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ORIGINAL PAPER

Comparison of different rheological parameters for rutting susceptibility of SBS + WMA modified binders

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Abstract It is important to understand rutting susceptibility of asphalt binders at laboratory scale to ensure a long lasting pavement. Researchers have reported applicability of four rheological parameters: (1) Superpave parameter—$G^*/\sin\delta$ (2) Shenoy's parameter—$G^*/(1-(1/\tan\delta\sin\delta))$, (3) non-recoverable creep compliance—J_{nr}, measured from multiple stress creep recovery test and (4) zero shear viscosity (ZSV) to evaluate rutting resistance of binders. However, comparison of these rutting parameters for warm mix additives (WMA) modified asphalt binders have not been reported in open literature. Thus, this study was undertaken to evaluate rutting performance of a SBS co-polymer modified binder (PMB40) containing three WMA additives using four rheological parameters listed above. Three different WMA additives: wax based (Sasobit®), water based (Advera®) and surfactant based (Rediset®) were selected in this study. Based on three parameters (Superpave, Shenoy and J_{nr}), it was found that addition of Sasobit® and Advera® help to improve rut resistance of PMB40 binder while Rediset® decreases rut resistance of the binder. The ZSV showed rut resistance improvement for all the additives, which is contrary to the results obtained from other three parameters. Both the Superpave and Shenoy parameters showed a similar trend in rutting resistance of the binder. The optimum dosage of Advera® and Sasobit® was determined based on the Superpave, Shenoy and J_{nr} parameters. Since, the addition of Rediset® resulted in decrease in rutting behavior, optimum dosage of Rediset® could not be ascertained. A good correlation was found between the Superpave rutting parameter ($G^*/\sin\delta$) and other three parameters ($G^*/(1 - (1/\tan\delta\sin\delta))$, ZSV, and J_{nr}). The outcome of this study showed that, J_{nr} may be considered as a reliable rut parameter due to realistic test conditions associated with it. The Superpave parameter is more conservative compared to Shenoy parameter, and thus it may still be considered as an important rutting parameter in the absence of J_{nr}. The ZSV needs further validation to comment on its applicability.

Keywords Warm mix additive · Multiple stress creep and recovery

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Introduction

Rutting is one of the major distresses of a flexible pavement. It is mainly contributed due to insufficient structural strength of asphalt mix or pavement layers. Two ways to evaluate rutting behavior at laboratory scale are (1) performance tests on asphalt mixes (2) performance tests on asphalt binders. Different types of asphalt binders (modified, unmodified, crumb rubber modified, fiber modified, nanomaterial modified) are selected to mitigate rutting susceptibility of pavements. Earlier, conventional tests namely, softening point and penetration were widely used to understand rutting behavior of asphalt binders and its influence on overall performance of pavement [1, 2]. The penetration test reflects stiffness of a binder, while the softening point shows tendency of a binder to flow at higher temperature. These tests are simple to conduct and gives indication of rutting behavior of a binder, however, they are empirical in nature and do not account for performance under different loading and unloading conditions, and hence they are not reliable to adopt for new generation materials [1, 3]. These conventional tests were developed when there was scarcity of advanced instrument and testing methodology. Sybilski [4] and Dreessen et al. [2] correlated results of conventional tests (penetration and softening point) of modified and unmodified binders with rutting behavior of asphalt mixes under accelerated loading facilities. They reported that conventional tests were unable to correlate with rutting behavior of asphalt mixes. Several limitations of the conventional tests such as single test temperature, simple loading condition, empirical in nature, no correlation with mix properties, and unreliable performance for modified binders, have prompted researchers to develop comprehensive and mechanistic rut parameter which can be adopted for evaluating rutting performance of asphalt binders. The first development in this direction came with adoption of the Superpave binder specification [5]. The Superpave binder specification developed test method and parameters to capture rutting, fatigue and low temperature performance of asphalt binders. The Superpave rutting parameter—$G^*/\sin\delta$, is inversely proportional to the dissipated energy. A binder with high $G^*/\sin\delta$ will have lesser dissipated energy, and thus higher rut resistant. The $G^*/\sin\delta$ showed satisfactory results for unmodified binders [6–8]. However, this parameter showed unconvincing trend for polymer modified binders due to its inability to capture delayed elastic recovery [6, 9–14]. Thus, applicability of $G^*/\sin\delta$ parameter for modified binders needs to be investigated thoroughly. Some of the drawbacks of The Superpave rutting parameter are: (1) test conducted at a fixed frequency (10 rad/s), keeping strain within linear visco-elastic range (LVE) (i.e., below 12 %). However, usually rutting is observed in non LVE range where strain exceeds 12 %, thus there is a need to change test condition, (2) cyclic loading with complete reversal in stress, which does not reflect field condition. The rutting occurs due to irreversible cyclic loading resulting in unrecoverable permanent strain, and (3) behavior of binder with few numbers of loading cycles, particularly for modified binders.

