Accepted Manuscript

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PII: S0958-9465(13)00194-7

DOI: <http://dx.doi.org/10.1016/j.cemconcomp.2013.11.009>

Reference: CECO 2276

To appear in: *Cement & Concrete Composites*

Received Date: 21 November 2012

Revised Date: 2 October 2013

Accepted Date: 20 November 2013

Please cite this article as: Galao, O., Baeza, F.J., Zornoza, E., Garcés, P., Strain and damage sensing properties on multifunctional cement composites with CNF admixture, *Cement & Concrete Composites* (2013), doi: <http://dx.doi.org/10.1016/j.cemconcomp.2013.11.009>

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Strain and damage sensing properties on multifunctional cement composites with CNF admixture

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Abstract

Both strain and damage sensing properties on carbon nanofiber cement composites (CNFCC) are reported in the present paper. Strain sensing tests were first made on the material's elastic range. The applied loading levels have been previously calculated from mechanical strength tests. The effect of several variables on the strain-sensing function was studied, e.g. cement pastes curing age, current density, loading rate or maximum stress applied. All these parameters were discussed using the gage factor as reference. After this first set of elastic experiments, the same specimens were gradually loaded until material's failure. At the same time both strain and resistivity were measured. The former was controlled using strain gages, and the latter using a multimeter on a four probe setup. The aim of these tests was to prove the sensitivity of these CNF composites to sense their own damage, i.e. check the possibility of fabricating structural damage sensors with CNFCC's. All samples with different CNF dosages showed good strain-sensing capacities for curing periods of 28 days. Furthermore, a 2%CNF reinforced cement paste has been sensitive to its own structural damage.

Keywords: CNF; Electrical Properties (C); Cement Paste (D); Composite (E); Fiber reinforcement (E).

1 Introduction

Recently the demand for smart structures, capable of being sensitive and responding properly to certain stimulus, has created a necessity of new construction materials, which besides their adequate structural properties and durability, also present additional functional properties (e.g. strain or damage

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sensing). Hence, several researches have focused on the development of multifunctional materials, which combine both mechanical properties and functional applications [1-18]. The latter includes such different topics as strain sensing capacity, damage sensing, temperature sensing, heating control, vibration damping or electromagnetic waves reflection and absorption.

Multifunctionality can be briefly defined as the possibility to use a structural material for other functional (non-structural) purposes without any kind of external device, neither embedded nor attached. With this type of materials the design would be simpler and the durability enhanced, as the external sensors will be removed and the whole structure will be functional. And furthermore costs could also be reduced.

These functionalities can be easily achieved on an excellent civil engineering material such as concrete (or other cement matrix composites). Just a conductive admixture will be needed, e.g. steel fibers or carbon materials: carbon fibers, graphite powder, carbon nanofibers (CNF) or nanotubes (CNT). In fact the list of carbon materials which guarantee the preservation of good mechanical strengths in cement matrix composites is wide. With regard to the addition of CNF specifically good results have been previously reported [1, 19-20]. In the last years this new way of fabricating multifunctional cement composites with CNF has been opened. Actually, these CNFCC are more efficient and with more functional possibilities than other cement composites.

A material's strain sensing capacity can be defined as the response on the volumetric electrical resistivity (proportional and reversible) due to its strain state. If a longitudinal compressive stress is applied the electrical resistance on that direction is reduced. However, if the material is upon tension then the effect will be the contrary, i.e. an increase on the electrical resistance will be registered. Both effects are reversible in the material's elastic range; therefore the electrical resistance comes back to its initial value once the load is removed. This application of cement composites is interesting for structural service state monitoring, room occupancy control or vehicle weighing. Nevertheless, damage sensing mechanism begins at the yielding point, corresponding to the material's plastic behavior, and can be seen on irreversible changes on the electrical resistivity.

The strain sensing sensitivity will be measured using the gage factor (GF), which can be defined as the fractional change on the electrical resistance per strain unit. This parameter can be calculated according to Equation 1 [11, 21].

$$GF = \frac{\Delta R/R_0}{\Delta l/l_0} = \frac{\Delta R/R_0}{\epsilon} \quad \text{Equation 1}$$

Where:

ΔR : change on electrical resistance;

R_0 : initial electrical resistance;

Δl : specimen's deformation;

l_0 : initial length;

ϵ strain.

