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Self-sensing concrete made from recycled carbon fibres

I Segura[1,2], G Faneca[3], J M Torrents[4] and A Aguado[2]

[1] Smart Engineering Ltd, C/Jordi Girona 1-3, Parc UPC—K2M, E-08034, Barcelona, Spain
[2] Department of Civil and Environmental Engineering, Universitat Politècnica de Catalunya—Barcelona Tech, C1, E-08034, Barcelona, Spain
[3] Escofet 1886 Ltd, E-08760 Martorell Barcelona, Spain
[4] Department of Electronics Engineering, Universitat Politècnica de Catalunya—Barcelona Tech, C4, E-08034, Barcelona, Spain

E-mail: ignacio.segura@upc.edu

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Abstract

The electrical and piezo-resistive responses of recycled carbon fibre (rCF)-reinforced concrete is analysed in this article. Two different PAN-based rCFs (monofilament rCF and fibrillated rCF sheets) incorporated into dry concrete mix were investigated. Piezo-resistivity was evaluated by simultaneously monitoring the variation in the applied DC voltage during both flexural and compressive tests. Although both plain and rCF-reinforced concrete samples showed piezo-resistive responses, the latter show increased signal-to-noise-ratio and thus behave like self-sensing materials. The electrical behaviour suggests a mixed control owing to both ionic and electronic conductivity, with the dominant one depending on the rCF content and rCF dispersion. This work enhances the possibility of generalising the use of smart cementitious materials in the civil engineering industry.

Keywords: self-sensing concrete, strain sensing, recycled carbon fibre, smart material

(Some figures may appear in colour only in the online journal)

1. Introduction

Since the last 15 years, there is a revolution to turn civil infrastructures and buildings all over the world into smart structures. Our current society is increasingly demanding that the infrastructures and cities become smart and provide other functionalities in addition to their mechanical performance and durability. Furthermore, the recent failures in the summer of 2018 of a motorway bridge in Genova, Italy and of a concrete pier in Vigo, Spain, have brought the focus on how our society deals with infrastructure monitoring and maintenance. Moreover, there is a need to reduce monitoring costs and to avoid further collapse of existing infrastructures.

This revolution has mainly considered the incorporation of multi-functional devices and sensors into civil infrastructures and architectural heritage. Nowadays, optical fibres are widely employed for monitoring civil infrastructures [1], and wireless sensor networks (WSN) are being extensively used to help preserve the building heritage [2]. One of the main challenges of this approach is the durability of the sensors since they may become *external agents* in the structures. Experience reminds us of the lack of durability of such sensors, as evidenced by dam auscultation and WSN systems. The inconvenient truth is that almost 70% of the sensors fail or are inoperative after 1 year of operation [3]. To describe this situation in medical terminology, we are facing a serious problem of '*transplant rejection*' by our infrastructures.

However, a very promising alternative to the use of conventional sensors is the development of smart cementitious materials with self-sensing abilities, which would allow detection of strain and damages in new and existing infrastructures. The incorporation of conductive phases into cementitious matrices has been one of the most popular methodologies to develop self-sensing cementitious materials. In 1993, Chen and Chung first reported the piezo-resistive effects of carbon fibre-reinforced cementitious materials [4]. The incorporation of conductive phases into the cementitious matrix modifies its conductive characteristic. Thus, piezo-resistive effect appears when stress is applied to the material, owing to the modification of the conductive characteristics of the material. For carbon fibre-reinforced composites, piezo-resistivity is considered to originate from the slight pull-out of crack-bridging fibres during crack opening and the consequent increase in the contact electrical resistivity of the fibre–matrix interface [5], or the conduction network degeneration resulting from fibre reorientation under finite strain [6].

The piezo-resistivity of carbon fibre cementitious materials has been extensively investigated until now [7–12], and nowadays, it is being explored through the incorporation of graphene [13], carbon nanotubes (CNTs) and nanofibers [11, 14–17], multiphasic mixes of conductive additives [18–21], and CNT-coated aggregates [22]. An interesting review on the development of self-sensing cementitious materials was published by Chan *et al* [23]. However, the incorporation of smart materials into novel or existing infrastructures has not taken off, and has been limited to some pilot studies only [8, 17, 24, 25]. One key reason for this situation is the high cost of the conductive phases that are being used in the development of smart cementitious materials. The use of recycled carbon fibres (rCF) is a very promising alternative in the development of sustainable smart cementitious materials. RCF are mainly obtained from aerospace composite scrap. Among many different methods, most of the commercially available rCF are obtained via pyrolysis. This process allow a high retention (up to 90%) of the properties exhibited by virgin carbon fibres [26, 27]. The use of rCF may allow to design economically affordable smart cementitious materials since most of recycling processes yield rCF with high retention of mechanical properties [26] but with a 30%–40% cost savings versus virgin carbon fibre (cost of commercial chopped carbon fibres: 15 €$\,kg^{-1}$ versus cost of rCF: 7–8 €$\,kg^{-1}$). In a recent paper [28], we demonstrated the possibility of using rCF to develop conductive cementitious materials, and realized electrical resistivities in the range of 3–0.6 Ω m for rCF contents ranging from 0.2 to 0.8% in vol.

As a continuation of this research, in this study, we explore the capability of recycled fibre cementitious composites as smart materials for self-sensing applications. Two different types of rCF (fibrillated and sheet-type) were evaluated as additives; these two were incorporated at different contents (0.1%–1.4% in volume) in ultra-high-performance concrete (UHPC) mix. Piezo-resistivity of the prepared concrete samples was evaluated under both flexural and compressive conditions, by taking into account the effect of the moisture content of the samples.

2. Materials and methods

2.1. Concrete dosage and raw materials

The concrete dosage used in our study is shown in table 1; this is characteristic of a UHPC dosage. This concrete dosage was selected because it is expected to enhance the electrical conductivity owing to the presence of a double percolation phenomenon, as described by Wen *et al* [5]. The cement selected to produce the UHPC mixtures was a CEM I 53.5R. The sand used was siliceous sand and fine calcium carbonate powder (Betoflow) was incorporated into the different dosages to achieve an optimum workability of the mixes with a low consumption of superplasticisers. Both a polycarboxylate superplasticiser (Glenium ACE425) and nanosilica suspension (Meyco MS685) were used as additives to provide self-compacting characteristics to the concrete mix. The water to cement (w/c) ratio of the concrete mixes was 0.14. Two different PAN-based rCF samples provided by ELG Carbon Fibre Ltd (C10/30, and CT12) were used in this study. The characteristics of the rCF are described in table 2; C10/30 are monofilament rCF and CT12 are fibrillated sheets of rCF. The fibre factor F given by equation (1), as proposed by Narayanan and Darwish, allows to account for the effect of both the geometrical characteristics of the fibres, length (L_f) and diameter (d_f) [29].

$$F = \beta \cdot L_f / d_f, \tag{1}$$

where, β is the fibre shape factor (0.50 for circular fibres), and the fibre was dosage varied from 0.1% to 1.4% in volume.

