken out to test their pressure sensitive, the mass, the resistance and the polarization time of the CNFC were measured once every four days until the variations of the three were negligible. The freezing and thawing condition was set up based on the test method for rapid freezing and thawing in accordance to Chinese Standard GB/T 50082-2009 [23]. The polarization time and resistivity response to strain of the CNF concrete specimens were measured after different days of drying or different freezing and thawing cycles. In this test, the polarization time was determined when the resistance variation rate with time drops to less than 0.1% per second for every specimen.

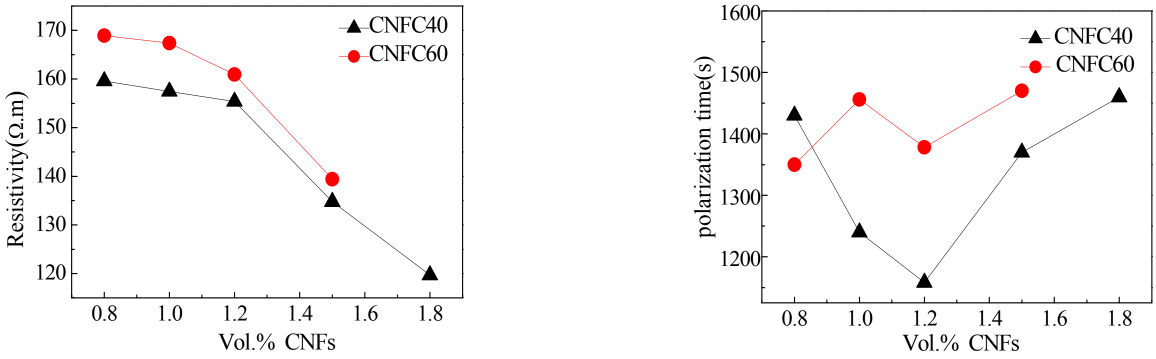
To study the influence of chloride ions, NaCl was added at different mass percentages of binder during mixing fresh concrete and the conductivity and piezoresistive of samples at 28 days age were tested.

3. Results and discussion

3.1 The conductivity and piezoresistive effect after standard curing

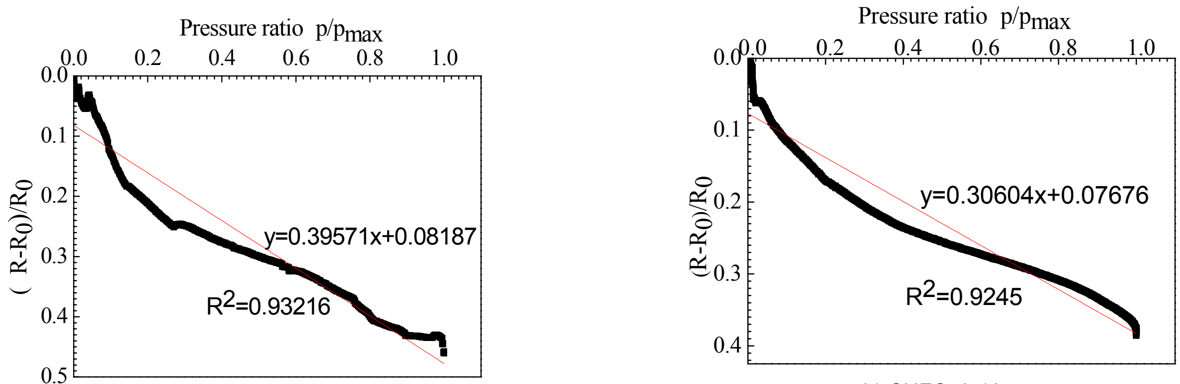
Figure 3 shows the conductivity and polarization time of CNF concrete specimens with various carbon fiber volume fractions at 28 days of standard curing. The electrical resistivity of CNFC decreased significantly with increasing fiber content and the polarization time fluctuates with fiber content.

Figure 4 shows the fractional change in resistance during compressive loading of the CNF concrete specimen admixed with different fiber content at progressively increasing strain amplitude up to the elastic limit.

