International Journal of Pavement Research and Technology (2023) 16:66–81
https://doi.org/10.1007/s42947-021-00113-2

社團法人中華鋪面工程學會
Chinese Society of Pavement Engineering

ORIGINAL RESEARCH PAPER

Rheological Analysis of Performance Grade Rutting and Fatigue Cracking Criteria in Asphalt Binders

Akanksha Pandey[1] · **Sumit K. Singh**[1] · **Sk. Sohel Islam**[2] · **G. D. Ransingchung R. N.**[2] · **Sridhar Raju**[3] · **Sham S. Ravindranath**[1]

Received: 17 February 2021 / Revised: 12 July 2021 / Accepted: 23 September 2021 / Published online: 20 October 2021

Abstract

This study critically examines the utility of the rheological parameters, such as phase angle δ, sinδ, complex modulus ($|G^*|$), rutting criterion ($|G^*|/\sin\delta$), fatigue criterion ($|G^*|\sin\delta$), etc., in the performance grading (PG) rutting and fatigue criteria. The results show that for unmodified asphalt binders at true PG upper limiting temperature, the PG rutting criterion '$|G^*|/\sin\delta$' can be equated to the viscosity of the binder. The equivalence of $|G^*|/\sin\delta$ and viscosity is valid over a wide range of testing conditions in oscillatory and rotation shear. Consequently, the correlation of $|G^*|/\sin\delta$ and viscosity with rutting in asphalt pavements was similar. The PG fatigue cracking criterion is based on the energy dissipating capacity (loss modulus $G'' = |G^*|\sin\delta \leq 5000$ kPa) of 'RTFO + PAV' aged binders. At true PG intermediate temperature, the loss modulus and storage modulus values of 'RTFO + PAV' aged binders were similar since the δ values were close to 45°. Therefore, G'' as the fatigue criterion will not provide any particular benefit in predicting the fatigue performance of 'RTFO + PAV' aged binders. Furthermore, using δ to forecast fatigue performance may lead to inaccuracies, as fatigue cracking and δ show opposite trends after aging in asphalt binders. The rheological properties of polymer modified binders (PMBs) are better quantified at frequencies ≤ 0.1 rad/s due to the sluggish dynamics of the polymer molecules, and the correlation between the PMBs rheological properties and rutting in asphalt mixes improves at lower frequencies. Hence, analysis at lower frequencies is critical for better grading and performance evaluation in PMBs.

Keywords Penetration grading · Viscosity grading · Performance grading · Polymer modified binder · Rheology

1 Introduction

Asphalt pavements are susceptible to rutting and fatigue cracking at upper and intermediate service temperatures, respectively [1–4]. Conventional binder grading methods such as penetration and viscosity grading may not adequately predict the performance of asphalt pavements over the entire range of service temperatures [5–7]. To overcome these limitations, the 'Strategic Highway Research Program' (SHRP) proposed the 'Superpave Performance Grading' (PG) methodology. In the PG system, rutting and fatigue cracking criteria are assigned so that the asphalt binders must fulfill at the corresponding pavement design temperature [5, 6, 8, 9]. PG grading of asphalt binders marked a significant shift in binder grading methodology compared to the conventional penetration and viscosity grading.

In the PG system, the upper limiting temperature (T_u) is assigned as the temperature where $|G^*|/\sin\delta \geq 1000/2200$ Pa (unaged/RTFO aged) at a frequency of 10 rad/s. Through regression analysis, literature studies have reported a correlation (R^2) ranging '0.8–0.92' between the PG rutting criterion ($|G^*|/\sin\delta$) and rutting in asphalt mixtures [3, 10–14]. These studies highlight that rutting in asphalt mixture is affected by several parameters, such as properties of binders, aggregates, gradation, mix preparation methodology, etc. [15, 16]. To enhance the correlation, alternative rutting parameters are suggested in the literature. These alternate

---

✉ Sham S. Ravindranath
sham.ravindranath@pe.iitr.ac.in

[1] Department of Polymer and Process Engineering, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand 247001, India

[2] Department of Civil Engineering, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand 247667, India

[3] Department of Civil Engineering, Birla Institute of Technology and Sciences Pilani, Hyderabad, Hyderabad 500078, India

rutting parameters can be broadly categorized as; amendments to the current $|G^*|/\sin\delta$ criterion [17, 18], revision to the testing parameters [11, 16], utilization of zero shear/low shear viscosity [10–15, 15–21], etc. In the case of polymer modified asphalt binders (PMBs), parameters such as elastic recovery by multiple stress and creep and recovery (MSCR), toughness, phase angle (δ) value, etc., are adopted in addition to $|G^*|/\sin\delta$ [17, 18, 22–30]. In the MSCR test, the PMBs stress-bearing and elastic recovery characteristics are considered to evaluate the rutting performance in pavements, and the results correlate better with rutting in mixes [10, 25, 26, 28–30].

Asphalt pavements are susceptible to fatigue cracking at intermediate service temperature due to the increase in the stiffness of the binder [1, 2]. In the PG grading system, the intermediate limiting temperature (T_I) is assigned as the temperature where the loss modulus $G'' = |G^*|\sin\delta \leq 5000$ kPa at 10 rad/s for RTFO + PAV aged binders [1–3]. Compared to the PG rutting criterion, the deviation in the correlation between the PG fatigue criterion ($|G^*|\sin\delta$) and the fatigue cracking in asphalt mixtures is prominent [31–39]. To enhance the correlation, alternative methods and parameters are suggested. These alternative parameters in general can be categorized as: amendments to the SHRP fatigue criterion to energy dissipation method [40–42], time sweep [31, 36, 37], linear amplitude sweep [33, 35, 36, 39], *R*-value [38], Glover-row parameter [32, 34], etc.

Though several alternate rutting and fatigue criteria have been proposed in the literature, studies have not been carried out that critically examine the utility of the parameters, such as δ, $\sin\delta$, $|G^*|$, $|G^*|/\sin\delta$, $|G^*|\sin\delta$, etc., in the PG rutting and fatigue criteria.

Thus, the key objectives of this study are

- Through strain sweep and frequency sweep studies in oscillatory mode, and shear rate ramp studies in rotation mode, to show that the $\sin\delta$ parameter in the $|G^*|/\sin\delta$ criterion has no benefit as the phase angle (δ) values are more than 80° at PG upper limiting temperature (T_u).
- Rheological and asphalt mixture studies demonstrate the equivalence of viscosity and $|G^*|/\sin\delta$ criterion. Furthermore, illustrate that all alternate rutting criteria are also surrogate expressions of the viscosity of the unmodified binder.
- At PG intermediate limiting temperature (T_I), demonstrates that the use of fatigue criterion $G'' = |G^*|\sin\delta$ has no benefit as δ values were close to 45°. Thereby, highlighting the shortcoming of correlating rheological parameters measured in the linear viscoelastic region (LVE) and fatigue cracking in asphalt mixture.
- Finally, highlight the important role of angular frequency in quantifying the properties of PMBs, and demonstrate that a better correlation can be obtained between the PMBs rheological properties and rutting in asphalt mixes at frequencies ≤ 0.1 rad/s.

2 Materials and Methods

The source, true PG upper limiting temperature (T_u), true PG intermediate temperature (T_I), and conventional properties of the 18 asphalt binders are given in Table 1. To demonstrate that the findings are not limited to binder samples having a narrow range of properties, samples were selected whose source and physical properties varied significantly. All the rheological and conventional measurements were carried out according to ASTM standards within the linear viscoelastic limits (LVE) [43–45]. In the LVE region, the rheological properties of the unmodified and modified binders, such as modulus, viscosity, etc., are independent of the applied strain amplitude. In addition to properties presented in Table 1, flash point, mass loss after RTFO, and solubility in trichloroethylene of the binders were evaluated according to ASTM D18, D2872, and D2042, respectively. Flashpoint, mass loss, and solubility in trichloroethylene of all the asphalt binders were > 230 °C, < 1%, and > 99%, respectively.

PMB preparation: polymer modified binders (PMB) were prepared by blending different weight % of linear SBS polymer in H-62 and L-64 binders. The linear SBS polymer (Kraton's D1101) with 30% styrene content was purchased from Rishi Chem distributors, India. The SBS polymer was first mixed with the binder at 180 °C using a Silverson high shear mixer (Model: L4RT) at 3000 rpm for 120 min. After high shear mixing, the blend was homogenized at 180 °C by mixing at 600 rpm for 120 min using a low shear mixer. To avoid phase separation of the polymer from the binder, the SBS polymer was cross-linked by adding 0.12% sulphur during low shear mixing. The preparation of the PMBs is schematically illustrated in Fig. 1. The basic properties of the PMB samples are given in Table 2.

Asphalt analysis: to measure the rut depth in asphalt mixes prepared using unmodified and modified binders, the analysis was carried out using the wheel tracking device (WTD) at 60 °C for 20,000 cycles. The aggregates used in the study were collected from a local quarry of Roorkee, India. The physical properties of aggregates are given in Table 3. The mid-point gradation with 19 mm nominal maximum size recommended by the 'Ministry of Road Transport and Highways' for bituminous concrete (BC-1) is depicted in Fig. 2.