Several researchers suggested refinement to the Superpave rutting parameter. For example, Chen and Tsai [15] estimated $G^*/\sin\delta$ at various test frequencies (10, 5, and 0.6 rad/s) and correlated it with rutting performance of mixes. They reported that lower test frequency (5 or 0.6 rad/s) should be adopted to accurately capture rutting behavior of binder. Shenoy [14] suggested refinement in the Superpave rutting parameter by introducing a new parameter: $G^*/(1 - (1/\tan\delta\sin\delta))$, which considers elastic component of binder and hence can be useful to determine rutting resistance of polymer modified binders [16, 17]. To have lower unrecoverable strain (permanent strain), $(G^*/(1 - (1/\tan\delta\sin\delta)))$ parameter should be high. However, the parameter gives unrealistic results for δ less than 52°. Later, in case δ is less than 52°, Shenoy [18] suggested to use $(\sin\delta)^9$ instead of $(1 - (1/\tan\delta\sin\delta))$ as both are approximately similar terms.

Some researchers suggested that zero shear viscosity (ZSV) provides good information on rutting susceptibility of binders. The ZSV indicates asphalt binder's viscosity corresponds to zero shear rate, i.e., approximately at very low shear rate [11, 13, 19]. Good correlation has been observed between the ZSV parameter and rutting of mixture containing different binders including polymer modified binders [4, 13, 19–21]. Measurement of ZSV test takes significant time to capture steady state of a binder. Some modified binders may never reach a steady state, thus making ZSV parameter as an unreliable approach [11, 12].

None of the above parameters, $G^*/\sin\delta$, $G^*/(1 - (1/\tan\delta\sin\delta))$, and ZSV are able to simulate behavior of binders under loading and unloading conditions, particularly for modified binder. Thus, recently a new test called multiple stress creep recovery (MSCR) is being developed to measure rutting susceptibility of modified binders. This test captures recovery and permanent deformation behavior of binders. Researchers have reported better correlation of non-recoverable creep compliance (J_{nr}) with rutting performance of asphalt mixes in laboratory as well as in the field [7, 8, 12]. The J_{nr} is considered to have a better correlation with rutting performance of asphalt mixes compared to $G^*/\sin\delta$ [6, 22]. The MSCR test can also help to grade a binder for different traffic loading categories namely, '*E*', '*V*', '*H*' and '*S*' based on J_{nr} value determined at 3.2 kPa as per AASHTO MP 19 [23]. The grade '*E*', '*V*', '*H*' and '*S*' indicate that a binder is suitable for extremely high traffic loading (i.e., Traffic level ESALs >30 million and speed <20 km/h), very high traffic loading (i.e., Traffic level ESALs >30 million or speed <20 km/h), high traffic loading (i.e., Traffic level ESALs = 10–30 million or speed 20–70 km/h), standard traffic loading (i.e., Traffic level ESALs <10 million and speed >70 km/h), respectively. Some of the drawbacks of MSCR are, few numbers of loading cycles, small loading and rest periods, which may not be appropriate for modified binders [24].

Researchers have reported applicability of each of the above four rheological parameters (Superpave, Shenoy's, ZSV, and J_{nr}) for evaluating rutting resistance of asphalt binders. It is important to know, whether all of the parameters rank rutting potential of polymer modified binder in a same order or not. Further, comparison of these rutting parameters for warm mix asphalt (WMA) binders have not been studied so far. The WMA offers construction of flexible pavements at reduced mixing and compaction temperatures, thus fuel saving and environmental benefits [25]. Different types of WMA additives such as organic, chemical and water based [26] are used to modify base binders. Though WMA mixes are beneficial for various reasons, many researchers have reported that these mixes may have poor rutting resistance due to lesser aging of asphalt binder at reduced production temperature. Inclusion of different types of WMA additives showed mixed trend on rutting potential of asphalt binders [26–29]. Thus, this paper evaluates rutting resistance of SBS co-polymer modified binder (PMB40) containing various WMA additives considering different rheological parameters (i.e., $G^*/\sin\delta$, $G^*/(1-(1/\tan\delta\sin\delta))$, J_{nr} and ZSV). Three different WMA additives—Rediset®, Advera® and Sasobit® represent chemical, water based and organic additive category, respectively, were selected in the present study. Further, a correlation was developed among different rutting parameters. It is expected that the outcome of this study would help to understand applicability of different rutting parameters for WMA modified binders. The Superpave parameter or $G^*/\sin\delta$, and the Shenoy's parameter or $G^*/(1-(1/\tan\delta\sin\delta))$ are used interchangeably in this paper.

Objectives

(a) Evaluate effects of three different WMA additives on rutting resistance of PMB40 binder.
(b) Compare rutting resistance of PMB40 containing WMA additives using four different rutting parameters.
(c) Develop correlation between Superpave rutting parameter—$G^*/\sin\delta$ and three other parameters: $G^*/(1-(1/\tan\delta\sin\delta))$, J_{nr} and ZSV for PMB40 containing WMA additives.

