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An investigation into the impact of warm mix asphalt additives on asphalt mixture phases through a nano-mechanical approach

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HIGHLIGHTS

- All warm additives improved the nano-mechanical properties of ITZ.
- The production temperature had a very clear effect on the mastic phase.
- Nanoindentation is a novel technique to reflect a real performance of asphalt mixtures.

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ABSTRACT

This paper presents the results of a novel investigation to evaluate the effect of Sasobit, Rediset WMX and Rediset LQ on the mechanical properties of asphalt mixture phases, aggregate, interfacial transition zone (ITZ) and mastic using Nanoindentation. All warm additives improved the nano-mechanical properties of the ITZ if the reduction in the production temperature was not more than 10 °C for an asphalt mixture with the 40/60 hard binder and 20 °C with the 100/150 binder. The nano-mechanical properties of mastic for all WMAs manufactured at 20 °C lower than the control using 40/60 mix were less than the control mix. However, as the reduction in the production temperature decreased to 10 °C, the modulus and hardness of the mastic and ITZ for all WMAs significantly increased. While, 20 °C reduction in the production temperatures was achieved using 100/150 with inclusion of warm additives and the values of nano-mechanical properties of ITZ and mastic was same or even higher than the control mix. It can therefore be concluded that, in order to produce a warm asphalt mixture that performs the same or even better than the traditional HMA, the effect of production temperature must be addressed. In summary, Nanoindentation provides new insight about the effect of warm additives on the nano-mechanical properties of asphalt mixture phases and predicts level of bonding between aggregate and binder.

1. Introduction

There has been extensive research conducted on the macro- and micro-mechanical properties of asphalt mixture composites and their constituents; however, there have been only a few studies on their nano-mechanical properties [1–4]. In fact, there is a need to characterise and understand the mechanical properties at the nano-scale because the interactions among the composite phases happen at this scale [5]. The combination of asphaltic mixture, asphalt binder film, mastic (binder filled by aggregate smaller than 0.075 mm) and aggregate plays a significant role on the stress-strain behaviour of asphalt mixture [1]. The hardness and elastic modulus of the asphalt binder film significantly have a direct effect on the low temperature fracture of asphalt mixture [6–8], whilst the mastic has a substantial effect on the healing behaviour of the asphalt mixture and the aggregate perceptibly impacts its durability [9,10]. Not surprisingly, there is little understanding of the fundamental properties of asphalt mixtures' phases at the nano-scale because of the inability to characterise the mechanical properties of asphalt mixtures at this scale. However, with the advent of nanoindentation, it has become possible to measure the mechanical properties of thin film asphalt and the interactions among the main components of asphalt mixture, binder and aggregate. Nevertheless, despite the fact that there are now efforts and endeavours made to study the influence of warm additives on fatigue cracking, moisture damage, rutting, healing, etc., the effect of warm additives on the nano-mechanical properties of asphalt has

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yet to be studied. Therefore, there is a need to understand to what extent warm additives have an impact on the interaction between aggregate and binder.

Generally, the evaluation of asphalt mixtures in terms of rutting, fatigue, etc., is based on the properties of the mixture as a whole, while nanoindentation is capable of differentiating the properties among mixture phases, mastic, interfacial transition zone (ITZ) and aggregate. Nanoindentation is a powerful technique to measure the hardness and elastic modulus. Elastic modulus measures the force that is needed to compress a material sample; a stiff material needs more force to deform compared to a soft material; while indentation hardness measures the resistance of a sample to material deformation due to a constant compression load from a sharp object.

Nanoindentation is a relatively new technique by which to measure the nano-mechanical properties of mixture phases. Stangl et al. (2007) [11] conducted a study to investigate the effect of styrene-butadienestyrene (SBS) on the characteristics of bitumen using nano- and micro-indentation tests. One control bitumen (B 50/70) and one polymer-modified bitumen (PmB 60/90) were considered in the experimental work. The study showed that the initial creep compliance obtained from nanoindentation correlates with rheological properties (complex shear modulus and phase angle) obtained from a DSR.

