An Innovative Nanosensor for Weigh-In-Motion Applications

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Abstract

This study deals with the development of an innovative weigh-in-motion (WIM) sensor. An electrically conductive nanocomposite material based on a mixture of graphene supported on sepiolite and carbon nanotubes was developed. Deposited on bituminous mix with copper electrodes, it is used as a force sensor. We detail the sensor fabrication process and study its sensitivity to a compressive force.

Keywords: *Weigh-in-motion, sensor, piezoresistive, C/sep-MWCNTs composite.*

Introduction

Low-speed and high-speed weigh-in-motion (WIM) technologies are used in infrastructure monitoring (prevention of overloading), truck safety advisory systems, pavement design, traffic management and data collection for research and environmental purposes. Different sensors are available, such as bending plates, strain gauges, load cells as well as fiber optic and piezoelectric sensors [1, 2]. Legal applications, such as tolling and weight enforcement, are of major socio-economic interest, but their present deployment is only marginal due to major reliability issues, especially for high-speed WIM. Altogether, the generalization of WIM systems is slowed by a variety of issues, such as difficult deployment, high cost and short lifetime.
A very promising route toward low-cost, large surface area WIM sensors lies in the "Smart materials" concept: Although asphalt and concrete (two classical road materials) are electric insulators and its (bitumen resistivity can reach up to $10^{13}\Omega$.m), they can be turned into conductive and piezoresistive materials by volume incorporation of electrically conductive materials [3-5]. In general, two kinds of conductive components are used: carbon based materials (such as carbon fiber, nanotubes, graphene sheets or carbon particles) and metal fillers (such as steel fiber and steel shavings). Directly embedded into road materials, sensors based on these piezoresistive nanocomposite materials can detect vehicles and assess their weight [6].
However, they suffer some significant drawbacks: they require an important quantity of nanoparticles to become conductive, raising the system cost; material fabrication is complicated because of sedimentation issues, which will prevent on-site fabrication; the presence of nanoparticules directly at road surface level raises the question of nanoparticles dispersion in the environment following regular wear.
In the present study, we propose a novel WIM sensor architecture relying on a thin piezoresistive layer of carbon-clay nanoparticles deposited within asphalt, promise for very low-cost sensors that could be fabricated on-site with no environmental risks [7]. In the present paper, we describe both the fabrication process and characterization results for the novel sensor.

1 Sensor's elaboration and characterization

1.1 Materials

We use a French dense asphalt mixture. The bitumen is chosen to have 35/50 penetration grade with a viscosity of 0.2 Pa.s at the mixing temperature of 160 °C. The following aggregate fractions are used: sand 0/2 mm and stones 2/4 mm, 4/6 mm, 6/10 mm and 10/14 mm. The filler is of the limestone type and comes from the French "Méac" quarry. Specimen slabs and beams (50*30 cm) are obtained by sieving slabs manufactured at 160 °C and compacted in laboratory.

The active material, in short C/Sep-MWCNTs, is a mixture of nanoparticles of graphene supported on sepiolite[1] and of multi-walled carbon nanotubes[2] (MWCNTs). The C/Sep-MWCNTs material is prepared as follows: Pangel® S9 sepiolite supplied by Tolsa is mixed with MWCNTs (0.1 to 0.5 wt%) and water. Homogenization of the system is reached by sonomechanical treatment using Sonics Vibracell VCX750 equipment [8]. The dispersion is partially dried at around 60-70 °C overnight. Liquid caramel (Royal™, 80% provided by Kraft) is added to the sepiolite-MWCNTs mixture at 2:1 w/w ratio caramel-clay. The homogenization is realized by kneading and the final mixture is again partially dried at 60-70 °C overnight. The sepiolite-MWCNTs-caramel mixture is heated up from room temperature to 800 °C under a nitrogen flux at a rate of 5 °C/min. The material is kept to 800 °C for 1 hour, transforming the caramel into a conducting carbonaceous material compound containing conductive graphene-like materials and supported by the sepiolite fibers [9]. The resulting material takes the form of a black power.

The C/sep-MWCNTs (0.5 wt%) powder is dispersed in water with sodium dodecyl benzene sulfonate (SDBS) at 0.1% wt as surfactant. The surfactant is first mixed with water using a magnetic stirrer for 5 minutes. C/sep-MWCNTs are then added into the aqueous solution. The resulting solution is finally stirred for 1h and sonicated for 1h, forming a homogeneous black solution.