Table 1. Concrete dosage used for the mixes.

Component	Dosage (kg m^{-3})
Cement	800
Betoflow	220
Sand (0–3/0–1 mm)	1161
Glenium ACE425	30
Meyco MS685	57
Water	110

Table 2. Properties of recycled carbon fibres.

	Value	
Property	C10/30	CT12
Diameter (μm)	7.5	7[a]
Nominal length (mm)	10–30	12
Average length (mm)	20	12
Fibre factor F	1428	12
Density (kg m^{-3})	1800	1760
Tensile strength (MPa)	3150	4150
Young modulus (GPa)	200	252
Electrical resistivity (Ω m)	0.103/0.34[b]	0.016

[a] The effective diameter of the fibrillated sheets is 500 μm.
[b] The electrical resistivity value varies depending on whether the measurement is made lengthways (0.103) or along the cross-section (0.34).

2.2. Sample fabrication

UHPC samples with dimensions of 40 × 40 × 160 mm were fabricated with the dosages indicated in table 1, according to UNE-EN 196-1 [30]. The concrete samples were produced at the industrial installations of the company, Escofet 1886, with a fabrication procedure replicating the industrial process as

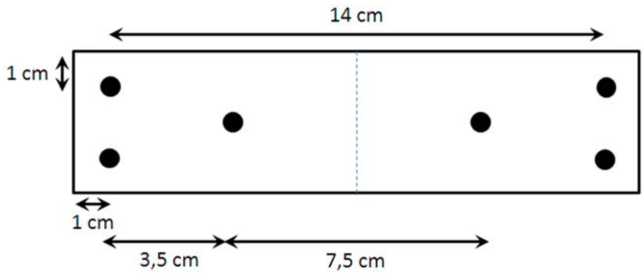

Figure 1. Location of the electrodes in the specimens.

closely as possible. Two sets of samples were fabricated from each mix, one set for mechanical measurements and another for electrical measurements. In this work, rCFs were added to the dry mix (D) after incorporating the cement and aggregates. No specific dispersion procedure was implemented since our main aim was to work as close as possible to the real practice and use the actual concrete compositions used in the precast concrete industry. Reference samples were prepared without adding rCF. The electrodes for the electrical measurements were stainless steel set screws of 5 cm length that were introduced 3.5 cm deep into the concrete samples. The samples were cured in a humid chamber (20 °C ± 2 °C; relative humidity of 95% ± 5%) for 28 d. The samples are designated according to the following code: U-Cf-f-M where, U stands for UHPC mixes, C_f indicates the fibre content (which varies from 0 for the reference sample to 14 for the 1.4% fibre content), f indicates the fibre type, and M indicates the mixing method of the fibres (D).

2.3. Characterisation

Slump flow was measured according to UNE-EN 1015-3 [31] prior to the development of the concrete samples. Flexural and compressive strength measurements were performed on the concrete samples in compliance with UNE-EN 196-1 [30]; three and six replicates were made for each dosage, respectively. The electrodes used for the electrical measurements were stainless steel set screws of length 5 cm, which were dipped 3.5 cm into the concrete samples. The samples for mechanical strength measurements did not included steel electrodes. Figure 1 shows a scheme on the electrodes positioning on the specimens.

The electrical properties of the samples were characterized with an Agilent HP 4192 A impedance analyser, using an instrumentation amplifier as a front-end to allow 4-probe measurements [32], with an effective voltage of 1 V AC to avoid polarisation effects in the electrodes [31, 32]. The measurements were conducted in the frequency scanning range of 10 Hz–1 MHz providing electrical impedance (Z, in Ω) and phase (ϕ, in degrees). The electrical impedance is described by equation (2) and is composed of a real part (resistance, R) and an imaginary part (reactance, X); R and X are given by equations (3) and (4):

$$Z = R + j \cdot X \tag{2}$$

$$R = Z \cdot \cos\left(\frac{\phi \cdot \pi}{180}\right) \tag{3}$$

$$X = Z \cdot \sin\left(\frac{\phi \cdot \pi}{180}\right). \tag{4}$$

The electrical resistivity (ρ, in Ω m) was calculated from the impedance data using equation (5), where, S is the effective transverse section (0.0016 m^2 in our study), and l is the measurement length (0.07 m in our study). All the samples were allowed to reach a hygrothermic equilibrium by storing them under laboratory conditions for 15 d after finishing the curing period. Lastly, the electrical conductivity (σ, S m^{-1}) of the samples was easily calculated as the inverse of the resistivity, using equation (6). The electrical conductivity values are expressed as the mean of values determined for three different specimens.

$$\rho = R\frac{S}{l} \tag{5}$$

$$\sigma = \frac{1}{\rho}. \tag{6}$$

Piezo-resistivity tests were performed on 40 × 40 × 160 mm specimens to evaluate the characteristics of the different conductive concrete samples. Samples were loaded both under flexural and compression conditions. Electric current was passed through the samples using an external DC current source (Keithley Model 6020) to monitor the resistivity variation during the mechanical tests, by fixing the output current to 3 V. Piezo-resistivity measurements were performed on one specimen of each dosage.

3. Results

3.1. Physical and mechanical properties

The influence of the rCF type and content, as well as the mixing method on the slump flow is depicted in figure 2(a). The rCF fibres supplied as fibrillated sheets (CT12) exhibited a larger slump flow compared to that of monofilament rCF (C10/30) at all fibre dosages. A larger slump flow is usually related with better dispersion of the rCF in the cementitious matrix and is strongly affected by the geometrical parameters of the fibre (fibre factor, F).

