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Comparison of various rutting parameters and modelling of creep and recovery behaviour of high modulus bituminous binders

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Abstract

This paper evaluates the rut resistance of various high modulus bituminous binders based on different rutting parameters including G*/sinδ, shenoys' rutting parameter, zero shear viscosity (ZSV), viscous component of creep stiffness (G_v) determined using burger's model and superpave plus rutting parameter i.e. non-recoverable creep compliance (J_{nr}). The main objective of the study is to develop high modulus bituminous binders and evaluate their performance in terms of rutting. Also, the creep and recovery curves obtained from the MSCR test were modelled to understand the viscoelastic creep behavior of the binders. From the results, it was found that ranking provided by G*/sinδ, shenoys' rutting parameter and ZSV approaches were identical whereas J_{nr} and G_v provided similar rankings. The rutting resistance improvement ratio analyzed for the binders showed the trend which is identical for G*/sinδ, shenoys' rutting parameter and ZSV. However, the ratio is identical for G_v and J_{nr}. Burger's model was unable to capture the nonlinear viscoelastic behavior of modified high modulus bituminous binders under creep and recovery loading. Weibull distribution function was used to simulate the creep and recovery behavior. It was found to be fit well with the experimental curves. The model parameters of the Weibull distribution function was able to explain the viscoelastic behavior of binders under creep and recovery loading. The composite modification of binder enhanced both the rutting resistance and percent recovery of high modulus bituminous binders.

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Keywords: High modulus bituminous binders; Rutting; Composite modified bituminous binders; Burger's model; Weibull distribution function

1. Introduction

High modulus asphalt (HiMA) mixtures have become one of the alternatives for sustainable pavements due to their reliable and consistent performance. Such mixes were developed initially by French engineers in early 1980's and gained popularity all around the world (Serfass et al. 1992). Since last decade, it was observed that several pavement research groups around the world were working on use of high modulus asphalt (HiMA) mixes for base course with

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a thin wearing course on it. Many countries such as South Africa, Australia, a few European countries, USA, China experienced the benefits of the HiMA technology (Nunn and smith, 1997; Komba et al. 2015). HiMA mixes displayed good performance in areas with slow moving traffic such as urban intersections, areas with restricted crust thicknesses, heavy trafficked areas, airfield pavements, sea ports etc., (Petho et al. 2014). An advantage of these HiMA mixes is the thickness reduction in the design and construction. The key element in the production of HiMA mixes is the usage of stiff bitumen of penetration 10/20 or 15/25 (Corte et al. 2001; Delorme et al. 2007). Stiffer binders for high modulus mixes can be produced by (i) adopting refining process to obtain hard grade bitumen from refineries without air blowing (ii) polymer modification, (iii) asphaltite modification, and (iv) air blowing the softer grade bitumen. The mixes with above binders and additives improve the performance and also reduce the thickness of bituminous pavement for given traffic (Nunn and Smith, 1997; Brosseaud et al. 2012; Hernández, 2015).

Bitumen plays a prominent role in the performance of the pavement throughout the design life. Research studies claimed that blowing process of bitumen leads to premature cracking of pavements (Corte et al. 2001). Thus, research has been directed towards development of hard bitumen through modification using additives (Serfass et al. 1992; Caroff et al. 1994; Komba et al. 2015). Commonly used modifiers include Gilsonite, Ethylene Vinyl Acetate (EVA), Styrene Butadiene Styrene (SBS), crumb rubber and hydrated lime etc. Modifier selection plays a crucial role to enhance the properties of binder. As mentioned earlier in the literature, modified bitumen performed better than the hard grade bitumen. The asphaltite or gilsonite was proved to produce HiMA mixes. However, these mixes become brittle at intermediate and lower temperatures. Hence the current study emphases on composite modified binders to improve rutting performance of HiMA mixes.

Permanent deformation is one of the major distress in flexible pavements and is observed as a continuous depression along the wheel path (Golalipour, 2011). The effect of rutting on the performance of pavement is significant at higher temperatures compared to service temperatures. Stiffer binder enhances the rutting resistance of bituminous mixes, especially mixes prepared with polymer modified binders (Geng et al 2013). Several researchers proposed parameters that are capable of explaining anti-rutting potential of bituminous binders including SHRP rutting parameter ($G^*/\sin\delta$), zero shear viscosity (ZSV), shenoys' rutting parameter ($G^*/(1-(1/\tan\delta^*\sin\delta))$), viscous component of creep stiffness (G_v) and non-recoverable creep compliance (J_{nr}) (Anderson et al. 1994; Anderson 2002;Bahia et al. 2001; D'Angelo 2009). This paper compares the improvement in the rut resistance through different parameters for the composite modified binders that can be used for HiMA binders.

Laboratory testing and evaluation of binders is limited and is not possible in all cases. Selection of binders for pavement construction requires well understanding on their behaviour. This requires well established laboratory testing as field testing and evaluation requires huge financial support. However, advanced testing facilities are not well established in India. This brings the utility of modelling binders and characterizing their viscoelastic properties. Hence, many researchers studied on the mechanical response of the bituminous binders through modelling (Delgadillo et al. 2010; Delgadillo et al. 2012; Celauro et al. 2012; Merusi 2012). There exists the mathematical models (Christensen-Anderson model; Christensen-Anderson-Marasteanu model, master curves etc.,), empirical models (relating the performance with the volumetrics and material properties) and analytical models (Maxwell model, kelvin-voigt model, generalised models, Burger's model, Dibenedetto-Neifar (DBN) model etc.,) (Shan et al. 2016). In contrast to these mathematical and empirical models, these analytical models could explain the viscoelastic behaviour of bituminous material physically using springs and dashpots (Shan et al. 2016). The response of these springs and dashpots arranged in different forms subjected under loading and relaxation period were better explained. The creep and recovery loading approach and modelling the behaviour of bitumen under the same was well accepted around the world (Liu and You 2009; Celauro et al. 2012; Merusi 2012; Saboo and Kumar 2015). Among these analytical models, Burger's model was used mostly due to its simplicity and the parameters has physical meaning (Liu and You 2009).

2. Research Motivation

The current study discusses about the HiMA binders which also includes polymer modified bitumen. HiMA binders produced using polymers comprises of higher polymer content which is uncommon. Their rheological behaviour has to be understood well as they behave differently from neat binders and are complex in nature to model using Burger's model. Modelling of these binders in non-linear viscoelastic domain may require more complicated set of Maxwell and kelvin-voigt models. Fancey (2001) used the weibull distribution function to represent the viscoelastic behaviour of polymeric materials. It was found to be applicable for bituminous binders as it explained the creep and recovery behaviour especially for modified binders (Liu et al.2013). Hence the main objective of the present study is to compare the rutting resistance of the composite modified binders and model their rheological behaviour. Both Burger's model and Weibull distribution function were used to model the viscoelastic behaviour of bituminous binder under and creep and recovery loading. In this paper, the terms bitumen, binders and asphalt binders were used mutually.

