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Multipurpose experimental characterization of smart nanocomposite cement-based materials for thermal-energy efficiency and strain-sensing capability

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ABSTRACT

Novel nanocomposite smart multifunctional materials are emerging as promising technological advances in construction industry, where thermal-energy efficiency needs should meet environmental sustainability and mechanical performance requirements. In this view, new cement-based materials showed encouraging results in terms of added functional properties combining all the above mentioned capabilities with electrical conductivity and self-sensing potential for a variety of field scopes, e.g. vibration measurements, damage detection, structural health monitoring, electromagnetic shielding, self-heating pavements for deicing and more. The present paper deals with the development and multipurpose experimental characterization of cement-based materials doped with different carbon nanoinclusions consisting of: multi-walled carbon nanotubes, carbon nanofibers, carbon black, and graphene nanoplatelets. The study investigates morphology, optical features, thermal characteristics, electrical properties and strain-sensing capability of the different composites, through a campaign of in-lab experimental measurements. The results highlight the peculiar behavior of each composite material, which is strictly related to the adopted nanoinclusions, that reveal to be suitable for specific purposes. In particular, all carbon nanoinclusions are seen to reduce solar reflectance capability, while they produce negligible variations in thermal emittance. Graphene nanoplatelets represent the most effective nanoinclusion to increase thermal conductivity and diffusivity, which is related to their structural and geometrical characteristics and better capability to distribute the thermal wave. Consistently, the same graphene samples produce the largest electrical conductivity and capacitance. However, multi-walled carbon nanotubes, even though providing comparatively smaller contributions to electrical conductivity, are seen to be the best nanoinclusions for providing strain-sensing capabilities to the cement-based composites.

1. Introduction

High environmental performance and smart materials are achieving increasing attention from the scientific community and the industrial one for their promising multifunctional behavior and their beneficial potentialities such as key environmental performance, promising energy efficiency optimization, high structural strength, enhanced durability and new construction technologies [1,2]. In this view, starting from the first structural development toward high strength concrete [3,4], innovative multifunctional cement-based materials are under development and testing with the final aim to optimize their further potentialities, by paying dedicated attention to their environmental sustainability behavior [5,6] and to the role that nanostructured particles play on such properties [7]. Among other applications, the analysis and the optimization of optic-energy and thermal properties of such cement-based media captured the attention of researchers aimed at optimizing thermal-energy performance in buildings and outdoor thermal comfort conditions [8,9]. Additionally, further potentialities of such materials, such as their electrical features for strain-sensing applications in constructions enabling direct crack detection capabilities and providing distributed strain data for Structural Health Monitoring (SHM), are currently under fast progress

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[10].

Within the wide and sprawling variety of new smart materials for building thermal-energy efficiency, carbon-based nano-additives for inclusion in cement-based materials certainly showed highly promising features with multipurpose optimization potential. Starting from this acknowledgment, this research paper is aimed at presenting a multipurpose study dealing with the experimental characterization of cement-based materials doped with different carbon nanoinclusions, by taking into account their (i) morphological and nanostructural characteristics, (ii) thermal-energy and optical features, (iii) mechanical behavior, (iv) electrical properties and (v) piezoresistive strain-sensing potential, with the final purpose to provide an exhaustive panorama around the potential applications of such innovative solutions for smart and multifunctional cutting edge constructions. To this aim, the present work presents the key research background in the field (Section 2), the considered materials and the acknowledged methodologies for their multipurpose characterization by means of multidisciplinary experimental procedures (Section 3). Then, the final discussion around the main achieved results is dealt with in Section 4, and the key conclusions are reported in the final Section 5.

2. Research background

The present work builds upon previous contributions mainly focused on the development and multipurpose characterization of innovative materials for building thermal-energy efficiency [11,12] by means of passive strategies such as materials with passive cooling potential [13], materials with sensible or latent heat storage capability [14,15], or other bioinspired systems incorporated into building envelope [16,17]. In this perspective, cement-based materials are preparing a breeding ground for interesting research development, given the huge diffusion and tradition of such materials for both structural and architectural purposes. About their optimization for building thermal-energy efficiency, one of the most investigated areas consisted of the inclusion of thermal storage particles such as phase change materials (PCMs) into the cement medium, in order to optimize its latent thermal storage capability, producing key benefits in stabilizing indoor temperature and also reducing building indoor overheating in summer [18]. In this area, many researches were carried out in the last few decades demonstrating the effect of microencapsulated PCMs into cement media, as it was reported in the review by Khudhair and Farid [19]. Another relevant issue that was addressed in the research on cement-based materials concerned the analysis of their environmental performance in terms of carbon footprint and embodied energy [20], aimed at minimizing the overexploitation of natural resources and raw materials in the construction sector, and also its effect on urban dense microclimate conditions [21]. Another study [22] about the same issue showed that the production and use of cement-based materials deserve to be environmentally optimized, given that they are not yet sustainable being cement production the highest contributor in terms of primary energy demand for the manufacture of 1 m^2 of gross floor area after the only steel and ceramic material. Also, it was considered as the main responsible manufacture process of the CO_2 emissions for the construction of 1 m^2 of gross floor area [23]. In this view, the research around this material was directed towards (i) minimizing its environmental impact and (ii) investigating innovative and promising cutting edge nanotechnology potentialities, that could motivate the use of such energy needy material, even in the view of a more sustainable construction industry.

