Construction and Building Materials 168 (2018) 31–40

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Effect of nanomaterials on ageing and moisture damage using the indirect tensile strength test

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HIGHLIGHTS

- The effect of nanoclay and nanoiron on ageing and moisture damage has been analyzed.
- Nanoclay seems to retard the hardening process provoked by the ageing phenomenon.
- Nanoiron modified mixtures show the best behaviour against moisture damage.
- Mixtures show similar trends against LTOA and TEAGE ageing but in different degrees.
- The TEAGE ageing procedure seems to replicate better the climate effect on mixtures.

ARTICLE INFO

Article history:
Received 14 July 2017
Received in revised form 15 February 2018
Accepted 16 February 2018

Keywords:
Ageing
Weather ageing simulation
Nanoclay
Nanoiron
Moisture damage

ABSTRACT

Environmental conditions as well as traffic loads lead to the deterioration of asphalt pavements during their service life. For this reason, the use of nanomaterials that improve the mixtures behaviour could be interesting. The behaviour of two mixtures made with binder modified with nanoclay and nanoiron, and their strength against ageing and moisture damage is studied. Mixtures have been subjected to ageing by two procedures: extended heating, Long-Term Oven Ageing (LTOA), and ultraviolet (UV) plus rainfall simulation, Tecnico Accelerated Ageing (TEAGE). The results show that nanoclay improves the mixture behaviour against ageing, while nanoiron does against moisture damage.

1. Introduction

The main factors affecting the durability of asphalt mixtures are ageing and moisture damage, assuming the pavement is well constructed [1,2]. This is why it is crucial to take into account the effect of the environmental conditions on the asphalt mixtures when designing them. Simulating the effect of these factors on asphalt mixtures is a complicated task as many of them such as temperature, water, air, solar radiation, and their combination influence on the durability of mixtures.

Ageing, phenomenon by which the behaviour of the binder and of the mixture changes, is an important factor in the context of cracking resistance of asphalt mixtures [3]. This phenomenon is characterized by a binder hardening, which increases the stiffness values of the mixture. This means, on the one hand, an increase of the mixture bearing capacity and, on the other hand, an increase in its resistance to deformation. However, these effects occurred just to a certain point once ageing also means fragility of the binder/aggregate bonding inducing much less resistance to fatigue and enhancing the aggregates' stripping.

Ageing is generally divided into two stages [4]: short-term ageing and long-term ageing. The short-term ageing occurs during the manufacturing, mixing, transport and laying of the asphalt mixture. During this stage, ageing is mainly associated with the loss of volatile components and the oxidation of bitumen. On the other hand, long-term ageing is associated exclusively with the degradation produced during the service life of the mixtures as a result of environmental factors such as temperature, available oxygen in the atmosphere, UV radiation and moisture [5]. In this stage, the oxidation rate decreases with the depth of the asphalt layer [6,7]. Consequently, the viscosity also decreases with the asphalt layer depth

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https://doi.org/10.1016/j.conbuildmat.2018.02.110
0950-0618/

[8]. This is due to a constant supply of oxygen, the high temperatures of the surface layer and UV photo-oxidation.

Evaluating and characterizing the effect of ageing on the behaviour of asphalt mixtures is a difficult task [9]. The basic procedure is to age artificially the mixture and then evaluate the effect of ageing through simplified approximations that relate to a mechanical property of the material. The most commonly methods used to evaluate ageing are dynamic modulus, diametrical resilient modulus and lost of ductility. Other methods related to the study of asphalt mixtures cracking such as the indirect tensile strength test, the semi-circular bending (SCB) fracture test or the Fénix test have been used to determine the effect of ageing [10,11,12]. However, there is not a good number of studies examining the effect of ageing on the indirect tensile strength, being an unresolved problem at present [10].

Throughout the literature, a number of methods have been defined for artificially ageing asphalt mixtures. However, the correlation of these methods with field data is extremely difficult as it depends on many factors such as the location of the road, the sun exposure, the weather, the type of mixture and the void content. Airey [1] divided the ageing methods for asphalt mixtures into four categories: prolonged heating procedures, oxidative procedures, ultraviolet and infrared light treatments and steric hardening. The simulation of ageing in the laboratory is usually carried out, especially for binders, under the influence of temperature and pressure. This differs from the conditions at which mixtures are aged in the field. One of the most followed ageing methodologies by the scientific community is the defined by the SHRP program [13], method on which AASHTO R 30 is based. The laboratory ageing procedure for asphalt mixtures defined by the SHRP program consists of the Short-Term Oven Ageing (STOA), where the loose mixture is placed in a convection oven at 135 °C for 4 h. Then, the mixture is compacted and placed in a convection oven at 85 °C for 5 days (Long-Term Oven Ageing, LTOA). Nevertheless, a method that takes into account environmental factors such as temperature, UV radiation and moisture (simulation of rain conditions) should be considered to perform a more realistic study of ageing [14,15]. In order to simulate the effect of daylight as well as the radiation from the sun, ultraviolet radiation treatments have been used in the literature. In this respect, some authors have used the wetherometer test that combines the effect of the temperature, the UV radiation and the moisture during ageing to simulate the service conditions of the mixtures [14,16,17,18]. The results show the importance of ultraviolet radiation in the ageing of the asphalt mixtures [18,19].

