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Smart Self-Sensing Cement-based Composites with Carbon microfibers: experimental tests on Small-scale Beam Elements †

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Abstract: Advanced composite cementitious materials with multifunctional properties can be created by incorporating fillers and inclusions via appropriate production, characterization, and assembly processes. These composites have unique characteristics tailored for specific applications. Particularly, cementitious composites with conductive particles and piezoresistive properties enhance mechanical strength and monitoring capabilities. They assess structural integrity, monitor stress, strain, load variation, and detect incipient hazardous conditions throughout building lifespans. This improves maintenance, renovations, and structural modifications, ensuring safer and longer-lasting facilities. This paper presents experimental results of cement-based materials with carbon microfibers for structural beam elements. The samples self-diagnose internal non-uniformities, defects, fractures, and evaluate deformation variations.

Keywords: Carbon-based fillers; Smart Composites; Structural health monitoring; Sustainable composites; Advanced materials; Carbon microfibers; Fiber reinforced concrete; Smart monitoring; Multifunctional building materials

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1. Introduction

Structural concrete is the most widely used construction material for building structures and infrastructure in civil engineering. The need to limit its environmental impact while retaining its advantages in terms of ease of execution and versatility has led to the development of multifunctional cementitious materials. This work explores the advanced topic of novel concrete with enhanced properties. In particular, it investigates concrete elements created by adding carbon microfibers, which provide self-monitoring capabilities. The idea is to construct structures that are not only resistant but also capable of monitoring their own performance, assessing their deformation status, and identifying any critical conditions, loss of strength, critical loads, or incipient crack formations. The study has highlighted the material's sensitivity at a medium scale, necessary for further real-world technology development. Through compressive load tests and electrical measurements, the concrete added with carbon microfibers has demonstrated sufficient self-monitoring properties for potential applications in the construction industry. With respect to available literature works, which focus essentially on cement paste or mortar samples investigating physical and mechanical properties at small-size dimensions, this paper is aimed at investigating the feasibility of applications in real structural elements, where the presence of coarse aggregates could affect the smart capabilities of the material. Results on both electrical and electromechanical experimentations paved the way to the possible realization of concrete structures able to characterize the evolution of strain fields, and the formation and propagation of damages and crack paths.

2. State-of-the-art

In recent years, concrete technology has seen significant advancements thanks to progress in the fields of chemistry and materials science. The availability of innovative fillers suitable for incorporation into cementitious matrices has opened up possibilities for enhancing the mechanical properties and durability of construction materials [1]. Particularly promising are carbon-based particles and fillers, which have gained attention for various engineering applications. In both the market and the literature, a variety of carbon fillers with nanometric or micrometric dimensions are readily available [2], all composed of carbon atoms. Examples of these carbon inclusions include carbon nano- and microfibers, carbon nanotubes, graphene, carbon black, and graphite, which find widespread use in civil engineering applications [3-5]. Research efforts in the literature typically focus on investigating the mechanical strength and multifunctional capabilities of cementitious materials infused with carbon fillers. These conductive fillers exhibit impressive mechanical and electrical properties, making them well-suited for self-sensing applications in structural health monitoring [6,7]. Smart cementitious materials containing carbon inclusions have the unique ability to monitor their own strain and stress states: this allows construction materials used in building structures and infrastructure to serve as sensors, providing insights into their performance and integrity [8-10]. They can even detect early signs of damage; such as cracks or structural changes resulting from exceptional events or variations in usage [11-12]. Existing literature predominantly focuses on cement-based matrices, including cement pastes and mortars, and small-scale samples [13,14]. However, the behavior of concrete smart composites and larger-scale elements remains an underexplored area. This paper sets out to investigate the feasibility of producing full-scale structural elements using self-sensing concrete for practical applications. Scaling up this technology presents challenges, including ensuring proper filler dispersion to achieve material uniformity, addressing potential adverse effects of coarse aggregates on strain sensitivity, and optimizing the selection and placement of electrodes in larger structures [15-16]. The authors have conducted various research endeavors aimed at enhancing the self-monitoring capabilities of cement-matrix materials [17,18]. In this paper, they extend their focus to self-sensing concrete elements. The paper begins by describing the custom-designed smart concrete materials and setup, presenting the results of experimental tests, encompassing both electrical and load sensing evaluations. Subsequently, the paper meticulously reports and discusses the findings from these experiments.