1.2 Device fabrication

Devices are fabricated either directly on compacted asphalt slabs. Aluminium electrodes (5*50 mm) are fixed at the surface of substrate with 5 cm spacing.
The C/sep-MWNT solution is deposited by drop coating (10 ml) between and on electrodes, forming a thin layer. The material is dried in air at room temperature for 2 h then by hot air flow (200 °C). The upper surface is then heated and deposited on top of a precompacted coated layer. Figure 1 shows a schematic of the sensors and an image of sensor without the asphalt cover.

[1] Sepiolite is a fibrous clay mineral with $Mg_4Si_6O_{15}(OH)_2{\cdot}6H_2O$ as ideal formula.
[2] Carbon nanotubes (CNTs) display a hollow tubular structure with one or several concentric walls formed by one-atom-thick sheets of carbon. Multi-walled nanotubes (MWCNTs) diameter is in the low nanometer range (5-50 nm); their length is in the 5 μm to 50 μm range.

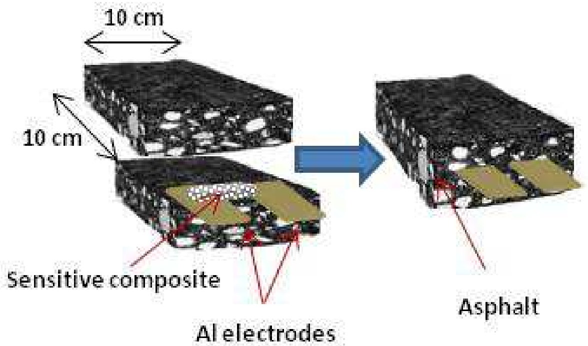

Figure 1: Sensor specimen.

1.3 Characterization methods

Scanning electron microscope (SEM) is used to investigate the micro-structure of the conductive layer. It is performed using a Philips XL-30S microscope in the second electron image mode at high voltages (15 and 20 kV).
The layer thickness is measured by DEKTAK IIA profilometer. The layer is the average of the values over the length of 3 mm. Before compression, the nominal layer resistance is measured between the two electrodes with a digital multimeter (Keithley 1200 A, Keithley instruments Inc.). The average of three successive measurements is given.
During mechanical loadings, the resistance of the asphalt based devices is sensed using a conditioning chain including a Wheatstone bridge, a tunable amplifier, an offset null stage, and a second order low pass filter. The voltage generated by the conditioning chain is fed to the differential input of a digital multimeter. Acquisition rate is 2 s.
Three-points bending configuration and compressive stress perpendicularly to the electrodes and the Slab surface are achieved with a MTS load unit (model 318.10) with effort applied over 10 cm^2 surface areas. The characterizations are carried out at room temperature.

2 Results

2.1 Microstructure and resistance of conductive composite

In order to confirm the dispersion state of the carbon nanomaterials, we carried out SEM analysis. The crystal size and shape of the various graphene powder and carbon nanotubes will be investigated to provide a physical explanation for their different effect of conductivity. SEM images of this nanocomposite revealed that the carbonaceous material was in the form of nanoparticles that remained associated to the silicate surface surrounding the sepiolite. They are also many conductive paths composed by carbon nanotube and graphene (Figure 2).

Depending on the number of drops (from 1 to 30 over a surface of 1 cm²), the thickness of the layer varies between 1µm and 10µm. Figure 3 shows that the resistance decreases exponentially with thickness, quite consistently with typical results from percolating networks [8,10]. Note that when C/Sep is deposited without mixed in MWNTs, reaching percolation requires a much larger number of drops (typically 30 drops), suggesting that the role of (highly anisotropic) MWNTs is to enhance the connectivity between the (roughly isotropic) C/Sep nanoparticles.

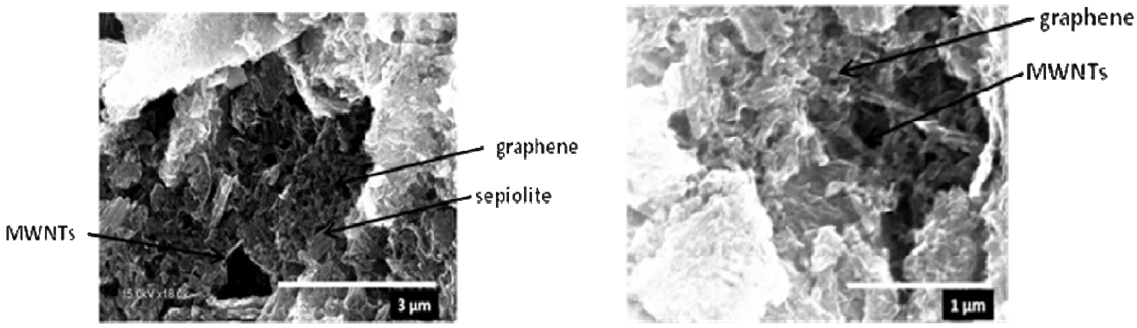

Figure 2: SEM image of C/sep conductive composites with 0.5% wt MWCNTs.

