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Binder rheological predictive models to evaluate rutting performance of asphalt mixtures

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HIGHLIGHTS

- Developed a promising approach to correlate asphalt binder and mixture performance.
- Quantified binder stiffness parameter for 11 asphalts covering 860 data points.
- Obtained resilient moduli parameters for eleven mixes encompassing 396 data points.
- Established excellent resilient modulus model using binder stiffness parameter.
- Estimated advanced viscoelastic indicators to assess asphalt mixture rutting.

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ABSTRACT

This study investigated the rutting performance of asphalt mixtures through prediction of resilient modulus (M_r) based on the binder rheological stiffness parameter: $G^*/\sin\delta$. A total of seven different asphalt binder types from three sources were used, including: (a) three viscosity grade virgin (VG-10, VG-30 and VG-40) binders; (b) two polymer-modified (PMB-40 and PMB-70); and (c) two crumb-rubber modified (CRMB-55 and CRMB-60) binders. A total of 860 data points were obtained for evaluation of $G^*/\sin\delta$ and a predictive model as a function of binder viscosity. In order to correlate binder properties with that of the mixes, eleven asphalt mixtures with three sample replicates each were prepared: six dense graded with virgin binders; two gap-graded with polymer-modified binders; and three gap-graded rubber-modified binders. M_r test parameters were obtained for the mixtures at 15, 25, and 35 °C and 0.5, 1, 1.5 and 2 Hz covering 396 data points. A M_r predictive model based on $G^*/\sin\delta$ stiffness parameter was established with excellent statistical goodness of fit measures. Finally, advanced viscoelastic M_r parameters were estimated and the viscoelastic indicators were correlated to binder stiffness parameter to assess rutting performance of asphalt mixtures. A novel attempt was made in this study that presents a promising approach to correlate asphalt binder and mixture performance by using only one single rheological parameter based on the DSR test: $G^*/\sin\delta$; so as to minimize the experimentation during binder and asphalt pavement material characterization in future.

1. Introduction

Asphalt (bitumen) binder being a viscoelastic material behaves partly as an elastic solid and partly as a viscous liquid, which simply means that its behaviour depends on both temperature and the rate of loading. Several researchers [1–4] have used conventional binder consistency tests to understand performance of asphalt binders. For instance, binder viscosity has a significant effect on permanent deformation characteristics of asphalt mixtures. Generally, binders with higher viscosities at higher temperatures have been found to provide higher rutting resistance than those with lower viscosities. In addition, researchers [5–12] have also used advanced rheological binder characterization tests such as Dynamic Shear Rheometer (DSR), Bending Beam Rheometer, and Direct Tension tests on virgin, and rubber- and polymer-modified asphalt binders. These binder properties were later correlated with mixture properties to understand pavement performance from the rutting perspective.

The two outcomes of the DSR test, namely, G^* (complex shear modulus) and δ (phase angle) have helped investigate rutting characteristics of asphalt binders [5,6]. Specifically, the binder stiffness parameter $G^*/\sin\delta$ has been found to be a suitable binder rutting

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indicator which correlates well with asphalt mixture performance [7,8,10,11]. G* represents the total resistance to deformation under load while δ represents the relative distribution of the total response between the in-phase component and out-of-phase component of the stress applied and the incurred strains simultaneously.

Globally, flexible pavement design is accomplished using asphalt mix stiffness property: modulus. The stiffness or modulus parameter is used to design the thickness of the different asphalt pavement layers that also account for repeated traffic loads and material properties along with temperature and climatic conditions. Modulus of a pavement layer is obtained by static or dynamic load pulse mechanical tests such as stiffness modulus, resilient modulus, and dynamic modulus. Resilient modulus designated M_r has been used as an input to characterize viscoelastic behaviour of different pavement materials (both unbound and bound) under static and dynamic loading conditions. Several design guidelines [13–19] use M_r as a fundamental input parameter in structural designs of flexible pavement systems. M_r is determined using [20] in the laboratory at varying temperatures and loading frequencies for conventional and modified mixtures. In addition, rutting and cracking performance characteristics of asphalt mixtures can also be estimated using the M_r parameter.

With this background, it is essential to note that the G*/sinδ parameter is of significant interest to correlate the binder characteristics with that of the mixture properties to assess rutting of asphalt mixtures. Currently, there are several test procedures that are required to quantify binder and asphalt mixture correlations, which are both time consuming and cumbersome. Therefore, there is a definitive need to develop a standalone correlation between the well-established G*/sinδ binder rheological rutting parameter and a robust mixture mechanical test such as M_r that can provide rutting performance characteristics of asphalt materials. Furthermore, there is also a need to compare virgin and modified materials based on the fact that modified asphalt mixtures have outperformed conventional ones in respect of rutting properties worldwide. In addition to these two important addressable problems, there is a need to advance the state-of-the-art and knowledge about the elastic and viscous components of the G*/sinδ parameter, which are better representatives of the mixture performance characteristics in comparison with various conventional binder consistency tests.