The conductivity of cement composites can be easily improved with the addition of any conductive admixture as mentioned above. Percolation can be defined as the situation where the conductive fibers or particles, randomly dispersed, touch one another to form a continuous electrical path along the material, which is related to low resistivity values [22]. The minimum admixture dosage that creates these conductive pathways is known as percolation threshold, as reported by several authors working with different admixtures [11, 22-25]. For cement composites, in order to show a reversible and stable strain sensing behavior, a conductive admixture is required. However it is not necessary to reach the percolation threshold, i.e. a high conductivity is not needed for strain sensing applications.

Strain-sensing [3-4, 26-30] and damage sensing [27, 30-32] properties of carbon fiber reinforced cement composites have been vastly studied. Nonetheless, the addition of nano-admixtures has been vaguely reported, and in the last years it has been focused on CNT indeed [33, 34]. Actually, some of the real applications that have been reported include traffic monitoring [35] or wireless and embedded CNT networks for damage detection in concrete structures [23].

Despite their potential advantages, CNF have been seldom used in multifunctional cement composites. An early study on strain sensing applications of CNFCC concluded that 0.1 μm diameter

carbon filaments (as CNF were formerly known) were not effective as strain sensors [11]. The CNF curved morphology was pointed as a possible reason by the authors.

Recently another study has been published where strain sensing tests were run on self-compacting concrete columns with addition of CNF, steel fibers or without any conductive admixture [36].

Afterwards, damage sensing was tested when all pillars were uniaxially loaded up to failure. CNF concrete showed better mechanical behavior than plain concrete specimens. With regard to strain sensing function neither steel fiber nor plain concrete were suitable for this purpose. However, correlation between electrical resistance and compressive strain could be established for CNFCC.

The main objective of the present paper has been to perform a systematic study of self-sensing (strain and damage) properties on CNF reinforced cement pastes. The effect of several variables on this function was studied, e.g. CNF dosage, cement pastes curing age, current density, loading rate or maximum stress applied.

2 Experimental procedure

2.1 Materials and sample fabrication

Standard prismatic specimens of dimensions $4 \times 4 \times 16 \text{ cm}^3$ were fabricated. Carbon nanofibers (CNF) cement pastes were made using Portland cement type CEM I-52.5R according to UNE-EN 197-1. Distilled water was used, and water/cement ratio (w/c) was fixed at 0.5 for all dosages. CNFs type GANF4 (supplied by Antolín-Irausa S.A.) were added as conductive admixture. Their main properties are included in Table 1. In order to attain a good dispersion and workability, a plasticizer was included. The final plasticizer dosage was determined from previous workability tests. For each CNF addition (0%, 0.5%, 1% and 2% by cement mass) flow table tests were made according to UNE 83258-05, and the plasticizer amount, shown in Table 2, was adjusted in order to obtain the same slump for every CNF dosage.

CNF were previously dispersed in the mix water. A double treatment was applied for this purpose based on prior work on polymeric matrices [37]. First of all CNF were added to the water and mechanically stirred in an automatic mixer. Afterwards, an ultrasounds treatment was applied to the

mix using an ultrasounds device, model Hielschier UP200S. Then all components (CNF dispersed in water, cement and plasticizer if needed) were poured into an automatic mixer for 5 min.

The fresh mix was then poured into prismatic steel molds and kept in controlled environment room (20°C and >99% RH) for 24 hours, then demolded and conserved at room temperature and water saturated ambient until 7, 14 or 28 days age. Afterwards this curing period samples were externally dried and silver electrically conductive paint (Pelco Conductive Silver 187) was applied around the perimeter at four interior planes which were parallel to the end surfaces (Figure 1). Moreover four copper wires were wrapped around each silver painted perimeter, in order to form four electrical contacts, as needed for the four-probe method.

For the electrical resistance measures during sensing tests (strain or damage) an electrical current intensity was fixed with an AC/DC current source (model Keithley 6220), and passed between the outer contacts, while the voltage was measured between the inner contacts using a digital multimeter (Keithley Model 2002) (Figure 1). Hence resistance may be calculated applying Ohm's law. All tests were made on an electromechanical press with loading cells with a maximum load of 20 kN for strain sensing tests (elastic behavior) and 100 kN for damage sensing (until failure). Strain was permanently monitored with a Vishay P3 extensometer and strain gages located in the middle point of the lateral sides of the samples, and oriented in the longitudinal direction (the same as loading direction).

