7-13-2017

Novel nanocomposite clay brick for strain sensing in structural masonry

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Abstract

The monitoring of civil structures is critical in ensuring users' safety. Structural health monitoring (SHM) is the automation of this monitoring task. It is typically used to identify incipient damages through a spatio-temporal comparison in structural behaviors. Traditional sensors exhibit mechanical characteristics that are usually very different from those of the structures they monitor, which is a factor limiting their durability. Ideally, the material of a sensor would share the same mechanical characteristics as the material onto or into which it is installed. A solution is to fabricate multifunctional materials, capable of serving both structural and sensing functions, also known as smart materials. Recent developments in nanotechnologies have given us various engineered nanoparticles with enhanced mechanical and electrical capabilities. Among them, conductive piezoresistive nanopowders, such as carbon-based ones, show promise at developing smart materials. The nanofillers, spread into a structural material matrix, can provide the material with self-sensing capabilities. Such materials can then be used to detect variations in their external stresses or strains by detecting variations in their electrical characteristics, such as electrical resistivity and conductivity. This paper presents a new smart clay brick for strain sensing in masonry structures. The optimal fabrication process in terms of stability of the nanoparticles at high temperature and the electromechanical properties of the smart brick are investigated. Results show a clear strain sensitivity of the brick sensors subjected to external loads and show their promise for SHM applications.

Keywords

carbon nanofillers, clay brick sensors, nanotechnology, self-sensing materials, structural health monitoring

Disciplines

Civil Engineering | Electrical and Electronics | Nanoscience and Nanotechnology | Structural Engineering | VLSI and Circuits, Embedded and Hardware Systems

Comments

This is a manuscript of a proceeding published as Ubertini, F., A. D'Alessandro, A. L. Materazzi, S. Laflamme, and A. Downey. "Novel nanocomposite clay brick for strain sensing in structural masonry." In Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), 2017 IEEE International Conference on, pp. 1-4. IEEE, 2017. DOI: 10.1109/EEEIC.2017.7977598. Posted with permission.

Novel nanocomposite clay brick for strain sensing in structural masonry

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***Abstract*—The monitoring of civil structures is critical in ensuring users' safety. Structural health monitoring (SHM) is the automation of this monitoring task. It is typically used to identify incipient damages through a spatio-temporal comparison in structural behaviors. Traditional sensors exhibit mechanical characteristics that are usually very different from those of the structures they monitor, which is a factor limiting their durability. Ideally, the material of a sensor would share the same mechanical characteristics as the material onto or into which it is installed. A solution is to fabricate multifunctional materials, capable of serving both structural and sensing functions, also known as smart materials. Recent developments in nanotechnologies have given us various engineered nanoparticles with enhanced mechanical and electrical capabilities. Among them, conductive piezoresistive nanopowders, such as carbon-based ones, show promise at developing smart materials. The nanofillers, spread into a structural material matrix, can provide the material with self-sensing capabilities. Such materials can then be used to detect variations in their external stresses or strains by detecting variations in their electrical characteristics, such as electrical resistivity and conductivity. This paper presents a new smart clay brick for strain sensing in masonry structures. The optimal fabrication process in terms of stability of the nanoparticles at high temperature and the electromechanical properties of the smart brick are investigated. Results show a clear strain sensitivity of the brick sensors subjected to external loads and show their promise for SHM applications.**

Keywords*— carbon nanofillers; clay brick sensors; nanotechnology; self-sensing materials; structural health monitoring;

I. INTRODUCTION

The availability of nanoengineered particles permits the development of materials with improved mechanical and electrical properties for engineering applications, including Structural Health Monitoring (SHM) [1-2]. Of interest are carbon nanoinclusions, which have shown promise for the fabrication of self-sensing or smart materials [3-5]. Such materials can be used to detect deformations (as caused by loads) through the variation of their electrical properties, such as resistance and impedance [6-7]. A particular advantage of these smart materials is that they can be easily integrated within conventional structural materials [8-10]. For instance, a smart mortar can be used to monitor historic structures. Such sensing strategy provides the structure with architecturally concealed sensors of high durability. In this paper, a smart clay brick is introduced for structural health monitoring applications. Such smart bricks could be used for the monitoring of cultural heritage structures and masonry buildings. In comparison to traditional sensors, they possess higher durability and ease of installation. Work on nanoengineered brick materials is limited [11,12]. Some research work has been conducted on the mechanical properties of ceramics [13-14] and specific applications [15-16]. Here, the effect of the fabrication process of a smart clay brick on the stability of the nanoparticles at high temperature and on the electromechanical properties of the brick is studied.