3. Background of Various rutting parameters

3.1 Superpave rutting parameter, G/sinδ*

The energy dissipated per cycle of loading causes rutting (Anderson et al 1994). Strain produced due to traffic loading is recovered partly by elastic component and partly dissipated by the viscous component. Using the dissipated energy concept, G*/sinδ was specified as a superpave rutting parameter and is shown in Equation 1.

$$\Delta U = \pi\tau_{max}^{2}\frac{1}{(G^{*}/sin\delta)} \tag{1}$$

Where, ΔU is energy dissipated per cycle, τ is the shear stress, G* is the complex shear modulus and δ is the phase angle.

The parameter, G*/sinδ is inversely proportional to ΔU. A higher G*/sinδ improves the rut resistance by reducing the energy dissipated from the material. Hence, the superpave research program considered G*/sinδ as a specification parameter to evaluate rut resistance.

3.2 Shenoy rutting parameter, G/(1-(1/tanδ*sinδ))*

Shenoy et al. (2001) proposed a parameter G*/(1-(1/tanδ*sinδ)) to refine the existing superpave rutting parameter, G*/sinδ. According to Shenoy, the non-recovered strain will be minimized if the term *G*/(1-(1/tanδ*sinδ))* was maximized. This parameter includes the damping coefficient, tanδ which was shown in equation 2.

$$\%\gamma_{unr} = \frac{100\sigma}{|G^{*}|}(1-\frac{1}{tan\delta.sin\delta}) \tag{2}$$

Where, γ_{unr} is the non-recovered strain percentage, σ is the applied creep stress, G* is the complex shear modulus and δ is the phase angle.

At high temperatures, tanδ captures the rutting resistance of bituminous binders better than G*/sinδ as sinδ becomes close to 1 at higher temperatures. This approach was found most suitable for modified binders too as it measures the non-recoverable properties of binder through oscillation test.

3.3. Zero Shear Viscosity, ZSV

The modification of bituminous binders introduce more elastic properties which could not be captured by G*/sinδ. It led to development of zero shear viscosity. Zero shear viscosity resembles the viscosity of bitumen at very lower frequencies and was found to have a better correlation with rutting of modified binders. Modified binders behave as pseudo plastic fluids i.e. with increase in shear rate, the viscosity of these binders' decreases. Initially, complex viscosity, η* was determined at various frequencies and the data was extrapolated to determine the viscosity at lower frequencies at which the binder will be in steady state. The simplified cross model (Equation 3) adopted by Biro et al. (2009) was used to estimate the ZSV.

$$\eta^{*} = \frac{\eta_{o}}{1+K\omega^{m}} \tag{3}$$

Where, η^* is the complex shear viscosity measured at frequency of 'ω'. η_o is the Zero shear viscosity. K and m are the coefficients.

3.4. Non-recoverable Creep compliance, J_{nr}

Creep and recovery test aids in better understanding the rheological behaviour of bituminous binders both in linear and non-linear domains. The delayed elasticity which has a prominent role in modified binders can be captured by creep and recovery tests. Multiple Stress Creep and Recovery (MSCR) test was formulated to determine the bituminous binder's resistance towards rutting (D'Angelo 2007; D'Angelo 2009). J_{nr} is used for binder selection and rank the binders based on rut resistance. The test is carried out at two stress levels, 0.1 kPa and 3.2 kPa with a creep loading of 1 s and rest period of 9 s. At each stress level, 10 creep and recovery cycles will be performed and the average will be considered as given in equation 4 and 5.

$$J_{nr} = \frac{SUM(J_{nr}(\sigma,N))}{10} \tag{4}$$

Where

$$J_{nr}(\sigma,N) = \frac{\varepsilon_N}{\sigma} \tag{5}$$

and J_{nr} is the Non-Recoverable Creep Compliance, σ is the applied stress, N =Number of cycles, 1-10, ε is the strain due to applied stress.

3.5 Burger's model and viscous component of creep stiffness, G_v

The creep and recovery response of the binders were modelled to further understand the rheological behaviour. Many models were used to explain the binder behaviour under flow such as generalised Maxwell model, generalised Kevin-voigt model, Burger's model, the six element solid model and the power law model. However, the model should be able to analyse the behaviour and its parameters should have a physical meaning (Liu and You 2009). Burger's model has four parameters to capture the mechanical response of the binder under the creep and recovery loading approach. The Burger's model is a combination of both Maxwell and kelvin-voigt model. The Burger's model consists of spring as well as dashpot both in parallel and series and has four elements (E_M, η_M, E_K, η_K). Each element represents a parameter in the model as shown in the Figure 1. E_M and E_K are the spring elements representing elastic behaviour and η_M and η_K are the dashpots representing the viscous behaviour induced in the Figure 1. Burger's model combination provides a viscoelastic strain response under a stress load. The strain response of the bituminous material depends upon the elastic and damping coefficients.

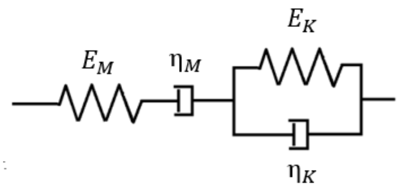

Figure 1 Components of Burger's Model

The strain during the creep loading and recovery periods are given in Equation 6 and 7 respectively.

$$\varepsilon(t) = \frac{\sigma}{E_M} + \frac{\sigma}{\eta_M}t + \frac{\sigma}{E_K}\left(1 - e^{\frac{-E_K t}{\eta_K}}\right) \tag{6}$$

$$\varepsilon(t) = \frac{\sigma}{\eta_M}t + \frac{\sigma}{E_K}\left(e^{\frac{E_K t}{\eta_K}} - 1\right).e^{\frac{E_K t}{\eta_K}} \tag{7}$$

Where, η_M, E_M , η_K and E_K are the model constants. η_M represents the viscous flow behaviour of the bitumen. σ is the applied stress and $\varepsilon(t)$ is the strain response of bitumen at time t.

To overcome the uncertainty on the rutting parameter, G*/sinδ, Bahia et al. (2001) introduced a parameter, viscous component of creep stiffness (G_v). This parameter is based on the creep and recovery test conducted by dynamic shear rheometer. The viscous component of creep stiffness is derived from the burger model and is calculated using equation 8.

$$G_v = \frac{\eta_M}{t} \tag{8}$$

Where, G_v = Viscous component of creep stiffness; η_M = Viscosity coefficient of Maxwell model and t = time at the end of creep period or start of rest period.

