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Comparison of Rut Susceptibility Parameters in Modified Bitumen with PPA

M. Khodadadi*, F. Moghadas Nejad, A. Khodaii

Department of Civil & Environmental Engineering, Amirkabir University of Technology (Polytechnic), Tehran, Iran

ABSTRACT: Pavement as a multi-layer structure is subjected to various distress mechanisms such as permanent deformation (Rutting) in its service time. Rutting resistance evaluation is one of the important components of pavement management system which plays a substantial role in the effective strategic development of pavement rehabilitation and maintenance. Improving the rheological properties of bitumen using one of the various additives is one of the practical approaches to reduce the rutting potential in the asphalt mixture. In this study, basic bitumen with an 85/100 penetration grade (PG58-22) was modified by 0.5, 1.0 and 1.5% poly phosphoric acid by weight of bitumen. The rutting resistance improvement of modified bitumen was investigated according to Superpave protocol. For this purpose, temperature sweep and frequency sweep tests were performed on all bitumen at 46, 52 and 58 ºC. Also, rutting resistance improvement ratio was calculated based on the Superpave specification ($|G^*|/\sin\delta$), Shenoy specification ($|G^*|/[1-(1/\sin\delta\times\tan\delta)]$) and zero shear viscosity. This ratio was employed to rank these specifications. The results of this study represent an improvement in rutting resistance of modified bitumen. According to specification ranking results, it can be concluded that zero shear viscosity has more potential and credibility to predict rutting damage occurrence as compared to Superpave specification and Shenoy specification.

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1- Introduction

Rutting is one of the main and dominant distresses of asphalt mixture, which is defined as permanent deformation. This damage occurs along the wheel path of traffic, which causes roughness and reduces driving safety [1]. Rutting happens for two reasons. The first reason relates to poor subgrade or underlying which does not have enough compaction level (95%). The second reason depends on asphalt mixture characteristics [2]. In this study, considering the bitumen properties as a component of asphalt mixture, the second reason was investigated. Bitumen is a viscoelastic-thermoplastic material, which has a certain level of rigidity of elastic in any temperature [3]. Also, it has viscoelastic behavior, which contributes to resistance against permanent deformation. Therefore, it is a considerable component affecting rutting damage. Individual properties of bitumen are obtained from experimental tests such as penetration grade, softening point, ductility and viscosity [4-6]. It is common to use these properties in order to determine rutting susceptibility [7]. However, previous studies showed that experimental results do not have acceptable confidence level to identify practical index and cannot be used in industry. In other words, these properties do not have acceptable estimation to predict rutting damage [8]. The study results of Dresson et al. about experimental properties indicated that any of individual properties of unmodified and modified bitumen does not have a good correlation with the measured rutting in the asphalt mixture. In another study, Siblisky showed that softening point property has a slight relationship with rutting potential, just in modified bitumen with the polymer [9].

These limitations forced the researcher to seek for a new efficient alternative. Finally, the results of Strategic Highway Research Program (SHARP) research program obtained new properties for bitumen, named Superpave. As a consequent, $|G^*|/\sin\delta$ was the first estimation, that was presented to evaluate rutting potential [10-12]. Although this parameter had satisfactory performance for several years, researchers concern for more precise prediction of rutting susceptibility increased. According to the basic concept and differential theory, Shenoy presented a new refinement of the Superpave specification parameter. However, this parameter does not have a proper test mechanism, such as sufficient loading cycles and strain level [13]. Donger et al. and Moria et al. claimed that using dynamic real viscosity is useful to evaluate rutting potential, due to a significant relationship with the measurement of mixture rutting results [13-15].

There are plenty of solutions to reduce rutting potential in the asphalt mixture. One approach is using an additive. For instance, polymer is an additive, which has a successful performance in locations with a high stress such as an airport, race tracks and etc. [16-18]. In this study, in order to improve rheological properties of bitumen, poly phosphoric acid (PPA) was employed as the bitumen modifier. The rutting resistance improvement of modified and unmodified bitumen was calculated based on Superpave protocol. To this end, Superpave index, Shenoy and zero shear viscosity (ZSV) were computed and finally, comparison of rutting indicators in bitumen was performed.