Considering the differences in the properties of the two types of rCF shown in table 2, larger differences would be expected in the slump flow of concrete with C10/30 and CT12 samples. However, the fibre dispersion in cementitious materials is affected not only by the fibre factor but also by the number of fibres per unit volume, N. This parameter can be calculated according to equation (7),

$$N = \frac{V_f}{\pi \cdot (d_f/2)^2 \cdot L_f}, \tag{7}$$

where, V_f is the volume fraction, d_f is the diameter (in mm), and L_f is the length of carbon fibres (in mm). Figure 2(b) shows the variation of N with the rCF content for concrete

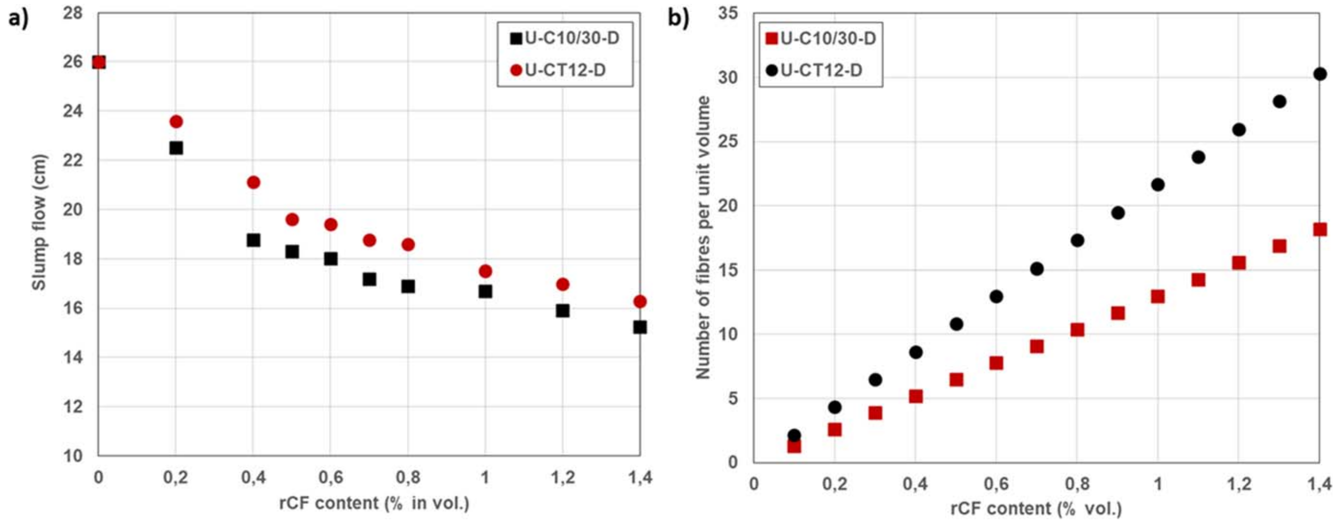

Figure 2. Variation of: (a) slump flow with the content of rCF for the different mixes, and (b) N per unit volume with the rCF content for C10/30 and CT12 fibres.

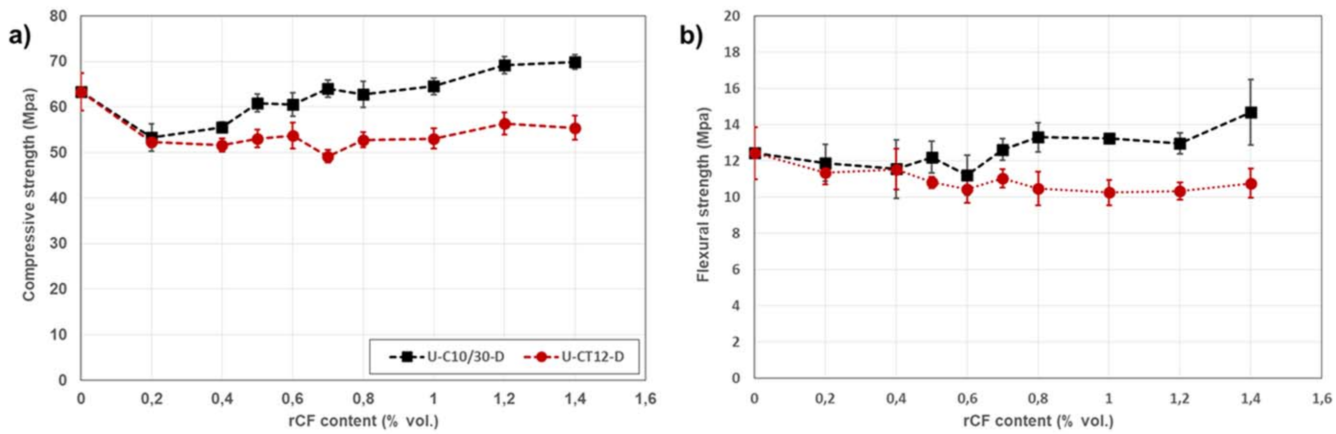

Figure 3. Variation of the (a) compressive and (b) flexural strengths with the fibre content for different concrete mixes.

samples containing C10/30 and CT12. For low rCF contents, the number of fibres per unit volume is very similar for both samples. As the rCF content increases, the difference between the N values of C10/30 and CT12 samples increases. Thus, the results of slum flow reflect this relationship between the geometrical factor of the fibres and the number of fibres per unit volume.

The mechanical properties of the specimens shown in figure 3 also reflect the relationship between the geometrical factor of the fibres and the number of fibres per unit volume. Considering the slump test results shown in figure 2, a larger mechanical response of CT12 samples is expected. However, an inverse trend is observed with the C10/30 specimens exhibiting a larger mechanical response both under compressive and flexural conditions. This result might be explained again in view of the number of fibres per unit volume (N). More carbon fibres in the bulk matrix can result in better mechanical performance up to a certain rCF content given by the fibre factor. Once this value is reached, a further increase in the carbon fibre content might have a weakening effect owing to the presence of air voids and low dispersion of the carbon fibres. As shown in figure 3(a), C10/30 and CT12 samples exhibit almost similar compressive strengths at a low rCF content, because the number of fibres per unit volume is very similar. As the rCF content increases, the difference between the N value of C10/30 and CT12 increases, and thus more defects (air voids and bundles of carbon fibres) might be present in the cementitious matrix.

