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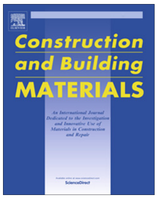

Estimation of phase angles of asphalt mixtures using resilient modulus test

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HIGHLIGHTS

- Phase angles were quantified for asphalt mixtures using resilient modulus test.
- Eleven different asphalt mixtures covering 297 data points were used in the study.
- Phase angle predictive model was established with very good correlations.
- Phase angle of resilient modulus test is a promising viscoelastic property assessor.

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ABSTRACT

The main objective of this study was to develop, derive, and estimate the phase angle (ϕ) parameter from resilient modulus (M_r) test, designated ϕ_{Mr}, at various temperatures and frequencies for eleven types of asphalt mixtures: two conventional dense-graded (DGAC), four polymer-modified gap-graded (P-Gap), four asphalt–rubber gap-graded (AR-Gap), and one asphalt–rubber open-graded (AR-Open) mix. ϕ_{Mr} were estimated for the eleven mixes with three replicates per mix totalling 33 samples at 15, 25 and 35 °C and at 0.5, 1, and 1.5 Hz. AR-Open mixes had the highest ϕ_{Mr} followed by AR-Gap and P-Gap, and then followed by DGAC mixes. Principally, with an increase in the asphalt content from conventional to modified mixes, there was an increase in ϕ_{Mr}, suggestive of the fact that the mixes that had higher asphalt contents have extra-viscous response or are highly viscoelastic. Furthermore, ϕ_{Mr} predictive model was developed based on asphalt material properties totalling 99 data points provided by R^2_{adj} (adjusted coefficient of estimation) = 0.8390, and S_e/S_y (ratio of standard error to standard deviation indicative of relative accuracy of the predictive model) = 0.3820; depicting very good correlation between the estimated and predicted ϕ_{Mr}, and with low bias and high precision. Additionally, ϕ_{Mr} master curves were constructed for the mixes with 35 °C as reference. Overall, it is envisioned that ϕ_{Mr} parameter obtained in this study will be helpful to comprehensively understand the viscoelastic properties of different asphalt mixtures, and incorporate ϕ_{Mr} as a viscoelastic characteristic assessor in futuristic flexible pavement designs.

1. Introduction

Viscoelastic materials such as asphalt concrete mixtures do not illustrate purely elastic and/or viscous behaviour. During traffic loading, the magnitudes of the loads are in the linear viscoelastic regime, which also produce irrecoverable (or plastic) strains, and permanent deformation in the asphalt materials. Thus, the accumulated strains produced due to multiple repetitions of stresses exceed the threshold limit(s) of the materials; thereby, reducing the structural performance of the pavement system.

Several parameters are used to depict viscoelastic behaviour of asphalt mixtures such as resilient modulus, stiffness modulus, dynamic modulus, strength, stresses and strains, deformations, dissipated energy, and so on. However, modulus which is a stiffness property of the asphalt material has been considered as the major input parameter in the various flexible pavement design methodologies found in the world, chiefly towards understanding and predicting the pavement performance [1–7].

One of the major input parameters used in the several flexible pavement design philosophies [1–5,7] is the resilient modulus (designated: M_r), which is defined as the ratio of the applied deviatoric stress to the recoverable strain at any particular temperature and frequency combination. M_r is a property of both unbound and bound materials used in pavement design and construction.

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Furthermore, the American Association of State Highway and Transportation Officials' Mechanistic-Empirical Pavement Design Guide [6] also uses M_r as a material property in characterizing base course and subgrade layers. It is noteworthy that although M_r is an input parameter to derive initial stiffness property of the asphalt mix, the technique usually follows linear elastic based theory for evaluation purposes due to the innate virtue of the property to yield recoverable strains (or deformations) of the asphalt mix. Therefore, M_r by itself may not be sufficient to elucidate the viscoelastic behaviour of the asphalt material in a comprehensive manner.

Viscoelastic properties of asphalt materials play a major role to also describe the associated time (or frequency) dependent response. Viscoelastic characteristics of the asphalt materials are generally derived from laboratory mechanical tests based upon stress–strain relationships, whose two major outcomes are modulus (stiffness) and phase angle generically designated ϕ (defined as the phase lag between the applied stress and the resultant strain over a specific time interval). Several researchers have utilized ϕ of both asphalt binders (normally designated: δ) and mixtures (ϕ) to characterize material properties, and compare conventional dense-graded and modified asphalt mixtures. The concept of both δ and ϕ are illustrated in [6,8] and since then, the asphalt binder evaluation has also included the δ parameter. However, very few studies have considered the asphalt mixtures' ϕ during design and performance prediction. Nonetheless, ϕ parameter has been investigated to assess the conventional and modified asphalt mixtures for their performance characteristics such as distress prediction [9–12], modification effect [9,10,13–15], thermal properties assessment [16], and fracture energy estimations [17]. Furthermore, ϕ has found prominence in assessing tyre/pavement noise properties for the different asphalt mixtures, which also entailed development of vibroacoustical damping relationships [13,14,18,19]. Recently, poroelastic road surfaces that show unconventional non-asphaltic mixture characteristics were also assessed using ϕ to investigate the damping characteristics of these mixtures [20,21]. In addition, only few research studies have established δ and/or ϕ predictive models for the different asphalt materials [14,22–27].

