

Article

Mechanical and Durability Investigation of Composite Mortar with Carbon Microfibers (CMF)

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Featured Application: The research is devoted to enhancing the understanding of the behavior of an innovative cement mortar composite with carbon microfibers, for its adoption as a multi-functional construction material. As an example, such a new composite material with conductive one-dimensional carbon fibers could become as a strain-sensing mortar for masonry or a smart repair material for concrete buildings, enabling self-monitoring capabilities.

Abstract: This paper investigates the mechanical properties and the durability implications of innovative cement-based mortars doped with carbon microfibers. In particular, mixes with different amounts of carbon additions are produced, and the properties of fresh and hardened samples are analyzed through workability, water absorption, and compressive and flexural tests under specific environmental conditions. These composites can be employed to enhance construction performance or provide structures with strain-monitoring capabilities. However, the analysis of their mechanical properties and their durability behavior is needed before extensive structural use. In this work, the preparation procedure is defined for the various mix designs, considering different amounts of carbon microfibers; then, fresh properties are evaluated, and different types of samples formed. After various curing times, the specific rheological and hardened properties of the specimens are tested in different conditions to consider the durability of the composites, essential for the real-scale adoption in structural elements. Preliminary electrical and sensing tests are first conducted to evaluate the monitoring potential of the investigated composites. The findings highlight the impact of carbon inclusions on the performance of cement-based mortars, offering valuable insights for their utilization in masonry construction or for repairing concrete structures. In particular, sensing capabilities are found to be highly enhanced by the presence of CMF. Additionally, the results of this research pinpoint key areas for further analysis in the material's development process.

Keywords: smart cement mortars; carbon microfibers; rheological and mechanical properties; fresh and hardened cementitious materials; durability; concrete building materials; cement-based composites; smart monitoring; conductive mortars



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1. Introduction

The enhancement of cementitious materials, the most used material worldwide in the construction field, is a crucial topic with quite interesting implications in the management of cities and on the impact of the quality of life of people. Safety and sustainability are the keywords for a better living, both at the personal and global levels. In this sense, the modification of mix designs of cementitious materials plays a significant role for the improvement of properties and the development of multifunctional composites [1,2]. This research is focused on the multi-purpose investigation into cementitious mortars enhanced with carbon microfibers (CMF) for construction purposes and to underscore the efficacy of integrating carbon fibers into cement-based materials, building upon the findings of the authors' prior research works [3,4]. Notably, these studies have elucidated the fibers'

capacity to not only bolster mechanical strength but also enhance various other attributes, thereby giving rise to versatile and multifunctional materials [5–8].

In particular, the present research endeavors to delve into the analysis of the feasibility of manufacturing innovative mortars tailored for construction applications, such as for masonry construction and for repairs of concrete structures, with the subsequent purpose of developing a composite with self-monitoring properties. The specific application, that will include the construction of real-scale masonry structures, represents a novelty that needed a peculiar investigation for tailoring the material for building practices. Prior to embarking on an extensive exploration of this intriguing aspect, the authors are committed to a general examination of the physical, rheological, and mechanical characteristics of the material. This prelude is essential to gain understanding of the material's mixes and unveil its potential as a composite, particularly with increasing concentrations of carbon microfibers. The selected carbon microfibers have been specifically chosen by the authors for their peculiar properties, having been previously evaluated as highly suitable for mechanical dispersion within the material, anticipating real-world applications on a substantial scale [9,10]. The article systematically recounts the laboratory tests conducted on standardized samples, adhering to tests prescribed by European standards [11–15]. Sensing performance of the developed doped composites is evaluated for demonstrating the feasibility of the novel proposed smart material. These tests serve as a crucial platform for unraveling the material's behavior under various conditions, offering valuable insights into its robustness and its potential for widespread practical use in the construction industry.

2. State-of-the-Art

Recent years have seen significant strides in concrete technology, propelled by advances in chemistry and materials science. The introduction of innovative fillers into cementitious matrices has played a crucial role in elevating the mechanical properties and durability of materials [16]. Shu et al. [17] demonstrated, through laboratory tests, that hybrid carbon fiber mixes exhibited superior tensile performance, improving the mortar's fracture resistance, although all the fiber reinforcement enhanced the pre-peak load energy absorbing capacity. In particular, carbon nanofibers (CNFs) and milled carbon microfibers (MCMFs) enhance the cracking resistance of cement-based materials by effectively bridging cracks [6]. The specimens' roughness exhibited an upward trend with an increase in fiber volume fraction, also demonstrating a positive correlation with mechanical properties, including the peak load in tension and flexure [7]. An experimental investigation on mechanical performance, energy absorption, electrical conductivity, and piezoresistive sensibility of carbon-doped cementitious mortars [8] indicated enhancements in flexural strength, toughness, and electrical conductivity, approximately by an order of magnitude, when compared to the reference specimens. Carbon-based particles and fibers hold promise for engineering applications. In the market and across the literature, various types and shapes of carbon fillers exist, all composed of carbon atoms, varying in size from nanometric to micrometric. Common carbon inclusions for civil applications include carbon nano- and micro-fibers, carbon nanotubes, graphene, carbon black, and graphite [4,18,19]. In particular, these carbon-based fillers exhibit excellent mechanical and electrical capabilities for building materials, with one promising application being the enhancement of conductivity, and other electrical properties, as the self-sensing capability for structural health monitoring [20,21]. Indeed, properly produced and tailored smart cementitious materials with carbon inclusions can monitor their state of strain and stress [22,23]. The construction material itself, forming structures and infrastructures, can serve as a strain sensor for assessing building performance and integrity conditions. Furthermore, it can identify cracks or incipient damages caused by exceptional events or variations in usage [24,25]. The existing literature predominantly explores cement-based matrices (such as cement pastes or mortars) and small-sized samples [26–28]. Nevertheless, the behavior of concrete smart composites and medium- to high-scale elements, together with the investigation of the tailored setup and implementation, remains largely unexplored territory,