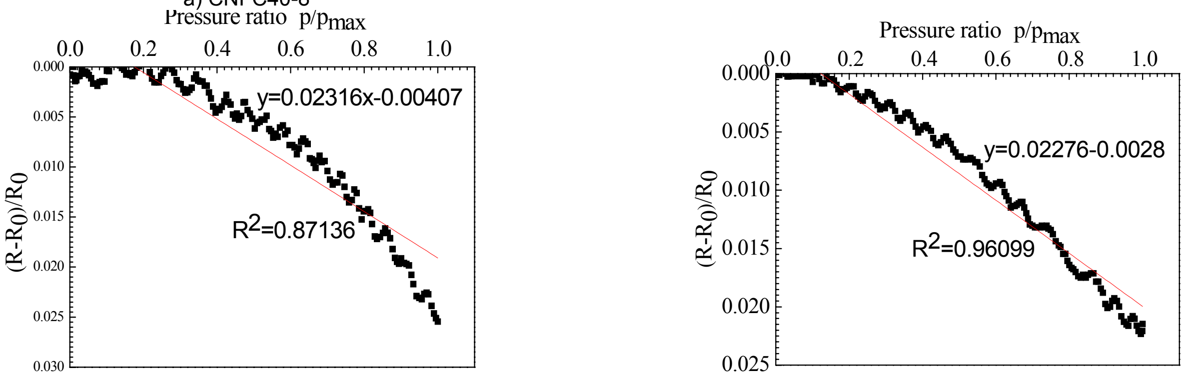


a)The specific resistance b) The polarization time

Fig.3 - The specific resistance and polarization time of CNFC.