3.2. Electrical conductivity

The electrical characteristics of carbon fibre-reinforced cementitious composites are strongly influenced by the applied frequency in AC measurements. Figure 4 shows the Bode diagrams of a reference sample and a sample containing rCF. The reference sample behaves like an insulator with almost no variation in the impedance with the frequency. The incorporation of the rCF modifies the electrical behaviour of the

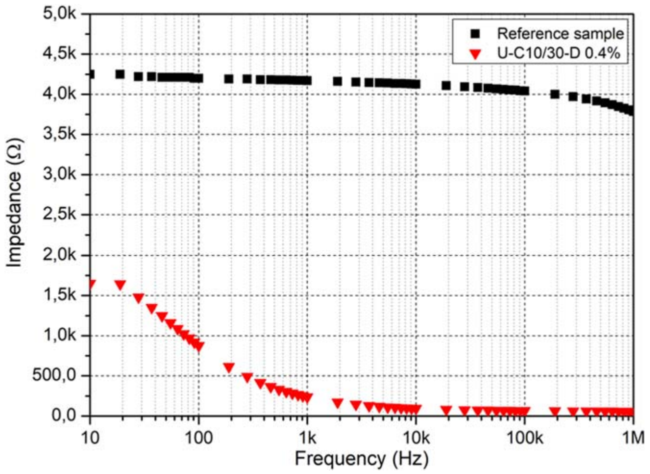

Figure 4. Bode diagrams for a reference concrete sample and an rCF-reinforced sample.

samples, and the impedance reduces as the frequency of the applied current is increased. As stated by several researchers, there is a cut-off frequency that permits bypassing of the cementitious matrix that surrounds the fibres in carbon fibre-reinforced materials [33], referred to as *cusp frequency*. This cut-off frequency is also displayed when rCF is used [28], and the values are 100 and 190 kHz, respectively, for C10/30 and CT12 samples. The electrical resistivities were determined at two different frequency values: 50 Hz and 190 kHz. The first value coincides with the standard frequency for AC, and the second was selected to perform the measurements above the capacitance threshold (C_t) value, and thus bypass the cementitious matrix that surrounds the rCF [26, 34].

The variation of the electrical conductivity with the fibre content for specimens with C10/30 and CT12 is shown in figure 5, where the y axis presents different limits to accommodate the different limits of both $\sigma_{50\ \mathrm{Hz}}$ and $\sigma_{190\ \mathrm{kHz}}$. For low frequencies (see figure 5(a)), specimens with C10/30 exhibit larger electrical conductivity and CT12 specimens present electrical conductivities that are quite similar to that of the reference sample without rCF. Furthermore, the electrical conductivity of samples with C10/30 decreases for fibre contents larger than 0.6% vol. This electrical behaviour is related to the presence of carbon fibre bunches in the cementitious matrix [25]. However, when the capacitance threshold is surpassed (figure 5(b)), the electrical behaviour is modified. Whereas the electrical conductivity of the reference sample remains almost invariant (it varies from 0.0178 S m^{-1} at 50 Hz to 0.0185 at 190 kHz), there is a strong increase in the electrical conductivity of the specimens containing rCF. The samples with C10/30 fibres present a seven-fold increase in the electrical conductivity on average, while the samples with CT12 fibres show a nineteen-fold increase on average. Although the number of fibres per unit volume of CT12 samples is larger than that of C10/30 samples, the presence of fibre bunches limits the electrical properties of the former. However, for frequencies above the capacitance threshold, the effect of the fibre bunches on the electrical conductivity is diminished and the electrical conductivity of both C10/30 and CT12 samples becomes equal.

The electrical properties of carbon fibre-reinforced cementitious composites depend mostly on two different parameters: the dispersion of the fibre in the cementitious matrix and the waviness of the carbon fibres. The goodness of fibre dispersion in the cementitious matrix will determine the presence of fibre agglomerates (clusters). Furthermore, the characteristics of the carbon fibres usually utilised in cementitious composites may affect its waviness and thus its actual length. Both parameters will determine the presence of a continuous path of fibres and thus the electrical conductivity of the composite. García-Macías [35] studied both the effect of clustering and waviness on the electrical conductivity of CNT cementitious composites. The results shown in figure 5 are consistent with the combined effect of clustering and waviness.

3.3. Piezo-resistive response of specimens under laboratory conditions

Figure 6 shows the load–voltage curves obtained for different concrete specimens made with different contents of C10/30 rCF during compression tests. First, it is noticeable that the reference specimen without rCF also shows a piezo-resistive effect. A small variation in the voltage curve can be observed repeatedly, coinciding with the maximum and minimum values of the applied load. The piezo-resistive responses were also observed using DC, and thus ionic effects can be observed in the voltage curve represented by the voltage drop from the start to the end of the test.

The introduction of the rCF has a remarkable effect on the voltage curve; it increases the amplitude of the voltage variation. The amplitude of the voltage variation depends on the rCF content and increases up to a fibre content of 0.8%. However, the introduction of rCF also affects the stability of the voltage curve and for fibre contents above 0.2%, the initial and final voltage is almost the same for different specimens. No evidences of the piezo-resistive effect were observed upon analysing the load–voltage curves obtained from flexural tests (see figure 7).

Similar load–voltage curves were obtained for the specimens containing CT12 fibres, indicating a piezo-resistive phenomenon during the compression tests (see figure 8), but no clear evidence of it was found during the flexural tests. The load–voltage curves in figure 8 present some distinctive features presenting more noise and more irregular patterns that those shown in figure 6. The different data obtained from the load–voltage curves during the compression tests are collected in table 3.

One of the parameters affected by the type of rCF used is the voltage drop measured during the piezo-resistive tests, as shown in figure 9. The voltage drop is related to the presence of the polarisation phenomenon because of the movement of electrical charges during the test. The polarisation phenomenon usually appears in cementitious materials when they are subjected to an electrical field. Wen *et al* have already shown that electrical polarisation diminishes when carbon fibres are

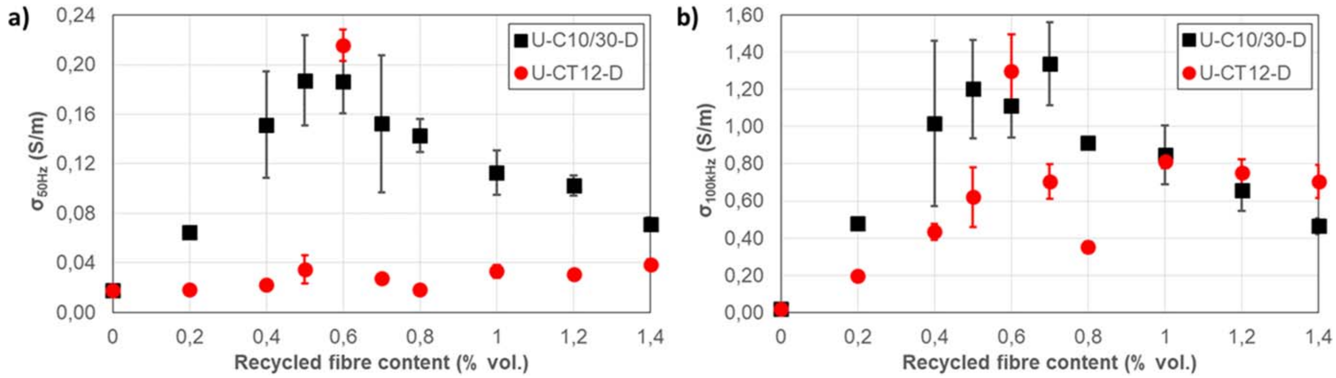

Figure 5. Variation of the electrical conductivity with the fibre content: (a) at 50 Hz, and (b) at 190 kHz.