Tarefder et al. (2010) [1] investigated the nano-mechanical properties such as hardness and Young's modulus of asphalt binders and asphalt concrete. Indentation tests were carried out on a base binder and two polymer-modified performance grade (PG) binders, PG70-22 and PG76-28, and also two Superpave asphalt mixes. Aggregate, matrix (Material Passing No. 4 sieve) and mastic (Material Passing No. 200 sieve) phases of each asphalt concrete sample were indented using both Berkovich (sharp and three-sided pyramidal) and Spherical indenters. In that study, the indentation load versus displacement data was analysed using the Oliver and Pharr method [15]. It was shown that the spherical tip is suitable for asphalt binder materials, but the attempts made in this study were not successful in measuring hardness and Young's modulus of the base binder because it is soft. This is because the unloading data are linear and vertical, which could not be analysed using existing analytical tools. It was also reported that both Berkovich and spherical indenters can be used on asphalt concrete, but it should be noted that the Berkovich indenter penetrates the asphalt samples more than the spherical indenter under the same load. Moreover, the average values of the modulus of limestone and dolomite aggregate are within the range of commonly accepted values from the literature. The authors concluded that nanoindentation provides micromechanical properties of mastic, aggregate and matrix without separating them from the asphalt concrete. Those properties may provide more realistic inputs for the micromechanical models such as a discrete element model of the characterisation of fracture, healing and ageing behaviour.

Tarefder and Faisal, 2013 [12] characterised the effect of ageing on aggregate and mastic of asphalt mixtures. They reported that the hardness and elastic modulus of mastic increases with ageing process and this increase resembles the age-hardening behaviour of the asphalt binder. However, the elastic modulus and hardness of aggregate remained constant after ageing process. The effect of moisture on mastic was studied by Hossain et al. [13]. It was reported that wet mastic is less viscous than dry mastic and the surface of wet mastic was stiffer than that of dry mastic because of erosion, viscosity loss of wet surface due to conditioning effects. The authors of previous research believed that beneath the surface, the wet mastic was softer than the dry mastic therefore suggestion was made the effect of moisture at different depths of mastic is recommended.

Khorasani et al. (2013) [4] also explored the local nano-scale mechanical properties of fine aggregate mixture (FAM) phases and interfaces. The interface between aggregate and binder was found to have hardness and modulus values between those of aggregate and mastic.

This paper presents a novel evaluation of the effect of warm additives on nano-mechanical properties of aggregate, ITZ and mastic with taking in account the effect of production temperatures which is a crucial factor affecting the performance of asphalt mixtures.

2. Principles of nanoindentation

2.1. Overview

In the indentation test, an indenter is used to indent a sample surface and the load applied by the indenter is plotted continuously with the displacement of the indenter into the sample. The shape of the loading and loading curves depends on the elastic and plastic properties of the sample material [1,14]. This technique is capable of producing contact areas and penetration depth characterised by nanometre dimensions for materials. The forces involved are in the milli-Newton range. The area of the contact is calculated directly from the measurements of the residual impression left in the specimen surface upon removal of the load. However, in nanoindentation tests, as the size of the residual impression is too small to be conventionally measured directly, therefore the contact area is measured indirectly from the depth of penetration of the indenter into the specimen and known geometry of the indenter [1].

2.2. Analytical method

In the test of indentation, a tip with a defined shape is pushed into a sample surface and the indentation load (P) and penetration depth (h) are measured as a function of time. A schematic of the load-indentation depth curve recorded during indentation is presented in Fig. 1 and Fig. 2. The quantities shown are the peak indentation load (P_{max}), the depth of peak load (h_{max}), the final

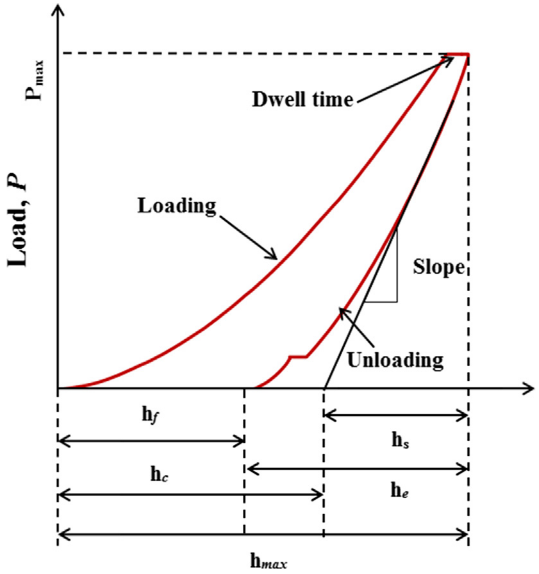

Fig. 1. Schematic of load versus indentation depth curve, H_f: final depth after unloading, h_s: displacement of the surface at the perimeter of the contact, h_c: Vertical depth along which contact is made, h_e: elastic depth recovery during un loading, h_{max}: depth at maximum load.