II. MATERIALS

A. Samples preparation

Nanomodified bricks were prepared adding different contents of Multi Walled Carbon Nanotubes (MWCNTs) Arkema Graphistrength C100 to clay in the percentages of 0%, 0.5%, 0.75% and 1% with respect to total weight. The MWCNTs were previously dispersed into deionized water through a dispersant and sonication. Then, the suspension was mixed with clay and the brick sensors were formed (Fig.1). The samples were prisms of 50 mm length, with four embedded stainless steel nets as electrodes placed at a mutual distance of 10 mm. The brick microstructure and the dispersion of carbon nanotubes were investigated through SEM micrographs. Figures 2 and 3 show the evolution of the microstructure of a brick throughout the fabrication process. The clay samples were first dried and then burned in an oven Moretti, type Kubo, capable of reaching temperatures up to 1100 °C.

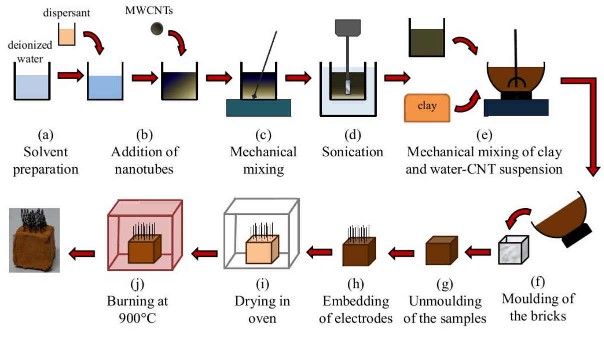


Fig. 1. Fabrication process of nanocomposite clay bricks.

The support of the Italian Ministry of Education, University and Research (MIUR) through the funded Project of Relevant National Interest "SMART-BRICK: Novel strain-sensing nanocomposite clay brick enabling self-monitoring masonry structures" (protocol no. 2015MS5L27) is gratefully acknowledged

978-1-5386-3917-7/17/$31.00 ©2017 IEEE

The bricks were dried at 50 °C for one hour and thereafter at 90 °C for one hour. Burning occurred through increasing the temperature of the oven from room temperature to 900 °C over six hours. The temperature was then kept constant for 15 minutes, followed by cooling. A set of control clay bricks were fabricated using a similar process, but without the nano particles. A second type of bricks was fabricated in a brick factory using an industrial burning process with a maximum temperature of 900 °C. Carbon nanotubes, previously dispersed in water through sonication, were added in a series of samples before the tempering stage. All the bricks were dried before the burning stage. The electrodes, consisting of stainless steel wires with 1 mm diameter, were embedded before the temperature cycles. After burning, the bricks were cut to obtain sensors with a section of 30 x 50 mm^2 and a height of 70 mm.

B. Setup of electrical and electromechanical tests

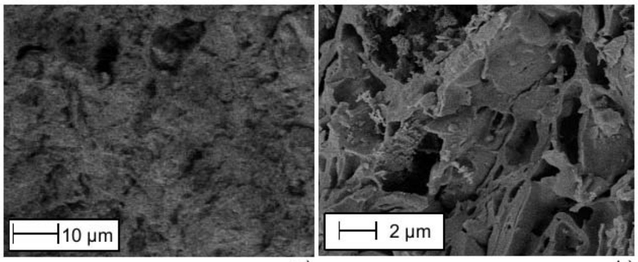
Figure 4 shows the setup of the electrical (Fig. 4a) and electromechanical (Fig. 4b) tests for the sensing investigation. The data acquisition system consisted of a National Instruments NI PXIe-1073 device with dedicated modules (a NI PXI-4130 for providing stable electrical input and a high speed digital multimeter, model NI PXI-4071, for current measurements). Different levels of voltage were applied to the electrodes following a DC-based two-probe measurement configuration: from 5 V to 30 V with increments of 5 V. The electromechanical tests with increasing loads were conducted using an Controls Advantest machine with a maximum capacity force of 15 kN. Step compression loads with increasing values, from the initial load of 0.5 to 2 kN, were applied on both the normal brick and on the brick with carbon nanotubes. In order to reduce the electrical drift related to the material polarization of the brick matrix, a 1 Hz square wave ranging from -10 V to 10 V with a duty cycle of 50% was used to investigate the sensing properties of the samples. Cyclical loads with a maximum value of 2.1 kN have been applied to the sensors using an electro hydraulic press OMCN mod. 156/ML with a maximum load capacity of 200 kN.