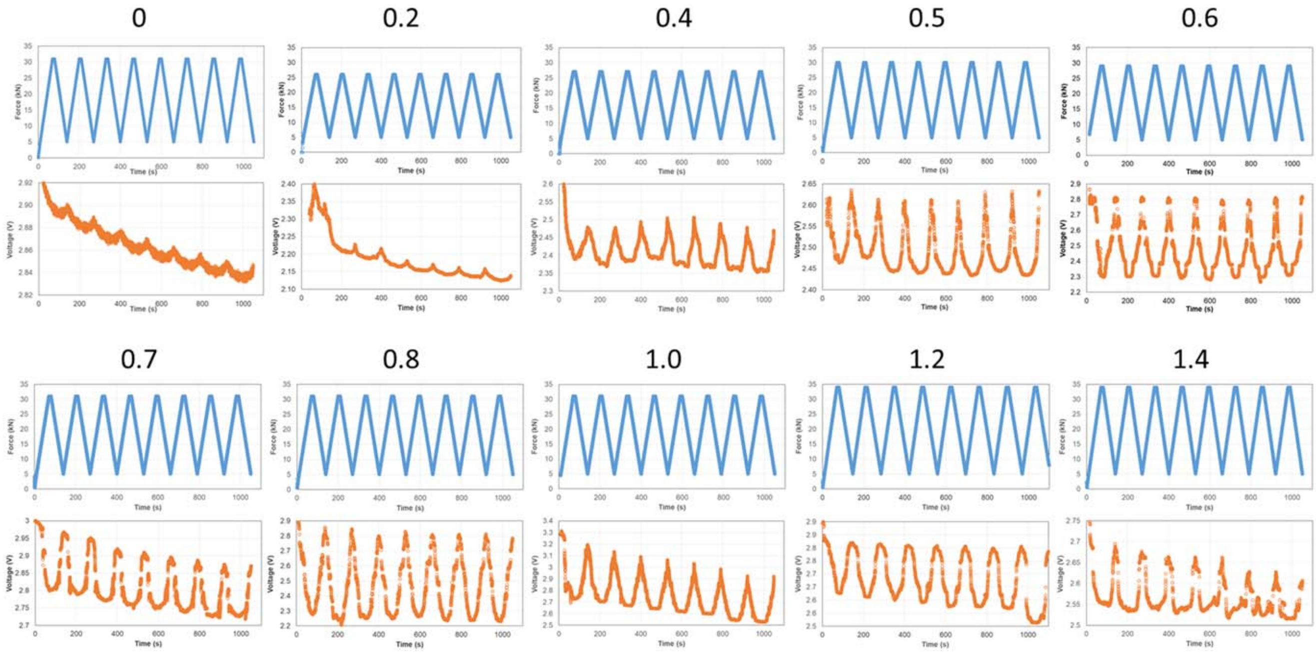

Figure 6. Load–voltage curves for the concrete specimens prepared with C10/30 rCF during the compression tests. The numbers above the curves indicate the rCF content of the concrete specimens.

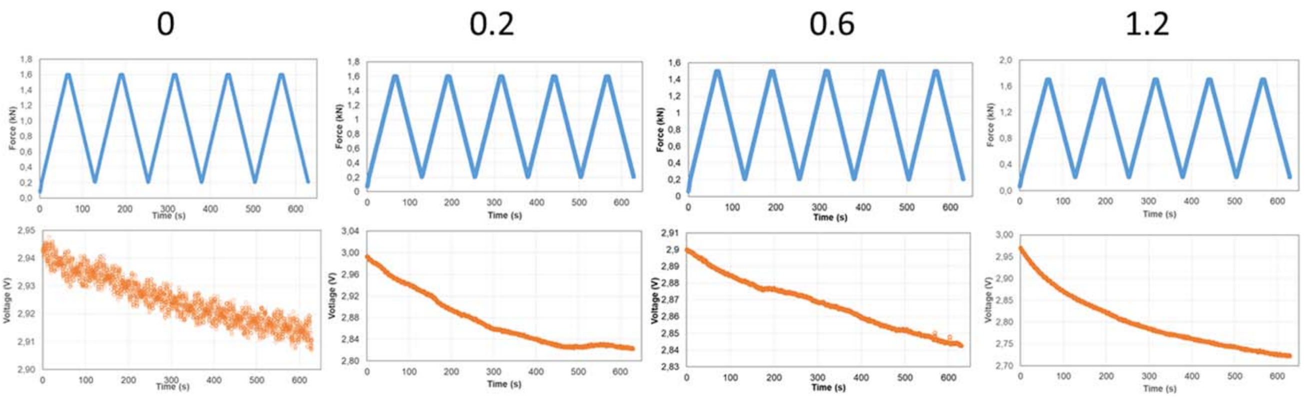

Figure 7. Load–voltage curves for the concrete specimens containing C10/30 rCF during the compression tests. The numbers above the curves indicate the rCF content of the concrete specimens.

