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Permanent Deformation Study of Pyro-Oil Modified Bituminous Binders using Various Rutting Parameters

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ABSTRACT

Permanent deformation is one of the major distresses observed in the bituminous pavements. The road construction industry all over the world is doing progressive research for improving the resistance to permanent deformation of pavements by modification of bituminous binders. Pyrolysis is a method to change the chemical composition of materials by thermal decomposition at high temperatures in inert conditions. The pyrolysis of scrap tires has been found to be a potential strategy of tire waste management. In the present study, the permanent deformation behaviour is studied with various rutting parameters for bituminous binders modified with oil obtained as a residue, from the conversion of scrap tires into fuel gas by thermochemical process, known as tire pyro-oil. The base bitumen VG30 is modified with 1%, 2% and 3% tire pyro-oil for comparing the rutting resistance of the modified binders. The rutting resistance is evaluated on the basis of determining different rutting parameters that include Superpave rutting parameter $G^*/\sin\delta$, Shenoy's parameter $J_{nr\_3.2}$ and zero shear viscosity (ZSV). Analysing and comparing these rutting parameters for the base and modified binders, the suitability of the percentage of tire pyro oil modifier in terms of permanent deformation resistance is determined.

Keywords: Permanent deformation, rutting parameters, Tire pyro-oil, modified bitumen.

INTRODUCTION

Rutting is one of the major distress mechanisms observed in bituminous flexible pavements. It is considered as the most important distress and used as a significant criterion for design of flexible pavements [1]. Rutting is the permanent deformation that occurs as longitudinal depressions under the wheel path of vehicles which reduces the service life of pavements and makes the ride uncomfortable for the driver and unsafe for vehicle [2]. The different factors that influence rutting in bituminous pavements include physical characteristics of aggregates, properties of binders and mixture volumetrics. Nonetheless, bitumen or bituminous binders play a significant role in the occurrence of rutting because of their time and temperature dependent behaviour, specially under slow and heavy traffic at greater in service temperatures [3,4]. Therefore, improvement in the mechanistic and rheological properties of bituminous binders is required to increase the quality and service life of pavements during all environmental conditions [5]. Nowadays, research is progressing for modification of bitumen with different modifiers to improve the properties and in service performance of bitumen.

Dealing with the recycling or disposal of solid waste produced by activities of human beings is a major challenge in front of today's society and engineers. Especially there is a great impact on the environment due to the scrap tires, similar to that of waste plastic. All over the world, over 1.5 billion tonnes of tires weighing about 17 million tonnes are discarded every year [6]. The waste plastic has been used by researchers as modifiers into the bitumen [7–10]. Ranadive et al. (2018) [11], used waste plastic as well as the fibres extracted from refrigerator door panels as modifiers in the stone matrix asphalt to improve the strength characteristics of the mixture. Hadole et al. (2021) [12], used the HDPE pyro-oil as modifier in bitumen to study the effect of modification on the moisture resistance of the binders. Pyrolysis is an advantageous method that can be used to recycle scrap tires and convert scrap tires into bio-oil. If done in a carefully controlled conditions, pyrolysis of scrap tires can produce valuable products such as gas, char, and liquid oil that can be used as fuels. Since this process of pyrolysis uses less costly fuels for application in large scale, it proves to be economical in addition to beneficial for environment and sustainable development [13]. In addition to this, there is an increasing need to use secondary resources as the natural resources are limited. Hence scrap tires should be considered as a source of economic and ecological importance for the coming centuries [13]. The oil obtained from the pyrolysis of scrap tires can be used in bitumen as modifier. Al-Sabaeei et al., (2021) [14], used tire pyrolysis oil along with crude palm-oil as modifiers for the bitumen to characterise the high temperature properties of the binders.

In this study the oil obtained from the pyrolysis of scrap tires, will be called as tire pyro-oil onwards, is used in 1, 2 and 3% as modifiers in the bitumen to characterise the rutting resistance of the modified binders. A comparative analysis is done for the virgin and modified binders in terms of evaluating the different rutting parameters, details of which are given below.