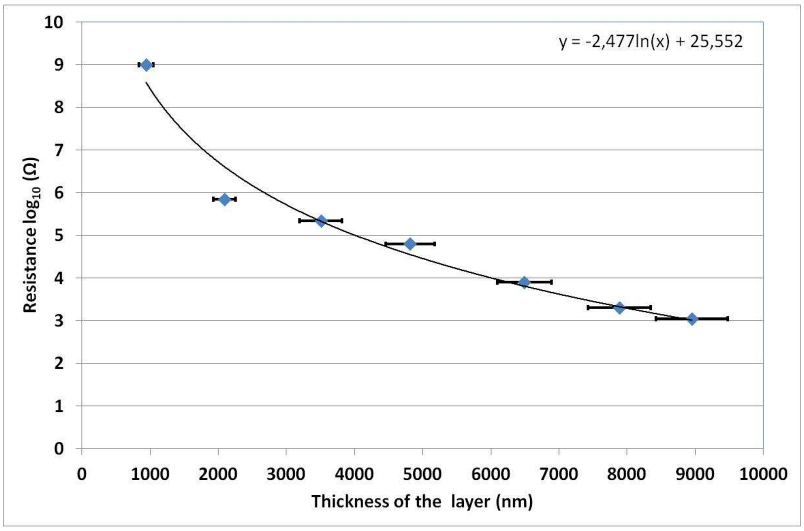

Figure 3: Effect of thickness of C/Sep-MWCNTs layer on their resistivity

2.2 C/Sep-MWNT on asphalt as a compressive force sensor

Figure 4 and 5 shows the change in resistance during repeated compressive loading cycles with increasing amplitude. The resistance values decreases from 5.2% with 5 kN increase in load. The response is non-linear, with about 7s in response time. The change of resistance under compressive load is reversible.

This behavior is interpreted either as a result of the direct piezoresistivity of the C/Sep-MWNTs material (under compression, the effective particle density increases, improving conductivity) or as a result of the improvement of the contacts between the C/Sep-MWNTs layer and the electrodes. Further experiments are in progress to further this analysis.

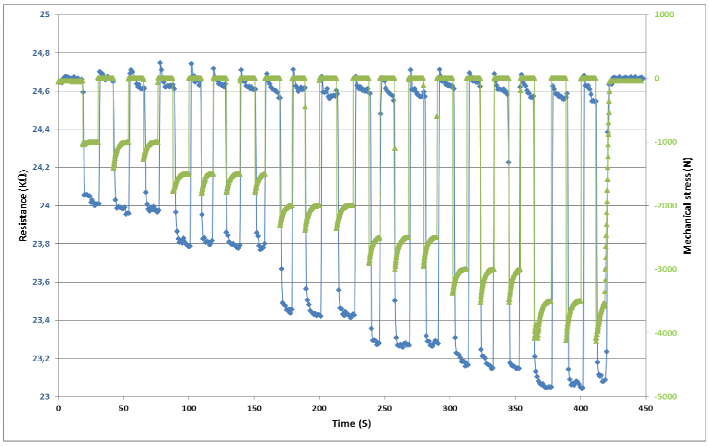

Figure 4: Piezoresistive response of C/sep-MWCNTs-asphalt composite

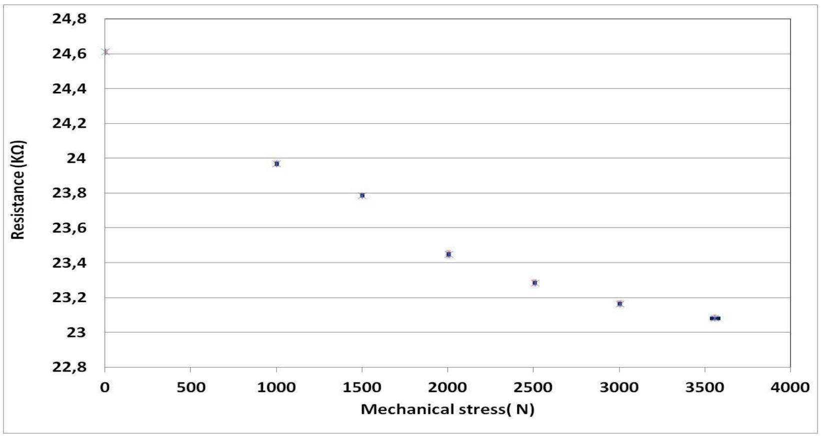

Figure 5: Piezoresistive behaviour of C/sep-MWCNTs-asphalt composite

2.3 C/Sep-MWNT on asphalt for bending and crack detection.

Figure 6 and 7 shows the response of the sensor to a three point bending experiment. The device resistance increases with increased bending. At 1000 N, cracking of the beam is observed; the sensor resistance clearly shows the effect of cracking. Primarily, this result suggests using of the sensor for crack detection.