2.2 Strain sensing tests

Each test consisted on, at least, three consecutive loading-unloading cycles (compressive). According to Equation 1 the gage factor (GF) was calculated for each semi-cycle (i.e. only the loading or unloading part of each complete cycle) and for each completed cycle (considering both loading and unloading parts). The following parameters were systematically studied:

- CNF dosage: pastes with 0%, 0.5%, 1% and 2% CNF by cement mass.
- Curing age: all samples were tested at 7, 14 and 28 days. Between each test the samples were kept in a desiccator at room temperature and water saturated ambient (100% RH).
- Current intensity: 0.1, 1 and 10 mA.

- Maximum load/stress of each cycle: 3, 6 and 9 kN loads, corresponding to stress values of 1.9, 3.8 and 5.6 MPa, respectively.
- Loading rates (velocity): 0.05, 0.1 and 0.2 kN/s for a 3kN maximum load, and 0.1, 0.2 and 0.4 kN/s for 6 and 9 kN maximum loads.

2.3 *Damage sensing tests*

After completing the strain sensing work plan, samples were loaded up to its ultimate strength. The testing procedure was similar as the one explained above. However, in this case the maximum load was progressively increased after each cycle until failure was reached. 0.4 kN/s was the only loading rate for every damage sensing test. During the first cycle a 10 kN load was applied (equivalent to 6.25 MPa compressive stress), afterwards the maximum load was increased by 5 kN per cycle (3.125 MPa) until 40 kN (25MPa). Thus the yielding point (limit between elastic and plastic behavior) could be detected. And from 40 kN up to failure the load was increased 10 kN per cycle, always unloading the specimens completely in each cycle.

3 **Results and discussion**

3.1 *Mechanical properties*

Previous compressive strength tests were made to determine the loading limits, with 3 specimens of each CNF dosage. In order to guarantee an elastic behavior, the loading conditions during strain sensing tests should be below 30% of compressive strength (according to Spanish Standard UNE 83316:1995). Figure 2 shows the specimens longitudinal axis compressive ultimate strength mean values. No significant variations can be observed at 7 or at 28 days for different CNF additions. This trend is consistent with prior research [1].

3.2 *Strain sensing tests*

Before and after every test performed on each sample, their masses were controlled. As the mass losses were always below 0.25% of the initial mass, the water saturation state can be considered constant for all experimental phases; i.e. electrical resistance changes are not expected to occur due to water losses (ionic conductivity). Moreover, before any load was applied, the initial electrical

resistance was measured. Therefore the initial resistance was controlled in order to calculate the GF after loading the samples.

Effect of curing age and current intensity.

Figure 3 shows the results of strain-sensing tests for carbon nanofiber (CNF) dosages of 0 and 2%, and at curing ages of 7 and 14 days. The maximum stress reached during these tests was 1.9 MPa and the loading rate was 0.050 kN/s. Fractional change on electrical resistance and compressive stress are both represented versus time. Strain-sensing behavior could not be seen in any of the tests for curing ages up to 14 days, whichever current intensity was applied.

However, for a curing period of 28 days, a relationship between the stress and electrical response could be detected. Figure 4 shows the results for strain-sensing tests of 0%, 0.5%, 1% and 2% CNF cement pastes for different loading conditions (6 and 9 kN, at 200 N/s), both strain and fractional change in electrical resistance data versus time. Reversible changes were seen for all samples with CNF additions, but there was not any reversible sensing behavior for the control sample (0% CNF). As it has been previously reported [4], cement composites with no conductive admixture do not show self sensing behavior, or this phenomenon is neither reversible nor repeatable. Consequently the following discussion will only consider the CNF reinforced dosages.

Prior work points at the contact resistivity between the matrix and the conductive admixture as responsible for the piezoresistive phenomena [38]. Then a possible explanation for the differences in cement pastes' behavior at 28 days (good sensing properties) and earlier (without sensibility neither at 7 nor 14 days) may be found at CNF-matrix debonding. In a recent study regarding mechanical properties of nanomaterials a lack of fiber-matrix adherence was seen on CNF cement pastes for early curing ages [20]. If tested at ages of 7 or 14 days the usual failure mode was CNF debonding, however at 28 days CNF tended to break upon tension than being pulled out from the cement matrix. Hence for the results included in the current research this preference for debonding may influence the contact resistivity and sensing capability at early ages.