but are essential for real application of this technology [9,29,30]. Challenges associated with scaling this technology include ensuring the proper dispersion of fillers to achieve a homogeneous material, addressing potential adverse effects of coarse aggregates on strain sensitivity, and optimizing the type and placement of electrodes in large structures [31–33]. The literature presents works about the enhancement of fibers dispersion that could be effective for real-scale constructions, and tailored applications at higher scales could have interesting developments, [34,35]. In light of the interest demonstrated in the literature, this paper seeks to examine the feasibility of producing cementitious cement mortar with carbon microfibers for full-scale applications in concrete structures (e.g., for local repairs) and masonry. The paper begins by describing the peculiarities of the materials and of the preparation procedures, and the tests/standards adopted for the fresh and hardened material characterization. Both rheological and mechanical tests are performed on composites with different amounts of microfibers, as presented in Section 3. The obtained results are discussed in Section 4, followed by an exploration of conclusions, evidence, and future perspectives in the subsequent section.

3. Materials and Methods

The composite materials investigated in this research are cement-based mortars with carbon microfibers. The purpose is to evaluate the workability properties of the composites with increasing amounts of fibers, and to test physical, rheological, and mechanical capabilities of the developed materials to identify the most promising one for full scale applications in constructions.

The following paragraphs will describe the materials, the preparation procedures for all the mixes, and the standards adopted for the experimental evaluations.

3.1. Mix Designs

Normal and doped mortar was achieved through the combination of Portland cement type 42.5R, quarry aggregates with grains in the dimensional range of $0 \div 3$ mm, and 6-mm chopped CMFs (SIGRAFIL[®] type C C6-4.0/240-G100) supplied by SGL Carbon. The sand was added in the ratio of 3.5 with respect to the volume of the cement, as is typical for mortars produced for construction. The specific microfibers were selected due to their compatibility with water-based systems. Such carbon fibers are obtained through the cutting of continuous carbon fiber tows, obtaining a short reinforcing filler for functional addition. Their primary application lies in the production of compounds for the enhancement of strength, stiffness, and conductivity of various types of binders. The main properties of the fibers are reported in Table 1. Microfibers were incorporated at relative amounts of 0, 0.01, 0.05, 0.1, 0.25, 0.5, and 1% with respect to the weight of the cement. Greater amounts of CMF were considered in the investigation for identifying the maximum theoretical doping level of this type of composites. A consistent water-to-cement ratio of 0.7 was employed across all mixes. Table 2 reports the composition of the mix designs adopted in the research.

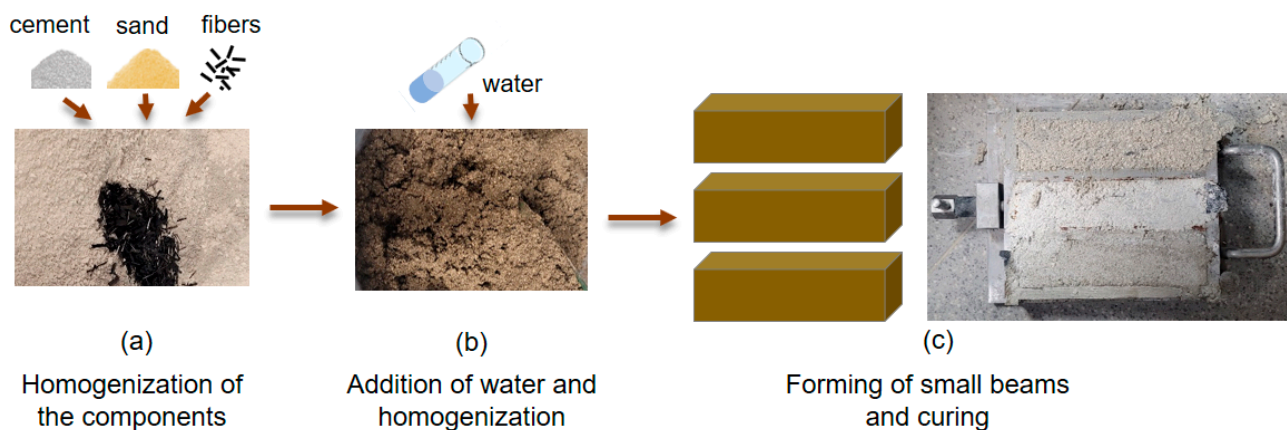
Table 1. Physical and performance properties of carbon microfibers.

Property	Value	Units
Fiber density	1.80	g/cm ³
Fiber length	6	mm
Fiber diameter	7	μm
Tensile strength	4.0	GPa
Tensile modulus	240	GPa
Bulk density	1.7	g/L
Single filament resistivity	15	μΩm
Sizing type	glycerin	-

Table 2. Mix design of the investigated cement materials with carbon microfibers.

Component	Normal Cement Mortar [g]	Doped Cement Mortar [g]
Cement C	600	600
Sand S	1950	1950
Water W	420	420
Carbon Microfibers	-	0.06 ÷ 6.00
W/C ratio	0.7	0.7

Figure 1 shows the main steps for the preparation of the mortar samples doped with carbon fibers. The procedure chosen for the preparation of all the mix designs adheres to typical standards used for masonry constructions. The use of chemical dispersants or procedures is not envisaged, since their effect could affect physical, mechanical, and electrical, performance of the composites. The aim is to produce comparable and replicable composites. First, the powder components were homogenized through manual mixing (Figure 1a). In particular, the carbon microfibers were first manually separated and then added to avoid, as much as possible, agglomerations during the pouring and mix. Then, the water was slowly introduced, and the compound mixed for five minutes until it became smooth (Figure 1b). The material was subsequently tested for density and for workability, and then poured into standard prismatic molds for mortar, namely $40 \times 40 \times 160 \text{ mm}^3$ (Figure 1c). The samples were unmolded after 24 h and cured in a laboratory environment for 28 days. After the curing time, permeability and mechanical tests were performed. For each mix, i.e., for the reference one and the six doped ones, six samples were produced. The seven types of investigated mortars, with different amounts of carbon doping, were labeled with three numbers that defined the percentage of microfibers, with the precision note in the second digit after comma (e.g., N005C is referred to a mortar with 0.05% of CMF with respect to the weight of the cement).

**Figure 1.** Preparation procedure of cement mortars with carbon microfibers.

All tests followed the indications of the European standards, as described in the next sections. Tests were performed on both the fresh and hardened material. In the fresh state, density and workability were carried out, while hardened samples were subjected to flexural, compressive, and permeability tests.

3.2. Type of Tests and Standards on the Fresh Material

3.2.1. Density

Density was determined following the standard “UNI EN 1015-6:2007 [11]. Determination of bulk density of fresh mortar” by use of a cylindrical bowl with an internal diameter of 125 mm and capacity of 1 L (Figure 2a). In particular, following the code prescriptions, the vessel was filled with the mortar two times (compacted and levelled).

The bulk density of fresh mortar was evaluated from the following formula:

$$\delta = \frac{m_2 - m_1}{V_v}$$

where:

- m_1 is the mass of the empty vessel (g);
- m_2 is the mass of the vessel filled with mortar (g);
- V_v is the volume of measuring vessel (l).

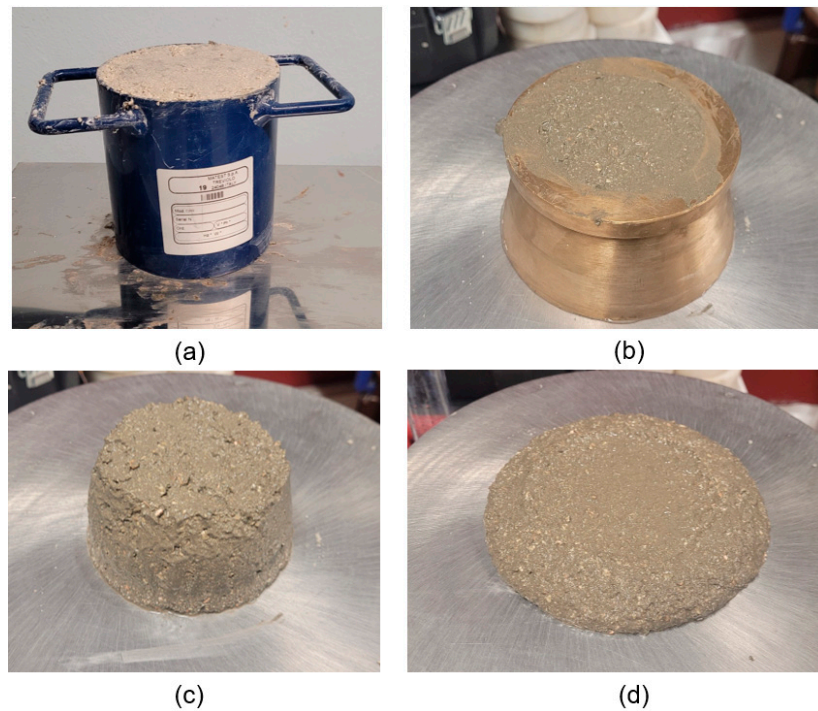


Figure 2. Instruments and procedures for testing of fresh materials: (a) weight of measuring vessel for density, (b) filling of the mold on the flow table for workability, (c,d) appearance of the material before and after the consistence test, respectively.

