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Evaluation of properties and fatigue life estimation of asphalt mixture modified by organophilic nanoclay

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HIGHLIGHTS

- The performance of asphalt mixtures with nanoclay was investigated.
- The incorporation of nanoclay into the mixtures improves their properties.
- The numerical simulation of the pavement revealed a better performance.

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ABSTRACT

This paper presents the results for the influence of an organophilic nanoclay on the properties of an asphalt mixture. The main mechanical and rheological properties of a nanomodified mixture were evaluated, including moisture-induced damage, resistance to permanent deformation, complex modulus and fatigue resistance. The results obtained show gains in the properties of the asphalt mixture modified by nanoclay. The beneficial effect of the nanoclay was also verified in the numerical simulation of a pavement structure, since the lifespan of the nanomodified asphalt surface increased with regard to the fatigue fracture, when compared to a conventional asphalt surface. The main conclusion of this study is that the addition of an organophilic nanoclay to an asphalt mixture can improve its resistance in relation to the main mechanisms involved in the deterioration of pavements.

1. Introduction

Asphalt pavements undergo a process of degradation after their construction, due to the action of traffic and in response to weather conditions. This process, which occurs throughout the lifespan of the pavement, can be retarded when the pavement is well constructed and if the materials used have better performance than conventional ones. In the case of asphaltic materials, the modification of the binders is one approach to improving their performance and, consequentially, that of the asphalt mixtures. Various types of modifiers have been employed as asphalt binders to improve the properties of an asphalt mixture, particularly with regard to its resistance to aging, cracks due to fatigue and thermal conditions, moisture-induced damage and permanent deformation.

In recent studies [1–3] in the field of nanotechnology, matrix reinforcement has been carried out using tubular fillers, such as carbon nanotubes, as asphalt binders. However, most research [4–12] has been directed toward the study of asphalt nanocomposites formed using nanolamellar silicates, for example, organophilic nanoclays, which are comprised of lamellae with a thickness of around 1 nm and diameters varying between 100 and 1000 nm. Some authors have reported improvements in various properties of asphalt binders, however, understanding the effect of organophilic nanoclay on the mechanical properties and rheological behavior of asphalt mixtures requires more in-depth investigation. In this regard, it is fundamental to understand the characteristics of the fracture of the materials involved in the construction of pavements, since the behavior of asphalt surfaces under bending and compression is characterized by specific laws, such as the fatigue law and permanent deformation law, which must be considered in the design of structural pavements.

In this context, this article presents the results of a study on the influence of the use of an organophilic nanoclay to modify asphalt mixtures, by investigating the rheology, mechanical resistance and fatigue life. The study starts from the development of the asphalt nanocomposite up to the asphalt mixture field.

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2. Materials and methods

2.1. Materials

In order to carry out this study, the following materials were used: conventional asphalt binder, organophilic nanoclay, aggregate minerals and hydrated lime (CH-I).

A conventional asphalt binder was used in the study, with a performance grade (PG) of 58–22 [13], penetration of 0.57 mm [14], softening point of 47.9 °C [15] and penetration index (PI) of −1.44 (Pfeiffer and Van Doormaal).

The organophilic nanoclay is composed of carbon (45.5%), silicon (33.42%), aluminum (16.08%), iron (3.60%), chlorine (0.80%), titanium (0.31%), potassium (0.27%), and strontium (0.02%) (obtained by X-ray fluorescence), with a crystalline structure consisting of tetrahedral silicon and octahedral aluminum (dioctahedral structure), particle size after dispersion of 1 × 500 nm and density of 1700 kg/m^3. The nanoclay is derived from a clay mineral called montmorillonite and it is modified with quaternary ammonium salts (dimethyl ammonium with two alkyl chains).

The aggregate selected for the formulation of the asphalt mixtures has a basaltic mineral origin and the following properties: absorption 0.8% [16], coarse aggregate angularity 100% [17], fine aggregate angularity 49.2% [18], flat and elongated particles 9.6% [19], sand equivalent 61.2% [20], Los Angeles abrasion 11.6% [21], soundness 2.1% [22] and the absence of deleterious materials [23]. The type of hydrated lime used was CH-I, dolomitic, classified according to AASHTO M 303 [24] as type II. The main characteristics of the hydrated lime are given in Table 1.

The conception of the granulometric curve, used in the formulation of the asphalt mixtures, adhered to the Superpave specification, that is, maximum nominal size of 19 mm. The granulometric curve is comprised of 43% coarse aggregate (3/4″ or 19.1 mm), 15.5% fine aggregate (3/8″ or 9.5 mm), 40% stone dust and 1.5% lime (Fig. 1).

2.2. Methods

To evaluate the effects of the nanoclay on the asphalt mixture, two mixtures were produced and investigated; one with the conventional asphalt binder (reference) and the other with an asphalt nanocomposite prepared with the nanoclay (conventional asphalt binder + nanoclay). The structure of the investigation was organized as follows: development of the asphalt nanocomposite with nanoclay, design of asphalt mixtures, and evaluation of the resistance to fatigue and permanent deformation of the mixtures. Finally, a numerical simulation of a pavement structure was carried out and the lifespan was estimated, considering the fractures caused by fatigue for the conventional and nanomodified asphalt surface course.

2.2.1. Development of the asphalt nanocomposite with nanoclay

The percentage of nanoclay added to the asphalt binder was established based on previous research studies [4–12], where improvements in the properties of the asphalt binder were achieved with additions of around 3% relative to the weight of the binder. Thus, the asphalt nanocomposite was developed with the addition of 3% nanoclay in the conventional asphalt binder, embedded using a high-shear mixer, with a shear level of 5000 RPM.

