Three-layered hot-mix asphalt mixture

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Abstract

Hot-mix asphalt (HMA) mixtures consist of three phases – aggregate, asphalt binder (mastic) and air voids – and generally can be considered as two-layered composite systems with aggregates dispersed in the asphalt matrix. Due to the nature of high inhomogeneity between aggregate and asphalt binder, significant stress and strain concentration occurs at the interface between the two phases, which causes adverse effects to HMA mixtures and potentially contributes to pavement distresses/failure.

This paper presents a novel idea to mitigate the stress and strain concentration and thus to improve the HMA mixture performance by introducing an intermediate layer between the aggregate and the asphalt binder in the HMA mixture. Microstructural analyses and laboratory experiments of the three-layered system were used to validate the idea.

Keywords: Hot-mix asphalt; Composite; Finite element

1. Introduction

Generally, hot-mix asphalt (HMA) mixtures consist of three phases: aggregates, asphalt binder (mastic) and air voids. During the blending procedure of an HMA mixture, every aggregate, regardless of its size, is coated with a thin film of asphalt. Therefore, the resulting asphalt mixture can be considered as a two-layered composite material with aggregates dispersed in the asphalt matrix [1].

Unfortunately, the properties of two constituents in HMA mixtures, aggregate and asphalt cement, are highly heterogeneous. The stiffness and strength of aggregate are so much higher than those of asphalt cement that excess stress and strain concentration will be induced at the interface between the aggregate and asphalt cement/mastic layers, which is disadvantageous to HMA performance.

It follows that if we were able to introduce a third material possessing the properties between asphalt cement and aggregate to form an intermediate layer between the asphalt cement and aggregate, then the stress concentration should be mitigated and subsequently the performance of HMA could be enhanced appreciably. Although a three-layer concept exists in cement concrete [2] and cold recycling asphalt mixtures using cement mortar [3, 4, 5], in which a soft interphase was introduced between harder aggregates and cement mortar layers, this is a new concept with an interphase between a harder aggregate layer and a softer virgin asphalt mix layer.

The objective of the present study was to investigate the concept of constructing a three-layered HMA mix structure to improve mixture performance. Theoretical analyses of HMA microstructure were considered based on the mechanics of composite materials [1,6]. To validate the theoretical analyses, a laboratory experiment was conducted to compare the performance of three-layered mixtures with those of conventional mixes by utilizing a very stiff natural asphalt, gilsonite, to form an intermediate layer between the asphalt cement and the aggregate.

2. Microstructural analyses of three-layered hot-mix asphalt mixture system

The three-layered asphalt mix is a particulate-filled composite material. Based on Eshelby's equivalent medium theorem, this type of composite material can be assumed as a stiffer binder (such as gilsonite) layer-

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coated aggregate dispersed in a virgin asphalt mix. Therefore, the gilsonite-coated aggregates are again covered with a virgin asphalt mastic layer, forming a three-layered building block. The composite modelling considered a cylindrical sample under an indirect tensile test. Because the load is applied along the axial direction during a split tensile test, macroscopically it can be treated as a plane-strain body. Using two parallel planes perpendicular to the axial direction to isolate a unit thickness piece from the sample, a circular cross-sectioned plane-strain body is obtained.

Microscopically, this unit thickness piece is a composite body consisting of the three-layered building blocks. For simplicity, the aggregate particles were assumed to be spheres in the plane-strain body. In order to better consider the interactions among the neighbouring coated aggregates, five three-layered building blocks were configured in a face-centred pattern and were surrounded by an equivalent asphalt mix (Fig. 1). Based on a previous study [7], it was found that the stress concentrates more at large particles than at small particles. Therefore, all the five particles in Fig. 1 were assumed to be three-layered building blocks with the maximum diameter. The distance between the composite particles in Fig. 1 was determined by finding the number of composite particles per unit area by assuming that: (1) the building blocks were distributed uniformly in the mix; (2) the coarse aggregate volume fraction was 30%; and (3) the probability for all cross-sections of the building blocks to be cut by a plane is the same.

The COSMOS/M software package was used to obtain the stress–strain distributions for the model in Fig. 1. The elastic moduli for equivalent asphalt mix, aggregate, gilsonite and virgin asphalt are 2000, 50 000, 5000 and 600 MPa, respectively. Their Poisson ratios are 0.35, 0.2, 0.25 and 0.25, respectively. In the finite element modelling, a three-node plain-strain element, TRIANG, was used to automatically mesh the composite structure. A total of 12 654 elements were used to mesh the model. A unit linear load was applied to simulate a split tensile test.

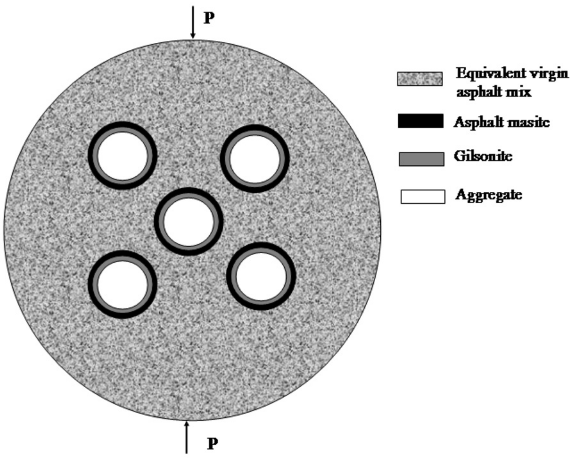

Fig. 1. Schematic of composite model.