The resistance to deformation depends upon the elastic and viscous components of binder. The viscous component should be minimum for reducing dissipation energy due to loading. This dissipation energy should be minimum and is inversely proportional to the viscosity coefficient of Maxwell model. Therefore, the viscous component of creep stiffness should be maximum for better rut resistance.

3.6. Weibull distribution function

Fancey (2001) used Weibull distribution function to represent the rheological behaviour of viscoelastic materials. As bitumen is a viscoelastic material, this model was adopted to simulate the creep and recovery response in MSCR test. This model does not have any theoretical basis and was a stretched exponential function (Fancey 2001). However, model provides better understanding through various parameters which is given in the Equation 9 and 10 respectively. Equation 9 represents the total strain of the material under creep loading and Equation 10 represents the strain after the release of the load.

$$\varepsilon_1(t) = \varepsilon_i + \varepsilon_c(1 - e^{(-(\frac{t}{\eta_c})^{\beta_c})}) \tag{9}$$

$$\varepsilon_2(t) = \varepsilon_r\left(e^{(-(\frac{t}{\eta_r})^{\beta_r})}\right) + \varepsilon_f \tag{10}$$

Where, ε_i is the initial instantaneous creep strain, ε_c is the final creep strain, η_c is the characteristic life parameter, β_c is the shape parameter from the creep test; ε_r is the initial viscoelastic strain, ε_f is the strain from viscous flow, β_r is the shape parameter, η_r is the characteristic life parameter after the removal of creep load and t is the time.

4. Materials and Methods

As per the Indian Road Congress guidelines, IRC 37:2012, VG40 should be used for the construction of flexible pavements at high temperature regions or/and with the traffic level more than 30 msa. Therefore, VG40 was used for the study which was supplied by the haldia refinery. A hard pitch binder produced through propane de-asphaltene method was also used which was supplied by the same. Gilsonite, Styrene Butadiene Styrene (SBS) and Ethyl Vinyl Acetate (EVA) were used as additives in this study. Gilsonite is a natural asphaltite used to stiffen the bitumen whereas EVA and SBS are plastomer and thermoplastic elastomer respectively.

SBS is a di-block copolymer and has 33% styrene bound to butadiene. It forms a matrix of polystyrene spherical domains attached to polybutadiene and has a two-phase morphology. It behaves as a rigid structure at high temperatures due to the presence of polystyrene and acts as an elastic material at intermediate and low temperatures because of polybutadiene content. EVA is a plastomer which forms a rigid complex network. The material is formed by the copolymerization of ethylene and vinyl acetate and is characterized using Melt flow index and vinyl content. The EVA used in the present study has 28% of vinyl content. Higher the vinyl content in EVA, lower the crystalline nature of the material due to amorphic nature of the vinyl acetate content.

4.1 Sample Preparation

A laboratory fabricated temperature-speed controlled stirrer (Figure 2) was deployed for binder modification. Gilsonite was added at 4 % and 8% into the neat binder VG40 whereas EVA was doped at 1, 3, 5% percentages. But the addition of gilsonite may lead to the brittleness of binders. So, to escalate the elastic properties i.e. recovery properties of binders, 1 and 2% of SBS was added to 4% gilsonite. Gilsonite and EVA stiffen the bitumen and SBS improves the elastic properties of the bitumen. To produce HiMA bitumen with good recoverable properties, it was proposed to blend Gilsonite and SBS at certain proportions with VG40 the neat binder.

The above mentioned modifiers were added to the neat binder when the temperature of the neat binder was about 150- 160 °C. After the addition, binders were blended for 60 min at a speed of 2500 rpm maintaining the temperature at 180 °C whereas the temperature was selected appropriately based on previous research studies (Liu and Li 2008; Kok et al 2011; and Liang et al 2016). Nomenclature provided for all the bituminous binders was given in Table 1. The prepared binders were tested for basic conventional tests and the results are presented in the Table 2. It was observed with increase in dosages of modifiers, a decrease in penetration and increase in softening point.

Fig 2. Blending setup used in the study

Table 1. Nomenclature given to all set of binders

Binder ID	Nomenclature
VG40	Viscosity grade 40
PEN23	Special hard binder with penetration of 23
E1	VG40+EVA 1%
E3	VG40+EVA 3%
E5	VG40+EVA 5%
G2	VG40+Gilsonite 2%
G4	VG40+Gilsonite 4%
G8	VG40+Gilsonite 8%
G4S1	VG40+ Gilsonite 4% + SBS 1%
G4S2	VG40+ Gilsonite 4% + SBS 2%

Table 2. Physical properties of bituminous binders

Tests \ Binder	VG40	PEN23	G2	G4	G8	E1	E3	E5	G4S1	G4S2
Penetration, 0.1 mm	42	23	35	28	22	39	35	30	24	22
Softening point, °C	54	63	59	64	67	56	5 9	63	66	68
Viscosity, Pa.s @60 °C	389.5	1791.3	563.3	861.7	1220	487.6	481.1	461.5	1180	1110

5. Experimental Program

5.1 Oscillation test and MSCR test

Two neat and eight modified binders were tested to understand the rheological behaviour at high temperatures. Dynamic shear rheometer (Figure 3) was used to conduct the frequency-sweep test and MSCR test. These tests were conducted in accordance with ASTM D7175-05 (2005) and ASTM D7405-10a (2011) respectively. A spindle of diameter 25 mm with a gap of 1mm bet was used. Frequency sweep test was performed at temperatures varying from 52 °C to 88 °C and frequencies 10 to 0.1 Hz. The test was conducted within the linear viscoelastic range and in controlled strain mode with a strain of 5%. The parameters acquired from the oscillation test were the complex modulus (G*), phase angle (δ), and the complex viscosity (η^*).

Figure 3. Dynamic shear rheometer used in the study

MSCR test was performed at 60 °C at both linear and non-linear viscoelastic range i.e., different stress levels, 0.1 kPa and 3.2 kPa as per test protocol. In addition, to evaluate the rutting resistance of binders at various stress levels, test was also performed at 0.8, 1.6, 6.4, 12.8 and 25.6 kPa respectively. A temperature of 60 °C was selected as it could represent the high service pavement temperature in India. At each stress level, 100 cycles were performed as preconditioning cycles and thereafter 10 cycles were applied. The average strain of ten cycles creep and recovery data obtained at the stress level of 3.2 kPa from the MSCR test was used to predict the non-linear viscoelastic behaviour.