3.2.2. Workability

The workability properties of all the compounds were evaluated through the methodology described in “UNI EN 1015-3:2007 [12]. Determination of consistence of fresh mortar (by flow table)”. Consistency evaluates the fluidity and the wetness of the material under stress and is essential for the real use of the material, as it characterizes the easiness and feasibility of handling the sample/element production before hardening. The test was carried out by filling a metallic conical mold with the fresh mortar in two layers (Figure 2b). The mortar (Figure 2c) was spread on the disc by jolting the flow table 15 times at a constant frequency of approximately one hertz (Figure 2d). The resulting measure of the consistency was achieved averaging the dimensions of two diameters at right angles.

3.3. Type of Tests and Standards on the Hardened Material

3.3.1. Water Absorption

Water absorption was evaluated from the procedure defined in “UNI EN 1015-18:2004 [13]. Determination of water absorption coefficient due to capillary action of hardened mortar”. After drying in oven at 60 °C to constant mass, one face of the specimen was immersed in 10 mm of water for 90 min; the increase in mass was measured after 10 min and at the end of the immersion period (Figure 3a). The samples were constituted by broken prisms, with the broken faces placed downwards.

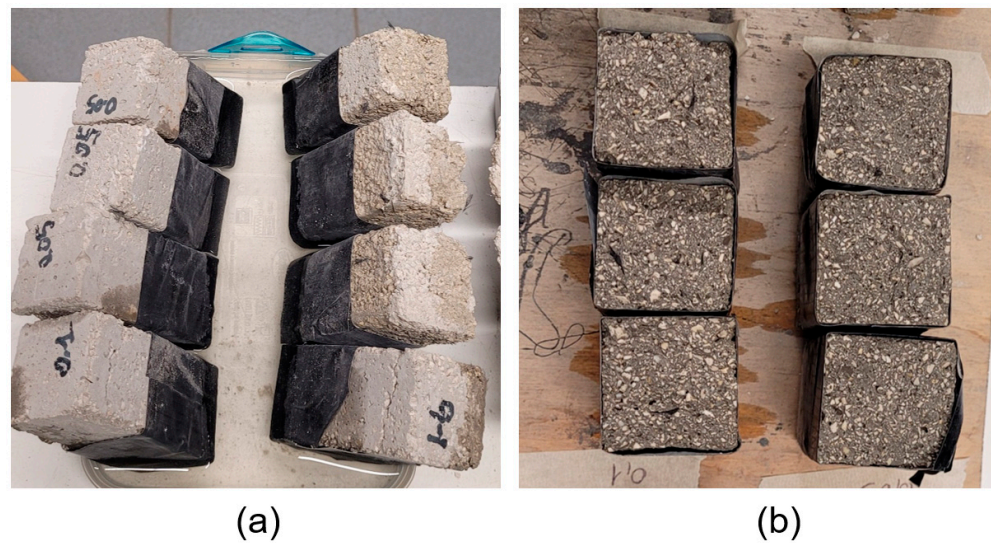


Figure 3. Samples and setup of water absorption test: (a) setup of a set of specimens, (b) contact surface after the water absorption tests.

The water absorption coefficient C was calculated from the formula:

$$C = 0.1 \cdot (M_2 - M_1) \frac{\text{kg}}{\text{m}^2 \cdot \text{min}^{0.5}}$$

where:

M_2 is the weight of the sample after 90 min, and
 M_1 is the weight of the sample after 10 min.

3.3.2. Flexural Tests

Flexural tests were carried out following the standard “UNI EN 1015-11:2019 [14], Methods of test for mortar for masonry. Determination of flexural and compressive strength of hardened mortar”. They were constituted by three-point bending tests on prismatic beams ($40 \times 40 \times 160 \text{ mm}^3$) cured for 28 days. The testing machine is a frame model Advantest by Controls S.p.A. with a maximum load of 15 kN (Figure 4), constructed with a standard device for flexural tests, consisting of two steel supporting rollers of length 50 mm and 10 mm diameter, spaced 100 mm apart, and a third steel roller of the same length and diameter located centrally between the support rollers (Figure 5a,b). The load was applied at a uniform rate of 50 N/s until failure. Figure 5a,b represent the initial and the final steps of the flexural test, respectively. Flexural strength, f , in N/mm^2 was obtained using the following formula:

$$f = \frac{1.5 \cdot F \cdot l}{b \cdot d^2}$$

where

F is the maximum load applied to the specimen, in Newtons,
 l is the distance between the support rollers, in millimeters (in this case 100 mm)
 b is the width of specimen, in millimeters (40 mm)
 d is the depth of the specimen, in millimeters (40 mm)

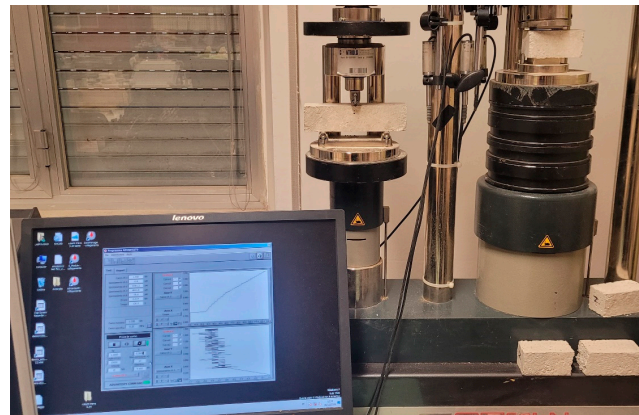


Figure 4. Setup of flexural and compressive tests: frames and placement of the samples.