Corresponding author, E-mail: m-khodadadi@aut.ac.ir

2- Background

2- 1- Superpave Specification Parameter

To identify Pavement performance, knowing bitumen rheological properties is required. Hence, Superpave suggested $|G^*|/\sin\delta$ as the first specification to determine bitumen rutting potential. The base of this specification is referred to the dissipated energy of asphalt mixture, which is shown in Equation 1. This equation indicates that bitumen rutting reduction is a subsequence of increasing the total energy of asphalt mixture (increasing in G^*) and its elasticity (reduction in δ).

$$W_C = \Pi.\tau_0^2 \;/[|G^*|/\sin\delta] \quad (1)$$

Where W_C is the dissipated energy; τ is maximum shear stress; G^* is shear complex modulus and δ is phase angle. The more $|G^*|/\sin\delta$, less W_C, that means rutting potential will decrease.

2- 2- Shenoy Specification Parameter

Shenoy presented a new corrector for the Superpave index, which is shown in Equation 2 [19]. Shenoy specification is based on the total strain in the material, reduction elastic (increasing in G^*) and delayed elastic (reduction in δ). The elasticity effect (δ) is more highlighted in this specification as compared to Superpave specification.

$$|G^*|/\left[1-\left(1/\sin\delta \times \tan\delta\right)\right] \quad (2)$$

It should be noted that this specification does not have a physical meaning for $\delta \leq 52^o$ because of the negative value obtained in this domain. Shenoy suggested a criterion in order to overcome this deficiency: 1) use Equation 1 for $\delta \leq 55^o$ and 2) use Equation 2 for $\delta \geq 55^o$ to determine rutting potential. It should be noted that to have more confidence level, the value of 55° was employed instead of 52° in this equations by Shenoy. Similar to Superpave specification, the higher values of Shenoy specification indicate more rutting resistance in the bitumen.

2- 3- Zero Shear Viscosity (ZSV)

ZSV is the measured viscosity when the shear rate is approaching zero, which means slow deformation appears in bitumen. This viscosity definition is independent of shear rate or frequency. Researchers such as Sybilski showed that ZSV has a direct relationship with the bitumen rutting resistance [8]. This specification can be calculated by several methods. In this study, frequency sweep test was conducted to determine ZSV. For this purpose, the curve which is plotted from the viscosity results is fitted by a cross model as below:

$$\frac{\eta - \eta_\infty}{\eta_0 - \eta_\infty} = \frac{1}{1+(K\dot{\gamma})^m} \quad (3)$$

Where η is the complex viscosity; η_∞ is the limiting viscosity in the second Newtonian region; η_0 is ZSV; $\dot{\gamma}$ is angular frequency (rad/s) and m and K are constant parameters. Since applied frequency in this test was in the range of 0.1 to 100 rad/s, η will be so much higher than η_∞. Thus Equation 3 can be simplified as Equation 4:

$$\eta = \frac{\eta_0}{1+(K\dot{\gamma})^m} \quad (4)$$

Finally, applying curve fitting tool to Equation 4, ZSV (η_0) will be obtained. The greater ZSV indicates more resistance against the rutting damage.

3- Methodology

3- 1- Materials

3- 1- 1- Bitumen

The study used basic bitumen with an 85/100 penetration grade (PG58-22), which was supplied by Pasargad Oil company in Tehran, Iran. Also, the classical test was performed to illustrate the basic and modified bitumen properties, results of these tests are presented in Table 1.