Table 1
Various stress and strain ratios

Case	P_1	σ_x	σ_y	σ_z	τ_{xy}	ε_x	ε_y	ε_{eq}
Ratio	0.84	0.83	0.86	0.87	0.82	0.88	0.89	0.87

Table 1 presents the ratios by dividing various stress or strain components having the gilsonite layer by those without this layer. From Table 1, it is seen clearly that all the stress and strain concentration has been reduced significantly with the introduction of the gilsonite layer. This indicates that the gilsonite layer was serving as a cushion layer between the hard aggregate and the soft asphalt mastic. In such a way, the stiffness changed more gradually, avoiding sudden changes in stiffness and reducing the stiffness mismatch. Consequently, the stress and strain concentration was reduced. The reduced stress or strain concentration suggested that the strength or ultimate strain could be increased with the three-layered composite concept. This conclusion agreed with the laboratory investigations conducted during the present study.

3. Laboratory experiments

A laboratory experiment was designed to validate the concept of three-layered asphalt mixtures. A natural asphalt, gilsonite, was considered to form the intermediate layer between the aggregate and the asphalt binder. Due to a higher softening point, the stiffness of gilsonite is much higher than that of conventional asphalt under room temperature.

Two groups of mixtures were considered in laboratory performance testing to compare the effects of three-layered asphalt mixture. The first group was a control mixture that consisted of conventional asphalt mixture specimens. The second group acted as three-layered composite mixtures, of which coarse aggregates were coated with a thin film of stiff gilsonite before being mixed with asphalt binder.

Laboratory performance tests for asphalt mixtures included the dynamic modulus, asphalt pavement analyzer (APA) rut, indirect tensile stress, beam fatigue, and moisture-susceptibility tensile strength ratio (TSR) tests.

Fig. 2 summarizes the comparisons of laboratory performance between the gilsonite-treated composite

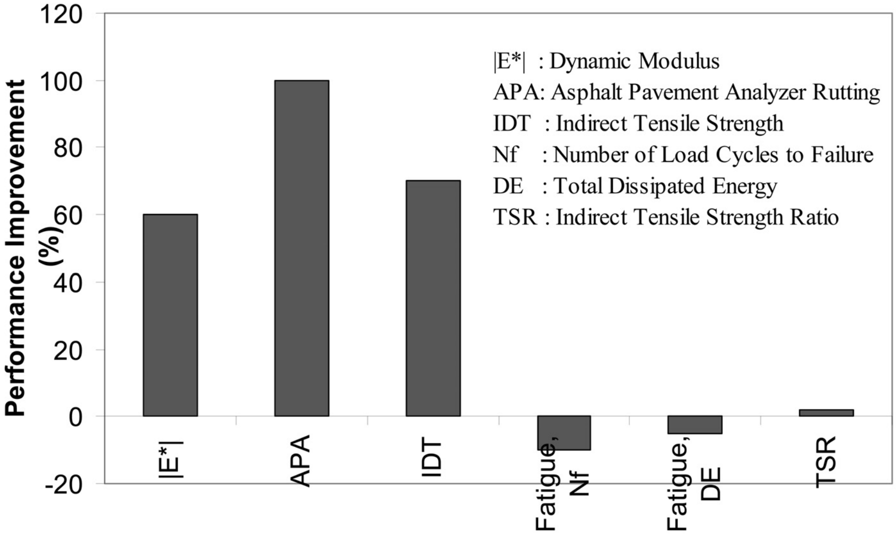

Fig. 2 Performance improvement of composite mixtures relative to control mix.

and the control mixtures. In Fig. 2, the performance improvements of the composite mixture were quantified in terms of percentage improvement to the control mixture. For example, since the APA rutting of the composite mixture was reduced to half of that of the control mixture, the improvement in APA was 100%. The fatigue failure cycles in terms of 50% reduction of initial stiffness for the composite mixtures were reduced by 10%, therefore, the benefit in that parameter was −10%, and so on. From Fig. 2, it appears that the benefits of composite mixtures were very significant whereas the negative factors seemed numerically insignificant.

4. Summary and conclusions

A study has been conducted to investigate the idea of incorporating a three-layered composite structure into HMA mixtures to enhance the performance of asphalt pavement. Based on the results from this limited study, the following can be summarized:

1. An intermediate layer between aggregate and asphalt binder would significantly increase the composite elastic modulus (stiffness) and reduce the stress and strain concentration.
2. The stiffness of the intermediate layer had great influence on the overall performance of the composite HMA mixture.
3. Natural asphalt (gilsonite) has the potential to serve as the intermediate layer in the proposed composite HMA mixture.
4. Limited laboratory experiments indicated improved mixture performance in dynamic modulus, rutting, indirect tensile strength, and potentially moisture susceptibility of the gilsonite composite asphalt mixture, compared with a conventional HMA mixture.
5. The results presented in this paper represent only the materials under the test conditions in this study. More complete analyses are recommended to cover a wide variety of materials under various conditions.

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