3. Materials and methods

The samples investigated in this paper are medium-scale concrete beams with Carbon Micro Fibers (CMFs), equipped with copper wires with diameter of 0.8 mm placed in diffuse points, to monitor different configurations according to applications (Figure 1(b)). In particular, the first configuration is obtained through the embedding of 12 electrodes placed in three lines, adopted for resistance mapping, while the second configuration consisted on 8 electrodes aligned in the center of the sample, used also for sensing tests (Figure 2(a)).

3.1. Components and devices

3.1.1. Raw materials

Smart concrete was obtained by mixing of Portland cement type 42.5R, fine and coarse quarry aggregates, and 6-mm chopped CMFs provided by SGL Carbon, type SIGRAFIL®. The fillers were added in the percentage of 0.05% with respect to the weight of the cement. The water to cement ratio adopted for all the mixes was 0.5. Such mix design was determined by the authors by previous research investigations [17-18].

3.1.2. Samples and setup

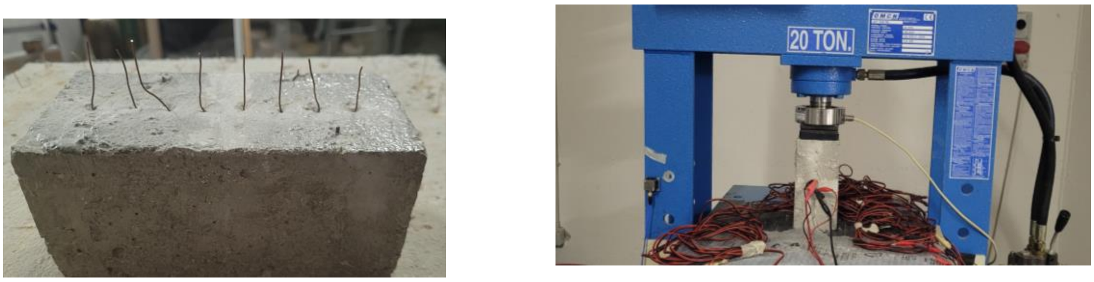
A function generator RIGOL DG1022, powered the samples with a 20V peak-to-peak voltage square wave, using a frequency of 1 Hz and a duty cycle of 50%. Voltage measurements were performed at every couple of electrodes by using a multichannel analog input module, model NI PXIe-4302, housed inside a chassis, NI PXIe-1073, with a sampling rate of 10 Hz. The electrical resistance of each section of the tested samples, R(t), was obtained from the first Ohm's law (Figure 1(a)):

$$R(t) = V / I\,(t) \tag{1}$$

where V is the voltage drop measured at a couple of electrodes, sampled at 80% of the positive signal output, and I is the current within the circuit, computed by considering the voltage drop at the reference resistor placed in line with the tested sample. The so obtained electrical resistance values were interpolated to obtain electrical resistance maps for the detection and location of defects, imperfections, voids, or cracks within the samples. The Ordinary Kriging interpolator was used to process the electrical data [19]. Load tests were performed recording the voltage drop was in the subsequent sections in the samples as well as at the reference resistor of 1 kΩ placed in series (Figure 1(b)).