Table 1 Source, true PG upper limiting temperature (T_u), and true PG intermediate temperature (T_I) of the 18 unmodified asphalt binders

Binders	Source	True PG upper temp. (°C)		True PG inter. temp. (°C)	Penetration @ 25 °C (dmm)	Softening point (°C)	Brookfield viscosity at 135 °C (Pa s)
		Unaged	RTFO				
A-58	Hotcrete Hyderabad	58	57	15	95	45	0.27
B-58	Space Petro Energy	58	58	17	100	46	0.28
C-59	Hindustan Colas	59	58	16	97	45	0.29
D-59	Hotcrete Hyderabad	59	58	17	92	44.8	0.30
E-60	Tiki Tar Industries	60	59	17	83	45	0.29
F-60	Shiva Bitumen	60	59	19	76	48	0.31
G-60	Tiki Tar Industries	60	59	22	62	47	0.31
H-62	Juno Bitumen	62	61	18	85	46.6	0.34
I-62	Hindustan Colas	62	61	22	64	49	0.35
J-63	Jalnidhi Bitumen Specialties	63	62	18	75	49	0.37
K-64	Space Petro Energy	64	63	20	70	48	0.40
L-64	Tiki Tar Industries	64	63	24	65	51.4	0.42
M-65	Juno Bitumen	65	64	22	60	52.8	0.43
N-65	Hotcrete Hyderabad	65	64	24	62	53.2	0.43
O-66	Jalnidhi Bitumen Specialities	66	65	25	52	53	0.44
P-68	Space Petro Energy	68	67	25	58	53.7	0.48
Q-70	Shiva Bitumen	70	69	26	55	54	0.54
R-72	Tiki Tar Industries	72	71	27	40	54.4	0.63

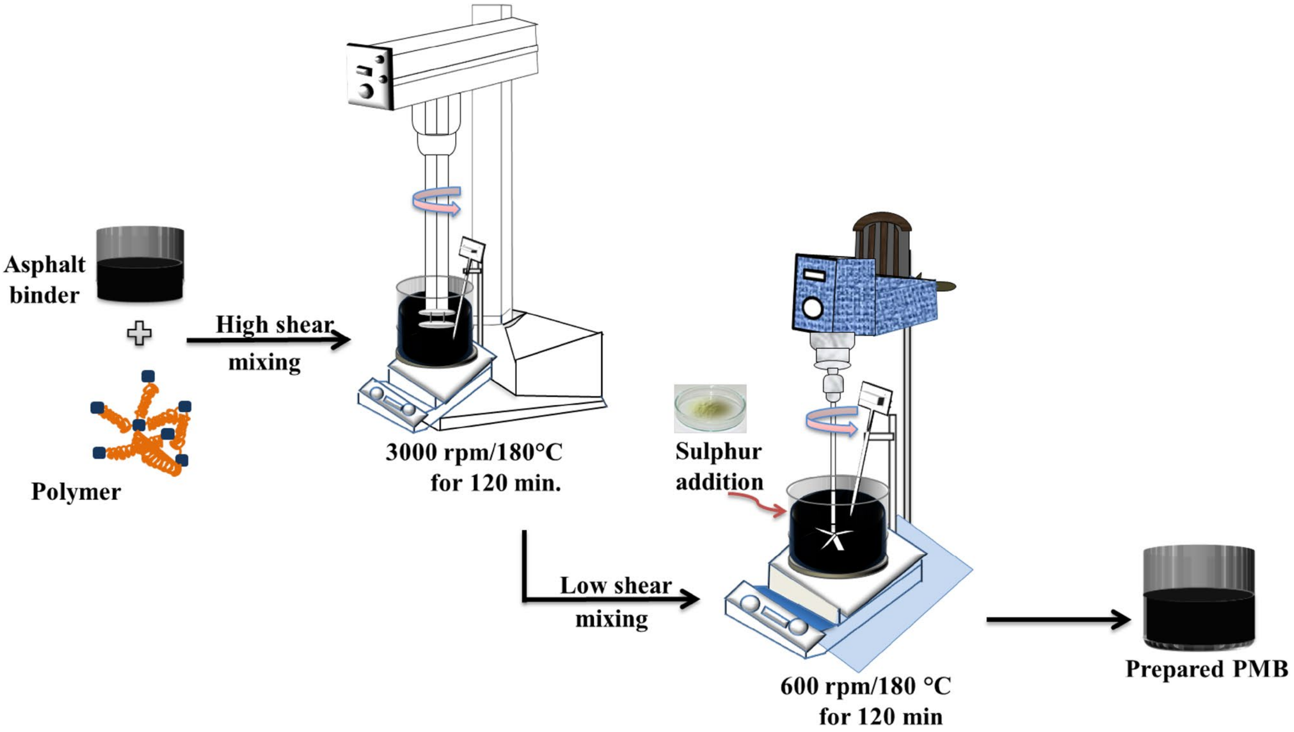

Fig. 1 Schematic illustration of PMB preparation

Table 2 Properties of the 6 polymer modified asphalt binders in H-62

Modified binders	SBS conc. (wt%)	True PG upper temp. (°C)	Softening point (°C)	Brookfield visc. @ 135 °C (Pa s)	Diff. in soft. point (°C)
PMB 2%	2	68	58	0.8	0.4
PMB 3%	3	72	62	1.15	0.6
PMB 4%	4	81	75	1.68	1.0
PMB 5%	5	87	87	3.2	0.8
PMB 6%	6	98	95	6.5	1.2
PMB 7%	7	101	98	7.1	1.4

Table 3 Properties of the aggregates

Test parameters	Test values	Specific limit
Specific gravity (coarse aggregates)	2.68	–
Specific gravity (fine aggregates)	2.71	–
Specific gravity (filler)	3.06	–
Water absorption (%)	0.54	< 2
Los Angeles abrasion (%)	27	< 30
Aggregate impact (%)	19.45	< 24
Aggregate crushing (%)	21.68	–
Flakiness and elongation index (%)	17.13	< 30

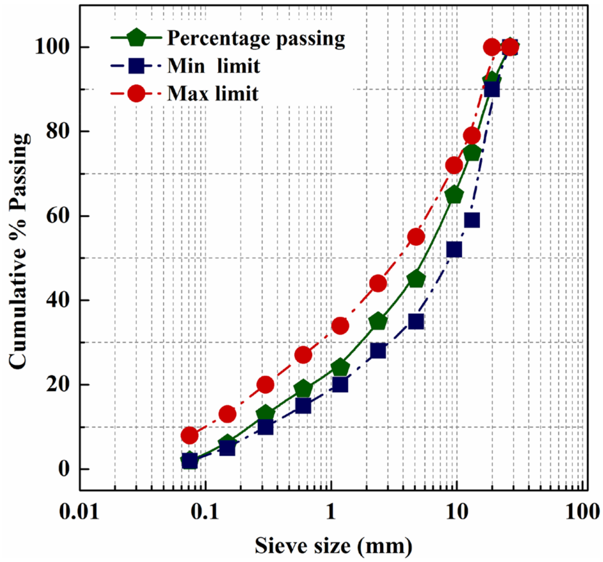

Fig. 2 Mid-point gradation for used aggregates

3 Results and Discussions

3.1 PG Rutting Criterion for Unmodified Asphalt Binders

In the PG grading system, the maximum 7-day average pavement temperature is categorized in 6 °C intervals (52, 58, 64, 70, 76 °C, etc.), and asphalt binders are graded based on the $|G^*|/\sin\delta$ value at these temperatures. Instead of measuring the $|G^*|/\sin\delta$ value at 6 °C intervals, the true PG upper limiting temperature (T_u) for the 18 unaged and RTFO aged asphalt binders was determined and is given in Table 1. The true PG upper limiting temperature (T_u) is the temperature where $|G^*|/\sin\delta \simeq 1000/2200$ Pa for the unaged and RTFO aged binders [45]. As shown in Fig. 3, the $|G^*|/\sin\delta$ value of the 18 unaged and RTFO aged binders were ≈ 1000 and 2200 Pa at their respective T_u.

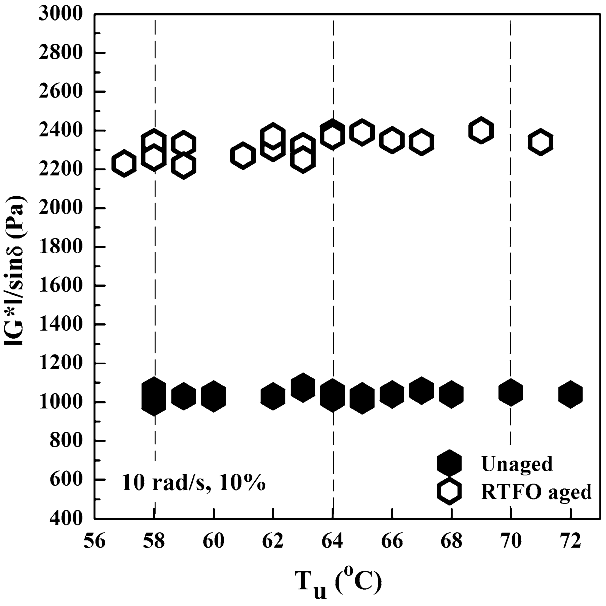

Fig. 3 $|G^*|/\sin\delta$ vs. true PG upper limiting temperature (T_u) for the 18 unaged and RTFO aged asphalt binders

A highly insightful understanding is obtained when the '$\sin\delta$' values of the 18 unaged and RTFO aged binders at T_u were analyzed. It can be observed in Fig. 4a and b that the '$\sin\delta$' values of the binders were above 0.990 (≈ 1) at T_u. The $\sin\delta$ values were ≈ 1 as the phase angle (δ) values of the binders were greater than 80°, as shown in Fig. 5a and b. Since $\sin\delta \approx 1$, the SHRP defined rutting criterion ($|G^*|/\sin\delta$) can be simplified to complex modulus $|G^*| \geq 1000/2200$ Pa (unaged/RTFO aged).

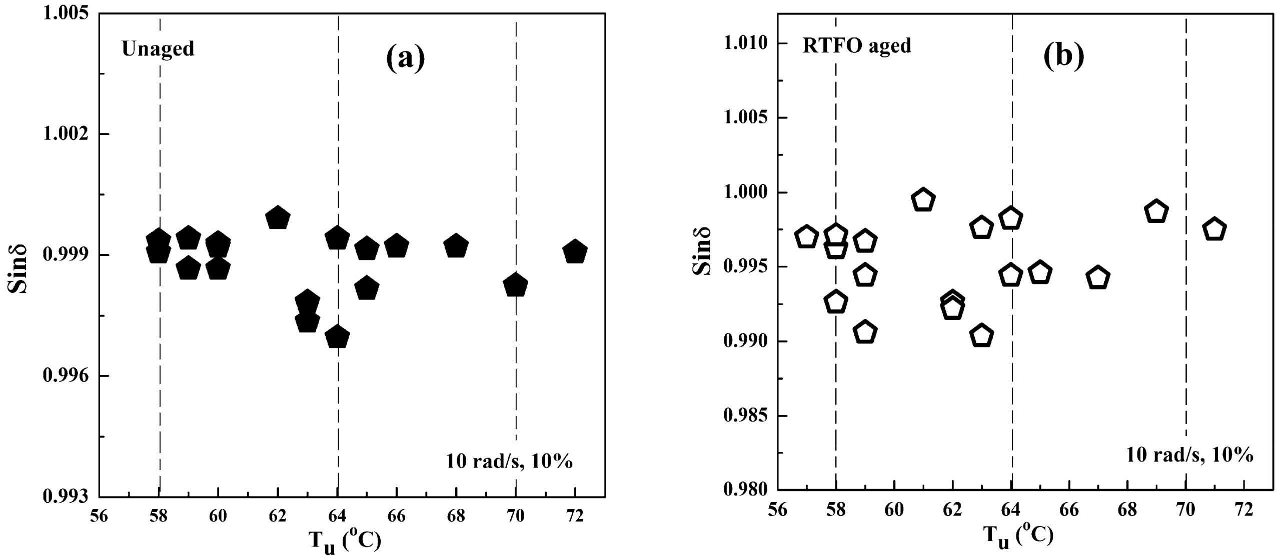

Fig. 4 Sinδ vs. true PG upper limiting temperature (T_u) for the 18 asphalt binders **a** unaged **b** RTFO aged