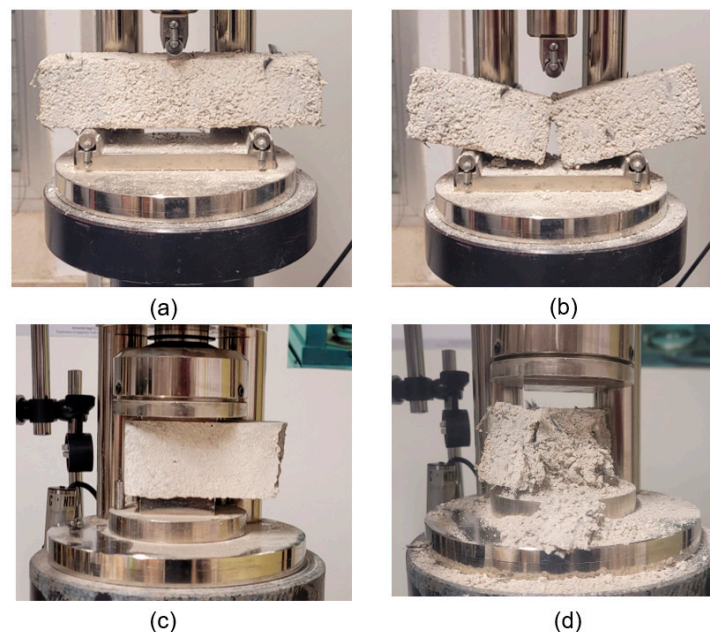


Figure 5. Samples and setup of mechanical tests on hardened material: (a,b) a flexural test and its failure configuration, respectively, (c,d) a compressive test and its failure configuration, respectively.

3.3.3. Compressive Strength

In accordance with the testing procedure suggested by “UNI EN 1015-11:2019. Methods of test for mortar for masonry; Determination of flexural and compressive strength of hardened mortar”, compression loads were applied on the two halves of the specimens previously broken by bending 28 days after casting. The load was applied to a loading area of 40 mm × 40 mm in each half. Following the European “Standard UNI EN 196-1:2016 [15]. Methods of testing cement—Part 1: Determination of strength”, the load increase was set to 2400 N/s until failure. The frame adopted for the test, connected to the testing machine, model Advantest9, provided by Controls S.p.A., had a maximum load of 250 kN.

The compressive strength was calculated as the maximum load carried by the specimen divided by its cross-sectional area of the bearing plate (nominally 1600 mm²):

$$C = \frac{F}{A}$$

where

F is the maximum load applied to the specimen, in Newtons,
 A is the Area of the loading plates, namely 1600 mm².

3.3.4. Preliminary Electrical and Sensing Tests

Electrical and sensing tests were executed to explore the percolation and the piezoresistive characteristics of the material, respectively. Each sample, constituted by a cube with two internal copper wires as electrodes, was powered with a square wave voltage input using a RIGOL DG1022 function generator, while the resulting output current was recorded using the two-probe method. Notably, samples were subjected to a 4 V peak-to-peak signal with a frequency of 1 Hz and a duty cycle of 50% as defined in [33]. Current measurements were acquired via a high-resolution multimeter, NI PXIe-4071, accommodated within an NI PXIe-1073 chassis, operating at a 10 Hz sampling rate. The electrical resistance, represented as $R(t)$, was determined employing Ohm's law:

$$R(t) = \frac{V}{I(t)}$$

where V signifies the positive value of the voltage input signal (+2 V) and I denotes the current value sampled at 80% of the positive output signal.

Sensing properties have been evaluated through compressive tests with maximum load of 7 kN. Strains were evaluated utilizing a pair of strain gauges positioned on lateral surfaces of the samples. The strain-sensing proficiency of the tested samples was assessed by computing the gauge factor, denoted as GF , utilizing the following equation:

$$GF = \frac{\Delta R/R_0}{\Delta \varepsilon}$$

Here, ΔR denotes the variation in electrical resistance relative to its baseline value R_0 while $\Delta \varepsilon$ represents the strain (negative in compression).

4. Results

Before presenting the results of tests on materials and samples at fresh and hardened states, a preliminary internal structure analysis is discussed. Micrographs were obtained by Nikon Epiphot 300 inverted microscope and a Nikon digital camera (Figure 6). Figure 6a represents the internal appearance of the base mortar characterized by cement and sand, while Figure 6b,c show the magnifications of cement mortars doped with 0.05% and 0.5% of carbon microfibers, respectively. The investigation reveals that the distribution of the fibers is quite homogeneous up to a 0.05% fiber content, while for higher amounts of microfibers agglomerations start to appear, causing discontinuity and weak zones in the local material and impairing its mechanical performance, as demonstrated by results of mechanical tests, described in the next sections.