6. Results and Discussion

6.1 Evaluation rutting resistance of binders

To evaluate the rutting resistance of the composite modified bituminous binders, test results of the MSCR test were presented in the Table 3. J_{nr} and percent recovery at all the stress levels were presented. MSCR test involves the creep and recovery curve which could directly measure the permanent strain occurred in the binder through the J_{nr} parameter. Analysis was based upon the 3.2 kPa stress level as it is in the non-linear viscoelastic range. It can be seen that J_{nr} was decreasing due to the incorporation of additives. VG40 was found to have poor rutting resistance with a J_{nr} of 2.5 and as expected additives enhanced the anti-rutting potential of the base binder. It could be clearly observed that gilsonite improved the J_{nr} exceptionally than EVA polymer. However, the brittle nature of the binder increased with incremental dosages of gilsonite which could be noticed from the percent recovery. It could be noticed that a dosage of 8% of gilsonite and composite modified bitumen with 4% gilsonite and 2% SBS (G4S2) resulted a Jnr similar to PEN23. EVA polymer did not improve the rutting resistance which is contradictory with other studies. This might be due to type of polymer (28% vinyl content) which was used in the current study.

Since the anti-rutting potential of a binder is significantly dependent upon the response of the binder under creep and recovery after the removal of load. The percent recovery is also important to consider for evaluation. It was observed from the percent recovery data that VG40 showed poor recoverable properties. As discussed earlier G8 and G4S2 has J_{nr} similar to PEN23. However, G4S2 lowered the J_{nr} and increased the recovery properties of base binder thereby ensuring superior rut resistance. This is due to the dispersed SBS polymer in the base binder. It is well known that SBS disperses in the bitumen and behaves softer at lower temperatures and stiffer at higher temperatures. Thus, it imparts elasticity. Higher recoverable properties are attained for G4S2 bitumen followed by G4S1. EVA modified binders improved neither J_{nr} nor recoverable properties and hence it was recommended not to use EVA polymer with 28% vinyl content. However, further investigations are needed for more assurance. The J_{nr} difference represents sensitivity to stresses and it should not be greater than 0.75 or 75% to ensure the binder is resistant to stress variations. From the Table 3, it could be noticed that none of the modified binders has a J_{nr} difference higher than 75%. As per AASHTO MP19, VG40 could be graded as standard grade (S), which is suitable a traffic of less than 3 million standard axles. Modification changed the grades of binders from standard to extremely heavy grade (E). Addition of EVA was found to have improved the grade from S to heavy (H) whereas other additives are able to improve the binder grades from S to E grade.

The incremental stress creep and recovery test results are also presented in the Table 3 and Table 4. It was observed that J_{nr} increased with stress levels. It can be seen that the J_{nr} of base binder, VG40 is higher than modified binders' especially composite modified binders even at higher stress levels. The rate of increase in Jnr has decreased for composite modified binders at high stress levels. As expected, percent recovery of binders was found to be decreasing with increase in stress levels. Even at high stress levels, composite modified binders are able to recover satisfactorily.

Table 3. Non-recoverable Creep Compliance (J_{nr}) at various stress levels

Binder ID	**J_{nr} at Stress level, kPa**						**J_{nr} Difference**
	0.1	0.8	3.2	6.4	12.8	25.6	
VG40	2.33	2.43	2.50	2.65	2.79	3.10	7.3
PEN23	0.48	0.50	0.54	0.59	0.61	0.64	12.5
E1	2.03	2.15	2.19	2.37	2.66	2.83	8.3
E3	1.80	2.01	2.14	2.30	2.52	2.68	19.6
E5	1.7	1.92	2.12	2.14	2.48	2.53	24.9
G2	1.43	1.50	1.55	1.63	1.75	2.15	8.3
G4	0.97	0.98	1.06	1.16	1.25	1.29	9.5
G8	0.49	0.50	0.53	0.65	0.74	0.79	8.0
G4S1	0.54	0.58	0.62	0.65	0.68	0.72	14.1
G4S2	0.41	0.45	0.50	0.56	0.59	0.62	22.0

Table 4. Percent Recovery at various stress levels

Binder ID	Percent Recovery at Stress level, kPa					
	0.1	0.8	3.2	6.4	12.8	25.6
VG40	0.63	0.41	0.27	0.20	0.09	0.03
PEN23	8.89	7.13	5.39	4.17	2.88	0.95
E1	1.68	1.25	0.52	0.31	0.1	0.087
E3	6.42	2.14	0.99	0.73	0.49	0.12
E5	11.91	6.13	1.65	1.04	0.53	0.39
G2	2.66	1.47	0.81	0.63	0.49	0.33
G4	7.00	3.73	2.11	1.59	1.33	1.07
G8	8.7	7.98	6.57	5.14	3.91	2.32
G4S1	19.48	16.13	13.69	10.47	6.91	5.12
G4S2	28.53	25.91	24.88	22.14	18.37	15.45

In addition to the MSCR test, the oscillation test was performed and various rutting parameters were determined as mentioned earlier in this paper. G*/sinδ and the Shenoy rutting parameter were determined from the data obtained from the oscillation test. ZSV was predicted using the simplified cross model as mentioned in section 2.3 and G_v was derived from burger's model. It was observed from Table 5 that all the parameters indicated an improvement in the rutting resistance of the bituminous binders. However, the evaluation using various parameters lead to different rankings. All the five parameters were considered for comparison and ranking was given as 1 to 10 as shown in Table 6. Rank 1 represents the best binder and rank 10 represents the worst binder against rutting. Moreover, G*/sinδ, G*/(1-(1/tanδ*sinδ)) and ZSV accord similar rankings. PEN23 binder was found to have highest G*/sinδ and G*/(1-(1/tanδ*sinδ)) next to G8 binder. It was shown that neither any modified binder reached a G*/sinδ value of PEN23 whereas J_{nr} and G_v showed the opposite trend. Ranking given using ZSV parameter was found to have slightly change and better compared to other two as it distinguished the rutting potential between G8 and G4S2. The parameters G_v and J_{nr} resulted same rankings with G4S2 as best binder towards anti-rutting potential followed by G8 and PEN23 binders. Through the observations, it was found that G_v is also a promising parameter to assess the permanent deformation characteristics of bituminous binders.

