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Conceptualization of permanent deformation characteristics of rubber modified asphalt binders: Energy-based algorithm and rheological modeling

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HIGHLIGHTS

- CRM binders prepared with three base virgin asphalts at three CR dosages.
- Performed rheological characterization of thirteen asphalts covering 5000 data points.
- *tanδ* master curves indicated energy dissipation much lower for CRM binders.
- Rubber inclusions in asphalt aid in improving binder's rutting resistance.
- Developed rheological algorithm helps design rut-resistant asphalt materials.

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ABSTRACT

The objective of this study was to conceptualize and develop energy-based algorithm to characterize the comprehensive rheological behaviour of different asphalt binders with and without rubber modification. The scope included advanced asphalt binder characterization and analyses using viscoelastic parametric relationships. A total of thirteen different asphalt binders covering over 5000 data points were utilized, including: three virgin binders, one industrially available crumb rubber modified (CRM), and nine laboratory prepared CRM binders with varying dosages. Dissipated energy parameter *tanδ* was estimated, which helped in assessing the rutting resistance of asphalt binders. CRM binders produced flatter *tanδ* master curves and with lower magnitudes compared to the virgin binders indicative of higher rutting resistance with reduced energy dissipation-temperature susceptibility. Further, Weibull distribution function modeling on Multiple Stress Creep and Recovery (MSCR) test data quantified the contributions of various viscoelastic components of the asphalt binders. Rheological modeling and dissipated energy methodologies conceptualized as part of the study indicated that rubber inclusions in asphalt binder would aid in the improvement of the materials' rutting resistance. Overall, it is envisaged that the algorithm developed in this research pertinent to asphalt binders' advanced rheological characterization would further the state-of-the-art in designing rut-resistant asphalts.

1. Introduction

Rapid urbanization draws a myriad of concerns towards the sustainable aspects of a community. In this infrastructure development framework, the use of rubber materials and products in various applications and disposal thereafter creates a major share of pollution in the built environment. To counter this concern, an attempt to recycle the rubber materials in various engineering and industrial processes has been considered as a sustainable solution. In this direction, the utilization of rubber obtained from discarded scrap tyres in pavement construction applications offers as an effective countermeasure to mitigate the increasing pollution due to dumping and burning of the used rubber.

In the last few decades, modification of asphalt binders with crumb rubber inclusions has been a successful attempt with a view to improve the asphalt binder performance in the flexible pavement system. The improvement in the properties of crumb rubber modified (CRM) binders in contrast to the virgin asphalts is chiefly due to the morphological changes, which is caused by the swelling of rubber particles in binders that absorb oils and resins, and form

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a viscous compound similar to asphaltenes [1–4]. Several research studies indicated that the presence of crumb rubber in asphalt binder improves various properties that lead to a reduction in several pavement distresses including, but not limited to: permanent deformation (or rutting), fatigue cracking, low temperature cracking, and moisture susceptibility [3,5–15]. Historically, excessive rutting in flexible pavements at higher temperatures has been found to affect the long-term pavement performance, and thus has generated research interest in order to comprehensively understand its complex nature at the global level [16].

Several binder performance criteria have been specified by various agencies to ensure long-lasting pavement performance, especially at high pavement temperatures. The measure of the binder rutting performance varies from conventional consistency tests such as: Penetration, softening point, and rotational viscosity tests to more advanced rheological test techniques: frequency-temperature oscillation and Multiple Stress Creep and Recovery (MSCR) tests. The Strategic Highway Research Program (SHRP) guidelines recommend a threshold value for rheological parameter, $G^*/sin\delta$ to classify the asphalt binders according to their rutting potential, which is 1.0 and 2.2 kPa for unaged and short term aged binders, respectively [17]. Similarly, non-recoverable compliance (J_{nr}) and recovery (R) obtained from the MSCR test provides rheological performance classification of asphalt binders as prescribed by the American Association of State Highway and Transportation Officials (AASHTO) [18].

It is important to note that these criteria were developed based on an extensive rheological performance evaluation of the virgin binders. Since the addition of crumb rubber into the asphalt binder changes the morphology and thereby constitutes a new viscoelastic domain, the applicability of these criteria for CRM asphalt binders necessitate rheological evaluation on the basis of fundamental viscoelastic theories. In this direction, several research investigations reported the inadequacy of $G^*/sin\delta$ to explain the early nonlinearity of the CRM asphalt binder [19–23]. More so, J_{nr} and R prescribed by AASHTO in [18] are also limited to characterize the rutting potential of asphalt binders based on recoverable and non-recoverable properties. Thus, there is certainly a need to develop a methodology, which can rationally explain the rutting performance of rubber modified asphalt binders with concepts that include fundamental rheological science and supported by advanced models based on energy transformation due to binder morphology.