III. EXPERIMENTAL RESULTS AND COMMENTS

Experimental tests were conducted to investigate the thermal behavior of the nanoinclusions, the electric characteristics of the different bricks with increasing content of nanofillers, and the sensors' sensing capabilities.

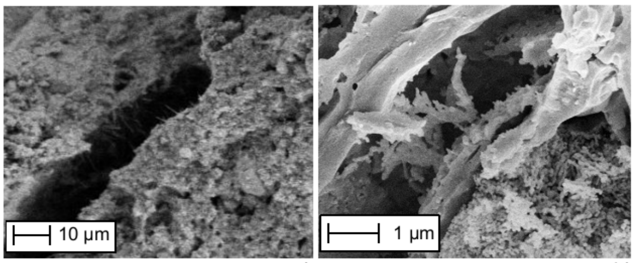
A. Filler investigation

One of the issues related to the fabrication of clay bricks with nanoparticles is the behavior of the inclusions at high temperature. Literature studies about self-sensing cementitious materials identify carbon-based nanofillers as particularly suitable for the realization of smart piezoresistive sensors with good sensing performance. Here, different types of nanofillers have been subjected to increasing temperatures, from 300°C to 900°C into covered ceramic cups, in order to investigate their behaviors at different high temperatures (Fig. 5a). The fillers were all carbon-based: multi walled carbon nanotubes (MWCNTs), carbon black (CB) and carbon nanofibers (CNFs). With respect to original conditions at room temperature (Fig. 5b), the CB appeared completely burned at 900°C (Fig. 5c).



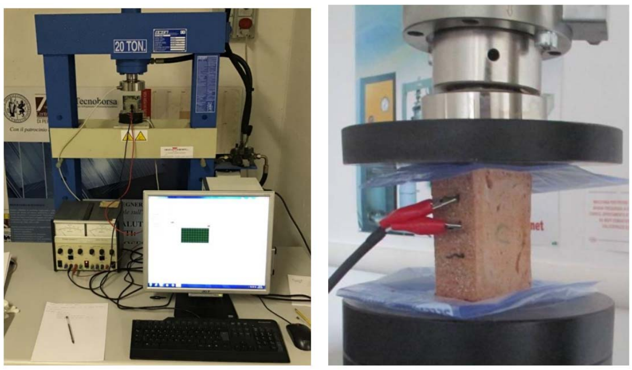
a) b)

Fig. 2. SEM images of normal clay bricks after drying (a) and after burning at 900 °C (b)



a) b)

Fig. 3. SEM images of nanocomposite clay bricks after drying (a) and after burning at 900 °C (b)



a) b)

Fig. 4. Laboratory setup for electrical and electromechanical cyclical tests for sensing detecting (a) and a detailed view of the setup during an electromechanical test with incresing loads (b)

TABLE I. MASS LOSS OF CARBON NANOTUBES, CARBON BLACK AND CARBON NANOFIBERS AFTER EXPOSITIONS AT INCREASING MAXIMUM BURNING TEMPERATURE

Type of nanoparticles	**at room temperature of 20°C**	**after cycle at 300°C**	**after cycle at 500°C**	**after cycle at 700°C**	**after cycle at 900°C**
MWCNTs	0.70 g	0.69 g	0.68 g	0.37 g	0.04 g
CB	0.70 g	0.67 g	0.60 g	0.14 g	0.01 g
CNFs	0.70 g	0.67 g	0.68 g	0.51 g	0.06 g

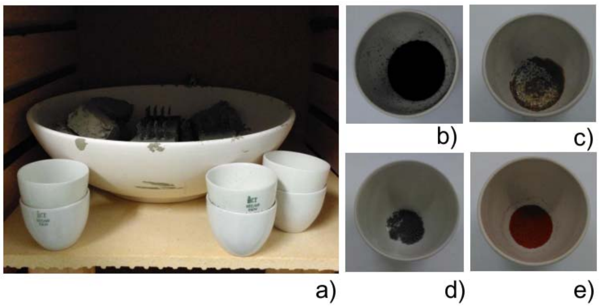


Fig. 5. Setup fot the burning of samples and nanofillers (a); carbon nanotubes at room temperature (b); carbon black (c) carbon nanofibers (d) and carbon nanotubes (e) after burning at 900°C (c).