Details on rutting parameters

Superpave rutting parameter ($G^*/\sin\delta$)

The Superpave rutting parameter ($G^*/\sin\delta$) is derived from concept of dissipated energy [5]. The dissipated energy of binder per cycle of loading can be estimated using Eq. (1)

$$\Delta U = \int \sigma d\varepsilon \tag{1}$$

where, $\Delta U =$ Energy loss per cycle/dissipated energy, $\sigma =$ shear stress, $\varepsilon =$ shear strain. After integrating Eq. (1) for sine wave loading from 0 to 2π,

$$\Delta U = \pi \times \varepsilon_{\max} \times \sigma_{\max} \times \sin\delta \tag{2}$$

where, $\sigma_{\max} =$ maximum shear stress, $\varepsilon_{\max} =$ maximum shear strain,since, the complex modulus (G^*) can be shown by Eq. (3)

$$G^* = \frac{\sigma_{\max}}{\varepsilon_{\max}}. \tag{3}$$

The dissipated energy under constant stress condition can be represented using Eq. (4) after substituting Eq. (3) in Eq. (2).

$$\Delta U = \frac{\pi \times \sigma_{\max}^2}{G^*/\sin\delta} \tag{4}$$

It can be seen that ΔU can be minimized by maximizing $G^*/\sin\delta$. A binder with a higher $G^*/\sin\delta$ value will have lesser ΔU and will show high rut resistance, and vice versa.

Shenoy's rutting parameter ($G^*/(1-(1/\tan\delta\sin\delta))$)

The total deformation of a binder consists of elastic and viscous deformation. The total strain percent ($\%\gamma_{\max}$) of a binder subjected to stress (σ_0, kPa) for time (t, s) can be estimated using Eq. (5) [14]

$$\%\gamma_{\max} = \frac{100\sigma_0}{G^*} \tag{5}$$

The elastic deformation is recoverable. So, the percent recoverable strain ((γ_{rec}) can be determined using Eq. (6) [14]

$$\%\gamma_{rec} = 100\sigma_0\left(\frac{G'}{G''^2}\right) \tag{6}$$

where, $G' =$ storage modulus $= G^*\cos\delta$, $G'' =$ loss modulus $= G^*\sin\delta$ and $G^* =$ complex modulusThe viscous deformation is irrecoverable. So, the percent unrecoverable strain (γ_{unr}) can be calculated using Eq. (7)

$$\%\gamma_{unr} = \%\gamma_{\max} - \%\gamma_{rec} \tag{7}$$

using Eqs. (5) and (7)

$$\frac{\%\gamma_{unr}}{\%\gamma_{\max}} = 1 - \frac{G^*G'}{G''^2} \tag{8}$$

Substituting value of G' and G'' in Eq. (8), γ_{unr} can be calculated using Eq. (9).

$$\%\gamma_{unr} = \frac{100\sigma_0}{G^*}\left(1 - \frac{1}{\tan\delta\sin\delta}\right) \tag{9}$$

Thus, to minimize unrecoverable strain (permanent strain), a parameter ($G^*/(1-(1/\tan\delta\sin\delta))$) should be maximized. Shenoy [14] suggested $G^*/(1-(1/\tan\delta\sin\delta))$ as a rutting parameter [14].

Zero shear viscosity (ZSV)

The ZSV of a binder can be estimated using Cross/Williamson's model shown in Eq. (10) [9, 13]. Higher ZSV value indicates asphalt binder with better rut resistant property and vice versa.

$$\eta^* = \frac{\eta_0 - \eta_\infty}{\left[1 + (\mathrm{kw})^2\right]^{m/2}} + \eta_\infty \quad (10)$$

where, η^* is complex viscosity, η_0 is first Newtonian region viscosity (absolute viscosity), η_∞ is infinite shear viscosity, w is frequency (rad/s), K is material parameter with dimension of time and m is dimensionless material parameter.

Non-recoverable creep compliance (J_{nr})

The J_{nr} of a binder can be determined using MSCR test in accordance with ASTM D7405. The MSCR test consists of 1 s loading time followed by 9 s unloading time at stress levels of 100 and 3200 Pa. A typical creep and recovery curve in MSCR test is shown in Fig. 1. At each stress level, ten cycles are applied with no time lag and corresponding strain values are recorded and the J_{nr} is determined at 3200 Pa using Eq. (12).

For each of the ten cycles at a creep stress (σ, Pa), the non-recoverable creep compliance, J_{nr} (kPa^{-1}) is given by Eq. (11)

$$J_{nr}(\sigma, N) = \frac{e_{10}}{\sigma}, \quad (11)$$

where, for N = number of cycles = 1–10. e_{10} = non recoverable strainat the end of 10th second/recovery period. Average non-recoverable creep compliance at σ (Pa) is given by Eq. (12),

$$J_{nr}(\sigma) = \frac{\mathrm{SUM}\ (J_{nr}(\sigma, N))}{10}. \quad (12)$$

Materials

Asphalt binders

A polymer modified binder (PMB40) with 3.5 % of SBS was used as control binder in this study. Basic tests were performed on the binder in accordance with IS 15462, and the results are shown in Table 1. The PMB 40 binder was found to be acceptable as per IS standard. The Superpave high temperature performance grade (PG) of this binder was found to be 76 °C (PG 76-XX). Since the primary purpose of this study was to evaluate rutting performance of binders at high PG grade, low temperature PG grade was not measured in this study.