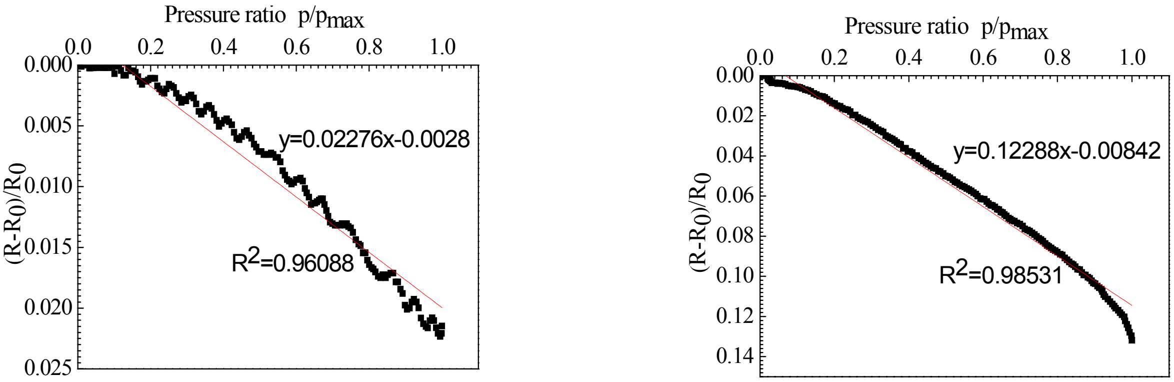


a) CNFC40-8 b) CNFC40-10



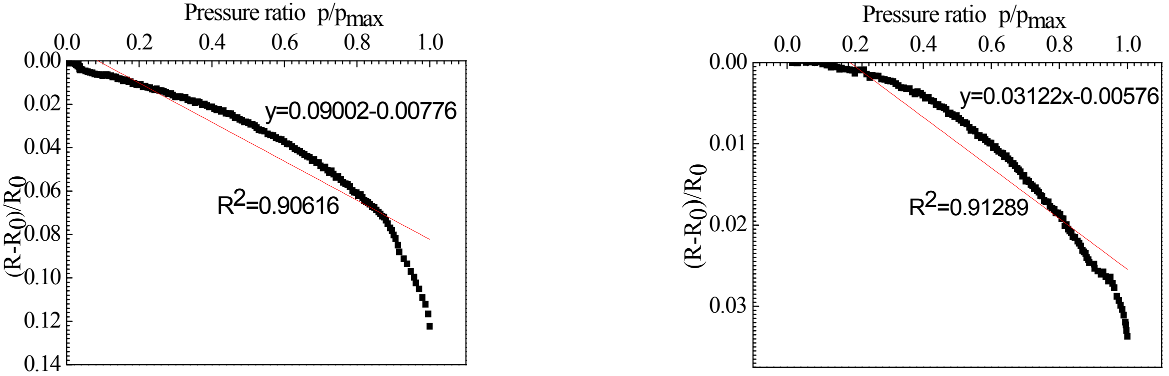
c) CNFC40-12 d) CNFC40-15

Fig. 4 continues on next page



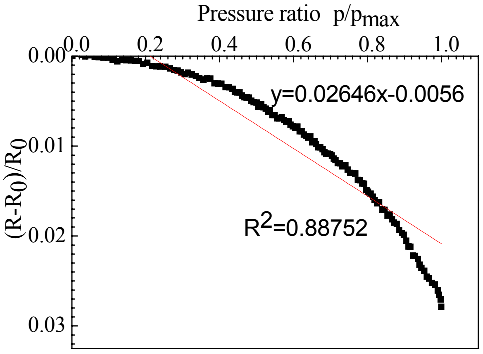
e) CNFC40-18

f) CNFC60-8



g) CNFC60-10

h) CNFC60-12



i) CNFC60-15

Fig.4 -The piezoresistivity of different CNF concretes.

For both the concrete CNFC40 and CNFC60 samples, the electrical resistance variation increases linearly with the increasing compression load ratio. The maximum fractional variation in resistance decreases as the fiber content increases. The maximum fractional variation in resistance of CNFC40 are 0.5, 0.4, 0.03, 0.025, 0.025, responding to the content of CNF in the CNFC40 are 0.8%, 1.0%, 1.2%, 1.5%, 1.8% respectively. The maximum fractional variation in resistance of CNFC60 are 0.14, 0.14, 0.03, 0.03, as the content of CNF in the CNFC40 are 0.8%, 1.0%, 1.2%, 1.5%, respectively. The maximum fractional variation in resistance of CNFC40 is larger (by 72%) than that of CNFC60 in the presence of 0.8% fibers.

3.2 Influences of relative humidity

Figure 5 and Figure 6 show the conductivity and the piezoresistive effect of the CNF concrete specimens after exposure to different relative humidity(RH) for 28 days. It can be found that the. resistivity of two strength grade concretes increases with the lower relative humidity of exposure environment, being attributable to the more moisture loss under the severer drying condition. On the other hand, the polarization time is decreased by the lower relative humidity.

For all the concrete CNFC40-8 samples, the electrical resistance variation increases linearly with the increasing compression load ratio. There is little difference among these samples. Therefore, the relative humility of exposure environment has little effect on piezoresistive performance of CNF concrete as shown as the results of the test in this study. In other words, the CNF concrete can be potentially applied to structures under different climates for long-term self-monitoring.

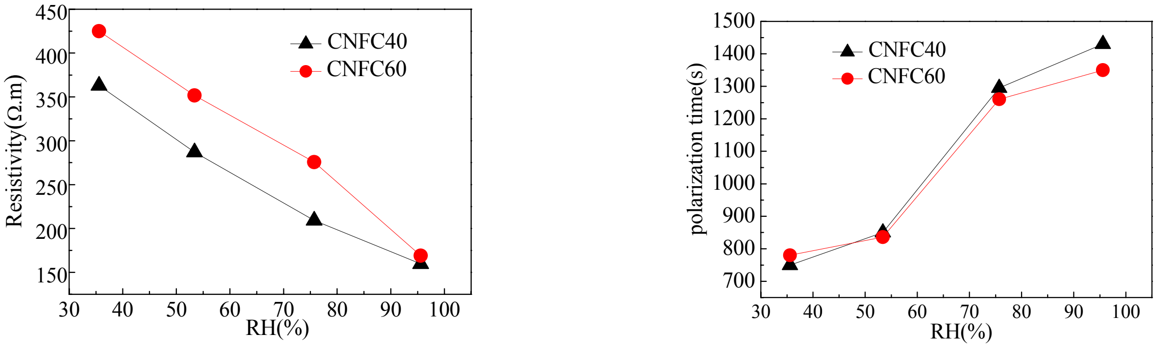
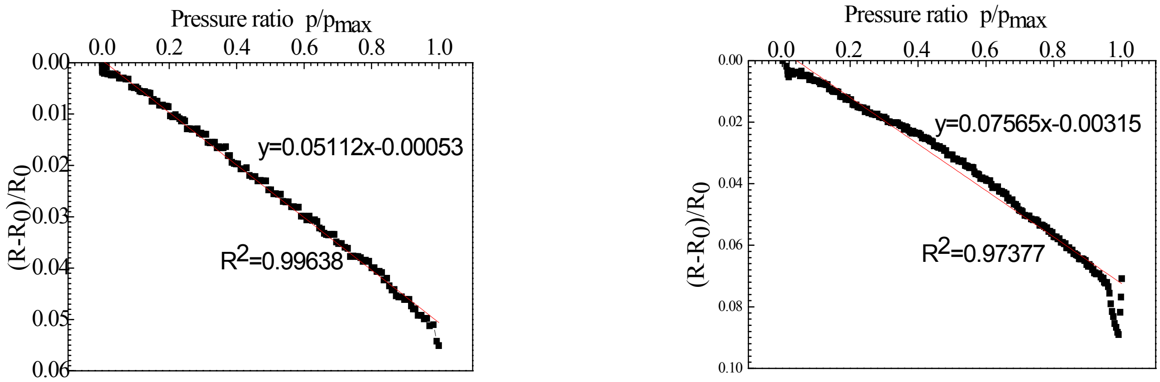
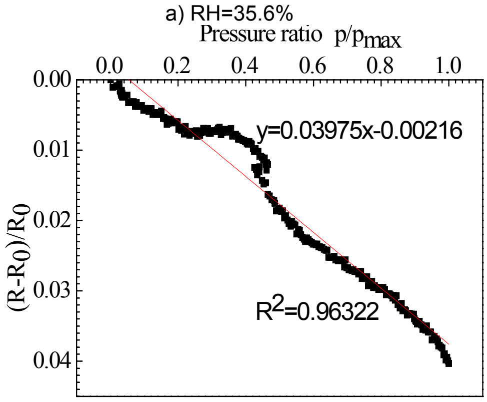