Additionally, the sensor may also be sensitive to tensile stress, here probably due uniquely to the piezoresistivity of the layer itself (under tensile stress, the effective particle density decreases, resulting in degraded conductivity).

For use in an actual road structure, the sensor will undergo both compressive and tensile strength; careful system optimization will be needed to ensure that the two effects do not compensate, decreasing sensitivity.

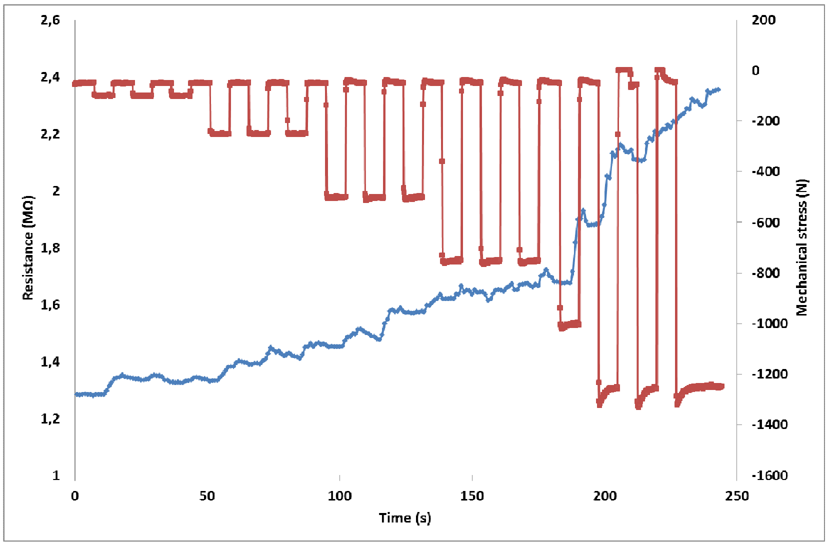

Figure 6: Piezoresistive response of C/sep-MWCNTs-asphalt composite when applied compressive three-points bending configuration

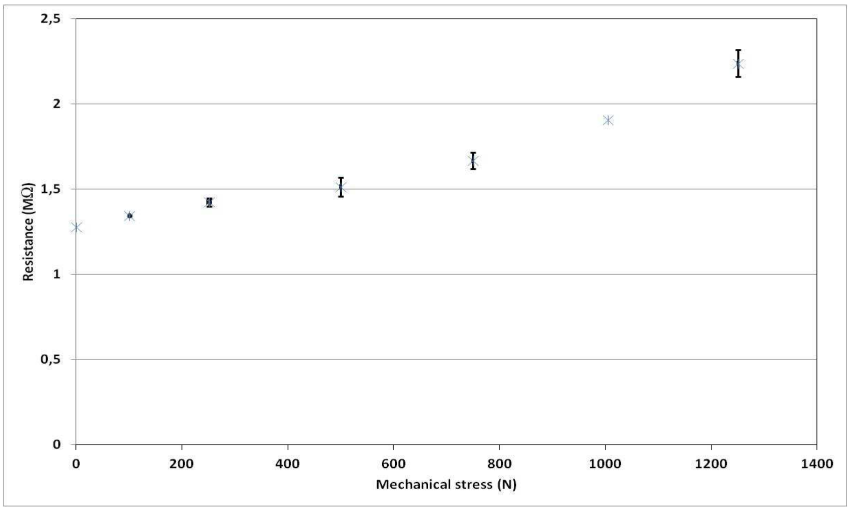

Figure 7: Piezoresistive behaviour of C/sep-MWCNTs-asphalt composite when applied compressive three-points bending configuration

3 Conclusion

The novelty of this paper is the use of the C/sep-MWCNTs nanocomposite material as a thin piezoresistive layer at the core of an asphalt structure to sense compressive and tensile stresses. The base material being extremely cheap and the fabrication process requiring very few steps, this is the promise for a truly low-cost nanosensor for road monitoring (crack detection and weighing). It could be directly fabricated on-site, possible on large surface, and would merge seamlessly with the rest of the road, limiting causes for wear and tear and increasing system durability.

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