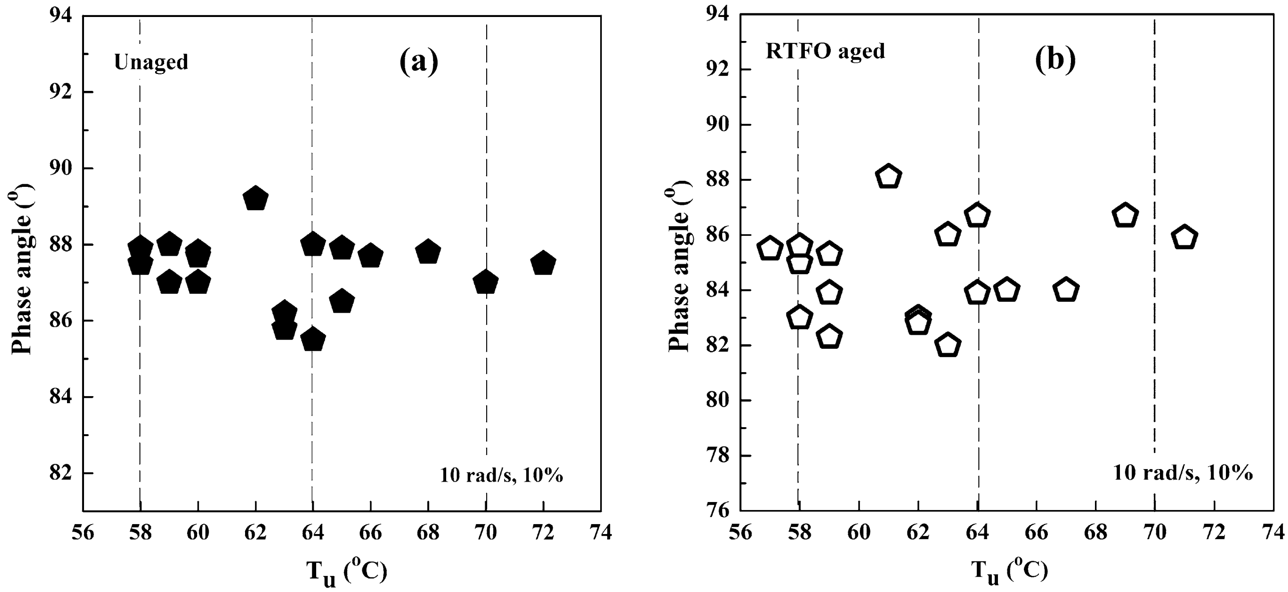

Fig. 5 Phase angle (δ) vs. true PG upper limiting temperature (T_u) for the 18 asphalt binders **a** unaged **b** RTFO aged

From elementary rheology [46, 47], it is known that the complex viscosity $|\eta^*| = |G^*|/\omega$. Since in PG grading the measurements are performed at $\omega = 10$ rad/s, $|\eta^*| = |G^*|/10$. This means that at T_u, the PG rutting criterion is equivalent to $|\eta^*| = 100/220$ Pa s (unaged/RTFO aged).

This is experimentally confirmed on plotting $|\eta^*|$ vs. T_u for the unaged and RTFO aged binders, as illustrated in Fig. 6. In other words, the true PG upper limiting temperature is also the temperature where $|\eta^*|$ of the asphalt binders is 100/220 Pa s (unaged/RTFO aged).

It is essential to know whether the equivalence of the PG rutting criterion and viscosity remains valid at test conditions beyond the fixed parameter of strain amplitude (10%) and angular frequency (10 rad/s). For this purpose, strain sweep and frequency sweep experiments were performed on all the 18 unaged and RTFO aged binders. The observations on the 18 binders were analogous, and only the results of H-62, L-64, M-65, and R-72 binders are presented in this section to avoid redundancy and overlapping

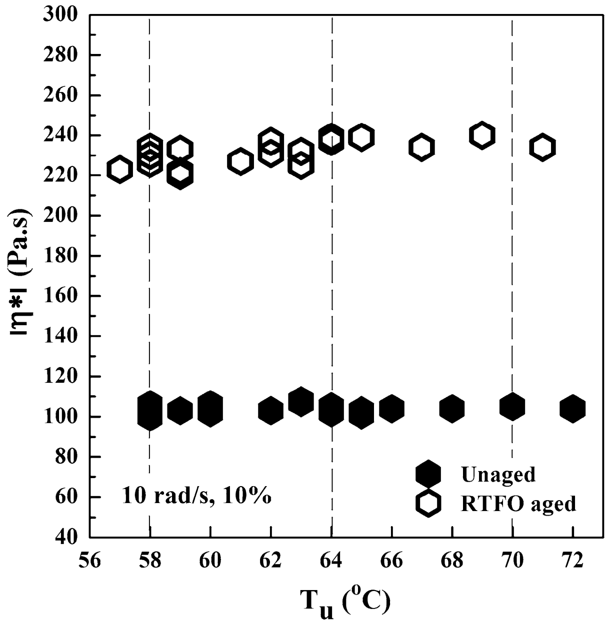

Fig. 6 Complex viscosity (|η^*|) vs. true PG upper limiting temperature (T_u) for the 18 unaged and RTFO aged asphalt binders

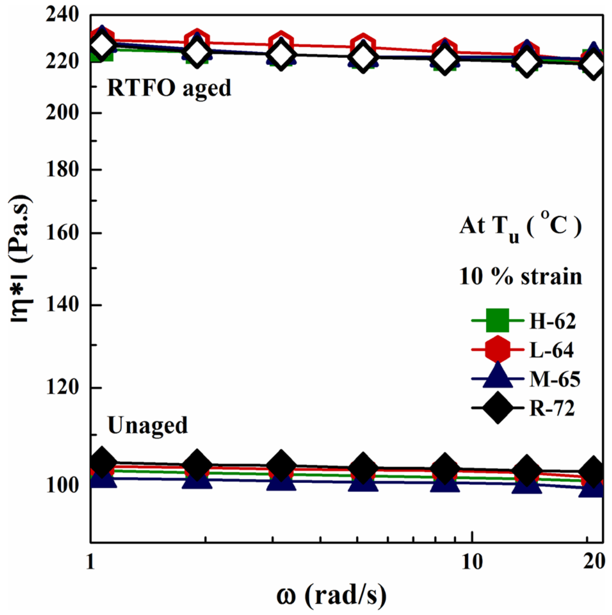

Fig. 8 Complex viscosity (|η^*|) vs. angular frequency (ω) at true PG upper limiting temperature (T_u) for the four unaged and RTFO aged asphalt binders

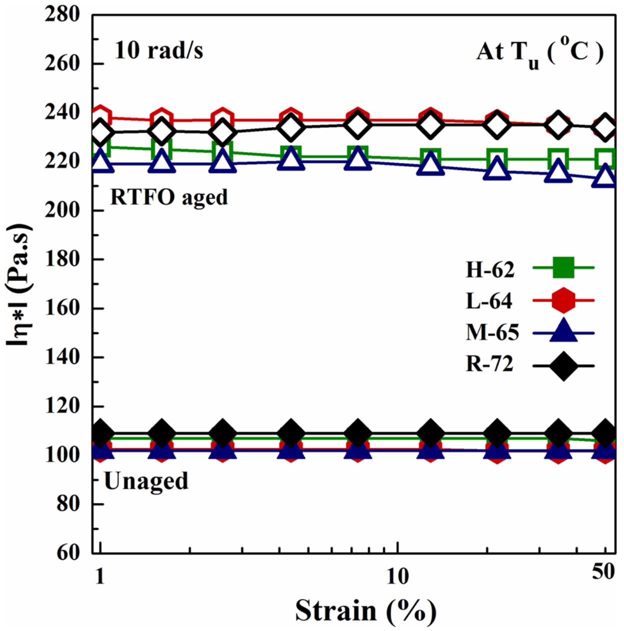

Fig. 7 Complex viscosity (|η^*|) vs. strain amplitude (γ_A) at true PG upper limiting temperature (T_u) for the four unaged and RTFO aged asphalt binders

of curves. The results of the remaining 14 binders are shown in the appendix section.

To evaluate the influence of oscillatory strain amplitude (γ_A) on the rheology properties of the asphalt binders at T_u, γ_A was varied from 1 to 50% at a constant $\omega = 10$ rad/s. The test was performed using the cone-plate geometry of 25 mm diameter and 2° cone angle to achieve a uniform strain rate across the entire gap. It can be noticed in Fig. 7 that across the entire strain range, the complex viscosity (|η^*|) of the binders was close to 100 Pa s (unaged) and 220 Pa s (RTFO aged). At higher strain values, edge instability started to occur, and hence it was not possible to test the samples at higher strain amplitude values. To analyze the effect of angular frequency (ω), ω was varied from 1 to 20 rad/s at a constant $\gamma_A = 10\%$. Similar to the results presented in Figs. 6 and 7, it can be noticed in Fig. 8 that across the entire ω range, |η^*| of the binders was close to 100 Pa s (unaged) and 220 Pa s (RTFO aged). Observations on the rest of the 14 binder samples were similar, and hence their results are presented in the appendix section (Figs. 16, 17). Thus, the equivalence of the |G^*|/sinδ to |η^*| (100/220 Pa s) can be extended beyond the PG testing conditions of $\gamma_A = 10\%$ and $\omega = 10$ rad/s.