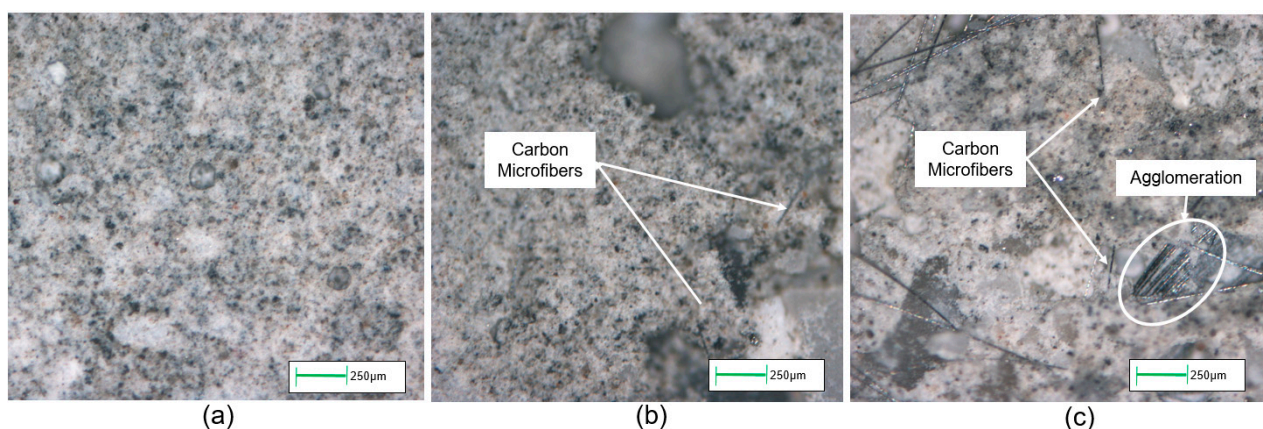


Figure 6. Micrographs of fragments of cement mortars at optical microscope: (a) normal mortar—N000C, (b) mortar with 0.005% of CMF—N005C, (c) mortar with 0.5% of CMF—N050C.

4.1. Tests on Fresh Composite

4.1.1. Density

The densities of the different mix designs are reported in Figure 7a. Density is found to decrease with the increasing amount of doping. The maximum variation was related to the higher amount of CMF (i.e., 1%), which evidenced a decrease in density of 6.6%. This variability is probably due to the presence of internal pores and voids associated with the fibers, representing points of discontinuity in the matrix. Such behavior is confirmed by micrographs of the internal structure obtained after curing on hardened material (see Figure 6).

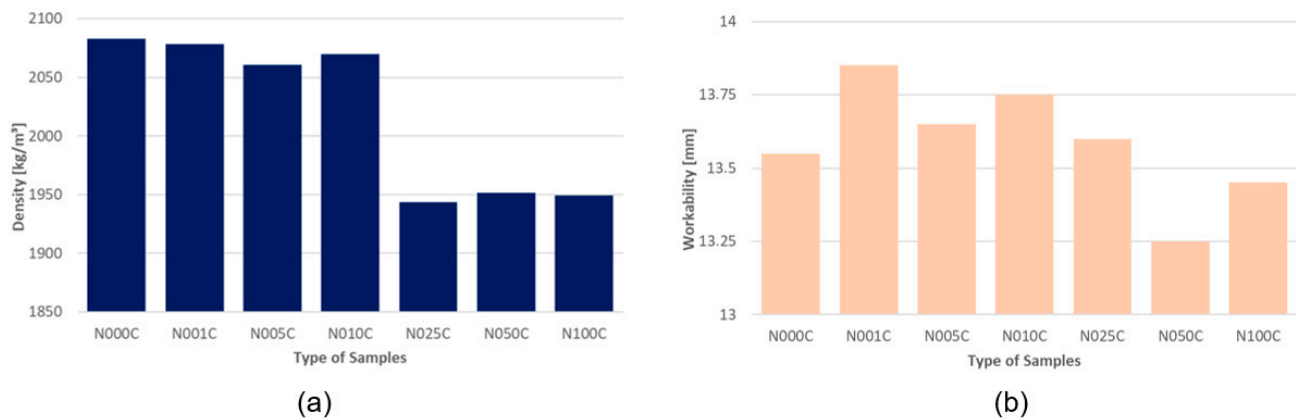


Figure 7. Evaluation of (a) density and (b) workability of all the samples.

4.1.2. Workability

Overall, the presence of microfibers had an impact on workability, as indicated in Figure 7b. Values are between 13.85 mm (for N001C) and 13.25 (for N100C). Specifically, higher quantities of carbon microfibers led to a reduction in workability by up to 2.2%; however, these levels still fall within ranges conducive to construction applications.