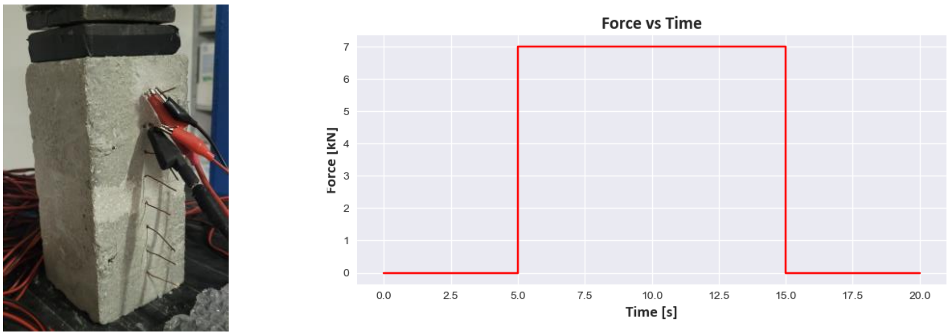
(**a**) (**b**)

Figure 1. Experimental setup: (**a**) Electrical tests; (**b**) Detail of a sample during electrical tests.



(**a**) (**b**)

Figure 2. Samples with aligned electrodes (**a**) After curing period; (**b**) Equipped during load tests



(**a**) (**b**)

Figure 3. Sensing tests (**a**) Detailed view during the compressive sensing tests, (**b**) Load history.

External loads were step constant forces of 7 kN (Figure 3) applied through a hydraulic press, with a maximum load capacity of 20 tons (Figure 2(b)).

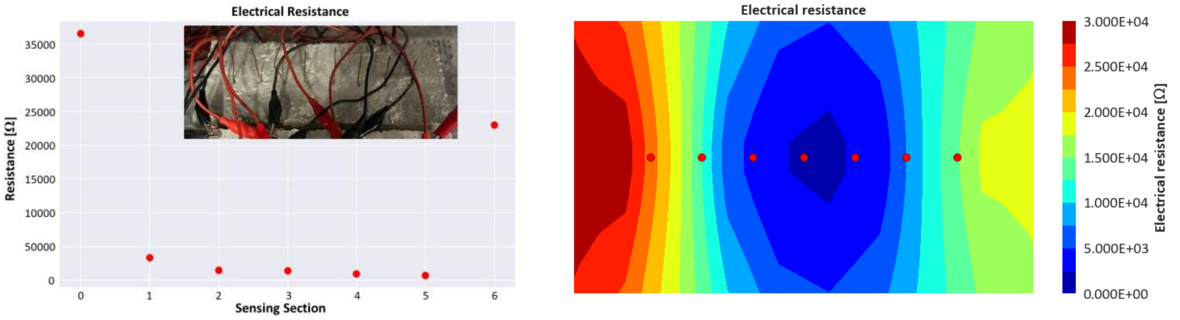
3.2. Tests

The tests carried out on the samples were designed to investigate the monitoring capabilities of different electrical setups on elements made of smart structural materials. The first ones were aimed at identifying the resistance of local segments, and the presence of inhomogeneities which could affect its distribution. The second type of experimental test analyzed the sensing capabilities of different sections of the elements.