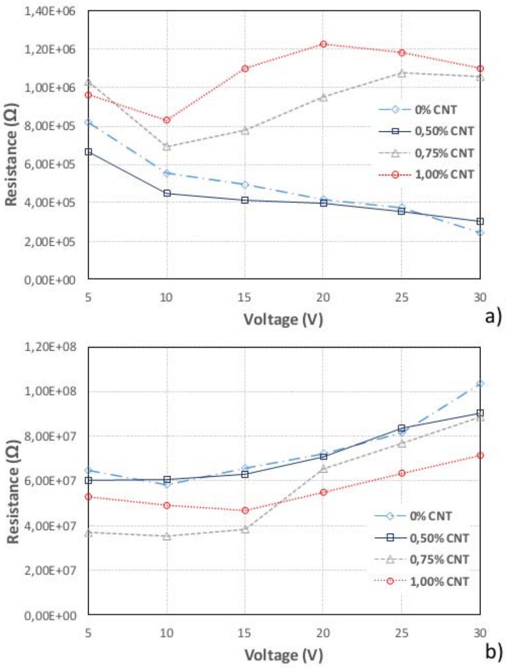


Fig. 6. Electrical resistance of composite clay brick sensors with various amounts of carbon nanotubes after drying (a) and after burning (b) versus different levels of applied voltage

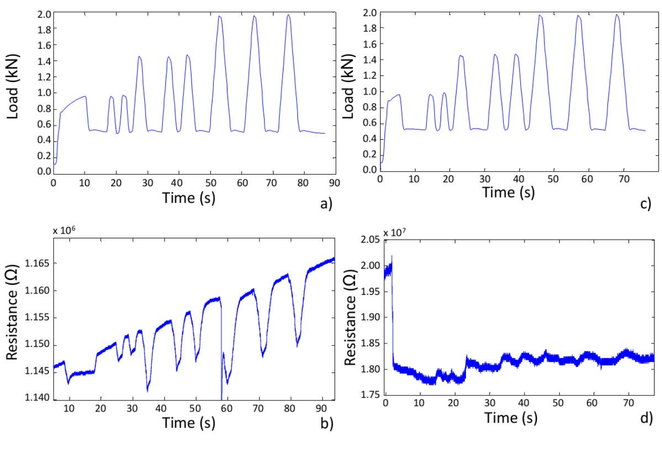


Fig. 7. Load applied during electromechanical tests with incresing loads and output of the brick sensors with carbon nano inclusions (a and b) and without fillers (c and d), under a stabilized voltage.

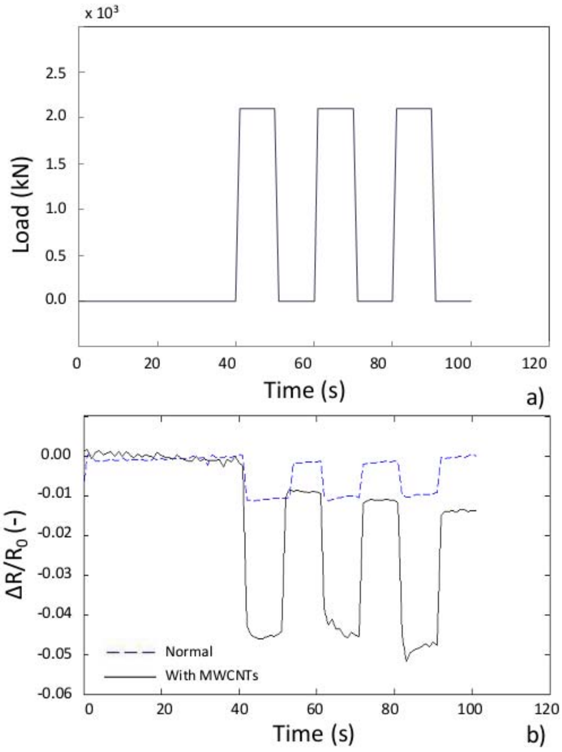


Fig. 8. Time history of the cyclical load applied during electromechanical tests (a) and normalized change in electrical resistance of the brick sensors with carbon nano inclusions and without fillers (b) under a square wave voltage (quantities are defined according to Eqs. (1) and (2)).