Generally, for viscous liquids with high δ values, complex viscosity (|η^*|) will be similar to shear viscosity (η) measured in rotational shear [48]. Therefore, for unmodified asphalt binders at T_u, similar viscosity values (100/220 Pa s) should be observed when determined in rotational shear. Moreover, one of the most common ways of determining the viscosity of liquids is through rotational shear. For this purpose, strain rate ramp experiments in the rotational shear mode were carried out at T_u using cone-plate geometry from 0.1 to 10/s. It can be seen in Fig. 9 that across the applied shear rate of 0.1–10/s, viscosity (η) of the four binders is close to 100/220 Pa s (unaged/RTFO aged). At shear rates > 10/s in

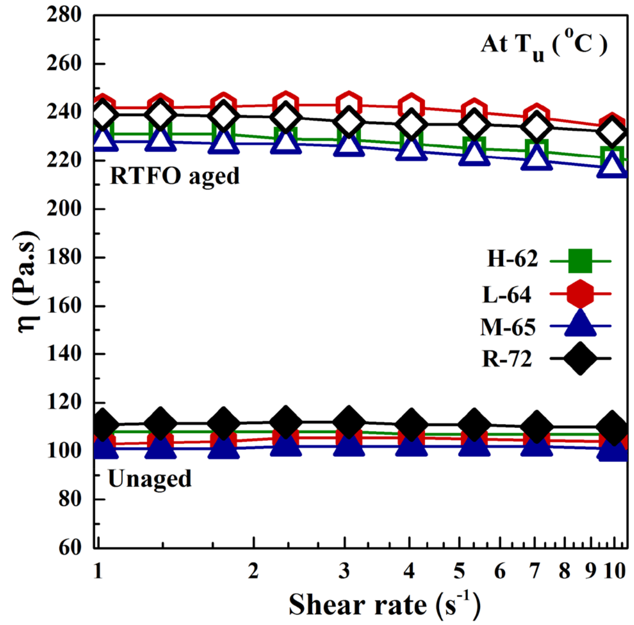

Fig. 9 Shear viscosity (η) vs. shear rate at true PG upper limiting temperatures (T_u) for the four unaged and RTFO aged asphalt binders in rotational mode

the cone-plate geometry, edge instability began to occur, due to which experiments were not carried out at higher shear rates. Thus, for unmodified asphalt binders at true PG upper limiting temperature and shear rate = 1–10/s, PG rutting criterion $|G^*|/\sin\delta$ equates to shear viscosity η. For Newtonian liquids, the viscosity will remain constant as a function of the applied shear rate, strain amplitude, and frequency. While for non-Newtonian liquids, the viscosity will either decrease (shear thinning) or increase (shear-thickening) as a function of the applied shear rate, strain amplitude, and frequency. It can be observed in Figs. 6, 7, 8 and 9 that the unmodified asphalt binders exhibited a behavior close to that of Newtonian liquids.

3.1.1 Correlation of |G*|/sinδ and |η*| with Rut Depth

Asphalt mix analysis was carried out to measure the rut depth of the asphalt mixes prepared using the 18 binders. The rutting analysis was carried out using a wheel tracking device (WTD) at 60 °C. The correlating factor (R^2) between rut depth at 20,000 cycles vs. $|G^*|/\sin\delta$ and $|\eta^*|$ of the unmodified binders are shown in Fig. 10a and b. It can be noticed from Fig. 10a and b that the R^2 value for $|G^*|/\sin\delta$ and $|\eta^*|$ is similar, supporting the observation made in Figs. 6, 7, 8 and 9. Similar to unaged binders, the $|G^*|/\sin\delta$ and $|\eta^*|$ of RTFO aged binders also had similar R^2 values against rut depth, as shown in Fig. 11a and b. Thus, due to the equivalence of $|\eta^*|$ and $|G^*|/\sin\delta$, the two parameters resulted in a similar correlation with rutting in asphalt pavements. Shenoy et al. suggested an alternate parameter '$|G^*|/(1-(1/\tan\delta\sin\delta))$' to predict the performance of asphalt binders at upper service temperature [18]. This is one way to measure the susceptibility to resist rutting in the pavements by measuring the non-recovered compliance of the

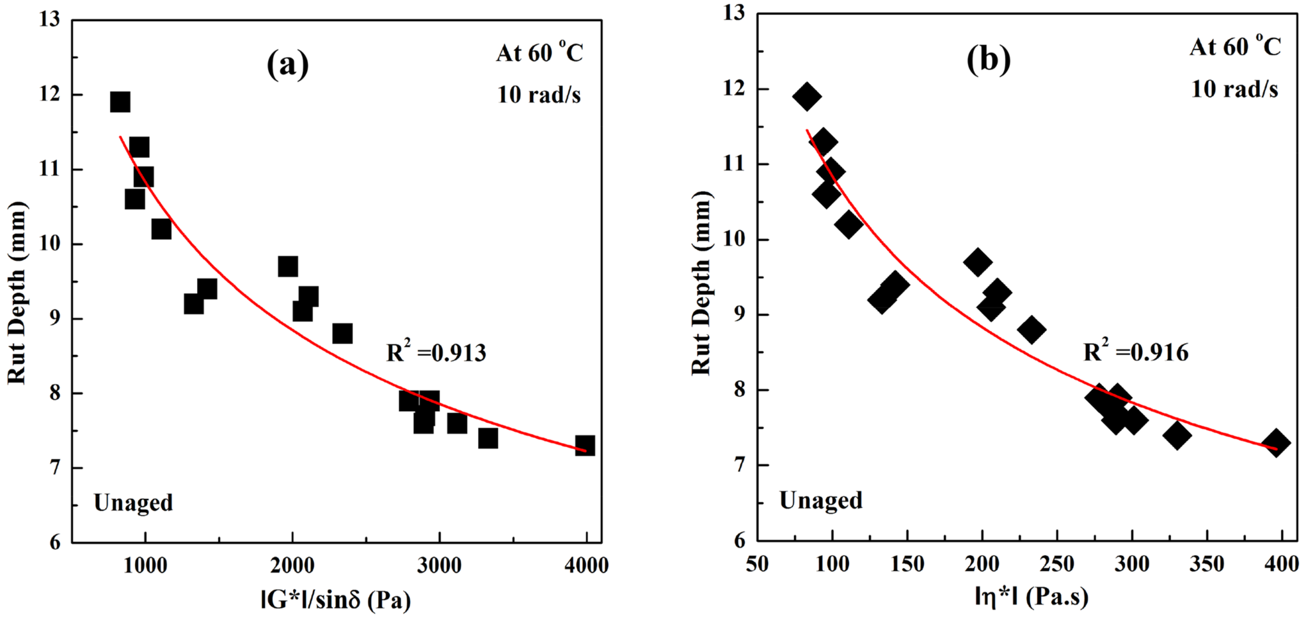

Fig. 10 Correlation between **a** rut depth and $|G^*|/\sin\delta$, **b** rut depth and complex viscosity ($|\eta^*|$) for the 18 unmodified binders

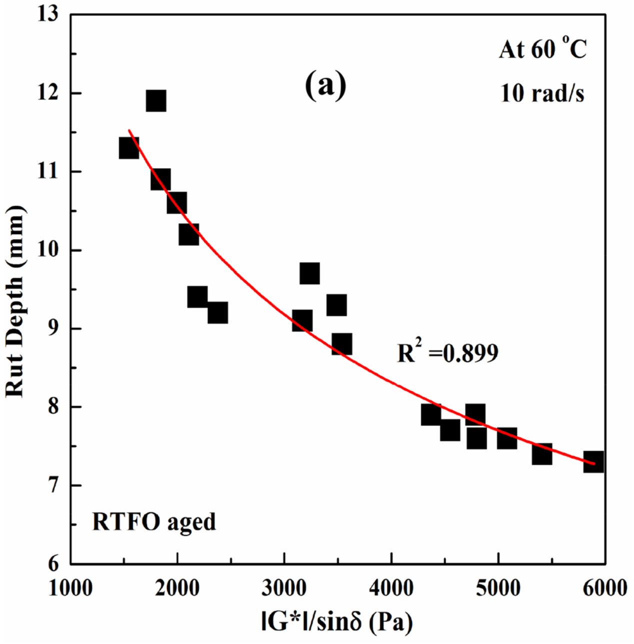

Fig. 11 Correlating factor (R^2) between **a** rut depth and |G^*|/sinδ, **b** rut depth and complex viscosity (|η^*|) for the 18 RTFO aged unmodified binders

binder [49]. The equation is valid in between $\delta = 52°$ and 90° to encompass most binder data in the high specification temperature regime. Since the δ values of the unmodified asphalt binders are more than 80°, even Shenoy's parameter can be equated to binder viscosity. Sybilski suggested the ZSV concept to characterize the rutting behavior of binders [50]. Since at upper service temperature and low shear rate, the viscosity is independent of the applied shear rate [19]. Therefore, PG rutting criterion, Shenoy's parameter, low shear viscosity, zero shear viscosity, and viscosity by vacuum capillary viscometer all are based on the same principle of correlating viscosity of the binder to rutting in asphalt pavements [16, 20, 21, 51].

3.2 PG Fatigue Cracking Criterion for Unmodified Asphalt Binders

In SHRP studies, a good correlation was demonstrated between fatigue cracking in asphalt mixture and loss modulus (G'') of asphalt binders. Hence, loss modulus $G'' = |G^*|\sin\delta$ indicating the energy dissipation capacity of the binder, was chosen as the fatigue cracking criterion. The specification requirement was set as the temperature where the loss modulus $G'' = |G^*|\sin\delta \leq 5000$ kPa for 'RTFO + PAV' aged binder at $\omega = 10$ rad/s and $\gamma_A = 1\%$. The true PG intermediate temperature (T_I) of the 18 'RTFO + PAV' aged binders is listed in Table 1.