Table 5. Various rutting parameters of all binders

Binder ID	Rutting Parameters				
	G*/Sinδ, Pa	**G*/(1-(1/tanδ*sinδ)), Pa**	**G_v, Pa**	**ZSV , Pa-s**	**J_{nr}, kPa^{-1}**
VG40	3883.30	4088.98	4002.50	398.83	2.50
PEN23	23517.62	26003.66	18610.15	2586.19	0.54
G2	8615.42	9421.83	6411.13	1166.28	1.55
G4	12246.79	14007.66	9506.82	1745.93	1.06
G8	13684.17	16211.13	18623.21	1924.13	0.53
E1	4614.94	5053.27	4560.4	497.95	2.19
E3	4803.61	5165.31	4619.7	634	2.16
E5	4875.30	5177.64	4721.3	664.22	2.12
G4S1	11050.00	12963.53	15513.4	1598.67	0.62
G4S2	11710.00	14494.40	20840.3	2280.155	0.50

Table 6. Ranking of rutting parameters

Binder ID	Ranking of Rutting Parameters				
	G*/Sinδ, Pa	G*/(1-(1/tanδ*sinδ)), Pa	G_v, Pa	ZSV , Pa-s	J_{nr}, Pa
VG40	10	10	10	10	10
PEN23	1	1	3	1	3
G2	6	6	6	6	6
G4	3	4	5	4	5
G8	2	2	2	3	2
E1	9	9	9	9	9
E3	8	8	8	8	8
E5	7	7	7	7	7
G4S1	5	5	4	5	4
G4S2	4	3	1	2	1

In order to estimate and compare the five test methods, improvement of rutting resistance was considered as rutting resistance improvement ratio and plotted for each set of modifiers. Figure 4 presents the rutting resistant improvement ratio for gilsonite modified binders evaluated using the five parameters. The rutting resistance increased with larger content of modifiers which was evident in all cases. The trend of the ratio with increase in dosages was found to be identical for G*/sinδ, G*/(1-(1/tanδ*sinδ)), and ZSV whereas G_v and J_{nr} followed different trend (Pouria et al 2015). It can be also seen that for lower percentages of gilsonite G*/sinδ, G*/(1-(1/tanδ*sinδ)), and ZSV showed a significant increase in rutting resistance whereas J_{nr} and G_v did not demonstrated the same. It can be interpreted from Table 3 that gilsonite do not improve recoverable strain compared to SBS polymer. However, all the parameters are in the same region at higher percentages which makes it inconclusive. This shows the non-reliability towards the G*/sinδ, G*/(1-(1/tanδ*sinδ)), and ZSV.

The similar trend was also observed for EVA modified binders as shown in the Figure 5. Yet in case of EVA modified bitumen, at lower percentages, rutting resistance improvement ratio was found to be in approximate region whereas at higher percentages only ZSV was found to follow different trend implying higher viscosity. ZSV was similar to that of G_v and J_{nr} for the composite modified binders as observed in Figure 6. This clearly indicates that the three parameters (G*/sinδ, G*/(1-(1/tanδ*sinδ)), and ZSV) were not able to judge the rutting resistance of modified bituminous binders.

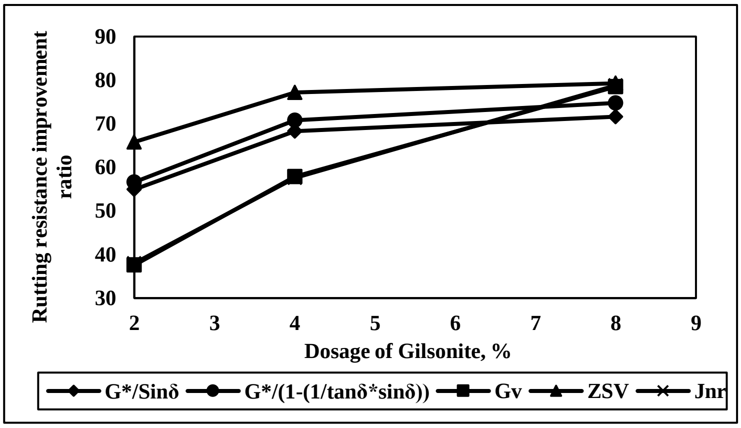

Fig 4: Rutting resistance improvement ratio of gilsonite modified binders based on various rutting parameters

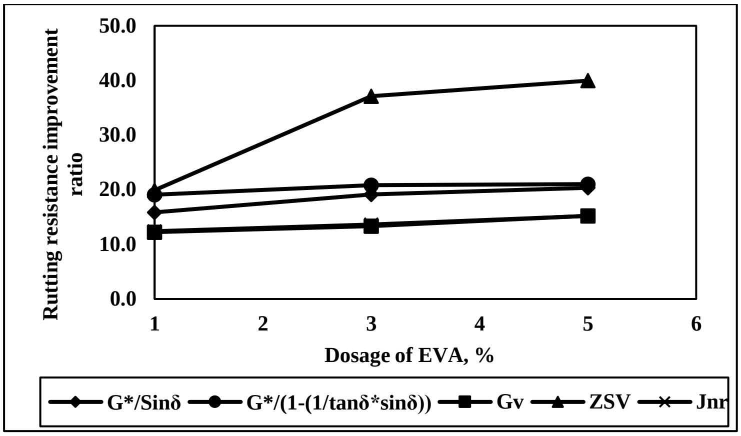

Fig 5. Rutting resistance improvement ratio of EVA modified binders based on various rutting parameters

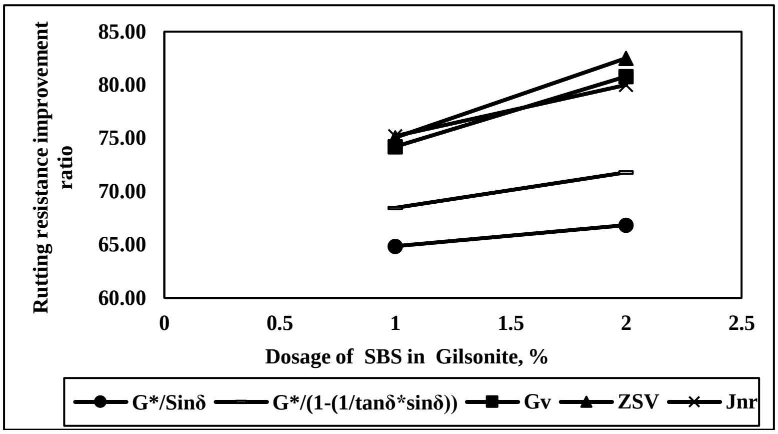

Fig 6. Rutting resistance improvement ratio of composite modified binders based on various rutting parameters

6.2 Modelling the creep and recovery behaviour

Creep and recovery curves of different binders measured at 60 °C and stress level of 3.2 kPa were modelled. Only some plots are shown in this paper for representation. Burger's model was found to be well fit for base binders as well as the gilsonite and EVA modified binders. In the case of composite modified binders, there is deviation from the experimental curves which was shown in the Figure 7. Some part of the recovery portion of the curves were deviated which can be clearly observed from the same Figure. Burger's model was unable to model the modified bitumen's viscoelastic behaviour. Table 6 presents the burger's model constants and it was found that η_M, the viscous behaviour of bitumen was increasing due to additives. It describes the recovery strain of the bitumen after the removal of creep load and is related to rutting. Higher η_M represents that the binder is more resistant to rutting. A value of 4.00E+03 was found for VG40 and is the least of all binders. Highest value was found for G4S2 binder as expected which proves that composite modification improves rutting characteristics better than other binders. G8 binder had shown same value of η_M along with the PEN23 binder. EVA modified binders were found to increase the rutting potential but was found to be very not as much of composite bituminous binders in any approach. Overall, the burger's model was proved to be not an appropriate modelling technique to model modified bituminous binders. Hence weibull distribution function was adopted in the study to simulate the creep and recovery behaviour.