Table 1. Classical Properties of Basic & Modified Bitumen

Test	Standard	bitumen (85/100)	0.5% PPA	1.0% PPA	1.5% PPA
Penetration (100 g, 5 s, 25°C), 0.1 mm	ASTM D5-73 (ASTM 1973)	94	84	75	69
Ductility (25°C, 5 cm/min), cm	ASTM D113-79 (ASTM 2007)	125	>150	>150	>150
Softening point (°C)	ASTM D36-76 (ASTM 1976)	49	53	57	61
Flash point (°C)	ASTM D92-78 (ASTM 1978)	237	244	251	256
Viscosity (m Pa s) 115°C	ASTM D2171-07 (ASTM 1985)	0.632	0.722	0.793	0.856
135°C		0.285	0.330	0.481	0.733
150°C		0.186	0.201	0.318	0.562

3- 1- 2- Modifier

Poly Phosphoric Acid (H_3PO_4) is a liquid mineral polymer, which was provided by registry code of 8017-16-1 Produced by Merck company (Germany). This modifier is a material driven from ortho phosphoric acid and has a low acid treatment as compared to sulfuric acid [20]. Specifics of PPA used in this study are presented in Table 2.

Table 2. Properties of PPA Used in This Study

Specification	Result
Molecular formula	PPA
Color	Bright Color
Appearance @ 25 °C	Viscous liquid
Bulk density@ 25 °C (g/cm³)	2.00
Viscosity @ 25 °C in cP	840

3- 2- Bitumen modification procedure

For the bitumen modifying purpose, the small container which contained 1 kg of basic bitumen was heated at 160°C for 1 hour. 0.5% of PPA by weight of bitumen was added gradually to the container, while the bitumen was mixed by the low shear mixer at a shear rate of 450 rpm at a constant temperature. To have homogenous bitumen, this modification process has continued for 60 min and the bitumen temperature was controlled by using a thermoelectric heater. PPA usage percent was extended to 1% and 1.5% for preparation of other specimens. In order to use labeling system, samples containing 0, 0.5, 1 and 1.5% of PPA, were labeled as N, M5, M10, and M15, respectively. It should be noted that the dosage of 2% of PPA caused extremely stiff bitumen. High stiffness causes problems such as un-normal increasing in mixing and compaction temperature. Also, the potential of thermal cracking will increase. In other words, the bitumen workability would be decreased in this dosage of PPA. This phenomenon is related to change in bitumen chemical structure. According to previous studies, bitumen modification with PPA causes a change in the proportion of asphaltene and resin in the bitumen [21]. Therefore, the dosage of 2% was removed from selections.

3- 3- Aging process

In order to simulate short-term aging condition, the basic and modified bitumen were subjected to rolling thin film oven (RTFO), according to ASTM D2872-97.

3- 4- Test Methods

In order to determine the rut susceptibility parameters, which was mentioned earlier, it is needed to perform the temperature sweep test and frequency sweep test.

Temperature sweep test was done according to AASHTO 2012a at 46, 52, and 58 °C at the frequency of 1.59 Hz (10 rad/s). The shear rate of 1.0% was selected for all bitumen to assure that the bitumen behavior remains in the linear viscoelastic (LVE) range. The samples were prepared in 25 mm diameter and the thickness of 1 mm, using silicon mold method. An Anton Paar rheometer (Austria) was used for three samples of each bitumen in order to achieve reproducibility in results. Finally, the values of $|G^*|/\sin\delta$ and $|G^*|/[1-(1/\sin\delta\times\tan\delta)]$ were calculated from this test.

Frequency sweep test was applied to all bitumen at 46, 52, and 58 °C according to ASTM D7175-05, as well. For this purpose, the range of 0.1 to 100 rad/s was used for the samples prepared for the temperature sweep test. As a result, complex viscosity curves were plotted versus frequency at every temperature. Finally, the MATLAB CFTOOL (Curve Fitting Toolbox) was used and best regression was fitted to the Equation 4 [22]. Therefore, the value of $\eta 0$ or zero shear viscosity was obtained at each test temperature.

4- Results and Discussion

4- 1- Superpave Specification

Results of 3 replicate of temperature sweep test ($|G^*|/\sin\delta$) at 46 to 58 °C for all samples are presented in Figure 1.

According to Figure 1, PPA modifier causes an improvement in the Superpave specification at all test temperatures. Hence, it would be useful to enhance rutting resistance. Also, the improvement in the ratio of the Superpave specification of modified bitumen can be obtained at each test temperature. Rutting resistance improvement ratio is calculated by dividing the $|G^*|/\sin\delta$ of the modified bitumen by the $|G^*|/\sin\delta$ value of basic bitumen. These results are shown in Figure 2.