1. RUTTING PARAMETERS

1.1 Superpave Rutting Factor (G*/sinδ)

The Superpave rutting factor is developed based on the dissipated energy concept [15]. The deformation period of asphalt binder consists of work done that can be divided into three portions. The first portion is the recovered energy from the elastic deformation, second portion consists of the dissipated energy of the viscous deformation and the third portion is the generated heat from the work done [16]. Rutting is assumed to be the consequence of the dissipated energy of binder in each cycle of loading, and is given by Eq. (1),

$$\Delta U = \int \sigma d\varepsilon \qquad (1)$$

Where ΔU= Energy lost or dissipated energy per cycle, σ= shear stress, and ε= shear strain.

After integrating Eq. (1) for sine wave from 0 to 2π, we get the following equation.

$$\Delta U = \pi \times \sigma_{max} \times \varepsilon_{max} \times \sin\delta \; (2)$$

Where, σ_{max} = maximum shear stress, and ε_{max}= shear stress.

Since, the complex modulus (G*) can be written as, $G^* = \frac{\sigma_{max}}{\varepsilon_{max}}$, Eq. (2) can be rewritten as follows,

$$\Delta U = \frac{\pi \times \sigma_{max}^2}{G^*/\sin\delta} \qquad (3)$$

It can be seen from Eq. (3), that the dissipated energy ΔU can be minimized by increasing G*/sinδ. Therefore, a binder with higher value of G*/sinδ will have dissipate less energy and in turn will be less susceptible to rutting.

1.2 Shenoy Parameter

Shenoy (2001) [17], suggested a new parameter by making refinement in the rutting factor, which is deduced by removing the unrecovered strain from the total strain developed in the binders. The total percentage of strain developed in the binder which subjected to stress (σ_0) for a particular time can be given by Eq. (4) as follows,

$$\%\gamma_{max} = \frac{100\sigma_0}{G^*} \qquad (4)$$

The elastic strain is recoverable and the percentage of recoverable strain ($\%\gamma_r$) is given by Eq. (5),

$$\%\gamma_r = 100\sigma_0 \frac{G'}{G''^2} \qquad (5)$$

Where, G'= G*cosδ = storage modulus and G''= G*sinδ = loss modulus.

The viscous part of the strain is irrecoverable and the percentage of irrecoverable strain ($\%\gamma_{ir}$) can be calculated as,

$$\%\gamma_{ir} = \%\gamma_{max} - \%\gamma_r \qquad (6)$$

From Eq. (4), (5) and (6)

$$\%\gamma_{ir} = \frac{100\sigma_0}{G^*}\left(1 - \frac{G^*G'}{G^{"2}}\right) \qquad (7)$$

Substituting the values of G' and $G^{"}$ in Eq. (7),

$$\%\gamma_{ir} = \frac{100\sigma_0}{G^*}\left(1 - \frac{1}{\tan\delta\sin\delta}\right) \qquad (8)$$

Thus, from Eq. (8), it is clearly seen that the irrecoverable strain can be minimized by maximizing the parameter $\frac{G^*}{\left(1-\frac{1}{\tan\delta\sin\delta}\right)}$. Shenoy (2001) [17], suggested to use this parameter as a parameter to characterize rutting of asphalt binders and thus is known as Shenoy parameter.

1.3 Zero Shear Viscosity (η_0)

DSR frequency sweep test is used to acquire the complex viscosity data for asphalt binders at various frequencies [16,18]. Zero shear viscosity can be calculated from the test data by using mathematical models relating the viscosity and shear rates to fit the non-linear regression with complex viscosity measurements of the asphalt binders [19]. The Carreau model, modified Carraeu model, Cross/Williamson's model and Cross/Sybilski's model are the most commonly used models to estimate zero shear viscosity [15,16,20].

The Cross/Sybilski's model is given by the Eq. (9) as follows,

$$\eta^* = \frac{\eta_0^*}{[1+(K\omega)^m]} \qquad (9)$$

Where, η^* = Complex viscosity, η_0^* = zero shear viscosity, ω = shear rate and K and m are model parameters.