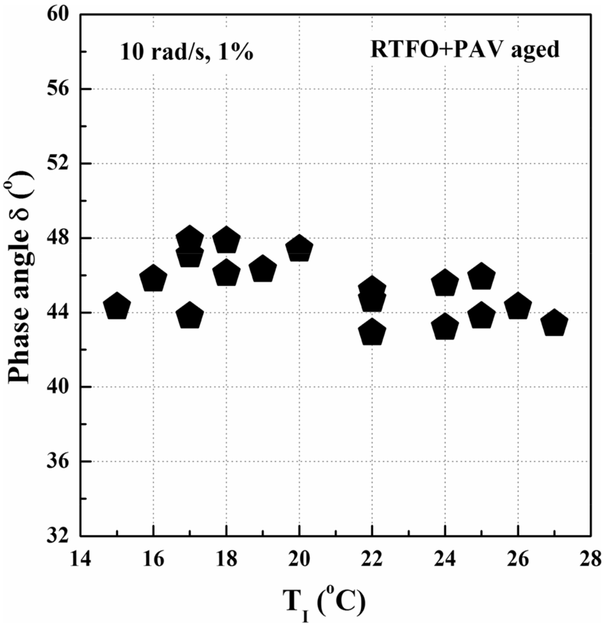

Fig. 12 Phase angle (δ) vs. true PG intermediate limiting temperature (T_I) for the 18 'RTFO + PAV' aged asphalt binders

An essential understanding of the rheological behavior of 'RTFO + PAV' aged asphalt binders was obtained when the δ values at the true PG intermediate limiting temperature (T_I) were analyzed. It can be seen in Fig. 12 that at

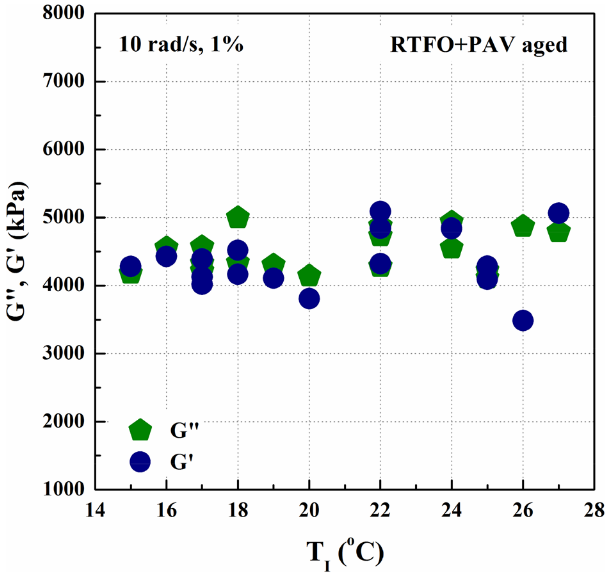

Fig. 13 Loss modulus (G'') and elastic modulus (G') vs. true PG intermediate limiting temperature (T_I) for the 18 'RTFO + PAV' aged asphalt binders

T_I and linear viscoelastic (LVE) condition of $\omega = 10$ rad/s, $\gamma_A = 1\%$, the δ values of 'RTFO + PAV' aged binders were between 40° and 50° [52]. In this δ range, the value of sinδ will be close to cosδ, which means that elastic modulus (G') and loss modulus (G'') values will be similar to each other, as shown in Fig. 13. In other words, the energy dissipation capacity of the 'RTFO + PAV' aged binders will be the same as its energy-storing tendency. Hence, in SHRP studies, a good correlation was found among several of the rheological properties of asphalt binders ($|G^*|$, G', and G'') and fatigue behavior of asphalt mixture [1, 2, 5, 6]. Thus, for 'RTFO + PAV' aged binders, using the loss modulus (G'') as the fatigue criterion will offer limited benefit. Since phase angle values of RTFO + PAV aged binders are close to 45°, the fatigue criterion of $|G^*|\sin\delta$ can also be represented as $|G^*| \leq 7000$ kPa. Along similar lines, '*R*-value' analysis utilizes the $|G^*|$ values obtained from the master curves of the 'RTFO + PAV' aged binders to determine the fatigue performance [38].

Moreover, the drawback in using δ of asphalt binders to predict the fatigue behavior in asphalt mixes is illustrated in Fig. 14. Figure 14 presents the $|G^*|$ and δ values of unaged and 'RTFO + PAV' aged R-72 binder. It can be seen in Fig. 14 that the $|G^*|$ of the binder increases significantly due to 'RTFO + PAV' aging. It is well documented that the brittleness of asphalt binders also increases after 'RTFO + PAV' aging, due to which failure by fatigue cracking increases considerably. On the contrary, it can be noticed in Fig. 14 that the δ value of the binder decreases after 'RTFO + PAV' aging implying that elasticity in the binder sample increases. Thus, if an analysis is made considering the δ value, it will lead to the incorrect conclusion that fatigue cracking reduces after aging [32, 53]. In studies such as linear amplitude sweep (LAS) and glover-row analysis, efforts are made to predict the fatigue performance of asphalt binders through $|G^*|$ and δ values [32–36, 38, 39]. But the results in Fig. 14 demonstrate that fatigue cracking and δ show opposing trends after aging in asphalt binders. Also, the 'RTFO + PAV' aged binders will be highly susceptible to detachment at the surface of measuring geometry during LAS testing due to the high stiffness [54].

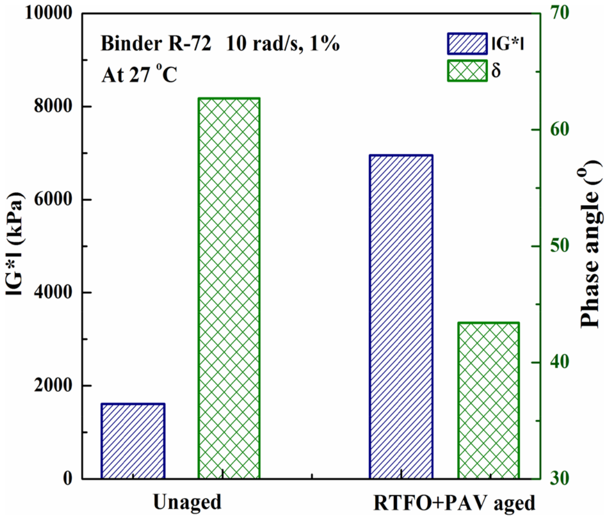

Fig. 14 Complex modulus ($|G^*|$) and phase angle for unaged and 'RTFO + PAV' aged R-72 binder at 27 °C

3.3 Rutting Criterion for Polymer Modified Binders

Polymer modified binders (PMBs) enhances the rutting, fatigue cracking, and thermal cracking performance of asphalt pavements [55, 56]. Pavements constructed using PMBs have a longer service life and lower maintenance requirements [57, 58]. Styrene–butadiene–styrene (SBS) is one of the most frequently used polymers for binder modification. Other polymers such as styrene–butadiene rubber (SBR), reactive terpolymer, ethylene-vinyl-acetate (EVA), ethylene-glycidyl-acrylate (EGA), etc. are also used for binder modification, but to a lesser extent [59–62]. In PMBs, it is widely documented that the rutting criterion ($|G^*|/\sin\delta$) is inadequate to predict the rutting performance of asphalt mixtures [12]. Hence, state highway organizations

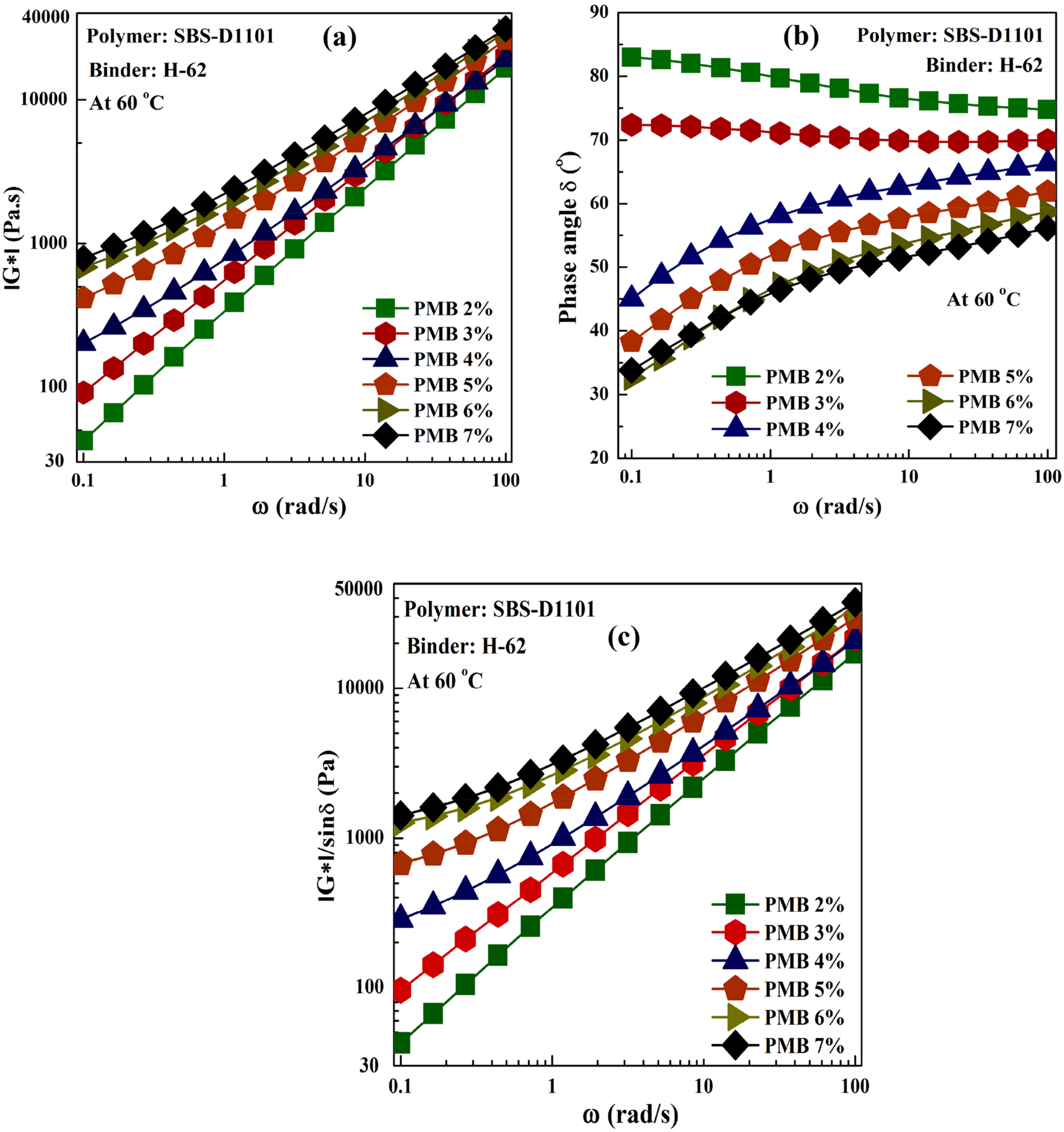

Fig. 15 **a** Complex modulus (|G^*|), **b** phase angle (δ), and **c** |G^*|/sinδ vs. ω at 60 °C for the PMBs in H-62 binder

have opted to incorporate additional tests such as multiple stress and creep and recovery (MSCR), minimum δ value, toughness, tenacity, etc. [17, 18, 24, 26]. After evaluating unmodified asphalt binders, rheological measurements were carried out on SBS modified binders to determine the reason for the poor correlation between the PG criterion |G^*|/sinδ and rutting in asphalt mixtures. H-62 and L-64 binders were modified by adding different weight percent of linear SBS polymer. A brief analysis of PMBs rheological behavior is presented in this paper, while a detailed study will be reported subsequently.