These results show that improvement in this ratio has a strictly increasing trend. Also, this improvement is observed significantly by increasing the test temperature. For example, the addition of 0.5, 1.0 and 1.5% of PPA causes an increase of 1.8, 2.9 and 5.7 times in rutting resistance, respectively at

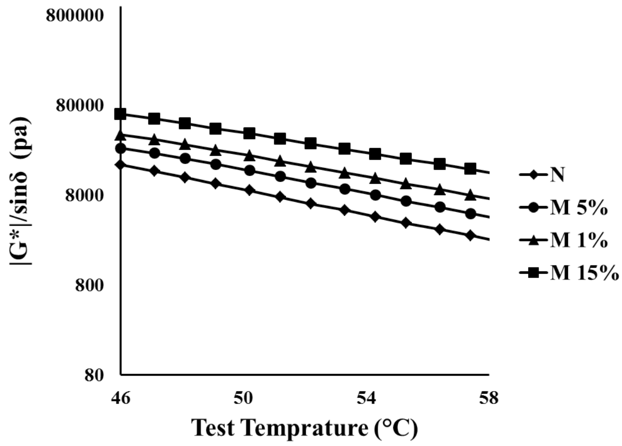

Fig. 1. $|G^*|/\sin\delta$ versus test temperature at the frequency of 10 rad/s.

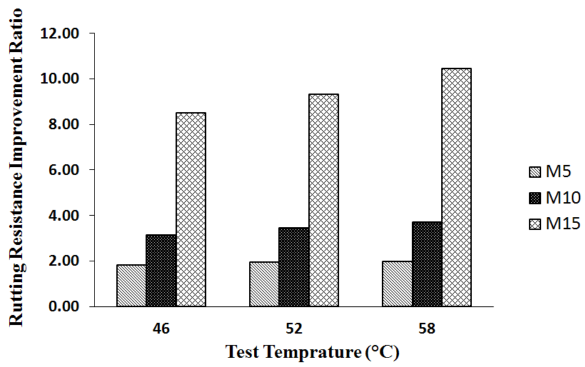

Fig. 2. Rutting resistance improvement based on $G^*/\sin\delta$.

58 °C.

4- 2- Shenoy Specification

Results of secondary specification ($|G^*|/[1-(1/\sin\delta\times\tan\delta)]$) are presented in Figure 3.

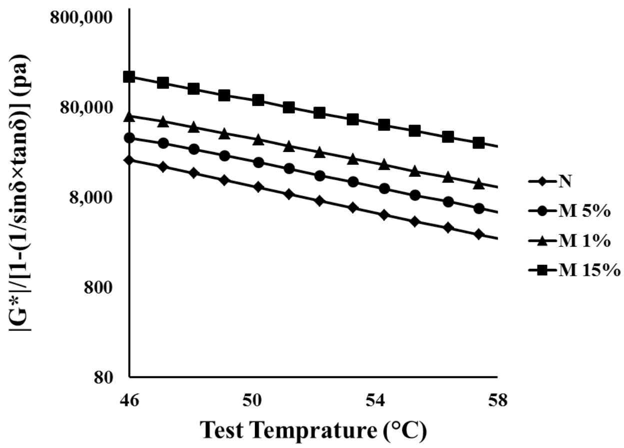

Fig. 3. $G^*/[1-(1/\tan\delta\times\sin\delta)]$ versus test temperature at the frequency of 10 rad/s.

As can be seen in Figure 3, PPA additive has a positive effect on the rutting resistance. Furthermore, Shenoy specification has a different value as compared to Superpave specification, but both specifications have the same trend on the basis of their results. Similar to Superpave specification, Figure 4 represents the improvement ratio based on Shenoy specification.