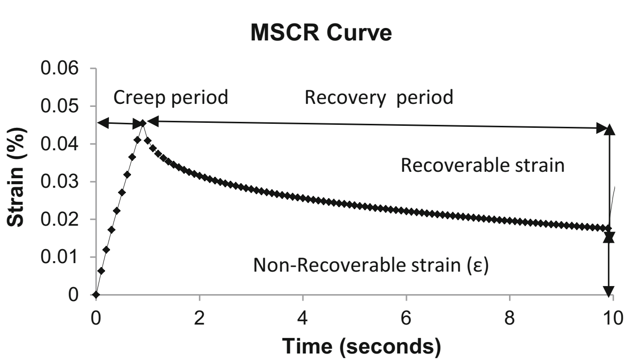

Fig. 1 A typical creep and recovery curve in MSCR test

WMA additives

Three different WMA additives: surfactant based-Rediset®, water zeolite based-Advera® and wax based-Sasobit® were selected in the present study. Figure 2 shows photographs of Sasobit®(pellets/solid form), Advera®(powder form), and Rediset® (liquid form).

Sasobit®

It is obtained using Fischer–Tropsch synthesis process from coal gasification. It is a long chain hydrocarbon having melting point in the range of 85–116 °C. Sasobit® forms homogeneous solution with base binder and facilitates reduction in viscosity and mixing and compaction temperature about 10–30 °C [9, 30]. Crystallization of Sasobit® forms lattice structure in the base binder which improves stability [9, 30].

Advera®

It is a zeolite, which contains moisture. The moisture is released into a mix and causes a micro-foaming effect in asphalt binder thus improving its workability.

Rediset®

It is a chemical based additive, which improves adhesive property of a binder. It reduces the production temperature of asphalt by 15 °C and can reduce the fuel consumption by at least 20 % and causes lower CO_2 emissions [31].

Table 1 Basic properties of PMB 40

Tests	Observed value	Limit as per IS 15462
Penetration (1/10) mm	49	30–50
Softening point in °C	61.8	Min. 60
Ductility in cm	>100	–
Viscosity at 150 °C, poise	7.1	3–9
High temperature PG	76 °C	–

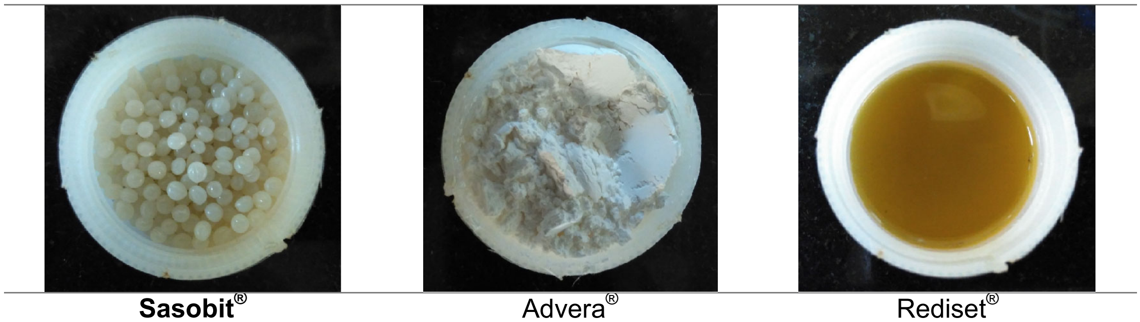

Fig. 2 Photographs of Sasobit®, Advera®, and Rediset®

Preparation of WMA modified binders

The PMB40 was mixed with three different dosages of selected WMA additives. For example, Sasobit® was selected as 1, 2, and 3 %, Advera® was selected as 4, 6, and 8 %, and Rediset® was chosen as 1, 2, and 3 % by weight of binder. As per manufacturer's recommendation, 2, 6 and 2 % are the optimum dosage of Sasobit®, Advera® and Rediset®, respectively [9, 32]. Thus, selection of one lower and one higher dosage from optimum amount are critical to understand the change in optimum dosage for modified binder, if any. A total of 10 binders (binder with 3 WMA additives × 3 percentages + one control PMB40) were prepared in the laboratory. The WMA additives were mixed to PMB40 binder using a high shear mixer (at 140 °C using 500 rpm) for half an hour to ensure homogeneous and uniform mixing. The WMA modified binders were short term aged using thin film oven at 143 °C for 5 h [27], while PMB40 was aged at 163 °C for 5 h.

Experimental methodology

The flow chart of experimental methodology is shown in Fig. 3. The short term aged PMB40 with different percentage of Sasobit® (1, 2, and 3 %), Advera® (4, 6, and 8 %) and Rediset® (1, 2, and 3 %) were tested using Dynamic Shear Rheometer (using 25 mm diameter plate and 1 mm gap) to estimate four rheological parameters: $G^*/\mathrm{Sin}\delta$, $G^*/(1-(1/\tan\delta\sin\delta))$, J_{nr} and ZSV. The average values of three replicates sample are reported in this paper. The rheological parameters were determined at 76 °C corresponds to high PG grade of the base binder (Table 1). The G^* and δ of WMA modified binders were measured in accordance with ASTM D 6373. The measured G^* and δ were used to determine ($G^*/(1-(1/\tan\delta\sin\delta))$). The frequency sweep test was performed in range of 0.1–100 rad/s. The MSCR test was conducted in accordance with ASTM D7405 at stress level of 100 and 3200 Pa.