Fig.5 - The conductivity and polarization time of CNFC under different RH.



a) RH=35.6%

b) RH=53.4%



c)RH=75.7%

Fig.6 - The piezoresistivity of CNFC40-8 after exposure to different RH.

3.3 Influences of NaCl addition

As shown in Figure 7, the addition of NaCl increases the electrical resistivity of CNF concrete, which can be explained by the higher concentration of chloride in concrete pore solution when NaCl was used. It can be attributed to the improved microstructure and lower porosity of concrete due to the accelerating effects on cement hydration [21]. When the addition of NaCl is further increased, the result will be determined by the interaction balance between the increased

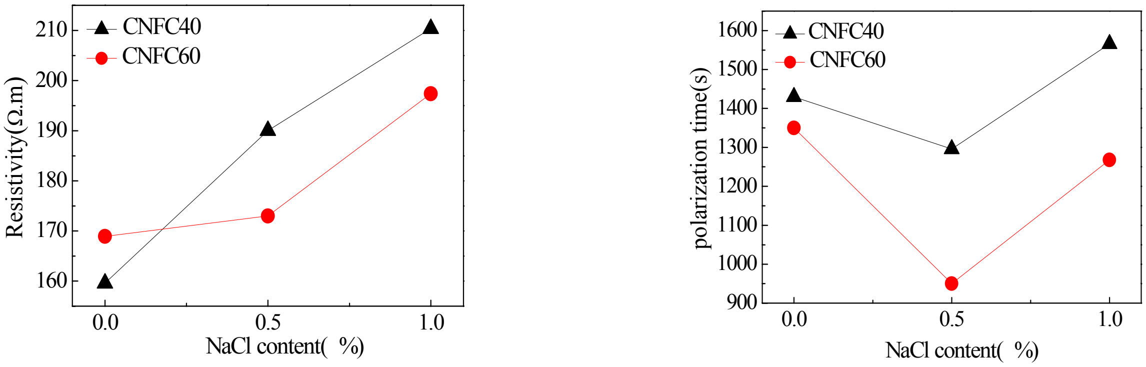


Fig.7 - The conductivity and polarization time of CNFC containing NaCl.

concentration of chloride and the improved microstructure. The polarization time is dependent on the addition of NaCl and all the C40 strength grade concretes have longer polarization times than C60 strength grade concretes when they have the same addition of NaCl.

Figure 8 shows the influence of NaCl addition on piezoresistive effect of CNF concrete with strength grade of C40. It can be found that the concretes with different dosage of NaCl behave the similar performance. When the addition dosage of NaCl was increased from 0.5% to 1.0%, the electrical resistance variation of CNF concrete was decreased from 7.1% to 5.2%. Both are much lower than the control sample. Therefore , the addition of NaCl decreases the scope of the electrical resistance reducing with the compression load or strain.