4. Results

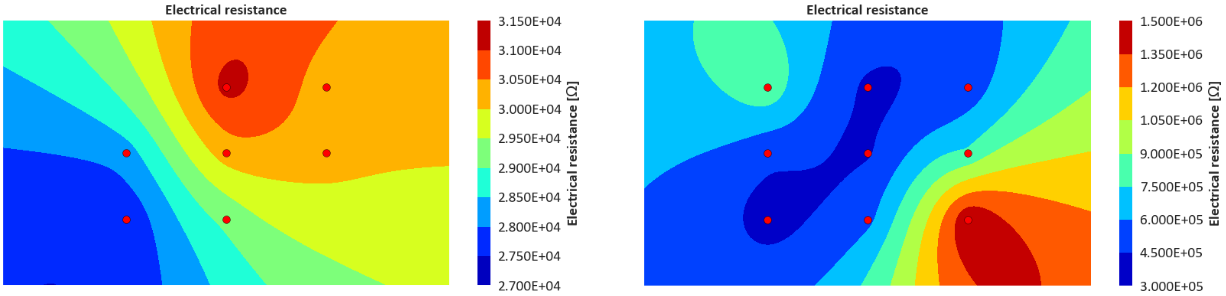
4.1. Resistance mapping

Figure 4(a) represents the resistance obtained on the samples with aligned electrodes, measuring simultaneously on all the segments the voltage drops under the same current. Clearly, the end segments show high variability due to the effect of the contact resistance. The map generated by all the segments (Figure 4(b)) identify a greater conductivity in the center of the sample, probably due to the higher level of compaction occurred during the preparation which corresponds to a minor presence of voids and imperfections. Electrical mapping on the sample with distributed electrodes is also investigated to explore the variability in the consistency of internal composite material. It should be noted, however, that the analysis of the bidimensional problem would necessitate to formulate an appropriate conduction model (e.g. a bidimensional mesh of resistors) which is left for future work. The aim, in this case, is to preliminarily verify the possibility of carrying out distributed measurements and checking to some extent the homogeneity of the material.



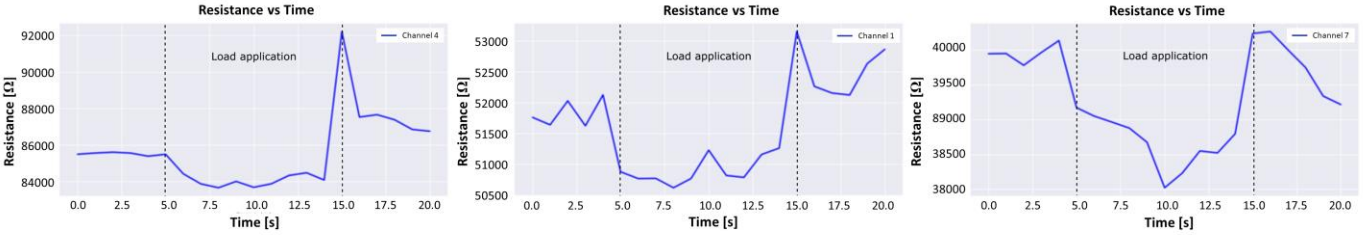
(**a**) (**b**)

Figure 4. Electrical mapping on the sample with aligned electrodes (**a**) Obtained resistance on the sections; (**b**) electrical resistance map in the unloaded state.



(**a**) (**b**)

Figure 5. Electrical mapping on the sample with distributed electrodes: (**a**) from central section; (**b**) from all the sections.



(a) (b) (c)

Figure 6. Resistance variation during sensing compressive tests on the sample with aligned electrodes from segments (**a**) on the top; (**b**) in the center; (**c**) on the bottom of the sample.

Variations could be due also by concentration of conductive fillers in specific areas of the sample, or to the imperfections which could occur near the electrodes due to the concrete shrinkage during the curing period. Moreover, Figures 5(a) and (b) demonstrate the differences that could occur through various electrical setups: in this case between the measurements achieved through the central electrodes, or through all the segments considered in series. This configuration permits to obtain an evaluation of the internal distribution of resistance, sign of variations in internal homogeneity of the composite.

4.2. Sensing tests

Figure 6 reports the time histories of the resistances obtained on the samples with aligned electrodes, from segments at different heights. The graphs of Figures 6(a), (b) and (c) were obtained during compressive step loads on the sample with aligned electrodes, positioned in vertical, through the electrical measurements taken at the segments located in the upper, central, and bottom zones, respectively. The variation in the internal material, contact resistance, local peculiarities provided differences in the output although the applied load was the same, and centered. In all the segments, a certain sensitivity is observable with a decrease in resistance under applied compression load. However, noise is significant and after removing the load the sample exhibits smaller values of electrical resistance compared to the initial part of the test. Both aspects deserve further study which go beyond the purposes of this preliminary investigation.

5. Conclusion

The present paper aimed at investigating the potential sensing properties of concrete elements doped with conductive and piezoresistive carbon microfibers, able to monitor their state of strain and stress, and their integrity, for possible Structural Health Monitoring of real-scale structures. The scaling, from small sample made of cement paste, whose investigation is quite diffuse in literature, to concrete elements needs the evaluation of key points, as the influence of aggregates, the local effects, the multiple electrodes setup. The preliminary results shown in this paper demonstrate the feasibility of the development of sensing concrete elements for the control of the performance and of the internal properties of complex elements.

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