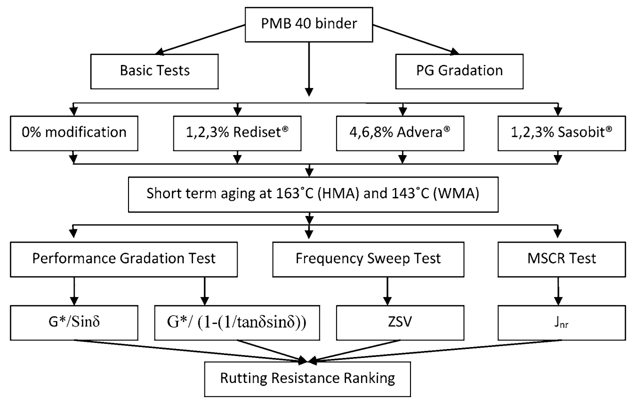

Fig. 3 Experimental Methodology adopted in the present study

Results and discussion

Rutting resistance using Superpave parameter

The Fig. 4 shows Superpave rutting parameter—$G^*/\sin\delta$ values for PMB40 with and without WMA additives. The results show that addition of Sasobit® increases $G^*/\sin\delta$, indicating higher rut resistance of binder with addition of Sasobit®. For example, $G^*/\sin\delta$ value for PMB40 binder with 1, 2, and 3 % Sasobit® was found to be 2.90, 4.41, and 5.92 kPa, respectively, compared to 2.21 kPa for control PMB40. Behl et al. [33] reported that presence of wax in Sasobit® creates crystalline structure, resulting in enhanced stiffness of a binder, similar trend can be seen in the present study. The percentage rate of change in $G^*/\sin\delta$ value increases up to 2 % Sasobit® (i.e., 52 % increase compared to 1 % Sasobit®) and then decrease for 3 % Sasobit® (i.e., 34 % increase compared to 2 % Sasobit®). Since, the maximum increase in $G^*/\sin\delta$ can be seen for 2 % Sasobit®, it may be considered as optimum dosage based on the Superpave rutting parameter.

$G^*/\sin\delta$ with the addition of 4, 6 and 8 % Advera® was found to be approximately 1.85, 2.27, and 2.12 kPa, respectively, compared to 2.21 kPa for control PMB40

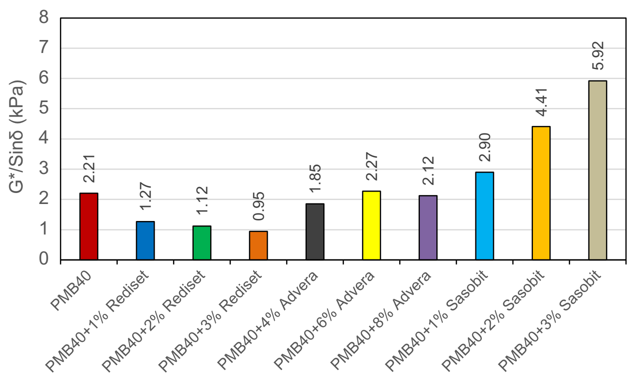

Fig. 4 Superpave rutting parameter—$G^*/\sin\delta$ of WMA modified binders

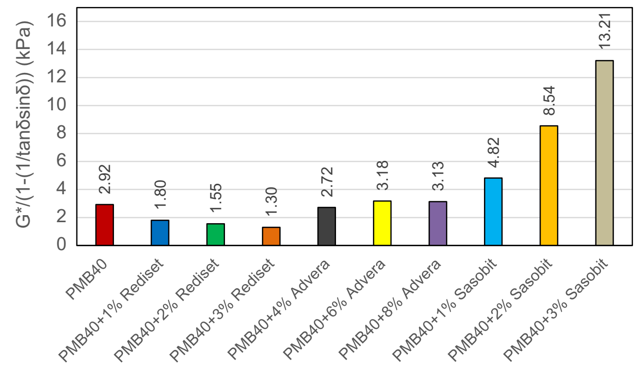

Fig. 5 Shenoy's rutting parameter—$G^*/(1-(1/\tan\delta\sin\delta)$ of WMA modified binders

binder. It can be seen that $G^*/\sin\delta$ decreases approximately by 16 and 4 % with the addition of 4 and 8 % Advera®, respectively. Whereas addition of 6 % Advera® showed increase in $G^*/\sin\delta$ by 0.02 %. Advera® did not result into significant improvement in $G^*/\sin\delta$ value of control PMB40. Since 6 % Advera® resulted in relatively higher $G^*/\sin\delta$, it may be considered as an optimum dosage for PMB40.

$G^*/\sin\delta$ with addition of 1, 2, and 3 % Rediset® was found to be 1.27, 1.12, and 0.95 kPa, respectively, compared to 2.21 kPa for control PMB40 binder. Thus, it can be concluded that inclusion of Rediset® resulted in decrease in $G^*/\sin\delta$ of PMB40 binder. Out of three WMA additives, Sasobit® seems to be more effective in enhancing rut resistant followed by Advera® and Rediset®. Based on this study, the optimum dosage of Rediset® could not be ascertained.