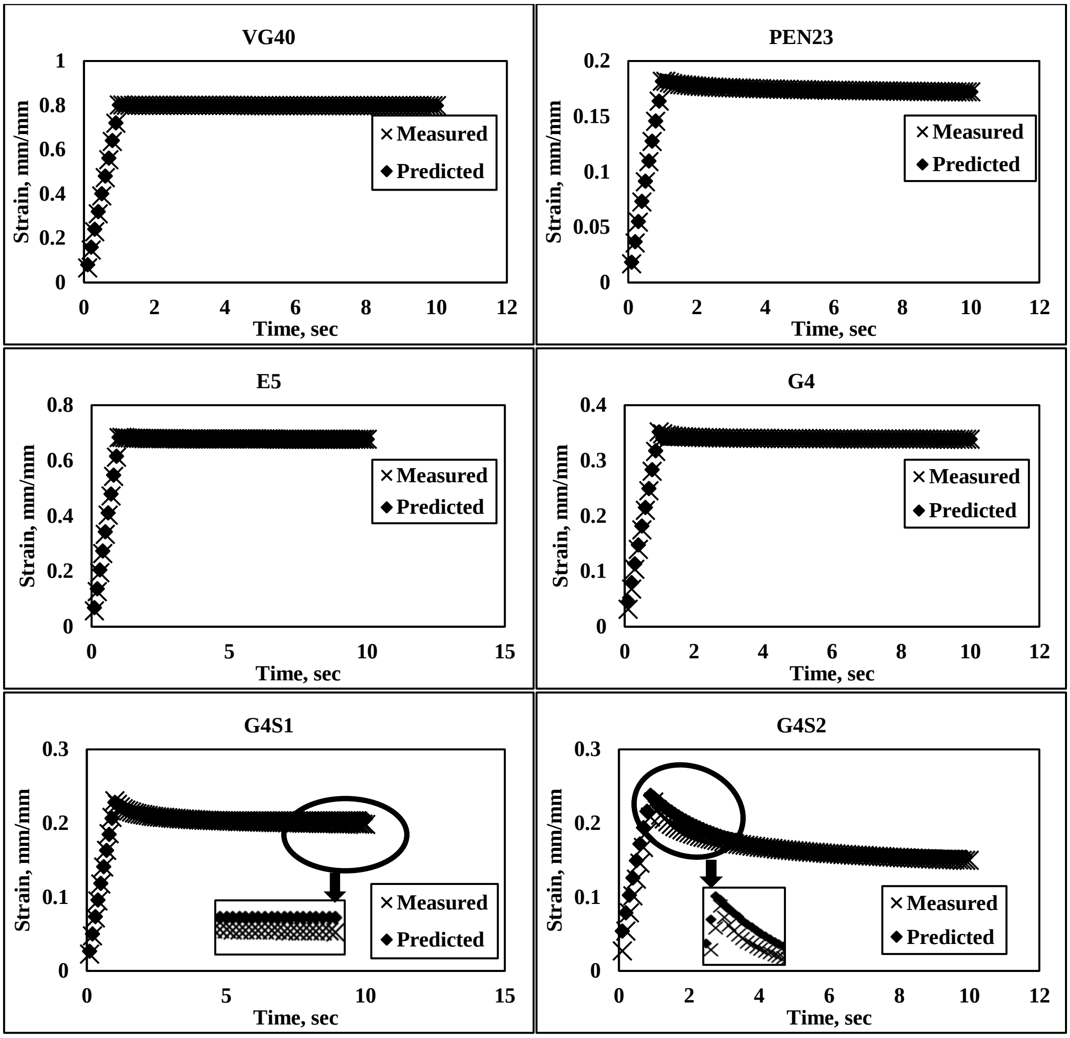

Fig 7: Creep and recovery curves of binders (Burger Model fit)

The creep and recovery curves were simulated and the Burger's model parameters were reported in the Table 7. Figure 8 represents the measured and predicted behaviour of binders. It is noticed that the modelled data fitted well with the experimental data. β_r and η_r represents the rate of recovery of bitumen after the removal of creep load. A lower values of β_r and η_r represents the increased rate of recovery and hence higher percent of strain will be recovered rapidly leading to lower non recoverable strain. Table 8 clearly shows the decrease in these values which demonstrates enhanced rutting potential of binders. β_r has decreased from 2.019(VG40) to 0.934(G4S2) and η_r from 2.493(VG40) to 2.212 (G4S2). ε_i is the initial creep strain and it was observed to be higher for modified binder with higher dosages of additives as well as for PEN23 binder. Therefore with the above results, it could be aforementioned that weibull model was able to explain the non-linear strain response of the modified bituminous binders using the model parameters and also was found to be in high agreement with the experimental data curves.

Overall, the composite modified binders were found to have lower creep strain due to higher stiffness and rapid recovery of strain immediately after the removal of load. Also, as these composite binders were stiff enough to produce lesser strains, will immediately recovery whatever the strain accumulated due to creep load.