The main factor influencing the correlation between the rheological properties of the PMBs to the rutting performance can be acknowledged in Fig. 15a–c. |G^*|, δ, and |G^*|/sinδ vs. ω of the six PMB samples at 60 °C are presented in Fig. 15a–c. Unlike unmodified binders, it can be seen in

Fig. 15a–c that |*G**|, *δ*, and |*G**|/sin*δ* of the PMB samples varies significantly as a function of *ω*. Most importantly, the difference among the PMBs is noticeable mainly at lower frequencies, which indicates that the effect of SBS polymer in the binder is better quantified at lower frequencies [16, 63]. At $\omega < 1$ rad/s, the |*G**| of the SBS modified binders began to plateau when the SBS content was ≥ 4 wt%, the concentration above which morphological observations have shown the formation of an interconnected polymer-rich network in the binder [58, 61]. Unlike unmodified binders, the complex viscosity of SBS modified binders varies strongly with applied frequency even in the LVE region because of the plateau of the |*G**| vs. *ω* curve. This can be further understood from the *δ* values of the PMBs, as shown in Fig. 15b. It can be noticed in Fig. 15b that up to 3 wt% SBS content, *δ* values are weakly dependent on the applied *ω*. However, above 3 wt%, *δ* varied significantly as a function of *ω*. Above 3 wt%, the decrease in *δ* value shows that the response from the SBS polymer is mainly reflected at lower frequencies. Lower *ω* implies deformation happening over a longer time scale which resonates with the sluggish dynamics of the long SBS polymer in the binder. At higher frequencies, the binder molecules and smaller segments of SBS polymer (Rouse, Kuhn, etc.) dominate the rheological response [64].

Several researchers have analyzed the viscoelastic behavior of PMBs through |*G**| and *δ* values, temperature sweep measurements, isochronal plots, Palierne model, etc. [65–69]. Airey et al. have examined the rheological properties of SBS-MBs through master curves [70]. Xia et al. have investigated the evolution in morphology and alteration in the viscoelastic properties of PMBs as a function of SBS content [64]. The study is based on quantifying the area shrinking kinetics through morphological observation, effects on rheological parameters, and Han plot due to the addition of SBS polymer. Along similar lines, Rossi et al. have measured the influence of SBS polymer on binder phase transition via temperature sweep analysis [71]. However, very few studies have directly signified the role of angular frequency in quantifying the properties of SBS modified binders, and its relevance in the correlation with rut depth.

The important role of *ω* in predicting the rutting performance of PMBs is demonstrated in Table 4, where the correlation between rut depth at 20,000 cycles and rheological properties of the PMBs at different frequencies are given. The rut depth of the asphalt mixes prepared using the six PMB samples was measured at 60 °C. It can be observed that the R^2 value between '|*G**|/sin' and rut depth approaches 1 (0.969) at lower frequencies. Another vital observation that can be made is that other rheological parameters also exhibited a good correlation with rut depth at lower frequencies. Similar results were obtained in the case of PMBs prepared using L-64 binder. Several studies have reported that the MSCR measurements provide a better correlation with the rut depth in asphalt mixes [12, 14, 72–74]. Sajjad et al. have also used the MSCR test method to compare the performance properties of SBS and green composite modified binders [72]. Hence, MSCR measurements were carried out on the six PMBs samples prepared in H-62 binder, and regression analysis was performed. The correlation (R^2 value) of elastic recovery (ER) and non-recoverable creep compliance (Jnr) with rut depth were 0.954 and 0.971, respectively. It can be seen in Table 4 that R^2 values between the rheological properties at 0.1 rad/s and rut depth were close to the MSCR value. Therefore, it can be concluded from Fig. 15a–c and Table 4 that for better grading and performance evaluation of PMBs, analysis at lower frequencies is highly beneficial.

4 Conclusions

In this study, the rheological parameters in the PG rutting and fatigue cracking criteria were evaluated. Based on the obtained results, the following conclusions can be drawn.

Table 4 Correlating factor (R^2) between the rut depth and rheological properties of PMBs in H-62 and L-64 binders

Parameters	Unaged PMB			RTFO aged PMB		
	10 rad/s	1 rad/s	0.1 rad/s	10 rad/s	1 rad/s	0.1 rad/s
PMBs in H-62 binder						
|*G**|/sin*δ*	0.931	0.967	0.969	0.901	0.986	0.992
Complex modulus, |*G**|	0.917	0.949	0.955	0.837	0.981	0.993
Phase angle, *δ*	0.965	0.971	0.975	0.974	0.974	0.980
Complex viscosity, |*η**|	0.917	0.949	0.955	0.838	0.981	0.993
PMBs in L-64 binder						
|*G**|/sin*δ*	0.921	0.971	0.980	0.910	0.934	0.936
Complex modulus, |*G**|	0.918	0.974	0.984	0.834	0.912	0.932
Phase angle, *δ*	0.911	0.927	0.952	0.954	0.977	0.987
Complex viscosity, |*η**|	0.881	0.946	0.965	0.878	0.932	0.956

- The phase angle (δ) values of the unmodified asphalt binders were > 80° at true PG upper limiting temperature (T_u), due to which the PG rutting criterion '$|G^*|/\sin\delta$' and viscosity of the binder becomes equivalent. Furthermore, the viscosity of the binders at T_u was independent of the applied strain amplitude (1–50%) and frequency (1–20 rad/s) in oscillatory deformation, and strain rate (1–10/s) in rotational shear. Thus, both '$|G^*|/\sin\delta$' and viscosity of the binder had identical correlation with the rut depth in asphalt mixes.

  At upper service temperatures, all the different rutting parameters, such as $|G^*|/\sin\delta$, Shenoy's parameter, low shear viscosity, zero shear viscosity, etc., are equivalent to viscosity. Thus, all the rutting parameters will have a similar correlation with rutting in asphalt mixes. At upper service temperatures, the viscosity of the binder is the dominant parameter, and therefore we recommend using viscosity to predict rutting in asphalt mixes.
- The PG fatigue cracking criterion is based on the energy dissipating capacity (loss modulus $G'' = |G^*|\sin\delta \le 5000$ kPa) of rolling thin film oven (RTFO) and pressure aging vessel (PAV) aged binders. But, at PG intermediate temperature (T_I), the phase angle (δ) values of 'RTFO + PAV' aged binders was close to 45° due to which the loss modulus G'' and elastic modulus G' values were similar. Since $G'' \approx G' \approx 1.4\ G^*$, the three parameters will have a similar correlation with the fatigue performance of asphalt mixes.

  Additionally, the stiffness and brittleness of asphalt binders increase significantly after 'RTFO + PAV' aging. On the contrary, the δ value decreases, falsely indicating an increase in elasticity in the asphalt binders. The conflicting observations arise due to the measurements carried out in the LVE region. In the LVE region, even highly brittle solid materials exhibit low δ values. Thus, similar to G'', fatigue analysis based on δ may result in incorrect analysis.
- The rheological properties of PMBs at upper service temperatures strongly depend on the frequency (ω), and the rheological signature of the polymer molecules manifests predominantly at lower ω. At $\omega \le 0.1$ rad/s, the correlation between rheological parameters of PMBs and rut depth is close to that obtained from the MSCR test. Hence, for PMBs analysis at $\omega \le 0.1$ rad/s is recommended.

Appendix

See Figs. 16 and 17 .

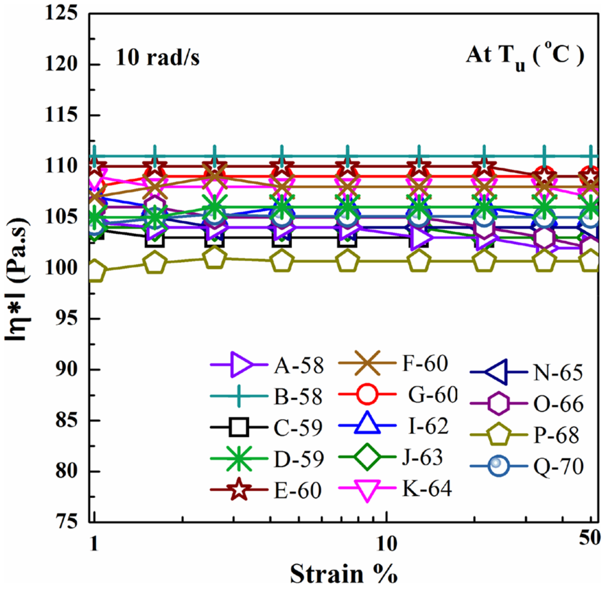

Fig. 16 Complex viscosity ($|\eta^*|$) vs. strain amplitude (γ_A) at true PG upper limiting temperatures (T_u) for the remaining 14 asphalt binders

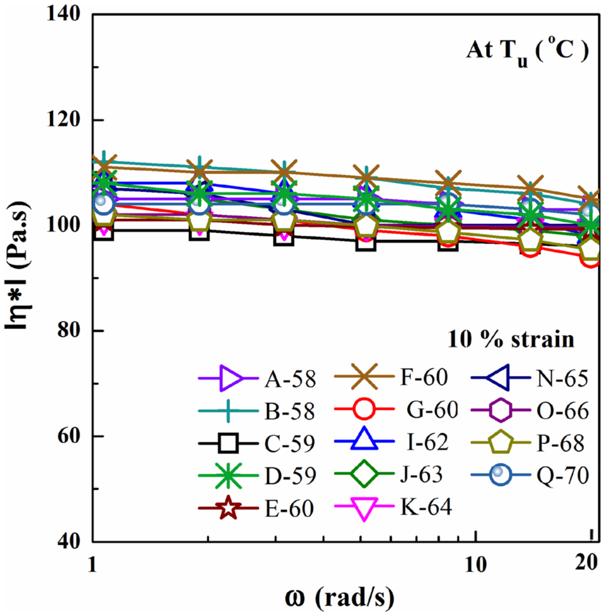

Fig. 17 Complex viscosity ($|\eta^*|$) vs. angular frequency (ω) at true PG upper limiting temperatures (T_u) for the remaining 14 asphalt binders