Rutting resistance using Shenoy's parameter

The Fig. 5 shows plot of the Shenoy's rutting parameter, $G^*/(1-(1/\tan\delta\sin\delta)$ for PMB40 with and without WMA additives. The Shenoy's rutting parameter is based on G^* and δ values, which were also used for estimating the Superpave rutting parameter. Thus, trend of both the Superpave and the Shenoy's rutting parameters is similar. The addition of Sasobit® showed significant increase in the Shenoy's rutting parameter. The effects of Advera® is not significant, while addition of Rediset® showed reduction in the Shenoy's rutting parameter. A similar trend was also observed for the Superpave rutting parameter: $G^*/\sin\delta$ (Fig. 4). It can be noted that the Shenoy's rutting parameter is higher compared to the Superpave rutting parameter. Thus, it can be concluded that the Superpave rutting parameter is more conservative as compared to the Shenoy's rutting parameter.

Rutting resistance using ZSV

The Fig. 6 indicates ZSV value for PMB40 binder with and without WMA additives. The addition of WMA additives (Sasobit®, Advera® and Rediset®) increases ZSV value of PMB40 binder. It should be noted that the ZSV parameter estimates rut resistant of Rediset® modified binder higher than control PMB40 binder, while $G^*/\sin\delta$ and $G^*/(1-(1/\tan\delta\sin\delta))$ parameters predicted a reverse trend for these two binders (i.e., PMB rutting resistant was higher than binder modified with Rediset®). Based on the ZSV parameter, it can be observed that all WMA additives improve rutting resistance of PMB40 binder. However, as discussed earlier, modified binders may never reach a steady state, thus use of the ZSV parameter may result into inaccurate rutting behavior [11, 12].

Rutting resistance using J_{nr}

The Fig. 7 shows J_{nr} value for control PMB40 and WMA modified binders. The J_{nr} value of control PMB40 was found to be 3.34 kPa^{-1}. J_{nr} value of PMB40 binder with addition of 1, 2, and 3 % Rediset® was found to be 4.61, 5.05, and 6.77 kPa^{-1}, respectively, indicating higher J_{nr} compared to control PMB40, hence reduced rut resistance. The J_{nr} value of PMB40 binder with addition of 4, 6, and 8 % Advera® was found to be 2.48, 2.33, and 1.84 kPa^{-1}, respectively, compared to 3.34 kPa^{-1} for control PMB40. Thus, it can concluded that addition of Advera® resulted reduction in J_{nr}, and hence better rut resistance. Similarly, J_{nr} value of PMB40 binder with addition of 1, 2, and 3 % Sasobit® was found to be 2.20, 2.06, and 1.56 kPa^{-1}, respectively, compared to 3.34 kPa^{-1} for control PMB40. Thus, it can be concluded that addition of Sasobit® reduces J_{nr}, and hence better rut resistance. Similar trend is also obtained based on the Superpave and the Shenoy rutting parameters, however, the ZSV parameter showed a

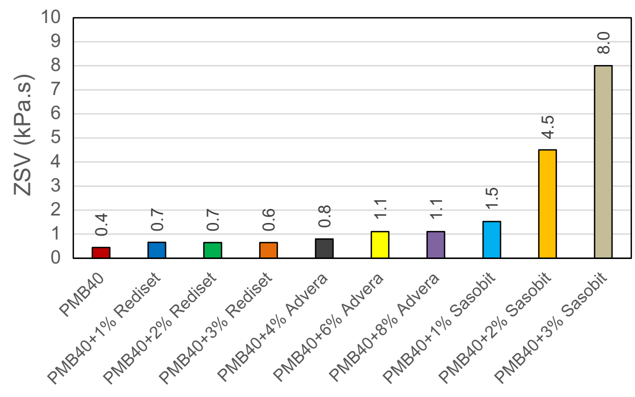

Fig. 6 ZSV of WMA modified binders

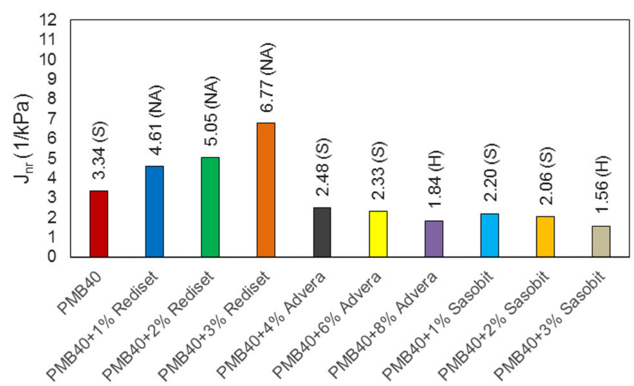

Fig. 7 J_{nr} of WMA modified binders

different trend. If optimum amount of WMA additives is to be decided based on J_{nr}, it would be 8 and 2 % for Advera® and Sasobit®, respectively. Since addition of Rediset® decreases J_{nr} value, which is not desirable, and hence the optimum amount was not estimated for this additive.

Figure 7 shows ranking of PMB40 binder with and without WMA additives for different traffic loading conditions. The ranking of the binder is shown in bracket. The control PMB40 was graded suitable for S category. The PMB40 binder with addition of Rediset® exhibited J_{nr} value above 4 kPa^{-1}, which is outside the range provided in AASHTO MP 19, thus the binder was not graded for any category, and marked as NA.