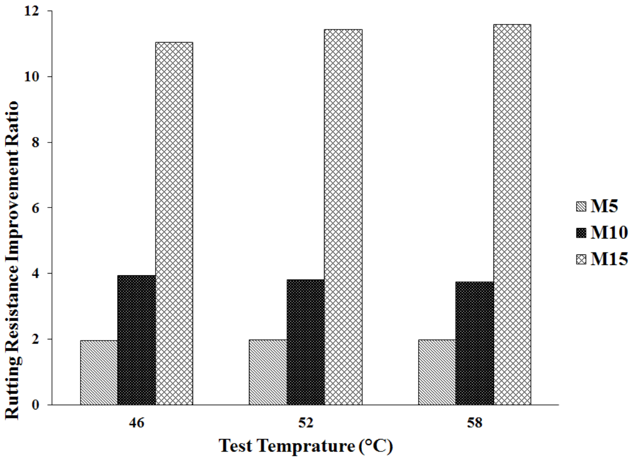

Fig. 4. Rutting resistance improvement based on $|G^*|/[1-(1/\tan\delta\times\sin\delta)]$.

According to Figure 4, rutting resistance has a significant improvement in all dosage of PPA additive, especially in the usage of 1.5%. These results showed that Superpave and Shenoy specification have different predictions of rutting susceptibility. For example, the addition of 1.5% of PPA improves bitumen rutting resistance 10.2 and 5.6 times on the basis of Shenoy and Superpave specification, respectively at 58 °C. Moreover, Shenoy specification does not have a Strict increasing trend of improvement in rutting resistance as compared to Superpave.

4- 3- ZSV Specification

The curve of complex viscosity versus angular frequency was obtained from frequency sweep test with 3 replicates. These curves presented at 46, 52, 58 °C in Figures 5 to 7, respectively. All of these curves have a hyperbolic shape. Hyperbolic shapes of these curves indicate that Equation 4 is suitable for the fitting curve.

As can be seen at each test temperature, the PPA modifier causes an increase in complex viscosity and therefore makes bitumen to be stiffer. Thus, the rutting potential in bitumen would decrease. Also, as expected, by increasing test temperature, the value of complex viscosity decreased. ZSV specification was obtained from fitting curve tool in

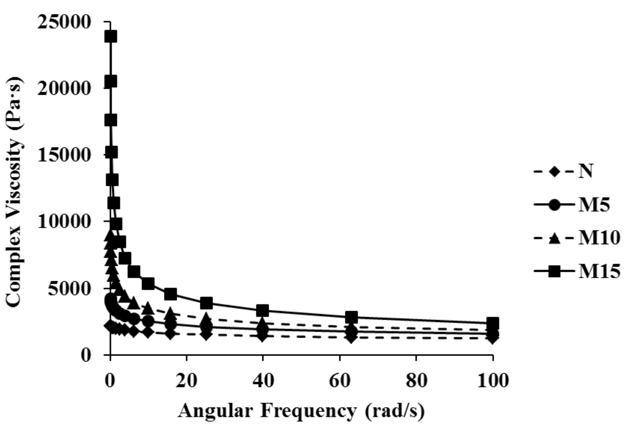

Fig. 5. Complex viscosity versus angular frequency at 46 °C.

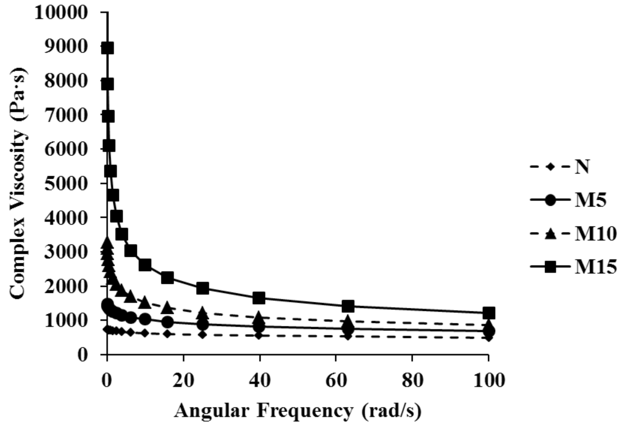

Fig. 6. Complex viscosity versus angular frequency at 52 °C.