Thus, the objective of this research study conducted as part of [21] was to investigate the rutting performance of asphalt mixtures and predict mix M_r based on the rheological properties of different binders using binder stiffness parameter G*/sinδ. A total of seven different asphalt binder types from three sources were used, including: (a) three viscosity grade virgin (VG-10, VG-30 and VG-40) binders; (b) two polymer-modified (PMB-40 and PMB-70); and (c) two crumb-rubber modified (CRMB-55 and CRMB-60) binders. A total of 860 data points were obtained for G*/sinδ evaluation. In order to correlate the binder properties with that of the mixes, eleven asphalt mixtures were prepared with three replicate samples per mix totalling 33 specimens: six dense graded with virgin binders; two gap-graded with polymer-modified binders; and three gap-graded crumb rubber-modified binders. M_r test parameter was obtained for the eleven mixtures at three temperatures and four frequencies covering 396 data points. The scope of the work included the following tasks:

- Review of literature relevant to rutting, binder rheological properties, and resilient modulus test.
- Establishment of A-VTS relationships for eleven binders using conventional consistency tests.
- Conducting of DSR test to estimate G* and δ of the binders over eight temperatures and ten frequencies.
- Development of G*/sinδ predictive model with binder viscosity as response variable.
- Preparation of eleven asphalt mixtures and conducting of M_r tests at three temperatures and four frequencies.
- Construction of M_r master curves for all eleven mixtures.
- Establishment of mixture M_r predictive model based on G*/sinδ binder stiffness parameter.
- Estimation of advanced viscoelastic M_r parameters and formulation of viscoelastic indicators to assess rutting performance of asphalt mixtures.

It is envisioned that this study will help understand the performance characteristics of asphalt binders as well as mixtures in respect of rutting properties in a coherent manner. This study will also throw light on the promising approach devised to correlate asphalt binder and mixture performance by using only one single rheological parameter based on the DSR test: G*/sinδ; so as to minimize the experimentation during binder and asphalt pavement material characterization in future. Overall, this study provides a novel approach towards understanding the rutting performance characteristics of asphalt mixtures using an asphalt binder stiffness parameter as the major input.

2. Materials and experimental program

2.1. Aggregates

Fig. 1 presents typical gradation curves of the two gradation types used along with appropriate asphalt binder grades to produce corresponding mixes. The two aggregate gradation types were: (i) conventional dense graded designated BC-1 as prescribed in [22]; and (ii) gap-graded gradation for crumb-rubber and polymer-modified mixtures as described in [23].

2.2. Binders

Viscosity graded (VG) virgin, crumb rubber modified binder (CRMB), and polymer modified binder (PMB) types were used from different crude sources. VG-10 binder from one source, VG-30 from two sources, and VG-40 from three sources was used. CRMB-55 from one source and CRMB-60 from two sources were also used along with PMB-40 from one source and PMB-70 from one source. CRMB-55 and CRMB-60 binders contain 8 and 10% rubber by weight of the binder, respectively. PMB-40 and PMB-70 binders, respectively contain 4 and 2% polymer by weight of the binder. The eleven asphalt binders were characterized by penetration at 25 °C [24], softening point [25], and Brookfield-viscosity tests for a range of 135–195 °C [26] along with DSR tests between 40 and 84 °C with 6 °C increments and for a range of frequencies between 0.1 and 10 Hz using [27]. A total of 860 data points were obtained for G*/sinδ evaluation using the DSR test.

2.3. Asphalt mixtures and experimental matrix

The virgin binders (VG-10, VG-30, and VG-40) were blended with aggregates of BC-1 dense gradation to prepare corresponding asphalt mixtures. The rubber- and polymer-modified binders (CRMB-55, CRMB-60, PMB-40, and PMB-70) were used to blend with aggregates of gap gradation to prepare modified gap graded asphalt mixtures. The addition of modifiers in conventional dense-graded mixes have shown poor performance attributed to insufficient voids in the mineral aggregates that is required to accommodate additives (inclusions) in the dense-mix matrix. However, literature [23] points out that modifiers could be successfully engineered with unconventional aggregate skeleton by using gap and/or open-graded gradation since these gradations provide enough room for additives to coalesce within the mix matrix.

Asphalt mixtures were prepared in the laboratory by blending the required amount of asphalt binder with the aggregate gradations. After the blending process, asphalt mixtures were kept at 135 °C for four hours in an oven to achieve the short-term aging criteria. Asphalt mixtures were then heated to compaction temperature and were compacted using a Superpave gyratory compactor as per [28]. Gyratory plugs of asphalt specimens were then produced that had a height of 170 mm and 150 mm diameter. The target binder contents and air voids levels for the different mixtures are shown in Table 1. The experimental program to conduct Indirect Diametral Tensile (IDT) and M_r tests are also shown in the Table whose details will be provided later. In order to conduct IDT and M_r tests as per [20,29], the gyratory specimens were cut into three discs of thickness equal to 50 mm. Thus, the dimensions of M_r test specimens were 150 mm diameter and 50 mm thickness. A total of 99 specimens were used in this study for IDT and M_r tests. The eleven mixes were designated as follows: