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Experimental evaluation of the influence of reinforcement with Multi-Walled Carbon Nanotubes (MWCNTs) on the properties and fatigue life of hot mix asphalt

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HIGHLIGHTS

- The performance of asphalt mixtures with MWCNTs was investigated.
- The incorporation of MWCNTs into the mixture improve their properties.
- The numerical simulation of the pavement revealed a better performance.
- Asphalt mixtures with MWCNTs are recommended for tropical climates.

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ABSTRACT

This paper reports the influence of reinforcement with Multi-Walled Carbon Nanotubes (MWCNTs) on the asphalt binder and, consequently, on the asphalt mixture. Two nanocomposites (asphalt binder + MWCNTs) were developed: one with 1% of MWCNTs and the other with 2% of MWCNTs, in relation to the conventional asphalt binder (w/w). The nanocomposites were evaluated with regard to their empirical and rheological properties and the sample with the best performance was selected for the production of the asphalt mixture. Two asphalt mixtures were produced: one with the conventional asphalt binder and the other with the selected nanocomposite. The asphalt mixtures were evaluated considering the main deterioration mechanisms of asphalt pavements: moisture-induced damage, permanent deformation and fatigue resistance. After the experimental stage, the results obtained were applied in the numerical simulation of a pavement structure. In general, it can be concluded that the addition of 2% MWCNTs to the asphalt binder and, consequently, to the asphalt mixture, is an appropriate approach to increasing the material resistance against the main defects that damage asphalt coatings, i.e., permanent deformation and fatigue failure, in tropical countries where temperatures below 0 °C do not occur.

1. Introduction

In materials science, nanotechnology is defined as the study and/or the modification of materials at the molecular level, which is strongly associated with the macroscopic properties [1]. An important aim in nanotechnology is to improve the physical and/or chemical properties of materials, leading to an intense interest in their technological applications [2].

In relation to asphalt paving, most improvements in the mechanical and rheological properties of asphalt binders and mixtures in recent decades have been achieved through their modification using polymers and tire rubber. However, the intensity of these advances has been decreasing, mainly with regard to the mechanical performance. Instead, new developments in the performance of these properties could come from the control and improvement of smaller structural scales, such as the nanometric scale, in the domain of the nanostructures of these materials. The modification of nanostructures could lead to new types of materials that cannot be developed using current techniques. The possibility of fluency control, self-healing, increased mechanical strength and the inclusion of functional properties in materials are some examples of what can be achieved with nanotechnology. In this respect, in road engineering, new materials developed with the aid of nanometric particles include coatings with

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photocatalytic properties, reported in several publications [3–7], and asphalt mixtures reinforced with nanolamellar silicates [8–11].

The application of nanoparticles as reinforcement loads for asphalt mixtures is currently gaining importance due to the development of mixtures with higher mechanical performance in relation to conventional mixtures. In this regard, researchers have been showing great interest in Carbon Nanotubes (CNTs), based on their unique characteristics. The modulus of elasticity values for CNTs can reach 1 TPa while, at the same time, they can be bent through large angles without breaking [12]. The methods for the production, purification and functionalization of CNTs are in constant evolution and thus they could be accessible for large-scale use within a few years. Some findings [13–20] have led to the study of CNTs as reinforcement loads for asphalt binders. However, these studies have been limited to investigating changes in the rheological characteristics of the binders, but the asphalt mixtures should also be studied. It is of fundamental importance to understand the rupture characteristics of materials used for pavement construction, since the behavior of asphalt mixtures under bending and compressive stresses is characterized by specific laws, such as the fatigue and permanent deformation laws, which must be considered in the structural design of paving. Thus, the evaluation of asphalt mixtures in terms of their fatigue behavior and resistance to permanent deformation is indispensable to the verification of the real performance that can be obtained on applying these new asphalt materials in a pavement structure.

This paper presents the results of an in-depth study on the mechanical performance of an asphalt mixture nanomodified with MWCNTs. Firstly, the development and rheological characterization of an asphalt binder modified with MWCNTs (asphalt nanocomposite) is described, and the study is then extended to the field of asphalt mixtures. Lastly, the performance of the nanomodified asphalt mixture is quantified through the numerical simulation of the structure of a flexible pavement.

2. Materials and methods

2.1. Materials

The following materials were used to carry out the study: conventional asphalt binder, MWCNTs, mineral aggregates and hydrated lime. The characterization and selection of the mineral aggregates and the conventional asphalt binder were carried out according to the criteria of the Superpave specifications.