It is very important to understand that M_r has been fully utilized to investigate and predict the stiffness characteristics of different pavement materials. However, M_r, which is the only output parameter from the test has similar characteristics as that of the dynamic modulus or stiffness modulus. On the other hand, ϕ is one of the two outcomes in both dynamic modulus and stiffness modulus tests, and has been well-utilized in different applications such as mentioned before. In specific, ϕ has been accorded as a special parametric index to comprehensively understand viscoelastic properties of different asphalt mixtures. Till date, no research studies have emphasized on obtaining ϕ from M_r test, plausibly due to its complexity. Furthermore, several successful studies indicate that ϕ is a potential parameter that can explain viscoelastic property of the asphalt material variants in a comprehensive manner. Thus, it is imperative to investigate if ϕ can be obtained from a very powerful mechanical test such as resilient modulus for both conventional and modified asphalt mixtures. In addition, there is a need to utilize ϕ obtained from M_r test to develop advanced predictive relationships with respect to material properties, and establish practical applicability of ϕ parameter in time (or frequency) domain to liken the scenario with actual traffic in the field.

Thus, the main objective of this research investigation was to develop, derive, estimate and quantify the ϕ parameter from M_r test, hereafter designated as ϕ_{Mr}, at various temperatures and frequencies for eleven different types of asphalt mixtures: two conventional dense graded asphalt concrete (DGAC), four polymer-modified gap-graded (P-Gap), four asphalt–rubber gap-graded (AR-Gap), and one asphalt–rubber open-graded (AR-Open) mix. Furthermore, a ϕ_{Mr} predictive equation was established based upon asphalt mix material properties, which assisted in the development of the ϕ_{Mr} master curves for all the eleven mixes. The scope of the work included:

- Literature review pertinent to resilient modulus and phase angle parameters (Section 2).
- Collection and assemblage of M_r test data on different asphalt mixtures (Section 3).
- Estimation of ϕ_{Mr} from the raw test data compiled from M_r test (Section 4.1).
- Development of a ϕ_{Mr} predictive model based on mix material properties (Section 4.2).
- Performance predictions of the final ϕ_{Mr} predictive model (Section 4.3).
- Construction of ϕ_{Mr} master curves (Section 4.4).
- Recommendation of ϕ_{Mr} as a potential viscoelastic property assessor for asphalt mixes (Section 5).

It is envisioned that ϕ_{Mr} parameter obtained in this study will be helpful to comprehensively understand the viscoelastic properties of asphalt mixtures, and incorporate the viscoelastic ϕ_{Mr} and associated correlations in futuristic flexible pavement designs. Furthermore, this study will help assess the performance characteristics and relationships such as rutting and fatigue cracking mechanisms that have potentiality for development in future. However, future field studies will be required to validate the findings of this laboratory-based estimation. Nonetheless, the research investigation undertaken in this study is first of its kind in the estimation of ϕ from the resilient modulus test and also in the development of its practical applications pertinent to asphalt mixes' viscoelastic properties.

2. Theoretical background

2.1. Resilient modulus M_r test

Resilient modulus M_r test methodology is a standard procedure to estimate resilient modulus (or initial stiffness) of different asphalt mixes based on indirect diametral tensile (IDT) strength test [28,29]. It is important to note that 10% of IDT strength magnitude provides as an initial seed load value to run M_r test. Both IDT and M_r tests are run at the same desired temperatures.

Similar to the IDT strength test, the samples used for the M_r test have cylindrical sample geometry with 150 mm diameter and 50 mm thickness that are diametrically dynamically loaded at the desired test temperatures and frequencies. Technically, M_r test is conducted through repetitive applications of compressive loads in a haversine waveform. Mathematically, M_r is given by:

$$M_r = \frac{P_{cyclic}}{\delta_h t}(I_1 - I_2 \times \mu) \tag{1}$$

where:

M_r = instantaneous or resilient modulus, MPa.

δ_h = recoverable horizontal (instantaneous or total) deformation, mm.

μ = instantaneous or total Poisson's ratio.

t = thickness of specimen, mm.

P_{cyclic} = cyclic load applied to a specimen, N.

I_1 and I_2 = constants [29].

2.2. Concept of phase angle from resilient modulus test – ϕ_{Mr}

As mentioned previously, the major aim of this study was to estimate ϕ from M_r test, whose concept is currently unavailable in the literature. In this connection, it was deemed essential that