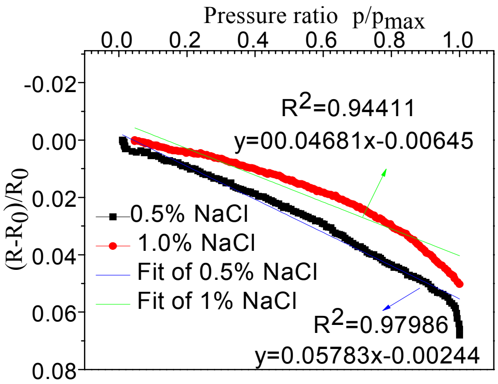


Fig.8 - The piezoresistivity of CNFC40-08 containing different dosage of NaCl.

3.4 Influences of freezing and thawing cycles

Figure 9 presents the electrical resistance variation of CNFC40-8 with compression load after 200 freezing and thawing cycles. With the increasing stress ratio, the electrical resistance decreased gradually and the decreasing rate was slightly far from a linear relationship. Therefore, the piezoresistive effect of CNF concrete is changed by the freezing and thawing cycles and the self-monitoring performance should be rechecked for further application. This deviation from linear relation is attributable to the micro-defects induced by freezing and thawing cycles. On the contrary, the freezing and thawing cycles has little influences on the piezoresistive effect of CNFC60-08 concrete due to the higher resistance to freezing and thawing cycles, also as shown in Figure 9.

4. Conclusions

1) With the drying exposure to a lower relative humidity, the electrical resistance of CNF concrete is increased more and the polarization time is decreased more. The piezoresistive performance of CNF concrete is little influenced by the drying exposure.

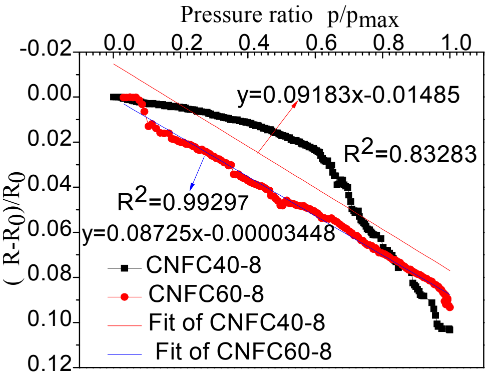


Fig. 9 - The piezoresistivity of CNFC after 200 freezing and thawing cycles.

2) The addition of up to 1.0% NaCl decreases the electrical resistance of CNF concrete and the electrical resistance variation of CNF concrete is decreased by the addition of NaCl.

3) The freezing and thawing cycles has little influence on the piezoresistive effect of CNF concrete if the concrete is prepared to have a high resistance to freezing and thawing cycles.

4) There is a good linear relationship between the stress ratio and the electrical resistance variation for specimens exposed to different environments in this study. Therefore, the piezoresistivity of CNF concrete has a potential for the long term monitoring of real structures under different humidity, chloride solution or freezing and thawing condition.

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MANIFESTĂRI ŞTIINȚIFICE / SCIENTIFIC EVENTS

FraMCoS 9 - 9th International Conference on Fracture Mechanics of Concrete and Concrete Structures, Berkeley, USA - From 28 May 2016 to 01 June 2016

Theme:
Many conferences include discussions of damage, cracking and fracture of concrete, but mostly outside the context of fracture mechanics. Other conferences cover the subject of fracture mechanics, but rarely with its application to concrete. IA-FraMCoS was founded to help fill this gap.

Concrete is an archetypical quasibrittle material. It consists of brittle constituents and is characterized by a non-negligible material characteristic length, which endows the material with a behavior that is transitional between the stress-strain relations for distributed damage at small scales and linear elastic fracture mechanics at large scales. This transitional behavior poses difficult challenges for theoretical, experimental and computational research.

Originally, IA-FraMCoS only activity was the triennial conference series with focus on concrete. Presently, it seeks to expand its activities to cover not only fundamental developments in concrete but also promotion of fracture-based approaches in engineering practice. Such an approach is long overdue in infrastructure life-cycle assessment (durability), environmental protection (long term waste storage, carbon dioxide sequestration), energy (nuclear vessels, fracking) and engineered design of new materials.

FraMCoS-9 welcomes paper contributions within, or spanning, the following themes:
A: Theoretical fracture mechanics
B: Experimental methodologies
C: Computational modeling
D: Durability/coupled problems
E: Novel cementitious and/or other quasi-brittle materials
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