The temperature used to modify the asphalt binder was defined based on the thermogravimetry analysis of the nanoclay powder. In this analysis, the highest temperature at which the nanoclay maintains its thermal stability was verified, indicating the best temperature at which to perform the modification of the asphalt binder, without decomposition of the nanomaterial. The thermal analysis was carried out from 25 °C to 500 °C, with a heating rate of 10 °C/min, in a nitrogen atmosphere at a flow rate of 100 ml/min.

The compatibilization time in the high-shear mixer was defined as a function of the complete exfoliation of the sheets (lamellae) of the nanoclay in the asphalt binder. The degree of exfoliation of the nanocomposite was determined by X-ray diffraction (XRD). The X-ray diffraction was performed using Cu-Kα (copper) radiation, scanning from 1° to 10° (2θ), at a rate of 0.02°/min. In this analysis, it was possible to obtain the interfoliar spacing, i.e. basal spacing (d_{001} plane), which is calculated applying Bragg's law according to Eq. (1).

$$n\lambda = 2d\sin\theta \tag{1}$$

Table 1
Characteristics of the hydrated lime.

Properties of the hydrated lime	Value
Carbonic anhydride (CO_2)	2.5%
Calcium oxide (CaO)	45.1%
Magnesium oxide (MgO)	33.5%
Total non-volatile oxides (CaO + MgO)	96.5%
Total non-hydrated oxides	27.6%
Non-hydrated CaO	0.0%
Calcium (Ca)	32.2%
Magnesium (Mg)	20.2%

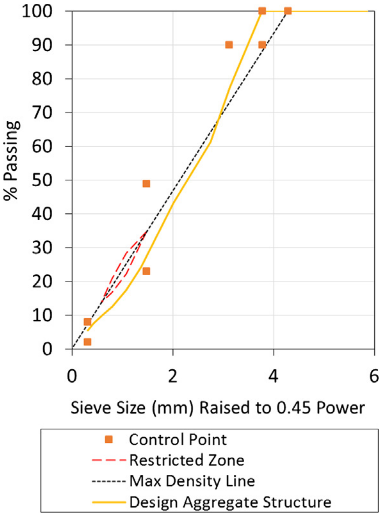

Fig. 1. Design of aggregate structure.

where:

n = order of diffraction;
λ = radiation wavelength of the X-rays used in the experiment (1.5418 Å);
d = spacing between the planes of the diffraction grating;
θ = diffraction angle measured.

After the development of the nanocomposite, its properties were determined and compared to those of the conventional asphalt binder. Comparisons between the two materials were made in terms of the penetration [14], softening point [15] and PI (Pfeiffer and Van Doormaal). The penetration and the softening point were defined in order to allow the determination of the penetration index. In addition, in several countries including Brazil, the penetration value is used to classify asphalt binders. With regard to the rheological evaluations, the effects of the nanomodification on the apparent viscosity [25] and PG [13] were evaluated. Rheological tests to determine the dynamic shear on a dynamic shear rheometer (DSR) [26] and the flexural creep stiffness using a bending beam rheometer (BBR) [27] were carried out to determine the PG.

2.2.2. Design of the asphalt mixtures

The design of the asphalt mixtures was carried out according to the requirements of the Superpave methodology, using a gyratory compactor. The procedures adopted for the formulation followed the recommendations of the standards AASHTO M 323 [28] and AASHTO R 35 [29]. Three parameters were fixed to model the specimens: compaction angle of 1.25°, compaction pressure of 0.6 MPa and gyration speed of 30 RPM. The mixture design was carried out considering a high volume of traffic ($N_{initial}$ = 9 gyrations, N_{design} = 125 gyrations, and $N_{maximum}$ = 205 gyrations). The asphalt binder content of the mixture design was defined as that which fulfilled the following Superpave criteria: percentage of air voids $N_{initial}$ > 11%, N_{design} = 4%, and $N_{maximum}$ > 2%; voids in the mineral aggregate (VMA) ≥13%; voids filled with asphalt (VFA) 65–75%; and dust proportion (DP) 0.8–1.6%. To validate the formulation obtained, the resistance of the designed asphalt mixtures to moisture-induced damage was verified, using the modified Lottman test, according to the standard AASHTO T 283 [30].

2.2.3. Evaluation of fatigue resistance of the asphalt mixtures

Prior to the fatigue tests, the rheological behavior of the asphalt mixtures produced was evaluated via complex modulus tests carried out applying various frequencies and temperatures on four-point fatigue test equipment (4PB). For both the rheological and fatigue resistance tests, prismatic specimens with dimensions of 50.8 × 63.5 × 381 mm were extracted from asphalt slabs (600 × 400 × 90 mm) molded on a compactor table IFSTTAR (Institut Français des Sciences et Technologies des Transports, de L'aménagement et des Réseaux), according to the specifications of AFNOR NF P 98-250-2 [31]. The complex modulus tests were conducted at the frequencies of 0.1 Hz, 0.2 Hz, 0.5 Hz, 1 Hz, 2 Hz, 5 Hz, 10 Hz and 20 Hz, and at temperatures of 0 °C, 5 °C, 10 °C, 15 °C, 20 °C, 25 °C and 30 °C, under controlled deformation with an alternating sinusoidal load and a maximum deformation by flexure of 50 μm/m, according to the guidelines of the standard EN 12697-26 [32].

The fatigue resistance of the asphalt mixtures was determined according to the standard EN 12697-24 [33], under continuous sinusoidal load and controlled deformation. The fracture criterion was 50% reduction of the initial complex modulus (determined in the hundredth cycle) and the load frequency was 10 Hz. The temperature for carrying out the fatigue tests was established considering the results for the rheological behavior of the asphalt mixtures produced, based on the dissipated energy approach. The critical temperature was determined. This is the tem-