A noticeable effect of the current intensity on the sensing ability was detected for the 28 days samples. Figure 5 includes resistivity changes and strain for 2% CNF pastes at three different

electrical currents (0.1 mA, 1 mA and 10 mA). For all CNF additions a minimum current of 10 mA was needed in order to obtain any reversibility on the measures and in order to make a correlation between resistance variation and compressive strain, and hence to calculate the corresponding GF. These data suggest that a certain current density is needed. Actually for all the dosages tested with resistivities around $1 \text{ k}\Omega\text{m}$, a 6.25 mA/cm^2 current density was necessary. Therefore the next studies (loading conditions and damage sensing) were all performed fixing the intensity at 10 mA. However, a specific study considering samples saturation conditions and conductivity is recommended to adjust that minimum current density in each case.

Effect of loading conditions.

The initial hypothesis of samples remaining in their elastic range during strain-sensing tests was first checked by plotting stress-strain curves. Figure 6 shows some examples for each CNF% which were loading up to 9 kN. The elastic moduli were stable during all tests with the same samples, and there was not any remnant of strain after loading had been completely removed. A similar modulus was observed for pastes with 1 and 2% CNF, and a higher modulus was obtained for pastes with 0.5% CNF.

Figure 7 includes the mean GF values calculated for specimens with CNF additions, for each maximum load applied (3, 6 and 9 kN). Three different loading rates were considered for each stress level, and GF values corresponding to loading and unloading cycles are plotted separately. Two important conclusions could be drawn from these results: (i) there were not mayor differences between loading and unloading cycles, thus the analysis of the mean value of all cycles would be accurate enough, regardless loading was being increased or decreased; (ii) the loading rate has almost no influence on the calculated GF. This last topic is especially important if traffic monitoring applications are desired, because if the materials' response is actually independent of the loading rate, hence it will be independent of the vehicle's passing velocity.

The next parameter to study was the stress level applied. Before any thorough analysis of the strain sensing phenomena, the resistivity values during these tests were also controlled, and have been represented in Figure 8. Three different applied load levels have been considered, and no difference

has been seen in the resistivity values of the same samples when stress was increased. However the higher CNF% included the lower resistivity was measured, especially for the 2% CNF addition (15% more conductive than the others). No big differences between 0.5% and 1% CNF were observed.

As previously discussed in Figure 4, the response of these two variables (strain and fractional change in electrical resistance data versus time) was reversible. GF values were calculated for all cycles according to Equation 1, and the mean GF values and their standard deviations are shown in Figure 9. Once again there was not a significant difference between loading and unloading cycles, thus only the mean values for all of them have been considered. As a general trend, higher GF values were obtained as the stress was increased. However, this effect was lower if CNF% was increased, i.e. there was not almost any difference between GF when 6 and 9 kN were applied on 2%CNF pastes. Actually these 2%CNF composites were the most sensitive, as shown in their GF values (around 50). But no trend could be stated between GF and CNF%.

From the formulation for GF (Equation 1) two aspects should be considered; higher GF values would be obtained if the fractional change in resistance were higher too (for a fixed strain level) but also if the strain were lower, i.e. for higher composite's stiffness (elastic modulus is the ratio between stress and strain). Resistivity changes are directly related to the conductive admixture; the wider changes in resistance were seen on the 2%CNF specimens, while the variations were similar for the 0.5% and 1% CNF pastes. On the other hand, 0.5% samples had lower strain values for the same stress levels (as concluded from the stiffness data in Figure 6) and in this case 1% and 2% CNFCC showed similar elastic behavior. As a result of this coupling effect, the GF included in Figure 9 can be explained. Resistivity changes prevailed in 2% specimens showing the highest GF, almost thrice the other CNF dosages, while the stiffness difference was the cause of the slightly higher GF of 0.5% CNF (with lower strains and similar variations of electrical resistance) than 1% CNF pastes (which had the lowest GF calculated).