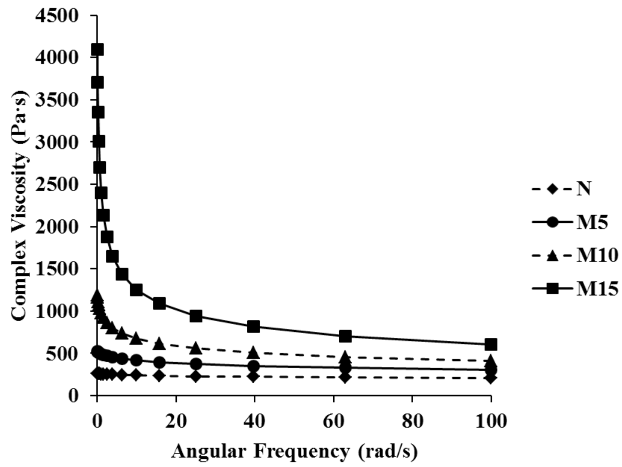

Fig. 7. Complex viscosity versus angular frequency at 58 °C.

MATLAB and improvement ratio on the basis of ZSV was calculated. These results are shown in Figure 8.

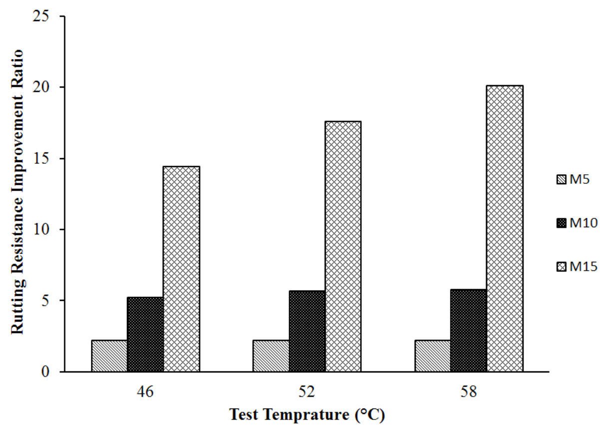

Fig. 8. Rutting resistance improvement based on ZSV.

The results of Figure 8 indicate that PPA has an improvement in the rutting resistance at all test temperatures, especially at 58 °C. Furthermore, this improvement ratio of ZSV is higher than Superpave and Shenoy specification at every test temperature. For example, rutting resistance improvement at 58 °C of Superpave, Shenoy and ZSV are 5.6, 10.3 and 20, respectively. Therefore, it can be concluded that ZSV specification can determine rutting susceptibility of bitumen more significantly and may show the difference of resistances clearly. However, the strict increasing trend of improvement in rutting resistance in all of the specifications indicates that using more dosage of PPA would be suitable, but it should be considered that using more than 1.5% dosage does not have sufficient workability. Thus, it is not reasonable to use more than 1.5% dosage. Low usage percentage of PPA is another reason to utilize this additive in bitumen because of its economic efficiency.

5- Conclusion

In this study, the effect of poly phosphoric acid on bitumen rutting susceptibility was investigated. For this purpose, three specifications of rutting susceptibility were applied to basic and modified bitumen. These specifications were: $|G^*|/\sin\delta$, $|G^*|/[1-(1/\sin\delta\times\tan\delta)]$ and ZSV, which were obtained from the temperature and frequency sweep test according to Superpave protocol. Improvement in rutting ratio was employed to compare these specifications and their responsibility in the rutting resistance. This ratio was obtained for the modified bitumen on the basis of each specification. The results of three specifications indicate that the bitumen modification with PPA has increased rutting resistance. However, PPA is an expensive polymer, but, since a low usage of PPA is needed to modify bitumen, utilizing this additive can be economical. Comparison of improvement in rutting ratio showed that there is a difference between the results of these specifications. According to this comparison, ZSV has a better predictability and representability to rutting resistance as compared to other specifications and shows the differences clearly. Also, Shenoy specification does not have a strict increasing trend of improvement in rutting resistance as compared to other specification. Therefore, it can be concluded that using Shenoy specification may lead to confusion in rutting potential prediction. To have a better judgment, it is suggested to compare these specifications with the asphalt mixture rutting performance. Hence, it can be investigated that which one of the rutting predictors in bitumen has more potential to extend the results to the asphalt mixture level.

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