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Piezoresistive response of conductive Hot Mix Asphalt mixtures modified with carbon nanofibers

Hashim R. Rizvi [a], Mohammad Jamal Khattak [a,*], Mohammad Madani [b], Ahmed Khattab [c]

[a] Department of Civil Engineering, University of Louisiana at Lafayette, 254J-Madison Hall, Lafayette, LA 70504, United States
[b] Department of Electrical Engineering, University of Louisiana at Lafayette, Madison Hall, Lafayette, LA 70504, United States
[c] Department of Industrial Technology, College of Engineering, University of Louisiana at Lafayette, Lafayette, LA 70504-2972, United States

HIGHLIGHTS

- Dispersing carbon nanofibers in HMA mixtures makes it a smart material with piezoresistive effect.
- Wire embedded electrode provide better results in comparison to plate electrodes.
- Modified HMA mixtures exhibited significant piezoresistivity response at various loading types and temperatures.

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ABSTRACT

In recent years, "smart structures" experienced significant popularity in civil engineering. Such structures, referred to as *intelligent structures*, are built with combination of smart and conventional materials and have intelligent systems that cannot only gather information and perform tasks, but also sense variation in conditions of the materials and adapt accordingly. Conductive Hot Mix Asphalt (HMA) mixtures are constructed by modifying with electrically conductive materials. Conductive HMA mixtures would potentially make many technologies applicable to pavements including, but not limited to; thermal electric de-icing of airport runways or highways, cathodic protection of concrete bridge decks, pavement damage sensing, truck weigh-in-motion, and so forth. Dispersing carbon nanofibers (CNF) in HMA mixtures makes it a smart material as it develops a piezoresistive effect. The main objective of the study is to develop a smart HMA mixture by using electrically conductive material such as carbon nanofibers (CNF). The CNF modified HMA mixtures would have the ability to respond to loading. An exploratory investigation for piezoresistive response of CNF modified HMA mixtures under various types of loading, frequencies, and temperatures were evaluated. Stress–strain response due to applied load and its relationship with the change in resistivity was discussed. It was found that out of two type of CNF used in the study one provide better piezoresistive response of HMA. It was determined that embedment of copper wire electrodes is the most effective method to achieve smooth and consistent electrical response. Furthermore, polymer modified binders showed promising piezoresistive effect for medium to high temperature range.

1. Introduction

In recent years, "smart structures" experienced significant popularity in civil engineering. Such structures, referred to as *intelligent structures*, are built with combination of smart and conventional materials and have intelligent systems that cannot only gather information and perform tasks, but also sense variation in conditions of the materials and adapt accordingly. High-performance structures, such as skyscrapers, long-span bridges, and dams are the most probable candidates for the application [1] of intelligent structures [1–13].

Conductive Hot Mix Asphalt (HMA) mixtures are constructed by modifying with electrically conductive materials. Commonly used materials for conductive HMA mixtures are graphite, coke, carbon fibers and stainless steel fibers. Conductive HMA mixtures would potentially make many technologies applicable to pavements including, but not limited to; thermal electric de-icing of airport runways or highways, cathodic protection of concrete bridge

* Corresponding author.
E-mail addresses: hrr9588@louisiana.edu (H.R. Rizvi), khattak@louisiana.edu (M.J. Khattak), madani@louisiana.edu (M. Madani), khattab@louisiana.edu (A. Khattab).

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decks, pavement damage sensing, truck weigh-in-motion, and so forth [1–19].

Recently, piezoresistive HMA mixture has also been explored by a few researchers. Piezoresistive HMA mixtures were developed by doping the HMA mixtures with conductive materials. Such HMA mixtures would exhibit change in electrical resistivity due to the change in stress or strain response of the material at room temperature. It was found that piezoresistive response would only be optimum in a certain range of compressive stress after which this effect will decrease [20]. It was determined through piezoresistive test results in compressive testing mode, that increase in conductive filler amount was related to piezoresistive response in reverse manner. It was also found that piezoresistive response decreased with the increase in loading cycles. The result of strain to resistivity relationship illustrated that the piezoresistive response of material can be segmented in three parts: initial part of rapid decrease in response, stabilized part of constant response and final part of rapid increase in response. This phenomenon illustrates that change in resistivity of the material decreases initially and then gets stabilized up to an extent where damage starts and this change increases abruptly at the end [20].

Xiao et al. used graphite as conductive filler in HMA mixtures. The mixtures were constructed using 8.5% binder and 5% graphite by weight of aggregates. Wired mesh was embedded in sample to perform two-probe resistivity test. Haversine waveform was utilized under constant stress mode with stress magnitudes ranging from 0.7 to 1.1 Mpa at room temperature. The results of the testing illustrated that effect of piezoresistivity may occur due to three reasons: proximity effect, micro cracks, and dislocation of conductive path due to shear motion of aggregates. It was also concluded that permanent deformation plays an important role in piezoresistive response variations of conductive HMA mixtures [21].