Other aspect that may be related to the differences in sensing behavior is the dispersion treatments efficiency. The type (ultrasound, mechanical, surfactants...) and effectiveness of different treatments is a crucial aspect of carbon materials reinforced composites [1, 15, 19]. Usually higher amounts of

conductive admixtures make the fresh mix less workable and carbon admixtures' clusters may appear [29]. In this paper the plasticizer amount was adjusted to avoid this problem. Although workability was the same for all dosages, probably the more CNF used, the less dispersion efficiency was achieved (a combined mechanical and ultrasound treatment was applied). Hence it is possible that a proper dispersion had not been achieved in some cases. However it may not be the real cause as the best results have been registered on the 2%CNF specimens. Thus the materials' stiffness remains as the other probable cause, and it is related to the different quantities of plasticizer used in each dosage (in order to maintain a constant workability of the fresh mix). Actually these mechanical differences have been reported in prior work, with 60% variations of the elastic modulus for different CNFCC [20]. Furthermore, other researches show that the addition of CNFs promoted pore refinement of the composites [1, 19].

One last aspect which is worth discussing is actually the use of GF as characteristic parameter for strain-sensing phenomenon. It is well known, and widely reported that a linear relationship can be stated between resistance fractional change and longitudinal strain on fiber reinforced composites. However, if these two variables are represented on the same graphic, curves like the included in Figure 10 are obtained. Some points of the previous discussion can be also seen here, e.g. there is not any difference for tests made at the same stress level but different loading rate. It is not so clear that the same behavior occurs whichever strain is reached. There seem to be three different stages: (i) a low sensitivity area up to $100 \mu\epsilon$, which would explain the lower GF values for very low loading; (ii) a linear resistivity-strain relationship, which coincides with the GF as indicated in Equation 1; and (iii) another low sensing range from approximately $450 \mu\epsilon$, which depends on the maximum stress applied to the material.

In any case all these nonlinear and time dependence phenomena have low effect on all topics discussed above, i.e. the linear regression curve calculated for every test had a r^2 Pearson's coefficient higher than 0.994. Thus GF can actually be used for strain-sensing purposes (even if third degree polynomial or sigmoid functions result in better regressions), but certain sensitivity issues should be considered for a real application. Besides some second order factors should be studied in order to propose a theoretical strain-sensing mechanism for CNFCC.

3.3 Damage sensing tests

After all strain-sensing tests, all samples were progressively loaded until failure. Figure 11 shows the resistance fractional change and longitudinal strain, versus time, for three different cement pastes: 0.5%, 1% and 2% CNF additions. Their ultimate stresses were 62.5, 49.8 and 58.6 MPa respectively. These strengths were from 11% to 33% higher than the 28 days characteristic values included in Figure 2. The strain at failure occurred between 0.5% (5000 $\mu\epsilon$) and 0.8% (8000 $\mu\epsilon$), consistent to specific literature [39]. For all samples tested, a nonlinear electrical response was seen when samples' damage had begun, i.e. if remnant strains had been induced, irreversible changes in resistivity would have occurred. This permanent effect on composite's resistance was more noticeable as the maximum stress was increased. The maximum stress-strain values for each cycle are represented in Figure 12. Also the range where previously elastic strain-sensing tests had been performed has been remarked. The change between elastic and plastic behaviors cannot be detected using these stress-strain curves, the only significant changes correspond to samples failure. Figure 13 shows a stress-strain curve for the whole tests with a 2%CNF cement paste. The typical hysteresis phenomenon is clearly seen as the stress is increased between cycles when surpassing the elastic range [39].

A pattern has been detected on the electrical response of CNFCC (Figure 11). First of all, for loads lower than 25% of the compressive strength, the previous discussion for strain sensing tests remains. A second stage appears until half the strength is reached, where the linear electrical behavior becomes a parabolic behavior during each half cycle. And from this point up to failure an inflection point appears, and so making linear regressions inaccurate (non-linear functions, such as sigmoid or polynomial functions, would be necessary). All maximum and minimum values of resistance fractional change ($\Delta R/R_0$) and strain occurred simultaneously. Table 3 includes all these extreme values for a 2% CNF cement paste test.