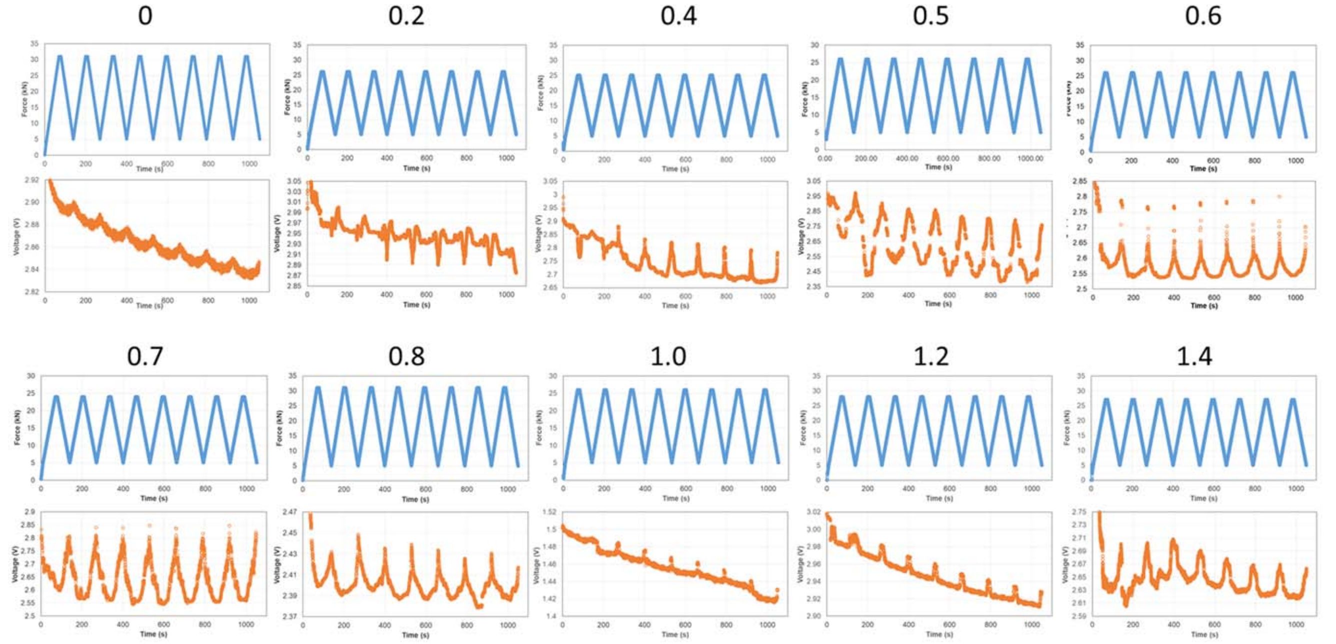

Figure 8. Load–voltage curves for the concrete specimens containing CT12 rCF during the compression tests.

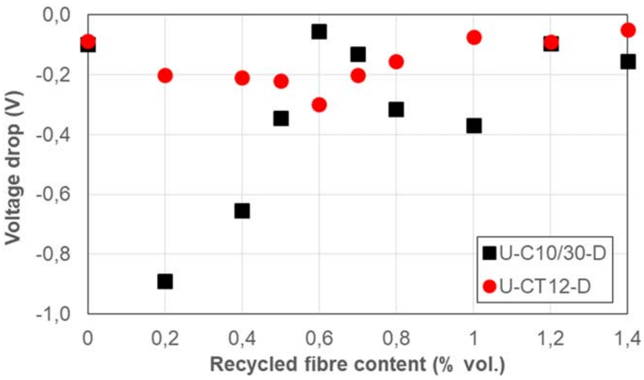

Figure 9. Voltage drop measured during the piezo-resistive tests.

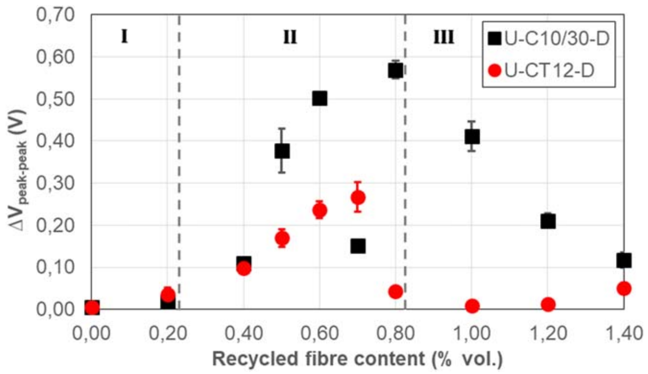

Figure 10. Variation of $\Delta V_{\text{peak–peak}}$ with the rCF content.

incorporated into cementitious matrices [36]. Samples incorporated with C10/30 fibres present very large voltage drops for low fibre contents, and the voltage drop diminishes with an increase in the rCF content. The voltage drop stabilises at approximately −0.1 to 0.2 V. A further increase in the voltage drop in C10/30 samples may be related to the presence of fibre bunches [28]. Samples incorporated with CT12 fibres present a voltage drop that almost shows no variation with the rCF content. For rCF contents below the percolation threshold value (∼0.6% vol), the voltage drop of CT12 specimens is lower than that of C10/30 samples.

The second parameter influenced by the type and content of rCF is the amplitude of the voltage variation ($\Delta V_{\text{peak–peak}}$). The variation of $\Delta V_{\text{peak–peak}}$ with the rCF content is very similar for concrete samples with both rCF types, C10/30 and CT12, as shown in figure 10, where three different zones can be identified. In zone I, for low rCF contents (below

Table 3. Parameters obtained from the load–voltage curves of concrete specimens with C10/30 and CT12 during the compression tests.

	C10/30		CT12	
rCF Content (%)	Voltage drop (V)	$\Delta V_{\text{peak–peak}}$ (V)	Voltage drop (V)	$\Delta V_{\text{peak–peak}}$ (V)
0	−0.09	0.005	−0.09	0.005
0.2	−0.89	0.02	−0.20	0.04
0.4	−0.66	0.11	−0.21	0.10
0.5	−0.35	0.38	−0.22	0.17
0.6	−0.06	0.50	−0.30	0.24
0.7	−0.13	0.15	−0.20	0.27
0.8	−0.32	0.57	−0.16	0.04
1	−0.37	0.41	−0.07	0.009
1.2	−0.09	0.21	−0.09	0.01
1.4	−0.16	0.12	−0.05	0.05

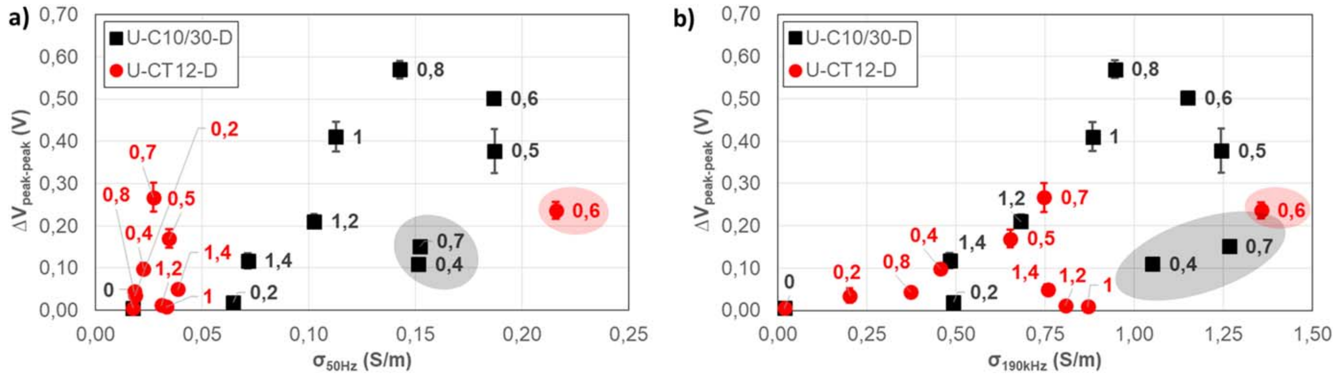

Figure 11. Variation of $\Delta V_{\text{peak–peak}}$ with the conductivity for each rCF type: (a) $\sigma_{50\ \text{Hz}}$, and (b) $\sigma_{190\ \text{kHz}}$ (outliers identified by shaded areas).