Wu et al. [22] used carbon black, graphite and carbon fiber to design and prepare electrically conductive HMA mixtures. They studied the effects of filler type, filler content and mixed fillers on the resistivity of HMA mixtures. They concluded that the addition of small amounts of expensive carbon fibers to larger amounts of cheaper carbon black or graphite could be a cost effective system. It was observed that the conductive filler particles developed short-range connections whereas the fibers exhibited a long-range conductive bridging effect because of the high aspect ratio [22].

An important consideration while developing a conducting material is resistivity measuring technique. There are two methods available to measure resistivity of the material: one is two-probe and second is four-probe method. Pan et al. showed that two-probe method is functionally applied to the materials showing resistance more than $10^6\ \Omega$-cm [4]. Wu et al. used two-probe method in order to evaluate the electrical behavior of conductive HMA mixtures. They used steel electrodes with graphite powder to fill in empty spaces on the mixture texture to reduce contact resistance [22]. Two-probe test was not recommended for such testing, as contact resistance could be a potential problem while measuring the resistance. Moreover, wired mesh was also not the right approach to measure the response under loading. Chung found that two-probe method was unreliable due to resistance associated with electrical contacts which would become a part of the final measured resistance [23]. On the other hand four-probe method eliminated the effect of contact resistance thereby providing reliable resistivity readings.

Nano-reinforced materials hold the potential to redefine traditional materials both in terms of performance and potential applications [24–30]. Smart HMA i.e. conductive Hot Mix Asphalt mixture, is a new area of research and requires in-depth study to understand and evaluate interaction of conductive additives with HMA mixture. Dispersing carbon nanofibers (CNF) in HMA mixtures makes it a smart material as it develops a piezoresistive effect. The electromechanical capabilities of carbon fibers i.e. to sense its own strain due to effect of strain on electrical resistivity can be utilized to develop piezoresistive HMA mixtures. This study has initiated exploratory testing and analysis to evaluate the effective piezoresistive response measuring technique of CNF-modified HMA and the piezoresistive effect at different loading frequencies, temperatures, CNF types and asphalt binder types. This study is a step forward towards the basic understanding of developing smart HMA mixtures using nanofibers.

2. Objective

The main objective of the study is to develop a smart HMA mixture by using electrically conductive material such as carbon nanofibers (CNF). The CNF modified HMA mixtures would have the ability to respond to loading. The specific objectives are:

1. To evaluate and compare different electrode types and embedment techniques to achieve reliable and effective piezoresistive response under dynamic loadings.
2. To evaluate piezoresistive response of HMA mixtures modified with different types of CNF under various loading conditions and at different test temperatures.

2.1. Test materials and sample preparation

2.1.1. Materials

Two types of binders; viscosity graded asphalt AC5 (PG52-22) obtained from a vendor in Atlanta, GA and Polymer modified PAC30 (PG70-28) was used for this research study. PAC 30 and angular limestone were supplied by a local vendor from Abbeville, LA, USA. Two types of Vapor-grown CNF PR-24XT-XTPS and CNF PR-24XT-LHT (Polygraf III) produced by Applied Sciences were utilized for HMA modification. Both CNF has a diameter of 60–150 nm, length of 30–100 μm, average tensile modulus of 600 GPa and average tensile strength of 7 GPa. The CNF has an Iron and Polyaromatic Hydrocarbons content of <1400 ppm and <1 mg PAH/g, respectively. The fiber has a high performance per cost ratio and good interfacial bonding with materials. Thin copper wires of gauge size 12 having diameter of 2.05 mm and thin 0.5 mm copper plates were utilized as electrodes.

2.1.2. Mixing of CNF

It was utmost important to develop a feasible, applicable and time conserving mixing technique in order to blend CNFs in asphalt binder. Authors have published extensive research on mixing techniques and possible solutions to the potential problems related to mixing of CNF and asphalt binder [28,29]. Brief descriptions of the two procedures that were used in the study are as below.

2.1.2.1. Wet mixing process. Partial amount of CNF (usually 1.5% by weight of binder) was homogenously dispersed in cut back solvent by sonication and high shear mixing. The CNF-solvent mixtures were then mixed with asphalt binder at mixing temperature of 150 °C for AC5 and 175 °C for PAC30 using the shear mixer until all the solvent had evaporated. Remaining amount of CNF (depending on the total dosage to be mixed with HMA) was homogenously dispersed in solvent using by sonication and high shear mixing. The solvent was allowed to evaporate at room temperature followed by oven heating to obtain fully dried and dispersed CNF. Finally, all required amounts of HMA components including aggregates, CNF modified asphalt binder, and oven dried CNF was heated in an oven at the mixing temperature. All the components were mixed thoroughly using the bench mixer. Homogeneous dispersion