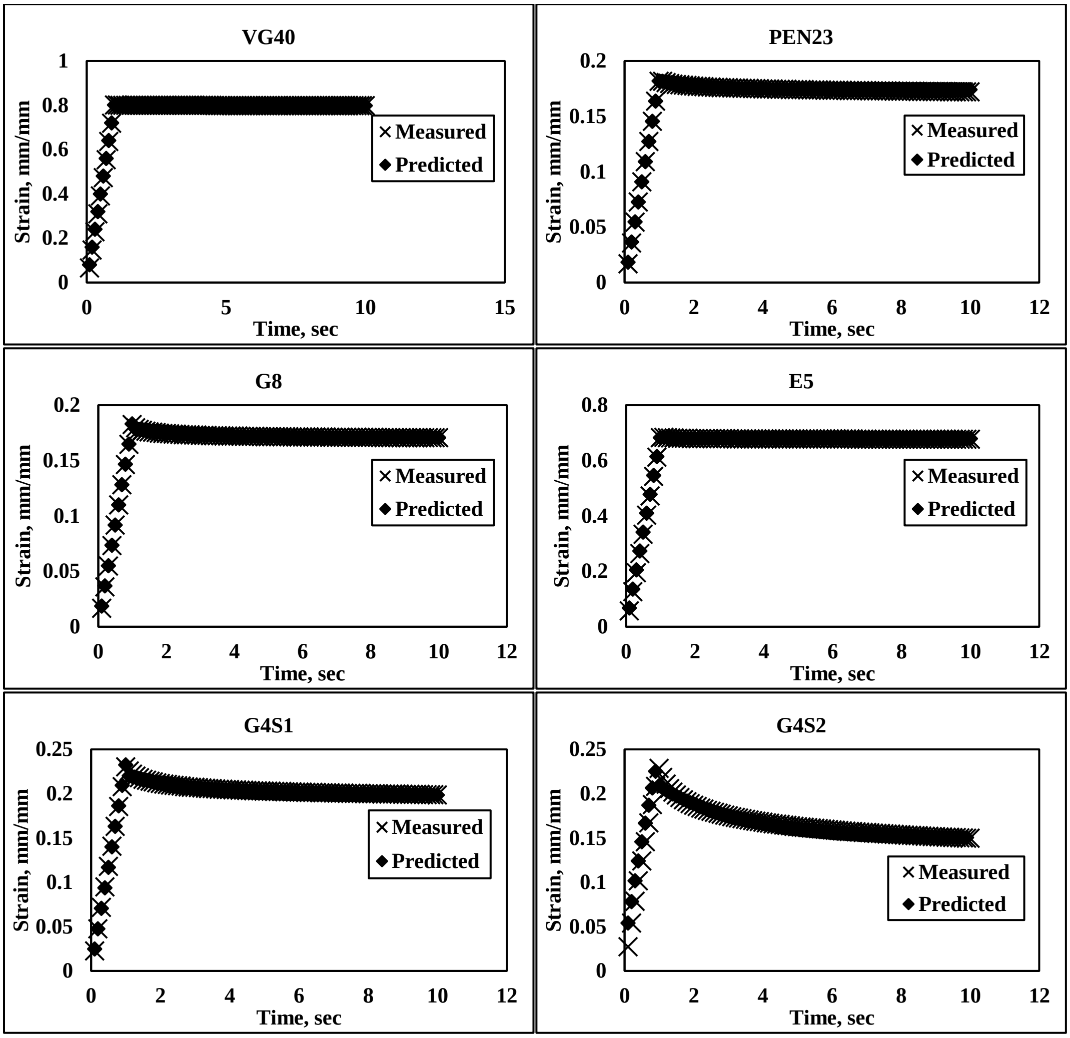

Fig 8: Creep and recovery curves of binders (Weibull Model)

Table 7. Burger Model Parameters

Binder ID	Model Parameters				
	E_M	η_M	E_K	η_K	SSE
VG40	4.95E+17	4.00E+03	8.12E+05	1.01E+06	8.34E-04
PEN23	1.86E+07	1.86E+04	1.16E+05	2.68E+05	3.37E-05
E1	1.70E+14	4.56E+03	1.73E+03	2.24E+07	5.32E-04
E3	2.15E+13	4.62E+03	2.34E+05	2.87E+10	8.10E-04
E5	8.05E+11	4.72E+03	2.43E+05	3.73E+05	6.83E-04
G2	1.88E+13	6.41E+03	3.61E+05	2.72E+10	1.29E-03
G4	2.78E+05	9.51E+03	5.10E+04	8.18E+05	8.06E-04
G8	1.09E+06	1.86E+04	2.61E+05	2.51E+05	9.75E-05
G4S1	1.16E+06	1.55E+04	1.24E+05	8.97E+04	1.79E-03
G4S2	9.05E+05	2.08E+04	1.66E+04	3.06E+04	5.40E-03

Table 8. Weibull Model Parameters

Binder ID	Model Parameters								
	ε_i	ε_c	η_c	β_c	ε_r	ε_f	η_r	β_r	SSE
VG40	0	8.94E+03	1.81E+00	1.62E-04	3.17E-03	0.800	2.493	2.019	0.000784
PEN23	0.00011	4.15E+03	1.76E+00	7.73E-05	1.71E-02	0.174	5.314	3.963	0.000086
E1	0	5.10E+04	4.71E+00	6.43E-05	8.10E-02	0.702	1.078	3.038	0.000369
E3	0	9.51E+04	1.00E+01	7.29E-05	4.20E-02	0.690	1.356	2.132	0.000593
E5	0	8.69E+04	8.61E+00	6.77E-05	7.66E-02	0.680	1.219	3.138	0.000747
G2	0	6.05E+04	9.00E+00	7.33E-05	6.74E-03	0.495	4.800	2.164	0.000125
G4	0	6.31E+04	4.63E+02	2.58E-03	1.29E-02	0.339	2.532	1.048	0.000093
G8	0.00043	4.62E+04	4.71E+02	1.86E-03	1.46E-02	0.171	2.502	1.340	0.000028
G4S1	0.00155	4.46E+04	2.88E+02	1.49E-03	3.85E-02	0.198	0.793	0.412	0.000175
G4S2	0.00303	7.38E-01	2.06E+00	7.37E-01	9.52E-02	0.149	2.212	0.934	0.000407

7. Conclusions

The current study had focussed on the improvement of rut resistance evaluated using various parameters for the modified high modulus bituminous binders. These parameters include superpave rutting parameter (G*/sinδ), shenoy rutting parameter (G*/1-(1/tanδ*sinδ)), zero shear viscosity (ZSV), viscous component of creep stiffness (G_v) and Non-recoverable creep compliance (J_{nr}). This study also tried to simulate the viscoelastic behaviour of modified binder using both Burger's model and Weibull distribution function to understand the rut resistance in a much appropriate manner. Various conclusions of the study were as follows:

- The superpave rutting parameter, shenoy rutting parameter and ZSV were found to follow same trend whereas G_v and J_{nr} were following the same trend in evaluating the rut resistance. However, depending upon the type of additive, rut resistance improvement ratio based on ZSV was different from G*/sinδ and shenoy rutting parameter.
- Based on the G*/sinδ, G*/1-(1/tanδ*sinδ) and ZSV, PEN23 binder was found to be more rut resistant than the composite modified binder which was later found that composite modified binder has the highest rut resistance based on J_{nr} and G_v.
- The stress sensitivity of composite modified binders is less than the base binder as well as EVA modified binders.
- In most of the cases, the resulting rutting resistance improvement ratio found to be different for G*/sinδ, G*/1-(1/tanδ*sinδ) and ZSV while the ratio is same for G_v and J_{nr}.
- Through all the rutting parameters, it was observed that EVA with 28% vinyl content was not able to improve the rutting potential of the base binder.
- The composite modified high modulus bituminous binders has a remarkable stiffness along with recoverable properties to ensure better rutting performance.
- Burger's model was proved to be incapable to explain the non-linear viscoelastic strain response of the modified binders due to creep and recovery.
- Weibull distribution function modelled the strain response of bituminous binders with more appropriate fit with the experimental data and the parameters were better in explaining the rut resistance.