In order to analyze the damage sensing function the parameters represented in Figure 14 have been studied. For each cycle (i-cycle) the total cycle time (L_i), the strain amplitude (B_i , as the mean strain value for each cycle), and the $\Delta R/R_0$ amplitude (H_i , obtained just like B_i for strain values) have been calculated. Table 4 includes for each cycle the maximum loading values, and the L_i/B_i (strain related parameter) and L_i/H_i (resistivity related parameter) ratios for a 2%CNF cement paste test. Figure 15

shows both calculated ratios versus the applied maximum stress in each cycle, for a 2% CNF cement paste test. It can be observed that up to 25 MPa (7th cycle) the electrical L_i/H_i ratio (i.e. electrical resistance change rate) increases linearly, but after this stress it continues increasing faster up to failure. The strain counterpart, L_i/B_i , progressively increases up to the 25 MPa stress, moment when the damage to cement composite begins (and the damage sensing mechanism is triggered [31]), afterwards stays constant and when failure approaches it starts to decrease. Hence two changes in behavior can be seen, one when the yielding point is surpassed and other when failure is near, corresponding with the three areas distinguished in Figure 15.

Furthermore, if L_i/H_i derivation (increment of the L_i/H_i ratio between cycles) is represented, the curve included in Figure 16 is obtained, where these three different stretches can be clearly defined. Three linear functions can be adjusted for the stress intervals 0-25 MPa (elastic range), 25-50 MPa (damage sensing) and until failure is reached. The L_i/H_i ratio increases faster as the damage level is more severe, and the material is closer to its compressive strength.

4 Conclusions

Cement pastes with different CNF additions were fabricated. Tests were performed in order to check their possible strain and damage sensing abilities. After all results have been analyzed the following conclusion can be drawn:

Strain-sensing properties could not be seen in CNF pastes for curing ages of 7 and 14 days. But for a curing age of 28 days it was possible to use a CNF cement paste as strain sensor under compression.

Nevertheless, a certain current density level was necessary in order to show a reversible behavior.

Loading rate did not affect the strain-sensing response of the composites. However the sensitivity (gage factor) was increased with the maximum compressive load applied.

Furthermore, a 2%CNF reinforced cement paste has been sensitive to its own structural damage. L_i/B_i and L_i/H_i parameters have been defined and proposed as indicators of irreversible damage on CNF cement composites.

Acknowledgements

Authors want to acknowledge the Spanish Ministry of Science and Innovation for their economic support on this research (Ref: Mat 2009-10866).

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Tables and figures

Table 1. CNFs, type GANF4, properties.

PROPERTIES	UNIT	GANF4
FIBER DIAMETER (TEM)	nm	20-80
FIBER LENGTH (SEM)	μm	>30
BULK DENSITY	g/cm^3	>1.97
APPARENTE DENSITY	g/cm^3	0.060
SURFACE ENERGY	mJ/m^2	≈ 100
SPECIFIC SURFACE AREA BET (N_2)	m^2/g	150-200
GRAPHITIZATION DEGREE	%	≈ 70
ELECTRICAL RESISTIVITY	ohm·m	$1 \cdot 10^{-3}$
METALLIC PARTICLES CONTENT	%	6-8

Table 2. Plasticizer dosages with respect to cement mass, used for each CNF addition.

CNF	Plasticizer dosage
0.0%	0.00%
0.5%	0.15%
1.0%	0.30%
2.0%	0.55%

Table 3. Maximum and minimum values of stress (Q), strain (ϵ) and resistance fractional change ($\Delta R/R_0$) for a 2%CNF cement paste, obtained in cycle of damage-sensing tests.

Maximum cycle values					Minimum cycle values				
CYCLE	Q (MPa)	t (s)	ϵ	$\Delta R/R_0$	CYCLE	Q (MPa)	t (s)	ϵ	$\Delta R/R_0$
1	-6.27	23	-0.001034	-0.016	0-1	-0.44	0	-0.000145	0.000
2	-9.35	81	-0.001326	-0.022	1-2	-0.59	46	-0.000324	0.001
3	-12.47	164	-0.001608	-0.027	2-3	-0.61	117	-0.000373	0.001
4	-15.58	272	-0.001885	-0.031	3-4	-0.60	212	-0.000401	0.001
5	-18.71	405	-0.002158	-0.035	4-5	-0.60	333	-0.000441	0.000
6	-21.88	563	-0.002442	-0.038	5-6	-0.59	478	-0.000462	-0.002
7	-24.99	746	-0.002729	-0.042	6-7	-0.64	648	-0.000505	-0.005
8	-31.27	966	-0.003302	-0.047	7-8	-0.65	844	-0.000559	-0.008
9	-37.44	1236	-0.003930	-0.052	8-9	-0.64	1088	-0.000616	-0.016
10	-43.68	1555	-0.004664	-0.059	9-10	-0.61	1383	-0.000703	-0.024
11	-50.01	1925	-0.005533	-0.067	10-11	-0.60	1728	-0.000859	-0.036
12	-56.24	2344	-0.006610	-0.075	11-12	-0.60	2122	-0.001055	-0.048
13	-58.57	2797	-0.007701	-0.082	13-failure	-0.61	2566	-0.001362	-0.059

Table 4. Calculated values, Li/Bi and Li/Hi, according to Figure 14, for damage sensing test analysis of 2% CNF cement pastes.