Thus, the main objective of this research was to conceptualize, develop, and utilize an advanced algorithm based on energy theory to characterize and evaluate the comprehensive rheological behaviour of various asphalt binders with and without crumb rubber inclusions. The study encompassed fundamental and advanced rheological evaluation of the thirteen different asphalts in respect of their rutting performance.

The scope of the work included: literature review pertinent to rheological characterization of viscoelastic materials emphasizing on energy dissipation followed by laboratory preparation of CRM binders with different dosages (10, 20, and 30%) by weight of the base asphalt virgin binders. Rheological characterization was carried out on all the asphalt binders using temperature-frequency oscillation and MSCR tests. Viscoelastic properties of the binders were analyzed and evaluated based on the energy dissipation concept. Further, advanced rheological analysis of asphalt binder recovery data was investigated by viscoelastic modeling.

It is envisioned that the energy concept and rheological models discussed in this study will help comprehensively understand the viscoelastic properties of the CRM asphalt binders. Furthermore, this study will aid in the assessment of the rutting performance characteristics and relationships of both virgin and modified asphalt binders.

2. Background to dissipated energy in asphalT

As proposed by Widyatmoko et al. [24], dissipated energy in asphalt can be defined as 'the amount of energy which is dissipated by viscous flow and/or plastic flow, and leads to potential damage (*e.g.* fatigue cracking and/or permanent deformation) when a bituminous material is subjected to repetitive loading'. The concept can be explained by considering a dynamic sinusoidal loading of stress (or strain) applied on the specimen and during the measurement of the resulting strain (or stress). The aforementioned loading and response are recorded in the oscillation test conducted on asphalt binders using Dynamic Shear Rheometer (DSR). The sinusoidal stress wave results in a sinusoidal strain wave with the same angular frequency but lagged in phase by an angle (δ). The strain and stress functions can be written as [25]:

$$\varepsilon = \varepsilon_0 \cos \ \omega t \tag{1}$$

$$\sigma = \sigma_0 \cos(\omega t + \delta) \tag{2}$$

where ε_o = equilibrium/initial strain, %; σ_o = equilibrium/initial stress, kPa; ω = angular frequency, rad/s; t = time at measurement, s; δ = phase lag, degrees.

Thus, complex stress may be written as:

$$\sigma^* = \sigma_0' \cos \omega t + i\sigma_0'' \sin \omega t \tag{3}$$

For calculating the dissipated energy, the mechanical work done per cycle is considered. Work done per cycle is given by:

$$W = \oint \sigma d\varepsilon = \oint \sigma \frac{d\varepsilon}{dt} dt \tag{4}$$

$$= \int_0^{2\pi/\omega} (\sigma_0' \cos \omega t)(-\varepsilon_0 \omega \sin \omega t) dt + \int_0^{2\pi/\omega} (\sigma_0'' \sin \omega t) \times (-\varepsilon_0 \omega \sin \omega t) dt \tag{5}$$

$$= 0 + \pi \sigma_0'' \varepsilon_0 \tag{6}$$

where σ'_o = elastic/storage stress, kPa; σ'' = viscous/loss stress, kPa.

Eq. (6) indicates that the strain energy of a viscoelastic material in a cycle is comprised of two components: in-phase and out-of-phase strain energy. The former one, which is represented by zero in Eq. (6) accounts for the elastic behaviour where strain is reversible. On the other hand, the viscous behaviour, which is explained by $\pi\sigma_o''\varepsilon_o$ is irreversible and dissipated as heat or flaws observed in the materials. The out-of-phase strain energy results in a net dissipation per cycle equal to:

$$W_{dis} = \pi \sigma_0'' \varepsilon_0 = \pi \sigma_0 \varepsilon_0 \sin \delta \tag{7}$$

Further, the maximum energy stored in a cycle can be quantified by integrating the in-phase strain energy at the quarter-cycle point. The maximum stored energy in a cycle can be calculated as follows:

$$W_{stored} = \int_0^{\pi/2\omega} (\sigma_0' \cos \omega t)(-\varepsilon_0 \omega \sin \omega t) dt \tag{8}$$

$$= -\frac{1}{2} \sigma_0 \varepsilon_0 \cos \delta \tag{9}$$

Thus, the relative dissipated energy in a cycle is given by:

$$\frac{W_{dis}}{W_{stored}} = 2\pi \tan \delta \tag{10}$$

Eq. (10) indicates that the relative dissipated energy is only dependent on δ of the viscoelastic system. Hence, $tan\delta$ can be used as a dissipated energy parameter to understand the rutting potential of various asphalt binders. Research studies [26–29] in the past