0.2% vol.), the $\Delta V_{\text{peak–peak}}$ values are very similar to that observed for the reference sample without rCF. Further increase in the rCF content results in a linear increase in $\Delta V_{\text{peak–peak}}$ up to the percolation threshold value. The slope of the linear variation in zone II is different for C10/30 and CT12 fibres, with the corresponding slopes being 1.02 and 0.49, respectively.

The observed behaviour can be explained considering the number of fibres per unit volume, N. For rCF contents below 0.4%, the differences in the numbers of fibres per unit volume of CT12 and C10/30 fibres are small, and thus low differences in is expected in the fibre dispersion. However, as the rCF content increases, so does the difference in N. Lastly, in zone III, $\Delta V_{\text{peak–peak}}$ diminishes with the fibre content because of the formation of fibre bunches in the cementitious matrix, although the variation is clearly influenced by the fibre type. The samples incorporated with CT12 fibre display a more drastic reduction in $\Delta V_{\text{peak–peak}}$ for rCF contents above the percolation threshold. Thus, the number of fibres per unit volume seems to play a specific role in the conductivity of the concrete, and thus on the observed piezo-resistive phenomenon.

However, some differences are observed when $\Delta V_{\text{peak–peak}}$ is analysed considering the conductivity of the samples (see figure 11). Considering the hypothesis presented, $\Delta V_{\text{peak–peak}}$ could be expected to increase with the conductivity of the specimens up to a maximum value related to the percolation threshold. The samples incorporated with C10/30 fibres agree with this hypothesis at both 50 Hz and 190 kHz, with some outlier values (clearly identified in figure 11 by shaded areas), which will be analysed further. However, samples incorporated with CT12 fibres do not agree with this behaviour when analysed at 50 Hz, but they agree when the values of $\Delta V_{\text{peak–peak}}$ are compared for $\sigma_{190\ \text{kHz}}$, with some outlier values.

The two values identified as outliers in the $\Delta V_{\text{peak–peak}}$ versus σ curve of the C10/30 samples were also outliers in the $\Delta V_{\text{peak–peak}}$–$V_f$ curve and correspond respectively to the values immediately below and above the percolation threshold (0.4 and 0.7% vol.) Similarly, the outlier in the $\Delta V_{\text{peak–peak}}$–$\sigma$ curve of the C10/30 sample corresponds to the rCF content at the percolation threshold (0.6% vol.). However, the trends observed in the $\Delta V_{\text{peak–peak}}$–$\sigma$ (figure 11) curves do not correlate completely with the σ–V_f curves (figure 5).

4. Discussion

Several researchers have proposed models to account for the piezo-resistive responses of conductive cementitious materials. The first studies on this topic were presented by Sun *et al* [37] and Wen and Chung [5]. More recently, García-Macías *et al* [35] presented a very detailed review on the available models and proposed a new three-dimensional mixed micromechanics-FEM modelling of piezo-resistive CNT smart concrete. Sun *et al* [37] described the observation of piezo-resistive effects in plain cementitious materials and explained it in terms of a solid–liquid interface double-layer model. In this situation, when a compressive force is applied, the ions in the double-layer are transported to the cement pore solution because of the interface shear stress. Thus, charges accumulate and a streaming potential difference arises. The load–voltage curve of the reference samples (figure 6) presents two different phenomena during loading and unloading. During the loading of the sample, the voltage decreases because of a leakage of charges through the conductive paths of the cementitious matrix and the flow of the cement pore solution. During unloading, a part of the solution refills the vacated pores and the voltage is increased. When the rCFs are incorporated into the cementitious matrix, the mechanism is mostly similar because of the cementitious paste that coats the carbon fibres. Two adjacent carbon fibres will always be surrounded by cementitious paste, but the thickness of this interface reduces as the rCF content is increased.

Thus, the incorporation of rCF does not alter the main mechanism of piezo-resistivity but amplifies the effect by increasing the signal-to-noise ratio. The signal-to-noise ratio, *SNR*, (in dB) is estimated by equation (8), as the ratio of the value of a given parameter ($\sigma_{50\ \text{Hz}}$, $\sigma_{190\ \text{kHz}}$, or $\Delta V_{\text{peak–peak}}$) for a concrete sample with a given rCF content to that of the same parameter for the plain concrete sample:

$$\text{SNR} = 10 \cdot \log(P_{signal}/P_{noise}). \tag{8}$$

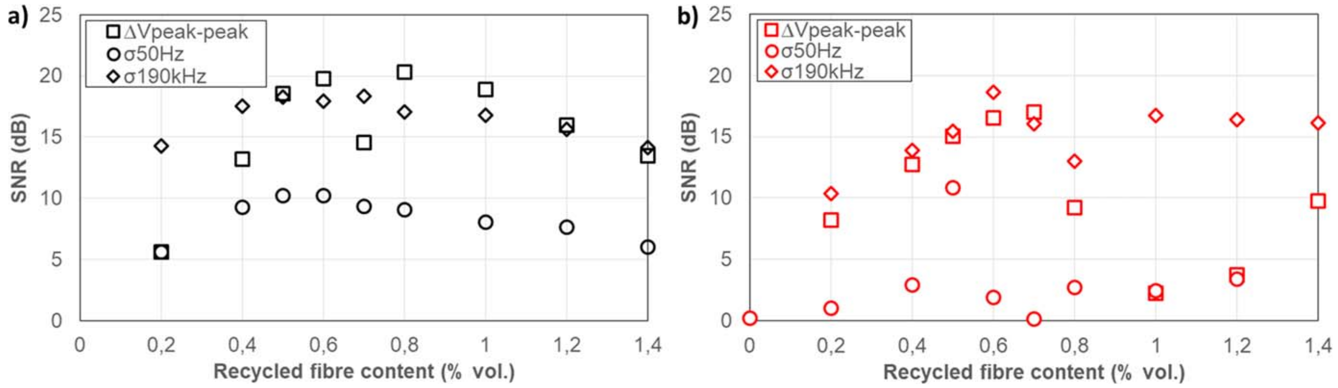

Figure 12. Variation of the SNR of $\sigma_{50\ \mathrm{Hz}}$, $\sigma_{190\ \mathrm{kHz}}$, and $\Delta V_{\mathrm{peak-peak}}$ for (a) U-C10/30-D specimens, and (b) U-CT12-D specimens.