4.2. Tests on Hardened Composite

4.2.1. Water Absorption

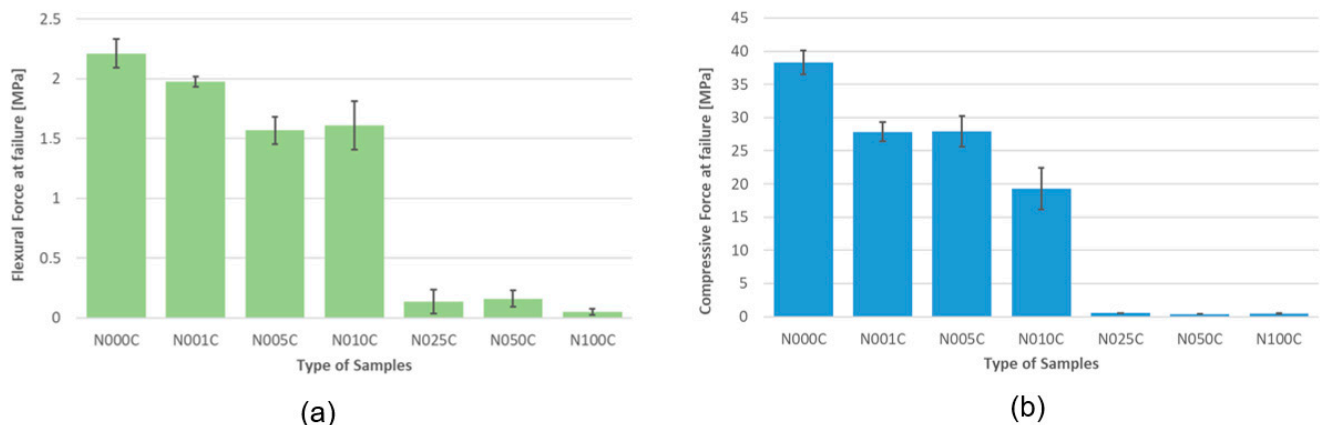
Table 3 reports the values of the water absorption coefficient, as defined in UNI EN 1015-18:2004. The results demonstrated a lower value for higher amounts of inclusions, which seems to be related to a higher stability of the doped composites with respect to normal ones. However, this behavior is due to the higher porosity of the mortars with greater percentages of CMF, which are subjected to a fast capillary penetration of water. This aspect was evident during the tests, suggesting their higher rates of wettability. As proof of this claim, Table 3 reports the increase in weight of samples after 10 and from 10 to 90 min; the values clearly demonstrate the different behavior of the doped samples with respect to the reference one. From the results, it can be noted that doped mortars with more than 0.05% of CMF appear significantly sensitive to environmental effects of water and humidity, and in general of external substances; this is very critical for their durability performance over the service life of construction. The samples with 1% of CMF exhibit the highest water absorption for both ranges.

Table 3. Experimental water absorption results.

Title 1	Water Absorption Coefficient	Water Absorption after 10 min	Water Absorption 10–90 min
N000C	0.80	0.05	0.03
N001C	0.80	0.05	0.03
N005C	0.75	0.05	0.03
N010C	0.40	0.08	0.01
N025C	0.15	0.11	0.01
N050C	0.25	0.11	0.01
N100C	0.10	0.11	0.03

4.2.2. Flexural Tests

Flexural tests on all types of samples evidenced the fragility of materials with high amounts of microfibers. As a matter of fact, samples with more than 0.25% of CMF showed a similar behavior, with the failure occurring during the application of the pre-load of the testing machine. The low standard deviation and CoV demonstrated by these specimens (see Figure 8a and Table 4) is due to this occurrence, so it is not significant for the evaluation of the mechanical performance of the material. The other doped samples showed a lower flexural strength with respect to the reference one: samples with 0.01% of CMF had an average decrease of about 10%. This variation is probably due to the presence of points of fracture initiation that strongly affected the flexural strength. This is also proved by the values of CoV, which is almost an order of magnitude greater with respect to that of the plain mortar.

**Figure 8.** Experimental mechanical results. Average maximum forces obtained from (a) flexural and (b) compressive tests (error bars represent plus/minus the standard deviation σ).**Table 4.** Experimental mechanical results. Average flexural and compressive strength calculated from flexural and compressive tests and Coefficients of Variation (CoV).

Mix Design	Flexural Strength [N/mm ²]	CoV	Compressive Strength [N/mm ²]	CoV
N000C	5.184	0.054	23.945	0.047
N001C	4.632	0.520	17.414	0.050
N005C	3.678	0.425	17.470	0.083
N010C	3.776	0.717	12.057	0.165
N025C	0.324	0.127	0.365	-
N050C	0.377	0.072	0.250	-
N100C	0.116	0.021	0.275	-

4.2.3. Compressive Strength

As previously described, compressive tests were carried out on the two halves of the prismatic samples after flexural tests, for a total of six samples for each mix design. As for the results of the previous mechanical test, samples with more than 0.25% of CMF demonstrated a low strength, and the samples collapsed during the pre-load phase (Figure 5d). Consequently, their strength values, standard deviation, and CoV are not reliable and they do not appear to be suitable for construction applications. The other doped samples showed a good repeatability, with coefficients of variation between 0.05 and 0.165. Samples containing up to 0.05% of CMF demonstrated suitable values for real-world use, comparable with those of traditional mortars. In addition, their fracture paths after failure were satisfactory. However, the obtained experimental compressive strengths evidence a decrease with respect to normal mortar associated with fiber addition. Figure 8b and Table 4 report the results of compressive force/standard deviation and compressive strength/CoV, respectively.