Acknowledgements This work was supported by 'Early Career Research' grant from the Science and Engineering Research Board (SERB), India (ECR/2016/001427). The authors also thank Ministry of Human Resource Development, Government of India for providing student scholarship.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Anderson, D. A., Christensen, D. W., Bahia, H. U., Dongre, R., Sharma, M. G., & Charles, E. A. (1994). Binder characterization and evaluation, volume 3. In Strategic Highway Research Program, National Research Council, Washington, D. C., Report: SHRP-A-369.
2. Harrigan, E. T., Leahy, R. B., Narsiah, J., & Michael, J. (1994a). Stage 1 Validation of the relationship between asphalt properties and asphalt-aggregate mix performance. Strategic Highway Research Program, National Research Council, Washington, D. C., Report: SHRP-A-398.
3. Leahy, R. B., & Harrigan, E. T. (1994). Validation of relationships between specification properties and performance. Strategic Highway Research Program, National Research Council, Washington, D.C., Report: SHRP-A-409.
4. Abdulmajeed, S. G., & Muniandy, R. (2017). The effect of binder type and temperature differential on the rutting performance of hot mix asphalt. *International Journal of Applied Engineering Research, 12*(17), 6841–6852. ISSN 0973-4562.
5. McGennis, R. B., Shuler, S., & Bahia, H. U. (1994). Background of superpave asphalt binder test methods. National Asphalt Training Center, Demonstration Project 101, Federal Highway Research Administration, 199508.
6. Petersen, J. C., Robertson, R. E., Branthaver, J. F., Harnsberger, P. M., Duvall, J. J., & Kim, S. S. (1994). Binder characterization and evaluation, volume 1. Strategic Highway Research Program, National Research Council, Washington, D. C., Report: SHRP-A-367.
7. Nattaporn, C., & Kunnawee, K. (2012). Development of performance grading system for asphalt binders used in Thailand. *Asian Transport Studies, 2*(2), 121–138.
8. Kennedy, T. W., Huber, G. A., Harrigan, E. T., Cominsky, R. J., Hughes, C. S., Von, Q. H., & Moulthrop, J. S. (1994). Superior performing asphalt pavements (superpave): the product of the SHRP asphalt research program. Strategic Highway Research Program, National Research Council, Washington, D. C., Report: SHRP-A-410. ISBN: 030905821X.
9. Ghuzlan, K. A., & Al khateeb, G. G. (2013). Selection and verification of performance grading for asphalt binders produced in Jordan. *International Journal of Pavement Engineering, 14*, 116–124. https://doi.org/10.1080/10298436.2011.650697
10. John, A. D. (2011). The relationship of the MSCR test to rutting. *Road Materials and Pavement Design, 1*, 61–80. https://doi.org/10.1080/14680629.2009.9690236
11. Chen, J. S., & Tsai, C. J. (1999). How good are linear viscoelastic properties of asphalt binder to predict rutting and fatigue cracking? *Journal of Materials Engineering and Performance, 8*, 443–449. https://doi.org/10.1361/105994999770346747
12. Stuart, K. D., & Richard, P. I. (1995). Correlation of superpave $|G^*|/\sin\delta$ with rutting susceptibility from laboratory mixture tests. *Transportation Research Record*, *1492*, 176–183.
13. Subhy, A. S. (2017). Advanced analytical techniques in fatigue and rutting related characterisations of modified bitumen: literature review. *Construction and Building Materials, 156*, 28–45. https://doi.org/10.1016/j.conbuildmat.2017.08.147
14. Delgadillo, R., Kitae, N., & Bahia, H. U. (2006). Why do we need to change $|G^*|/\sin\delta$ and how? *Road Materials and Pavement Design, 7*, 7–27. https://doi.org/10.1080/14680629.2006.9690024
15. Morea, F., Agnusdei, J. O., & Zerbino, R. (2011). The use of low shear viscosity to predict permanent deformation performance of asphalt concrete. *Materials and Structures, 44*, 1241–1248. https://doi.org/10.1617/s11527-010-9696-3
16. Radhakrishnan, V., Ramya, S. M., & Reddy, K. S. (2018). Evaluation of asphalt binder rutting parameters. *Construction and Building Materials, 173*, 298–307. https://doi.org/10.1016/j.conbuildmat.2018.04.058
17. Shenoy, A. (2001). Refinement of the superpave specification parameter for performance grading of asphalt. *Journal of Transportation Engineering, 127*(5), 357–362. https://doi.org/10.1061/(ASCE)0733947X(2001)127:5(357)
18. Shenoy, A. (2004). High temperature performance grading of asphalts through a specification criterion that could capture field performance. *Journal of Transportation Engineering, 130*, 132–137. https://doi.org/10.1061/(ASCE)0733-947X(2004)130:1(132)
19. Morea, F., Agnusdei, J. O., & Zerbino, R. (2010). Comparison of methods for measuring zero shear viscosity in asphalts. *Materials and Structures, 43*, 499–507. https://doi.org/10.1617/s11527-009-9506-y
20. Morea, F., Zerbino, R., & Agnusdei, J. (2014). Wheel tracking rutting performance estimation based on bitumen low shear viscosity (LSV), loading and temperature conditions. *Materials and Structures, 47*(4), 683–692. https://doi.org/10.1617/s11527-013-0088-3
21. Mazurek, G., & Iwanski, M. (2016). Estimation of zero shear viscosity versus rutting resistance parameters of asphalt concrete. *Procedia Engineering, 161*, 30–35. https://doi.org/10.1016/j.proeng.2016.08.493
22. Wang, C., & Jhang, J. (2014). Evaluation of rutting parameters of asphalt binder based on rheological test. *IACSIT International Journal of Engineering and Technology, 6*(1), 30–33. https://doi.org/10.7763/IJET.2014.V6.660
23. Bahia, H. U., Hanson, D. I., Zeng, M., Zhai, H., Khatri, M. A., & Anderson, R. M. (2001). Characterization of modified asphalt binders in superpave mix design. National cooperative highway research program (NCHRP) report 459, Transportation research board, National research council, National academies, Washington, DC.
24. Chen, J. S., Chih, M., & Lin, C. H. (2003). Determination of polymer content in modified bitumen. *Materials and Structures, 3*, 594–598. https://doi.org/10.1007/BF02483278
25. Angelo, D., Kluttz, R., Dongre, R. N., Stephens, K., & Zanzotto, L. (2007). Revision of the superpave high temperature binder specification: the multiple stress creep recovery test. *Journal of the Association of Asphalt Paving Technologists, 76*, 01080569.
26. Wasage, T. L. J., Stastna, J., & Zanzotto, L. (2011). Rheological analysis of multi-stress creep recovery (MSCR) test. *International Journal of Pavement Engineering, 12*(6), 561–568. https://doi.org/10.1080/10298436.2011.573557
27. Soenen, H., Blomberg, T., Pellinen, T., & Laukkanen, O. V. (2013). The multiple stress creep-recovery test: a detailed analysis of repeatability and reproducibility. *Road Materials and Pavement Design, 14*, 2–11. https://doi.org/10.1080/14680629.2013.774742
28. Behnood, A., Ayesha, S., Rebecca, S. M., & Jan, O. (2016). Analysis of the multiple stress creep recovery asphalt binder test and

specifications for use in Indiana. Joint Transportation Research Program, FHWA/IN/JTRP-2016/07. https://doi.org/10.5703/1288284316330