Similarly, PMB40 with 4, 6, and 8 % Advera® is graded suitable for S, S, and H category, respectively. It can be seen that addition of Advera® did not change the category up to 6 %. Based on other three parameter ($G^*/\sin\delta$, $G^*/(1-(1/\tan\delta\sin\delta)$ and ZSV), Advera® modification did not show significant change in rutting resistance, whereas J_{nr} parameter identifies one grade improvement for 8 % Advera®.

Similarly, PMB40 with 1, 2, and 3 % Sasobit® is graded for S, S, and H category, respectively. It can be seen that addition of Sasobit® did not change the binder category up to 2 %. Based on other three parameter ($G^*/\sin\delta$, $G^*/(1-(1/\tan\delta\sin\delta)$ and ZSV), 2 % Sasobit® showed significant increase in rut resistance and may be considered applicable for higher traffic conditions, J_{nr} parameter identifies similar grade (S) for 2 % Sasobit®. Such quantification and asphalt binders applicability can be better understood by J_{nr} parameter than rest of the other three parameters discussed in this paper.

Comparison of different rutting parameters

Table 2 shows rut resistance ranking of PMB40 binders with and without WMA additives based on four parameters discussed above. The rank was numbered from 1–10, where rank 1 represents the highest rut resistant, and rank 10 shows the lowest rut resistant binder. It can be observed that all four parameters: $G^*/\sin\delta$, $G^*/(1-(1/\tan\delta\sin\delta))$, ZSV and J_{nr} ranked PMB40 + 3 % Sasobit® as 1, thus highest rut resistant. Likewise, three parameters: $G^*/\sin\delta$, $G^*/(1-(1/\tan\delta\sin\delta))$, and J_{nr} ranked PMB40 + 3 % Rediset® as ten, thus the lowest rut resistant. The control PMB40 binder is ranked 5, 6, 10, and 7 based on $G^*/\sin\delta$, $G^*/(1$

Table 2 Rutting resistant of binders based on different parameters

Asphalt binders	Rutting parameters			
	$G^*/\sin\delta$ (kPa)	$G^*/(1-(1/\tan\delta\sin\delta))$ (kPa)	ZSV (kPa s)	J_{nr} (kPa^{-1})
PMB 40	5	6	10	7
PMB 40 + 1 % Sasobit®	3	3	3	4
PMB 40 + 2 % Sasobit®	2	2	2	3
PMB 40 + 3 % Sasobit®	1	1	1	1
PMB 40 + 1 % Rediset®	8	8	7	8
PMB 40 + 2 % Rediset®	9	9	8	9
PMB 40 + 3 % Rediset®	10	10	9	10
PMB 40 + 4 % Advera®	7	7	6	6
PMB 40 + 6 % Advera®	4	4	4	5
PMB 40 + 8 % Advera®	6	5	5	2

−(1/tan*δ*sin*δ*)), ZSV and J_{nr}, respectively, indicating that the Superpave rutting parameter over-estimated rut resistance and ZSV parameter underestimated rut resistance of PMB40 binder. Both *G**/sin*δ* and *G**/(1−(1/tan*δ*sin*δ*)) ranked all the binders same, except for PMB40 and PMB40 + 8 % Advera®. It can be seen PMB40 with Rediset® ranked almost same by *G**/sin*δ*, *G**/(1−(1/tan*δ*sin*δ*)), and J_{nr} parameters, however, ranking for Sasobit® and Advera® is different. The results show that rutting susceptibility ranking of binder depends on the rheological parameters and type of additives used. Thus, it cannot be said that a binder is going to be ranked same based on the Superpave and other rutting parameters. The J_{nr} parameter may be considered as a reliable rut parameter because of its realistic test conditions and potential to capture behavior of binders under loading and unloading conditions. The Superpave parameter provides similar results as the Shenoy parameter, further, the Superpave parameter is more conservative, and thus it may still be considered important in absence of J_{nr} parameter. The ZSV needs further validation to comment on its applicability.

