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Laboratory evaluation of asphalt binder modified with carbon nanotubes for Egyptian climate

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HIGHLIGHTS

- The surface functionalization of MWCNTs did not improve the dispersion quality.
- The addition of MWCNTs improved the performance of the binder in terms of softening point, G*, and δ.
- Temperature susceptibility of modified binders improved with increase in MWCNTs.
- 3.0% MWCNT makes the modified asphalt more compatible with Egypt's hot climate.

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ABSTRACT

This paper mainly aims at investigating the effect of using multi-wall carbon nanotubes (MWCNTs) as an additive on the rheological properties of asphalt. Pristine (P-MWCNTs) were mixed at 120 °C with control asphalt at contents of 0.5%, 1.0%, 2.0% and 3.0% by asphalt weight. The empirical and rheological properties (using the Superpave testing) of the control and modified asphalts were evaluated at different aging conditions. The rheological properties of the modified asphalts were found to improve with increasing the percentage of P-MWCNTs. The high failure temperature and rutting resistance of both unaged and rolling thin film oven aged (RTFO) modified asphalts increased with increasing P-MWCNTs percentage and became suitable for the Egyptian climatic conditions as required by the Superpave binder characterization. At a given temperature, the fatigue cracking resistance and low temperature cracking resistance decreased with increasing P-MWCNTs percentage.

1. Introduction

Rutting, fatigue cracking, and thermal cracking distresses are related to the viscoelastic behavior of asphalt, which is also affected by the in-service temperature [1]. These distresses affect the mixture performance, causing premature failure of the pavement system. Over the last decades, different modifiers such as crumb rubber and polymers were used to improve the mechanical properties of conventional asphalts. Although asphalt modifiers improve the performance of asphalt, the increase in traffic loads and volumes in addition to the harsh weather conditions and the rising asphalt cost call for more research in this area.

In recent years, studying nanotechnology and its influence on improving characteristics and performance of asphalt pavements, received more attention from many researchers [2]. There are many types of nanomaterials that are widely used in the modification of asphalt such as nano clay, nano titanium oxide, nano silicon dioxide, nano zinc oxide, and carbon nano fibers. Carbon nanotubes (CNTs) are long hollow cylinders of graphene, which have a diameter starting from approximately 1 nm [3]. They were discovered and characterized in 1991 by Sumio Iijima [4]. Since then, an enormous amount of research has been conducted in the area of carbon nanotubes production and their applications due to the superiority of their electronic and mechanical properties [5]. CNTs are divided into single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs), based on the number of graphene sheets. Currently, several techniques are available to produce carbon nanotubes. The three most commonly used techniques are:

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arc discharge, laser ablation and chemical vapor deposition (CVD) [6]. As a modifier, MWCNTs are better than SWCNTs as they are stiffer, and easier and cheaper to produce on a large scale [7]. The most common use of CNTs is to disperse them in another material to promote its mechanical characteristics. However, they have strong cohesive forces (Van Der Waals forces) and easily cluster together when added to a composite, causing defective locations in the composite where CNTs will be few or missing [8]. Thus the homogeneous dispersion of CNTs into the modified material is a challenge in the area of carbon nanotube application. One of the methods for improving dispersion of CNTs in host material is the chemical surface modification of CNTs (functionalization) [9]. There have been only very few and limited research studies on carbon nanotubes (CNTs) modified asphalt in the literature [10].

2. Literature review

Few research studies were found in the literature regarding the application of carbon nanotubes in pavement engineering. Generally, these studies can be divided into two groups. The first group of studies focused on how the dispersion quality of CNTs in asphalt matrix or the properties of CNTs modified asphalt were affected by the mixing technique. These studies are summarized in Table 1. These studies concluded that mixing technique of CNTs and asphalt mainly affects the dispersion quality of CNTs in the asphalt matrix and hence the mechanical and rheological properties of the modified asphalt. The second group of studies focused on the improved properties of modified asphalts and/or mixtures. These studies are summarized in Table 2. The major outcome of these studies is that carbon nanotubes yielded an improvement in the mechanical and rheological properties of asphalts at high temperatures. In addition, the properties of the hot mix asphalts (HMA) modified with CNTs were also improved. However, these studied did not investigate the rheological properties of modified asphalts at long term aging and low temperatures. In addition, the majority of the few available literature studies only investigated the addition of small amounts of CNTs to asphalt.