29. Zahid, H., Debaroti, G., Musharraf, Z., & Kenneth, H. (2016). Use of the multiple stress creep recovery (MSCR) test method to characterize polymer modified asphalt binders. *Journal of Testing and Evaluation*. https://doi.org/10.1520/JTE20140061
30. Delgadillo, R., Cho, D. W., & Bahia, H. U. (2006). Nonlinearity of repeated creep and recovery binder test and relationship with mixture permanent deformation. *Transportation Research Record, 1962*, 2–11. https://doi.org/10.1177/0361198106196200101
31. Planche, J. P., Anderson, D. A., Gauthier, G., Le Hir, Y. M., & Martin, D. (2004). Evaluation of fatigue properties of bituminous binders. *Materials and Structures, 37*, 356–359.
32. Glover, C. J., Davison, R. R., Domke, C. H., Yonghong, R., Pramitha, J., Daniel, B. K., & Sung, H. J. (2005). Development of a new method for assessing asphalt binder durability with field validation. Texas Department of Transportation, US Department of Transportation Federal Highway Administration, report 1872-2, project number 0-1872.
33. Hintz, C., Velasquez, R., & Johnson, C. (2011). Modification and validation of linear amplitude sweep test for binder fatigue specification. *Transportation Research Record: Journal of the Transportation Research Board*. https://doi.org/10.3141/2207-13
34. Rowe, G. M., Anderson, R. M., Gayle, N. K., Douglas, I. H., & Phillip, B. B. (2011). Evaluation of the relationship between asphalt binder properties and non-load related cracking. *Journal of the Association of Asphalt Paving Technologists, 80*, 649–662.
35. Botella, R., Perez Jimenez, F. E., & Miro, R. (2012). Application of a strain sweep test to assess fatigue behavior of asphalt binders. *Construction and Building Materials, 36*, 906–912. https://doi.org/10.1016/j.conbuildmat.2012.06.059
36. Fujie, Z., Waala, M., Hongsheng, L., & Andrian, A. (2013). Evaluation of fatigue tests for characterizing asphalt binders. *Journal of Materials in Civil Engineering, 25*(5), 610–617. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000625
37. Wang, C., Zhang, H., Castorena, C., & Zhang, J. (2016). Identifying fatigue failure in asphalt binder time sweep tests. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2016.06.020
38. Reyhaneh, R. R., Daniel, J. S., & Gerald, R. (2017). Comparison of asphalt binder and mixture cracking parameters. *Road Materials and Pavement Design, 18*(4), 211–233. https://doi.org/10.1080/14680629.2017.1389071
39. Hajj, R., & Bhasin, A. (2018). The search for a measure of fatigue cracking in asphalt binders – a review of different approaches. *International Journal of Pavement Engineering, 19*(3), 205–219. https://doi.org/10.1080/10298436.2017.1279490
40. Daniel, J. S., & Kim, Y. R. (2004). Fatigue evaluation of asphalt mixtures using dissipated energy and viscoelastic continuum damage approaches asphalt paving technology. In Association of Asphalt Paving Technologists, Proceedings of the Technical Sessions, vol. 73, pp. 557–583. ISSN: 0270-2932.
41. Andriescu, A., Gibson, N. H., Simon, A. M., Youtcheff, Q. X., & John, S. (2006). Validation of the essential work of fracture approach to fatigue grading of asphalt binders. Journal of the Asphalt Paving Technologists, Proceedings of the Technical Sessions, vol. 75, pp. 27–29. ISSN: 0270-2932.
42. Shihui, S., Airey, G. D., Samuel, H. C., & Huang, H. (2007). A dissipation energy approach to fatigue evaluation. *Road Materials and Pavement Design, 7*, 47–69. https://doi.org/10.1080/14680629.2006.9690026
43. ASTMD 36. (1962). Standard test method for softening point of bitumen (Ring-and-Ball Apparatus). ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D0036_D0036M-09
44. ASTM D05. (1959). Standard test method for penetration of bituminous materials. ASTM International, West Conshohocken, PA.
45. ASTM D6373. (1999). Standard specification for performance graded asphalt binder. ASTM International, West Conshohocken, PA.
46. Macosko, C. W. (1994). *Rheology, principle, measurements and application*. Wiley-Vch.
47. Mezger, T. G. (2014). Applied rheology, Anton Paar.
48. Mouhamad, M., Arnaud, P., & Bruno, V. (2011). Correlation between thermal and rheological studies to characterize the behaviour of bitumen. *Rheological Acta, 50*, 169–178. https://doi.org/10.1007/s00397-011-0534-5
49. Shenoy, A. (2008). Nonrecovered compliance from dynamic oscillatory test vis-à-vis nonrecovered compliance from multiple stress creep recovery test in the dynamic shear rheometer. *International Journal of Pavement Engineering, 9*(5), 329–341.
50. Sybilski, D. (1996). Zero shear viscosity of bituminous binders and its relation to bituminous mixture's resistance. *Transport Research Record, 1535*, 15–21. https://doi.org/10.3141/1535-03
51. Lihan, L., Han, G., & Yanna, S. (2015). Simplified viscosity evaluating method of high viscosity asphalt binders. *Materials and Structures, 48*, 2147–2156. https://doi.org/10.1617/s11527-014-0299-2
52. Henglong, Z., Zihao, C., Guoqing, X., & Caijun, S. (2018). Evaluation of aging behaviors of asphalt binders through different rheological indices. *Fuel, 221*, 78–88.
53. Cong-hui, L. I. U., Shao-peng, W. U., Quan-tao, L. I. U., & Guojun, Z. H. U. (2008). Rheological characteristics of aged asphalt binder. *Journal of Central South University of Technology, 15*(1), 298–301. https://doi.org/10.1007/s11771−008−367−2
54. Cassie, H., & Bahia, H. (2013). Simplification of linear amplitude sweep test and specification parameter. *Journal of the Transportation Research Board, 2370*, 10–16.
55. Airey, G. D. (2004). Fundamental binder and practical mixture evaluation of polymer modified bituminous materials. *International Journal of Pavement Engineering, 5*(3), 137–151. https://doi.org/10.1080/10298430412331314146
56. Zhu, J., Birgisson, B., & Kringos, N. (2014). Polymer modification of binder: advances and challenges. *European Polymer Journal, 54*, 18–38. https://doi.org/10.1016/j.eurpolymj.2014.02.005
57. Singh, S. K., Yogesh, K., & Ravindranath, S. S. (2018). Thermal degradation of SBS in binder during storage: influence of temperature, SBS concentration, polymer type and base binder. *Polymer Degradation and Stability, 147*, 64–75. https://doi.org/10.1016/j.polymdegradstab.2017.11.008
58. Yogesh, K., Singh, S. K., & Ravindranath, S. S. (2020). Effect of molecular structure and concentration of styrene-butadiene polymer on upper service temperature rheological properties of modified binders. *Construction and Building Materials, 249*, 118790.
59. Yildirim, Y. (2007). Polymer modified asphalt binders. *Construction and Building Materials, 21*, 66–72. https://doi.org/10.1016/j.conbuildmat.2005.07.007
60. Sengoz, B., Topal, A., & Isikyakar, G. (2009). Morphology and image analysis of polymer modified bitumens. *Construction and Building Materials, 23*, 1986–1992. https://doi.org/10.1016/j.conbuildmat.2008.08.020
61. Behnood, A., & Modiri, G. M. (2019). Morphology, rheology, and physical properties of polymer-modified asphalt binders. *European Polymer Journal, 112*, 766–791. https://doi.org/10.1016/j.eurpolymj.2018.10.049
62. Sajjad, H. K., Perviz, A., Alexander, F., & Taylan, G. (2018). Investigation of physical properties of asphalt binder modified by recycled polyethylene and ground tire rubber. San Francisco USA, 20(6) Part V.

63. Singh, S. K., Pandey, A., Sohel Sk, I., Ransingchung RN, G. D., & Ravindranath, S. S. (2020). Significance of frequency in quantifying the deterioration in the properties of SBS modified binders and rutting performance. *Construction and Building Materials, 262*, 120872.
64. Xia, T., Jianhui, X., Ting, H., Jiufan, H., Yuxuan, Z., Jianxin, G., & Youbing, L. (2016). Viscoelastic phase behavior in SBS modified bitumen studied by morphology evolution and viscoelasticity change. *Construction and Building Materials, 105*, 589–594.
65. Airey, G. D. (2003). Rheological properties of styrene butadiene styrene polymer modified road bitumens. *Fuel, 82*, 1709–1719.
66. Airey, G. D. (2001). Viscosity-temperature effects of polymer modification as depicted by Heukelom's Bitumen Test Data Chart. *International Journal of Pavement Materials, 2*(4), 223–242.
67. Chen, Z., Henglong, Z., Haihui, D., & Chaofan, W. (2020). Determination of time-temperature superposition relationship of SBS modified asphalt based on special rheological phenomenon caused by SBS-formed structure in asphalt matrix. *Construction and Building Materials, 260*, 119835.
68. Dhawo, I. A., Jiantao, W., Quan, L., Norhidayah, A. H., Nur, I. M., & Yusoff, S. I. A. A. (2016). Physical and rheological characteristics of polymer modified bitumen with nanosilica particles. *Arab Journal of Science and Engineering, 41*, 1521–1530.
69. Andrea, T., Emmanuel, C., Fabienne, F., Cyrille, C., Bernard, M., & Nadege, B. (2016). Modeling the linear viscoelastic behaviour of asphaltite-modified bitumens. *Rheological Acta, 55*, 969–981.
70. Airey, G. D. (2004). Styrene butadiene styrene polymer modification of road bitumens. *Journal of Materials Science, 39*(3), 951–959.
71. Cesare, O. R., Assunta, S., Bagdat, T., Galiya, I., Yerik, A., & Villiam, B. (2015). Polymer modified bitumen: rheological properties and structural characterization. *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 480*, 390–397.
72. Sajjad, H. K., Perviz, A., Alexander, M. F., & Behnood, A. (2020). Rheological properties of asphalt binders modified with recycled materials: a comparison with Styrene-Butadiene-Styrene (SBS). *Construction and Building Materials, 230*, 117047.
73. AASHTO T 350. Standard method of test for multiple stress creep recovery (MSCR) test of asphalt binder using a dynamic shear rheometer (DSR). American Association of State Highway and Transportation Officials (AASHTO).
74. Nikhil, S., Rajiv, K., Praveen, K., & Ankit, G. (2018). Ranking the rheological response of SBS and EVA modified bitumen using MSCR and LAS tests. *Journal of Materials in Civil Engineering, 30*(8), 04018165.

Akanksha Pandey is pursuing her PhD from the Indian Institute of Technology, Roorkee, in the department of 'Polymer and Process Engineering'. Her research interests include characterization of asphalt binder, polymer modified binder, crumb rubber modified binder, and rheology of complex fluids.

Dr. Sumit K. Singh is working as an 'Application Specialist, Anton Paar, India. He has a keen interest in the rheology of complex fluids, along with understanding their practical applications. He completed his PhD in June 2020 on the thermal and rheological study of polymer modified bitumen from IIT Roorkee, India.

Sk. Sohel Islam is currently pursuing his PhD in the 'Transportation Engineering Group, Civil Engineering Department, IIT Roorkee, India'. His research interest pertains to evaluating the performance of asphalt mix prepared using modified binders, rheology of polymer modified binders, and sustainable pavement materials.

Dr. G. D. Ransinchung R. N. is currently working as a 'Professor' in the department of 'Civil Engineering, IIT Roorkee, India'. Before this teaching assignment, he has served IIT (BHU), Varanasi. He has rendered his services to the 'National Highway Development Projects' of the country in various capacities. He actively works with multiple agencies such as M/s Backbone Project Limited, M/s Sadbhav Engineering Limited, Lea Associate South Asia Pvt. Ltd., etc. Considering both field and teaching, he has a total experience of more than 19 years. He is involved in the evaluation of pavement materials, both flexible and rigid pavements.

Dr. Sridhar Raju is currently working as an 'Associate Professor' in the department of 'Civil Engineering, BITS Pilani, Hyderabad Campus'. Before this teaching assignment, he served as a senior researcher at 'Shell Bitumen R&D Center, Bangalore'. He has rendered his services at the flexible pavements division at 'Central Road Research Institute, India'. Considering both research and teaching, he has a total experience of more than 20 years. He is actively involved in the evaluation of pavement materials, utilization of waste plastics and crumb rubber for city roads.

Dr. Sham S. Ravindranath obtained his doctorate degree in polymer science from 'The University of Akron', USA. He is currently working as an 'Assistant Professor' at the department of 'Polymer and Process Engineering', Indian Institute of Technology (IIT), Roorkee. He currently works in the area of asphalt binder rheology, polymer modified binder, pavement materials, etc. His doctoral research was nominated for the Frank J. Padden award in 2009 by the division of polymer science, American Physical Society. He has numerous publications with over 900 citations.