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Replies to the reviewer's comments

Reviewer 1:

Many researchers have reported that ZSV parameter correlates to the rutting in pavements better than the G*/sin delta, whereas here authors have stated that both the parameters ranked the binders similar. Please provide enough references to corroborate this statement. Also it is an establish fact that Burger's model does not fit well for asphalt binders. Then why still this exercise was carried out? They could have tried with some other rheological model.

Ans: Reference was provided in the current study discussing the ranking provided by G*/sin delta and ZSV. Burger's model was selected initially for the study due to its easiness and its parameters has physical meaning which is also mentioned in the past studies. It could be observed that Burger's model fitted well for gilsonite and EVA modified binders whereas for only composite modified binders. Hence after realizing Burger's model was not fitting well, the authors tried other model.

Reviewer 2:

Overall Comment:
The authors have carried out extensive laboratory investigation and corresponding analysis for high temperature performance of asphalt binder containing different additives. The reviewer appreciates the effort put up by the authors to carry out this research work. However, there are certain queries which need to be clarified. Following are the pointwise comments for the same.
Pointwise comments:

1) The authors highlight the importance of HiMA. The reviewer believes that HiMA may play an important role in heavy vehicular loading and/or high temperature regions. However, this study did not consider higher creep levels such as 5kPa, 10kPa, 12.8kPa, 25.6kPa etc. which simulates higher axle loading as reported in the various literature in MSCR test. The reviewer encourages to investigate the impact of higher stress levels.

Ans: As suggested by the reviewer, the authors performed MSCR test at higher levels and results were provided in the revised paper.

2) The aim of the reported research work is not clear. This works largely discusses evaluating rutting performance using various methods used for evaluating high temperature performance and their inter-comparison. However, the motivation behind such a comparative study is completely missing. The authors are requested to put separate section which could clearly refract the research gap, and motivation of the presented work. It is not clear in the present form.

Ans: The aim of the paper is mentioned in the revised paper. A separate section was kept for research gap and objectives.

3) Page 2, second last para, line 2: This seems to be an open ended statement. The reviewer would like to know what cases the authors would like to point out which cannot be evaluated and tested at laboratory scale. Kindly clarify it and revise accordingly.

Ans:

4) The authors need to recheck Eq.7. There seems to be some error to this equation. It is also expected that the author should provide the physical meaning of the different components of the Burgers model. Also, the term "Burger's model" needs to be checked. As per the reviewer's opinion, it is popularly used as "Burgers model". Kindly check it and revise accordingly.

Ans: The author found two different equation in the past literature. However, after using both equations, it was found that the equation described in this paper is the right expression for Burger's model. As suggested, different components of burger’s model were described. Several literatures used the term Burger’s model in their studies. Hence the author expressed in the same way.

5) Kindly change "G*/sinδ" to "G*/Sinδ". Check the whole manuscript and revise accordingly.

Ans: Several literatures described the SHRP rutting parameter as G*/sinδ. Hence the author expressed in the same way.

6) In Eq.8, kindly clarify the time "t". Is this time measured from the start of creep period or is measured from the end of creep period or starting of recovery period? Kindly clarify and revise accordingly.

Ans: The time “t” is measured from the end of creep period i.e., 1 sec. The paper is revised accordingly.

7) This study tells that the stress level of 3.2 kPa is used for investigating non-linear behavior. However, many literatures advocate that 3.2kpa is not sufficient to induce strain in non-linear range. Therefore, it is recommended to utilize higher stress level such as 12.8kpa, 25.6kpa etc. to study the non-linear performance of asphalt binder. Moreover, the authors have evaluated MSCR test at 60 degree. However, it is recommended that MSCR test be conducted at corresponding high temperature PG. Therefore, further justification is needed for selection of test temperature for the MSCR test.

Ans: Indian pavement authorities, Indian Road Congress (IRC) follows viscosity grade for bituminous binder classification and the critical high temperature for flexible pavements is considered as 60 °C. Hence the author did not concern on PG upper grade and performed the test at 60 °C.

8) Discussion on vehicular grading as per AASHTO MP19 will be appreciated.

Ans: As suggested, vehicular grading was discussed in the results and discussion section.

9) The majority of the points in conclusive remark are just results obtained from the experimental investigation. The reviewer finds that there is a lot of scope for strengthening the conclusion section. The authors are advised to revise accordingly.

Ans: The conclusion section is revised.

Reviewer 3:

Good work. The authors have attempted to study the rutting resistivity potential of modified high modulus binders using different rutting parameters. However, authors are requested to address the following comments so that the quality can be further improved.

1) Grammatical mistakes were observed in the paper. It is suggested that the continuity of sentences and improvement in sentence formation be considered for better conveyance of information. Capitalization of proper nouns is also suggested.

Ans: Observed grammatical mistakes were corrected.

2) Section 3.1: What is the basis for selection of the dosage of Gilsonite and EVA? Since, as per the authors, Gilsonite addition leads to increase in the brittleness, please justify why SBS was added only to 4 %
Gilsonite modified binder.

Ans: Based on the previous literature, dosages of gilsonite and EVA were selected. SBS was added to gilsonite based on other trial and error experiment study done which is not included in this study. SBS in 4% gilsonite was found to be effective.

3) Section 3.1: Please justify the though process behind adoption of blending time of 60 minutes and speed of 2500 RPM. If any reference is available, please mention it.

Ans: References are mentioned in the paper.

4) Section 5.2: Please clarify whether Burger model is capturing the increase in rutting resistivity of EVA modified binders since table 6 is exhibiting increasing values of η_M for E1, E3 and E5. Please elaborate the reasons for discarding the Burger model.

Ans: Yes, the Burger's model is capturing rutting resistance of EVA modified binders. However the increment in η_M is much smaller compared to other binders. In addition to that, the burger's models was unable to capture the rheological behaviour of composite bituminous binders at high temperatures. Hence the Burger's model was discarded.

5) Section 6: Any recommendation regarding which approach is more effective for capturing the rutting resistivity of high modulus bituminous binders?

Ans: The current specification for evaluating rutting resistance of binders, ASTM D7405-10a is effective even for high modulus bituminous binders as it was found that the stress level 3.2 kPa is in non-linear viscoelastic region.