CYCLE	Q (MPa)	Li/Bi	Li/Hi
1	-6.27	57550	2796
2	-9.35	72624	3070
3	-12.47	77779	3379
4	-15.58	82662	3835
5	-18.71	84945	4327
6	-21.88	86805	4921
7	-24.99	89192	5547
8	-31.27	89881	6975
9	-37.44	90204	9278
10	-43.68	88845	12167
11	-50.01	86103	15597
12	-56.24	82199	20794
failure	-58.57	-	-

Figure 1. $4 \times 4 \times 16 \text{ cm}^3$ specimen and electrical contacts configuration. 1 and 2 contacts for current input and 3 and 4 contacts for voltage measure. (a) Dimensions and electrode's setup; (b) Photograph of a prepared specimen.

Figure 2. Compressive strength for CNF cement pastes, at 7 and 28 days. Tests were performed on the specimens' longitudinal axis.

Figure 3. Strain-sensing tests for different CNF dosages, 0% (upper row) and 2% (lower row) at curing ages of 7 days (left column) and 14 days (right column). Fractional change on electrical resistance, $\Delta R/R_0$, and compressive stress are both represented versus time.

Figure 4. Strain-sensing tests at 28 days, for different CNF cement pastes dosages (0, 0.5, 1 and 2%, by cement mass). Fractional change on electrical resistance, $\Delta R/R_0$, and compressive stress are both represented versus time. All tests were run at a constant loading rate of 200 N/s. Two different maximum loads are shown, 6 kN (3.8 MPa) and 9 kN (5.6 MPa).

Figure 5. Fractional change on electrical resistance ($\Delta R/R_0$) and longitudinal strain ($\mu\epsilon$), versus time, for 2% CNF cement pastes strain-sensing tests, at 28 days, for 0.1 mA, 1.0 mA and 10.0 mA current intensities, at a maximum load of 6 kN (3.8 MPa) and a loading rate of 400 N/s.

Figure 6. Stress-strain diagrams, of 0.5, 1 and 2% CNF cement pastes, at 28 days, with a maximum load of 9 kN at 200 N/s. Linear polynomial regressions and r^2 Pearson correlation coefficients are also included.

Figure 7. Average GF and standard deviation for different CNF dosages and for 3, 6 and 9 kN maximum loads, loading (left, negative values) and unloading (right, positive values) cycles are plotted separately.

Figure 8. Mean electrical resistivity, obtained in 0.5, 1 and 2% CNF cement pastes strain-sensing tests, for three different maximum loads, including standard deviations.

Figure 9. GF mean values and standard deviations, according to Equation 1, for 0.5, 1 and 2% CNF dosages, maximum loads of 3 kN (1.9 MPa), 6 kN (3.8 MPa) and 9 kN (5.6 MPa), for loading semi-cycles, unloading semi-cycles and completed cycles.

Figure 10. Resistance fractional change ($\Delta R/R_0$) versus strain (ϵ), for different strain-sensing tests, with 2% CNF specimens, at 3, 6 and 9 kN maximum loads, and 100 and 200 N/s loading rates. Linear and polynomial regression for 2% CNF, 9 kN and 200 N/s test are included.

Figure 11. Resistance fractional change and longitudinal strain, versus time, for three different cement pastes: 0.5%, 1% and 2% CNF additions, corresponding to damage-sensing tests.

Figure 12. Stress-strain diagram according to Figure 11 maximum values. Remarked square represents strain tests working zone.

Figure 13. Stress-strain diagram according to Figure 11 complete test for 2% CNF cement paste.

Figure 14. Sketch for Li/Bi and Li/Hi parameters, for damage sensing tests.

Figure 15. Li/Bi and Li/Hi parameters versus each cycle maximum stress values, for 2% CNF damage sensing test.

Figure 16. Li/Hi derivation for 2% CNF damage sensing test.