3. Objectives and scope

This study aims at evaluating and quantifying the properties of a conventional asphalt binder modified with different amounts of Carbon Nanotubes. The specific objectives of the study are to:

- Perform chemical treatment of MWCNTs surface (functionalization).
- Evaluate the effect of functionalization on the dispersion quality of MWCNTs.
- Evaluate the rheological properties of original and MWCNTs modified asphalts.

In this study, the experimental work was divided into two parts. The first part focused on the surface chemical treatment of MWCNTs. Then evaluating the properties of original and functionalized MWCNTs through Scanning Electron Microscopy (SEM) images and Electron Dispersion X-ray (EDX) analysis. Comparing the dispersion quality between the original and functionalized MWCNTs was done to choose the appropriate type for asphalt modification. The second part focused on evaluating the rheological properties of control and modified asphalt using different percentages of the MWCNTs (0.5%, 1.0%, 2.0% and 3.0) selected from the first part. Fig. 1 shows the outline of the conducted laboratory work.

Table 1
Summary of literature studies focusing on the effect of mixing technique on dispersion quality of carbon nanotubes in asphalt matrix and/or the properties of modified asphalt.

Physical properties of MWCNTs	Nano percentages*	Mixing technique	Asphalt testing	Results	Remarks	Reference
- Average Length = 30 μm - Carbon Purity > 95% - Density = 2.1 g/cm^3	3.0%	(1) Mechanical stirrer (5, 10 and 15 min) (2) High shear mixer (1000, 1500 and 2000 rpm) (3) Ultrasonic mixer (60 W for 10 and 15 min. – 65 W for 15 min.)	SEM images for modified asphalt	• SEM images showed that ultrasonic mixer yielded the best results • High shear mixer and mechanical stirrer separated CNTs in micro scale • High shear mixer yielded more homogeneous asphalt than mechanical stirrer	The study did not show detailed information regarding mixers characteristics and mixing steps. For example, high shear mixing time, mechanical stirrer rotational rate and mixing temperature for all mixers	[2]
- Average Length = 1.5 μm - Average Diameter = 9.5 nm - Carbon Purity = 90%	0.5% and 1.0%	(1) Simple shear mixing (mechanical stirrer 1550 rpm for 90 min.) (2) Shear mixing plus sonication (at 150 °C) for two different sonication times (30 and 60 min.)	DSR (stress controlled mode)	• Shear mixing plus sonication showed a remarkable increase in fatigue resistance than simple shear mixing technique only • Increasing sonication time improved asphalt fatigue response		[11]
- Average length = 10–30 μm - Outer diameter = 10–20 nm - Inner diameter = 5–10 nm - Carbon purity > 95% - Density = 2.1 g/cm^3	0.1%, 0.5% and 1.0%	(1) Mechanical stirrer (1550 rpm at 160 °C for 40 min) (2) Sonication process and high shear mixing (CNTs are dispersed in kerosene solvent then sonicated 240 W at 50% pulse rate for 25 min along with using high shear mixer for 2 min. at 2500 rpm), then evaporating the solvent using low shear mixer at 160 °C and time depended on CNTs percentage in modified asphalt	- Penetration - Softening point - Ductility - Rotational Viscometer - DSR (unaged asphalt) - SEM images	• SEM images wet mixing process had better uniform dispersion of CNTs in asphalt matrix than simple shear mixing process • Simple shear mixed asphalt had better softening point, viscosity, complex shear modulus values ($G*$), phase angle values (δ) and rutting factor ($G*/\sin\delta$) than wet process which only improved asphalt results in terms of penetration degree and ductility of asphalt	• Although mixing process was helpful in increasing the dispersion quality of CNTs, it showed a negative effect on most of the mechanical and rheological properties of asphalt due to the use of kerosene solvent with asphalt • Wet mixing process is more complicated and not feasible from the economical point of view	[10]

* By weight of asphalt.