The reduction in the asphalt mixture resistance is not only a result of ageing but also of moisture damage, contributing to the development of several types of pavement deterioration such as cracking, rutting and collapse [20,21,22]. As a consequence, the pavement life decreases [23].

Moisture damage is normally associated with five different mechanisms: detachment, displacement, spontaneous emulsification, pore pressure and hydraulic scour [24,25,26,27,28,29]. Authors such as Hamzah, et al. [30] add the effect of environmental conditions as a contributing mechanism to moisture damage. In addition to the above mechanisms, Kinggundu & Roberts [31], Little and Jones [32] and García [33] include the pH of water.

The development of tests to determine the moisture sensitivity of asphalt mixtures began in the 1930s [34]. Since then numerous procedures have been developed in an attempt to identify the asphalt mixture susceptibility to moisture damage. Generally for laboratory tests on compacted mixtures, specimens are conditioned in water to simulate service conditions. The moisture damage assessment is measured by the ratio between the stiffness or strength of the conditioned and the unconditioned mixtures. Some of these tests are the immersion-compression test [35,36] and the Marshall stability test [35].

Currently, the study of the asphalt mixtures properties during their service life has led to the implementation of different test methods, which intend to improve the quantification of ageing together with the moisture damage. Thereby, researchers from the Nottingham Transportation Engineering Center (NTEC) developed the Saturation Ageing Tensile Stiffness (SATS) test that combines oxidative ageing along with the moisture damage in the specimens conditioning [37,38,39].

Over time, asphalt pavement layers are exposed to great stresses, in addition to the effect of the continuous climate changes, which leads to the deformation of the lower asphalt layers, the stiffness of the upper asphalt layers and the relative displacement of the mixture mineral particles of the upper layers [40]. For this reason, the use of materials (nanomaterials) that modifies and ultimately improves the behaviour of mixtures becomes interesting [41]. This is why the use of nanomaterials is currently being studied. Different types of nanomaterials have been used to improve the behaviour of mixtures such as carbon nanotubes, nanoclay or nano-SiO2 [42]. Thus, the nanoclay can be applied to improve the mechanical behaviour and the resistance to ageing of the asphalt mixtures [43,44].

In this study, the effect of ageing by UV radiation and moisture damage on the asphalt mixtures cracking has been investigated. For this purpose, unconditioned and aged mixtures, subjected or not to moisture damage, are tested by the indirect tensile strength to analyse their cracking resistance and their sensitivity to moisture damage. Ageing by UV radiation has been carried out with a new test protocol developed by the Instituto Superior Técnico (IST), TEAGE (from the acronym of TEcnico Accelerated aGEing). This test takes into account not only the UV radiation but also the effect of the rain on the asphalt mixtures, adapted for the total conditions observed for a specific site, meaning that UV and rain simulation incidence over mixtures are the same that the ones verified in average during a certain number of years in that site. In addition, the results from the indirect tensile strength performed on the mixtures aged with the TEAGE procedure are compared with those obtained on mixtures aged with the procedure defined by the SHRP, LTOA. Furthermore, the effect of modified bitumen with nanoclay and nanoiron on ageing and moisture damage is analysed.

2. Methodology

2.1. Materials and sample preparation

An asphalt concrete mixture with a maximum aggregate size of 14 mm (AC14) was selected. The aggregate type was granite with limestone filler. The AC14 aggregate gradation is presented in Fig. 1. Specimens were prepared with different binder: a conventional one (35/50), a nanoclay modified one and a nanoiron modified one. For all the cases, the binder content was 4.5% by the weight of the mixture. The modification of both nanomodified bitumen was performed by mechanical dispersion of the nanoparticles in the neat binder using a high speed stirrer. For the two nanomodified bitumen, the nanoparticles content was 4% by weight of modified binder.

The nanoclay is a hydrophilic bentonite ($H_2Al_2O_6Si$). The particles of this material form agglomerates with an average size of less than 25 μm, has a density of 2400 kg/m^3 and pH in the range of 6 to 9. The nanometric dimension of the nanoparticle is determined by its thickness and the spacing of the laminar structures it forms (between 1 and 2 nm).

The iron nanoparticles have an average size of less than 50 nm. These are nanoparticles with zero valence electrons, Fe (65–80%), and iron oxides, FeO and Fe_3O_4 (20 to 35%). This material has a