The latter aforementioned research topic marked the path to the analysis of high performance concrete achieved by means of silica nanoparticles, silica fume, fly ash [24], and other carbon-based nanoparticles such as those investigated in this work, i.e. carbon nanotubes and nanofibers, carbon black, and graphene nanoplatelets [25–27]. Carbon nanotubes received much attention and gained important success given their capability to make the cement-based material behaving as a piezoresistive medium, with key strain-sensing functional properties having multiple potential applications in smart constructions [10,28–30]. More in particular, smart piezoresistive cement-based materials doped with conductive nanoinclusions have the potential to provide any concrete structure with self-sensing capabilities by correlating the change of strain with the change of proper electrical properties, such as resistance or conductivity [31–34]. Several factors may affect the electrical characteristics' of the composites: the intrinsic resistance of functional fillers, the bonding between functional fillers and matrix, the contact between functional fillers, the tunneling distance between functional fillers and their electrical capacitance [35]. The presented materials with conductive fillers permitted the fabrication of sensors with enhanced properties in comparison to off-the-shelf sensors: higher durability, the possibility to provide distributed strain data and the consequent potential for effectively scaling the principle of SHM to the case of large-scale structures.

Possible applications of nano-modified cement-based materials were showed to be multidisciplinary and to pertain to the fields of SHM, construction industry, smart structures and smart cities [36–39]. Owing to their large and multidisciplinary innovation potential, the scientific literature shows a growing interest in the study of these multifunctional materials. However, much research work still needs to be done concerning prerogatives and issues related to composites' production, performance and modeling [40–42].

Framing into the panorama presented above, this work aims to contribute to a more aware understanding of the multifunctional properties of emerging cement-based materials doped with different carbon nanoinclusions, with a focus on the effects of such additives in modifying the thermal-energy and optic properties of the composites that have been rarely investigated in the literature. In particular, feeling that multiperspective analysis of such materials deserves further research attention as recently dedicated by the scientific community, a multipurpose experimental characterization of cement paste samples doped with multi-walled carbon nanotubes, carbon nanofibers, carbon black and graphene nanoplatelets, is presented, investigating these composites from multiple perspectives, including (i) thermal-energy and optic characteristics, as well as (ii) electrical and piezoresistive behavior for strain-sensing purpose and mechanical properties.

3. Materials and methods

3.1. Description of the materials

The samples prepared for the experimental campaign were made of cement paste doped with carbon-based conductive nanoinclusions. Four different nanofillers were used: Multi-walled Carbon Nanotubes (MWCNTs), Carbon Nano-Fibers (CNFs), Carbon Black (CB) and Graphene NanoPlatelets (GNPs).

The MWCNTs chosen for the samples were Arkema Graphistrength C100. They belong to the structural family of Fullerene and they consist of multiple concentric rolled graphene sheets. Carbon atoms were arranged in a hexagonal pattern with strong covalent bonds, type σ-σ, while the tubes were connected through Van der Waals forces. Such attractive forces determine the development of bundles, undesirable structures that complicate the task of achieving a homogeneous material [43–45]. MWCNTs had a macroscopic appearance as black powder, with a very high specific surface area (of the order of 100–250 m^2/g) and very low apparent density (of the order of 50–150 kg/m^3) [46–48].

The Carbon Nanofibers used for preparing the cement paste specimens, type Pyrograf-III Carbon Nanofiber PE-19-XT-LHT, had a unique stacked-cup structure consisting of graphene plane surfaces canted from the fiber axis. They were produced by a low heat treatment with temperatures up to 1500 °C, which partially chemically graphitized the vapor deposited carbon on the surface and allowed to obtain