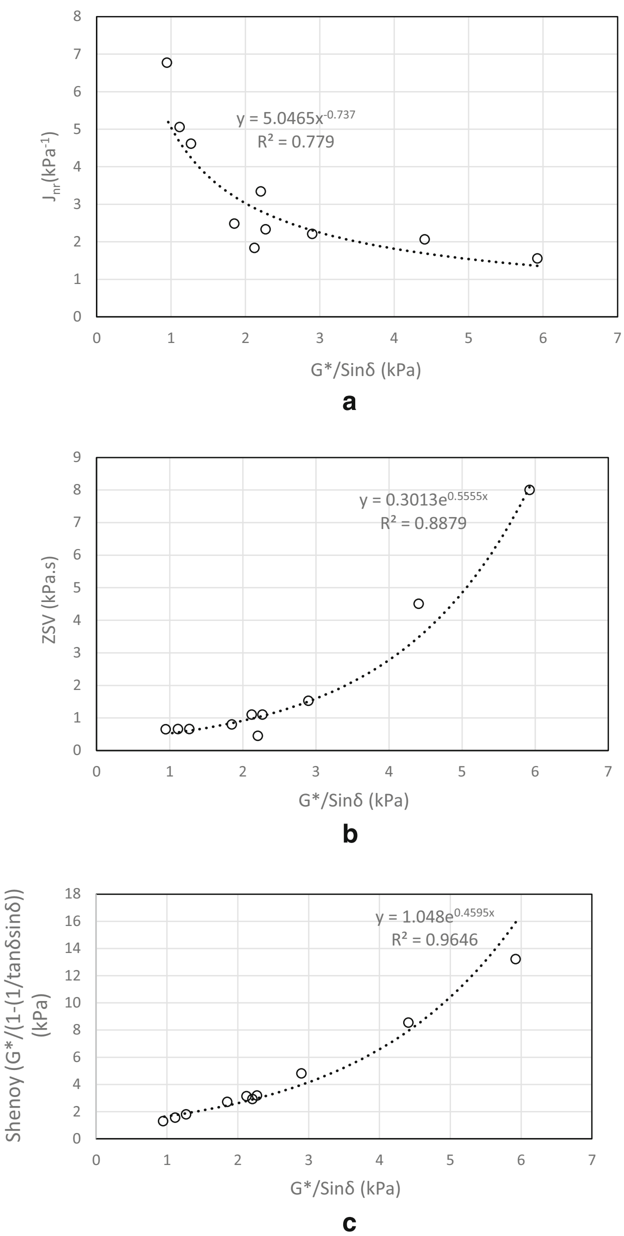

Fig. 8 Relationship between **a** *G**/sin*δ* and J_{nr}, **b** *G**/sin*δ* and ZSV, and **c** *G**/sin*δ* and Shenoy parameter

Based on J_{nr}, the order of rut resistance of binders can be seen as PMB40 + 3 % Sasobit® (rank 1) > PMB40 + 8 % Advera® (rank 2) > PMB40 + 2 % Sasobit® (rank 3) > PMB40 + 1 % Sasobit® (rank 4) > PMB40 + 6 % Advera® (rank 5) > PMB40 + 4 % Advera® (rank 6) > PMB40 (rank 7) > PMB40 + 1 % Rediset® (rank 8) > PMB40 + 2 % Rediset® (rank 9) > PMB40 + 3 % Rediset® (rank 10). It shows that addition of Sasobit® and Advera® resulted in high rut resistant binder compared to control PMB40. Overall binder with Sasobit® showed better rut resistant followed by Advera® and Rediset®.

Relationship between different rutting parameters

Figure 8a–c show correlation between *G**/sinδ and J_{nr}, G*/sin*δ* and ZSV, and *G**/sin*δ* and *G**/(1−(1/tan*δ*sin*δ*)), respectively. The best fit trend line was selected for the correlation. It can be seen that increase in *G**/sin*δ* resulted in decrease in J_{nr}. As expected, a higher *G**/sin*δ* value shows a stiffer nature of a binder, and hence better rut resistant. Both ZSV and *G**/(1−(1/tan*δ*sin*δ*)) parameters increase with an increase in *G**/sin*δ*. The critical value of *G**/(1−(1/tanδsinδ)), ZSV, and J_{nr} for limiting *G**/sin*δ* value for short term aged binder (i.e., *G**/sin*δ* = 2.2 kPa) was found to be 2.87 kPa, 1.03 kPa s, and 2.82 kPa^{-1}, respectively. Particularly such correlation may be helpful to estimate J_{nr} value of a binder based on other parameters.

Conclusions

The study evaluates rutting resistance of PMB40 binder containing WMA additives using four different rheological parameters (i.e., *G**/sin*δ*, *G**/(1−(1/tan*δ*sin*δ*)), ZSV, and J_{nr}. The following conclusions can be drawn based on the results and discussion presented above.

- The Superpave and the Shenoy rut parameters showed a similar trend in rutting resistance of binder. The Superpave rutting parameter was more conservative compared to the Shenoy's rutting parameter.
- Three parameters: (Superpave, Shenoy and J_{nr}) showed that addition of Sasobit® and Advera® may help to

improve rut resistance of PMB40 binder while Rediset® may decrease rut performance the binder.

- The ZSV showed that all three additives improve rutting resistance of PMB40 binder, which is contrary to the results obtained from the Superpave, Shenoy and J_{nr} parameters. The ZSV parameter seems to provide unrealistic results.
- The optimum dosage of Sasobit® was found to be 2 % by weight of binder, based on all three parameters: Superpave, Shenoy, and J_{nr}. The optimum dosage for Advera® was found to be 6 % based on the Superpave and the Shenoy parameters, while it was 8 % based on J_{nr} parameter. Since Rediset® resulted in a decrease in rutting behavior, optimum dosage could not for this additive.
- Based on the rheological parameters, PMB40 + 3 % Sasobit® and PMB40 + 3 % Rediset® found to have the highest and the lowest rut resistance, respectively.
- A good correlation was found between the Superpave rutting parameters and other three parameters ($G^*/(1-(1/\tan\delta\sin\delta))$, ZSV, and J_{nr}), which can help estimating alternative parameter in the absence of others.

The outcome of this study showed that J_{nr} may be considered as a reliable rut parameter considering its realistic test condition. The ZSV needs further validation to comment on its applicability. Further, it is recommended that rutting resistant of binders be validated by conducting laboratory tests on asphalt mixes. In addition, performance of polymer and neat asphalt binder with and without WMA additives may be compared.

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