Table 4. Average values of SNR for different parameters and rCF types.

SNR (dB)	Fibre type	
	C10/30	CT12
$\sigma_{50\ \mathrm{Hz}}$	8.4	2.8
$\sigma_{190\ \mathrm{kHz}}$	16.7	15.2
$\Delta V_{\mathrm{peak-peak}}$	15.6	10.5

The influence of the rCF content on the SNR is presented in figure 12, where two different behaviours can be identified. First, the SNR of $\sigma_{50\ \mathrm{Hz}}$ and $\sigma_{190\ \mathrm{kHz}}$ presents a slight increase for rCF contents below the percolation threshold and stabilizes for further increases in the rCF. The average SNR values of $\sigma_{50\ \mathrm{Hz}}$ and $\sigma_{190\ \mathrm{kHz}}$ differ significantly for a given fibre type, as shown in table 4. Moreover, the average SNR values $\sigma_{50\ \mathrm{Hz}}$ also differ significantly for C10/30 and CT12 fibres, however, on the contrary, the SNR values of $\sigma_{190\ \mathrm{kHz}}$ are very similar. The conductivity measurements for frequencies below the capacitance threshold (50 Hz) are controlled by the fibre–matrix interface, and thus by the dispersion of the carbon fibres.

As discussed previously, the specimens incorporated with CT12 fibres in our study are more likely to present fibre bunches than the ones incorporated with C10/30 fibres, because of the larger number of fibres per unit volume of the former. Therefore, the SNR of $\sigma_{50\ \mathrm{Hz}}$ reflects the influence of the fibre–matrix interface. However, for frequency values above the capacitance threshold (190 kHz), the conductivity values are mainly influenced by the electronic conduction and the effects of the fibre–matrix interface are reduced. Thus, the SNR of $\sigma_{190\ \mathrm{kHz}}$ is very similar for both fibre types. The variation in the SNR of $\Delta V_{\mathrm{peak-peak}}$ with the rCF content presents a mixed behaviour between $\sigma_{50\ \mathrm{Hz}}$ and $\sigma_{190\ \mathrm{kHz}}$. For values below the percolation threshold, the SNR values of $\Delta V_{\mathrm{peak-peak}}$ are similar to those of $\sigma_{50\ \mathrm{Hz}}$. This behaviour is observed in the samples incorporated with both C10/30 and CT12 fibres. For rCF contents above the percolation threshold, the SNR of $\Delta V_{\mathrm{peak-peak}}$ varies depending on the fibre type: for the C10/30 samples, the SNR almost shows no variation with increasing rCF content, whereas for the CT12 specimens, there is a strong decrease in the SNR followed by an increase for larger rCF contents. This mixed behaviour may be attributed to a mixed control of the piezo-resistive phenomena in these samples. For rCF contents below the percolation threshold, the main controlling factor is the fibre–matrix interface, whereas for larger rCF contents, the controlling factor varies between the electronic transfer mechanism and the fibre–matrix interface, depending on the characteristics of the fibre dispersion in the cementitious matrix.

The observed behaviour is in agreement with previous observations by Sun *et al* [38], which were more recently confirmed by Baeza *et al* [39], who proposed a constitutive model for the electrical behaviour of carbon fibre-reinforced composites. This model includes four possible conductive mechanisms: (1) ionic conductivity, (2) conductivity due to electronically conductive fibres in the cement matrix and conductive holes, (3) conductivity due to electronically conductive paths between the fibres and the continuous conductive holes, and (4) conductivity due to electronically conductive fibres passing through the conductive network past the conductive hole. For a sample with low carbon fibre content, the main conductive mechanisms are (1) and (2). As the fibre content increases, electrical conduction occurs mainly via mechanisms (2) and (3). When the fibre content is increased above the percolation threshold, mechanism (4) becomes the main pathway. Therefore, the piezo-resistive phenomena shown in figures 6 and 8 reflect both the influence of the fibre–matrix interface and the electronic transfer mechanism. For low rCF contents, the thickness of the fibre–matrix interface is large and so is the distance between the carbon fibres. Thus, for low rCF contents the fibre–matrix interface in the cementitious matrix will control the piezo-resistive response of the composite. As the rCF content is increased up to the percolation threshold, the thickness of the cementitious matrix surrounding the fibres reduces, and thus the electronic transfer mechanism becomes dominant in the piezo-resistive phenomenon. For rCF contents above the percolation threshold, the presence of fibre bunches and the effect of the fibre waviness will determine the observed behaviour, and thus the fibre–matrix interface increasingly influence the piezo-resistive behaviour.

5. Conclusions

The piezo-resistive phenomenon observed in cementitious materials is inherent to their porous structure and the enclosed aqueous solution. The piezo-resistive effect in these materials could be increased by incorporating carbon fibres. In this article, we demonstrated that rCFs can also be incorporated in cementitious composites to increase their piezo-resistive responses. Furthermore, we showed that the main parameters that control the electrical behaviour of carbon fibre-reinforced cementitious composites (fibre dispersion and fibre waviness) also determine the piezo-resistive responses of our cement composites. For rCF contents below the percolation threshold, the piezo-resistive response is mainly controlled by the thickness of the cementitious paste surrounding the rCF, and thus small piezo-resistive response was obtained. When the rCF was increased, the electronic transfer mechanism started to control the electrical behaviour, and thus the piezo-resistive response increased. However, for rCF contents above the percolation threshold, the presence of fibre bunches and the waviness of the carbon fibres determine the main parameter that controls the electrical behaviour: (i) the fibre–matrix interface and thus the ionic conductivity or (ii) the electronic conduction. The results presented in this paper open new possibilities for the development of smart cementitious materials that can be introduced into civil engineering structures. The use of rCF and of fabrication procedures similar to those used by the civil engineering industry allow the development of cementitious composites with properties that are equivalent to those of materials fabricated with expensive carbonaceous materials or using sophisticated fabrication and dispersion protocols.

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ORCID iDs

I Segura https://orcid.org/0000-0001-6519-9899
J M Torrents https://orcid.org/0000-0002-8289-6706
A Aguado https://orcid.org/0000-0001-5542-6365

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