TABLE II. RESULTS OF STRAIN TESTS ON NORMAL AND NANOMODIFIED SENSORS (R_0, ΔR AND ε ARE THE INITIAL RESISTANCE AND THE VARIATIONS OF RESISTANCE AND STRAIN, RESPECTIVELY, GF IS THE GAUGE FACTOR AND S THE SENSITIVITY)

Type of sample	R_0 (MΩ)	ΔR (MΩ)	ε ($\cdot 10^{-3}$)	*GF*	*S* (MΩ)
Normal	104.8	1.05	1.167	8.6	900
with MWCNTs	695.8	40.45	1.167	49.8	34662

In comparison, CNFs and MWCNTs presented a residual material after burning (Fig. 5 d and e). Table I reports the mass loss after cycles at different maximum temperatures. It should be noted that a quite less significant mass loss is expected inside the clay from burning.

B. Electrical investigation

The electrical resistance of the nanocomposite clay bricks with various amounts of MWCNTs has been investigated at different levels of applied voltage (Fig. 6). MWCNTs were selected as nanofillers for the brick because of their aspect ratio which makes them particularly suitable for electrical applications [6], e.g. for cementitious piezoresistive sensors. Figure 6 shows the variation of resistance in bricks after drying at 90°C and after burning at 900°C. The material's behavior after drying is probably due to presence of residual humidity. Indeed, after burning the effect of the carbon nanofillers is more visible.

C. Electromechanical tests

The samples were subjected to uniaxial step loads. Insulating paper was placed between the samples and the testing machine to prevent interferences. Figure 7 reports the time histories of the loads applied during the electromechanical tests and the electrical response of the brick sensors with nano inclusions of MWCNTs and without any inclusions. The tested samples were fired in the furnace with the same thermal cycle and production method of normal bricks, in order to reach higher reliability. The sensor with nanotubes shows a clear sensitivity to external loads (Fig. 7b) while the normal clay brick does not exhibit any relevant sensitivity (Fig. 7d). Indeed, in the output of the nanocomposite brick the single load cycles and their magnitudes are observable. A drift of the output signal is also evident, due to material polarization effect. A biphasic measurement approach, based on an applied square wave voltage between 10 and -10 V at a frequency of 1 Hz, was then adopted to reduce the electrical drift and investigate the sensing properties of the sensors [17]. Figure 8 shows the time histories of the applied loads and of the normalized variation of electrical resistance obtained from the electromechanical tests. The loads consisted of three cycles with a constant maximum force of 2.1 kN (Fig. 8a). The variation of the resistance derived from the electrical measurements and normalized to the value of the initial resistance (Fig. 8b) clearly shows the higher sensitivity of the sample with MWCNTs with respect to that of the normal one. Table II reports the values of the initial resistance, the variation of electrical resistance obtained from the experimental tests, and estimated strain, Gauge Factors (GF) and sensitivity (S). The electrical behavior of the brick sensors was modeled as an equivalent electrical circuit [18,19]. Gauge factor and Sensitivity were achieved through the following equations:

$$GF = \frac{\Delta R / R_0}{\varepsilon} \tag{1}$$

$$S = GF \cdot R_0 \tag{2}$$

where R_0 is the unstrained initial electrical resistance of the material, ΔR the variation of electrical resistance and ε the axial strain. The results demonstrate that the bricks doped with carbon nanotubes show higher strain sensitivity and GF with respect to normal samples, although exhibiting a larger electrical resistance, showing that, at the investigated amount of nanoinclusions, percolation does not occur.

IV. Conclusions

This paper investigates a new smart nanocomposite clay brick with self-sensing capabilities for monitoring of civil structures. Issues are related to the development of such a sensor, particularly concerning the optimization of the preparation procedure in terms of stability of the nanoparticles at high temperature and the electrical and electromechanical properties of the smart brick, were investigated. Results demonstrated that nanocomposite clay bricks exhibit higher sensitivity to applied strain and appear promising at SHM applications.

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