2.1.1. Conventional asphalt binder

The asphalt binder selected for this study was the conventional type with the following empirical and rheological characteristics: performance grade (PG) 58-22 [21], penetration 57 tenths of a millimeter [22], softening point 47.9 °C [23], penetration index −1.44 (Pfeiffer and Van Doormaal) and apparent viscosity 0.29 Pa.s at 135 °C, 0.15 Pa.s at 150 °C and 0.06 Pa.s at 175 °C [24].

2.1.2. MWCNTs

The CNTs used in this study were multi-walled with an external diameter of 50–80 nm (95+%) (according to the micrograph in Fig. 1), internal diameter of 5–15 nm (95+%), length of 10–20 μm (95+%), density of 2.1 g/cm^3 and specific surface area of 60–80 m^2/g (95+%). The X-ray fluorescence (XRF) results for the MWCNTs identified the principal constituents as: carbon (97.37%), nickel (1.86%), iron (0.55%), chlorine (0.20%) and sulfur (0.02%), indicating a high degree of nanomaterial purity. The properties of the MWCNTs were obtained from the manufacturer (Nanostructured & Amorphous Materials, Inc.). It should be noted that, according to the manufacturer, up to 5% of the MWCNTs can show variations from the properties informed above.

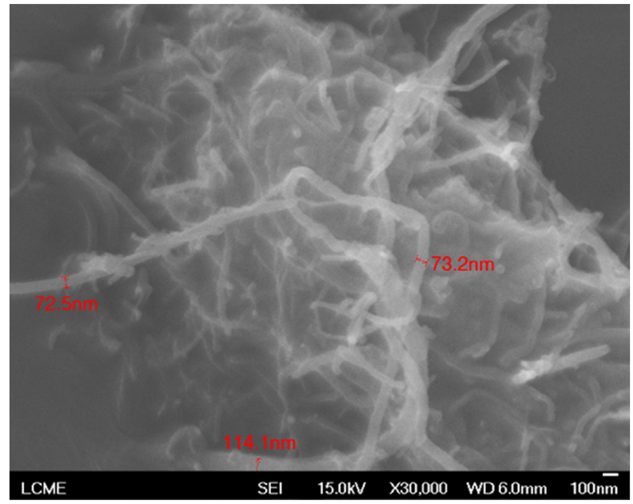

Fig. 1. Micrograph of MWCNTs (magnification 30,000×).

2.1.3. Mineral aggregates

The mineral aggregates used in this study are of basaltic mineralogical origin and were characterized according to the criteria of the Superpave methodology for a heavy volume of traffic. The aggregate properties are given in Table 1.

According to Table 1, all properties of the aggregates selected for the production of asphalt mixtures conformed to Superpave criteria. The angularity values for the coarse and fine aggregates are considered to be suitable. The coarse aggregate was completely fractured as a result of the crushing process, ensuring a high degree of internal friction between particles. The fine aggregate showed a high percentage of voids in the loose state (49.2%), due to the angularity and roughness of the particles (when these particles fall freely their sharp edges and corners keep them apart, increasing the void volume in the loose state). In relation to the particle shape, an average of 9.6% of the particles examined were found to be lamellar or elongated-lamellar elongated (which is below the tolerable limit of 10%) and 90.4% were cubic. The sand equivalent test showed a satisfactory result regarding the clay minerals on the surface of the particles, avoiding problems such as the disaggregation of the aggregate in the mixture due to the displacement of the asphalt film. The aggregates also showed a low value for the Los Angeles abrasion (11.6%), demonstrating resistance to various processes, including crushing, storage, mixture production, compaction and forces applied by traffic. In the soundness test, the aggregates presented a mass loss of 2.1%, after 5 cycles, expressing high resistance to weathering. The presence of friable materials together with the granular rock materials was not evidenced. After this careful evaluation of the aggregates, they were used to carry out the proposed study.

2.1.4. Hydrated lime

In the granulometric formulation of the asphalt mixture, besides mineral aggregates, a type CH-1, dolomitic, hydrated lime was used, with the physical and chemical characteristics shown in Table 2. The hydrated lime is classified as type II according to AASHTO M303 [35].

2.2. Method

Fig. 2 shows the structure of the method applied in the experimental investigation. According to the global flowchart in Fig. 2, in