4.2.4. Electrical and Sensing Tests

Electrical tests carried out on unloaded samples allowed the evaluation of the evolution of the conductivity properties of the materials with increasing percentages of carbon microfibers. Due to their weak mechanical strength, making them unsuitable for construction applications, composites with amounts over 0.25% were not considered. The outputs clearly showed a drop in electrical resistance for doping levels higher than 0.1%, identifying the percolation threshold and confirming that composites with slightly lower inclusion levels are the most suitable for smart monitoring (see Figure 9—line). Those types of samples were then tested for sensing evaluation. The obtained Gauge factors show the higher performance of doped composites, up to a GF of 435, strongly higher than values of traditional strain gauges that are around 2.

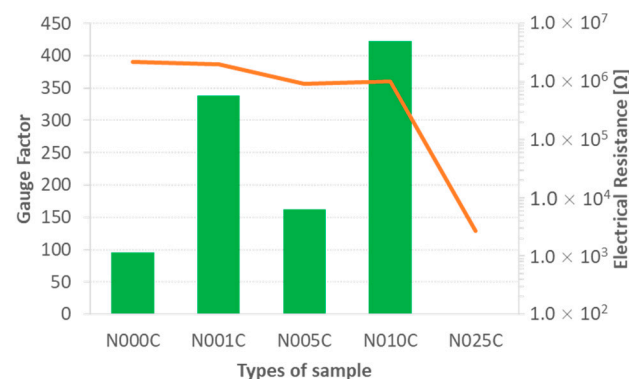


Figure 9. Electrical resistance (solid line) and Gauge Factors (columns) of the samples tested at compressive loading.

5. Discussion

The results of tests on fresh and hardened mortars doped with carbon microfibers showed interesting evidence. All the investigated materials, up to 1% of carbon inclusions, did not demonstrate bleeding or phase separation during the production, and results of workability tests proved their consistency for real use in constructions.

Mechanical test demonstrated a weak performance of materials, show that samples with more than 0.25% of CMF were not suitable for applications in civil engineering. This was probably due to the occurrence of micro-pores in the internal structure of doped samples, as noted from microscope analysis, that constituted points of crack initiation. An improvement of compactness of the hardened doped mortars, through a specific and more effective dispersion and mixing procedure of the fibers, could avoid this issue. Possible solutions could be the use of tailored dispersants, or enhanced components and

mixers. However, results obtained by composites with lower doping levels demonstrated mechanical properties comparable to those of reference material and of standard mortars.

Water absorption tests allowed us to identify the most promising mixes for a feasible application in real-scale structures subjected to environmental effects. As a matter of fact, mixes with more than 0.05% of CMF appeared to be too susceptible to degradation caused by external agents due to their high internal porosity and their mix design, suggesting that their components would need further development. However, future investigations are needed to prove the specific durability performance, tailoring the mix designs considering the peculiar absorption of the fine aggregates, which could also affect the strength results and their variability. Preliminary electrical and sensing tests on samples with sufficient mechanical strength were conducted to demonstrate the applicability of the investigated composite as a construction material able to monitor its internal strain conditions. Our results identified the percolation zone, which is around the percentage of 0.1% of CMF, and demonstrated the higher strain sensitivity of doped materials, particularly close to the percolation threshold.

6. Conclusions

This paper is aimed at investigating the performance of innovative cement mortars doped with carbon micro-fibers, both at fresh and hardened state. This type of material could be applied in civil engineering structures as multifunctional composites with self-sensing capabilities. The presented and discussed results constitute a preliminary assessment of physical, rheological, mechanical, electrical, and sensing properties of the composites for their development into specific tailored and effective building materials. The results of the research evidenced the promising properties and the problematic issues of the composites. In particular, (i) the rheological performance of the doped materials appeared similar to that of the normal mortars, demonstrating comparable performance; (ii) The amounts of CMF considered in this study do not modify the density of the final compound for percentages below 0.25%; (iii) Workability decreases with increase CMF doping, but remains in the range suitable for building applications; (iv) The hardened samples showed weak performance at high amounts of carbon inclusions (namely over 0.1% of CMF), an occurrence that proves the need to investigate, in future research studies, the optimal dispersion procedures for the microfibers and the most effective compaction process. However, the mechanical strength values exhibited by composites with lower doping are comparable to that of the normal material and common cement-based mortars; (v) Water absorption properties of the doped samples demonstrated a higher sensitivity to durability issues; (vi) Electrical percolation has been identified at a doping level of about 0.1% CMF; (vii) Below the percolation zone, doped composites demonstrated an enhanced strain sensitivity with respect to normal material.

Overall, this study, which constitutes preliminary feasibility research on smart cement-based mortars with CMF for masonry, identified the most promising doped materials for multifunctional building applications. Tailored components and mixing procedures could enhance the rheological, mechanical, and sensing capabilities for specific purposes. Moreover, the use of hybrid inclusions, including use of smaller fillers, could reduce the internal nano-and micro-pores, enhancing durability and multifunctional capabilities.

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