1.4 Non-recoverable Creep compliance (J_{nr})

The parameter non recoverable creep compliance is the output of MSCR test and which corresponds to the rutting of asphalt binders. As per ASTM D7405[21], J_{nr} at 3.2 kPa stress is considered to characterize the rutting behavior of asphalt binder and it can be calculated from the Eq. (10) as follows,

$$J_{nr} = \frac{\sum_{i=1}^{10}\left(\frac{\varepsilon_{10}}{\sigma}\right)_i}{10} \qquad (10)$$

Where σ = applied stress, i= cycle number, and ε_{10}= strain accumulated in one creep and recovery cycle which can be calculated as,

$$\varepsilon_{10} = \varepsilon_r - \varepsilon_0 \qquad (11)$$

Where, ε_r= strain at the end of one cycle and ε_0 = strain at the start of one cycle.

2. MATERIALS

2.1 Bitumen

Viscosity graded bitumen (VG30) received from IOCL, India was used as base bitumen for modification. The physical properties of base bitumen are presented in Table 1. Base bitumen was checked for VG30 in accordance with IS-73 and properties of binder were found to be within permissible limits as per IS guidelines. High-temperature grading as per Superpave well known as performance grade (PG) of VG30 was recorded as 64 ºC (i.e. PG 64-X) and other rheological parameters are reported in Table 2.

2.2 Tire-pyro-oil

Waste tires were used for generation of pyro-oil. Tire pyro-oil is a condensed product when decomposition is brought at high temperatures without oxygen. Scrap tires were collected from Devansh Industries, Wadaki, Pune, Maharastra, India. For the decomposition of scrap tires, the pilot pyrolysis plant was developed and set up in the Transportation Engineering Laboratory of the College of Engineering, Pune, India. The pyrolysis temperature for scrap tires was decided concerning the discussion given by Rowhani & Rainey (2016) [6], which concludes that thermal decomposition of scrap tires starts around 350ºC and about 57.6% yield tire oil is produced at temperatures of above 700ºC. The working procedure from sample collection to yield of pyro-oil was discussed by Kulkarni and Ranadive (2020)[22], in detail.

Table 1. Physical properties of virgin and modified binders

Test	Reference	VG30	TOMB1	TOMB2	TOMB3
Penetration at 25ºC (1/10th of mm)	IS 1203/ ASTM D5[23]	54	56	60	55
Softening Point (ºC)	IS 1205/ ASTM D36[24]	50	49	43	51
Ductility (cm)	IS 1208/ ASTM D113[25]	79	80	88	82
Viscosity at 60 ºC (poise)	IS 1206(2)	2806	2760	2074	2688
Kinematic viscosity at 135 ºC (cSt)	IS 1206(3)	341	-	-	-
Viscosity at 150 ºC (poise)	IS 1206(1)	-	1.4	1.8	1.3
After Rolling Thin Film Oven Test					
Loss in mass (%)	IS 9382	<1	0.99	0.98	1
Softening Point (ºC)	IS 1205/ ASTM D36[24]	80	67	64	68

The physical properties, Superpave high performance grade and other rheological parameters for tire oil modified bitumen were presented in Table 2.

Table 2. Rheological parameters and high temperature PG grading of binders

Binder	Unaged binder results					RTFO aged binder results					
	G* (kPa)	Phase Angle δ (°)	G*/sinδ (kPa)	Failure Temp. (°C)	Performance Grade Temp. (°C)	G* (kPa)	Phase Angle δ (°)	G*/sinδ (kPa)	Failure Temp. (°C)	Performance Grade Temp. (°C)	High Temp. PG grade
VG30	1.42	87.4	1.42	67.5	64	3.21	85.5	3.21	66.1	64	PG64-X
TOMB1	1.74	86.5	1.75	68.1	64	2.7	84.3	2.71	71.6	70	PG64-X
TOMB2	1.86	85.8	1.87	72.7	70	3.66	83.2	3.69	73.8	70	PG70-X
TOMB3	1.65	87	1.65	67.7	64	3.41	83.4	3.43	72.6	70	PG64-X

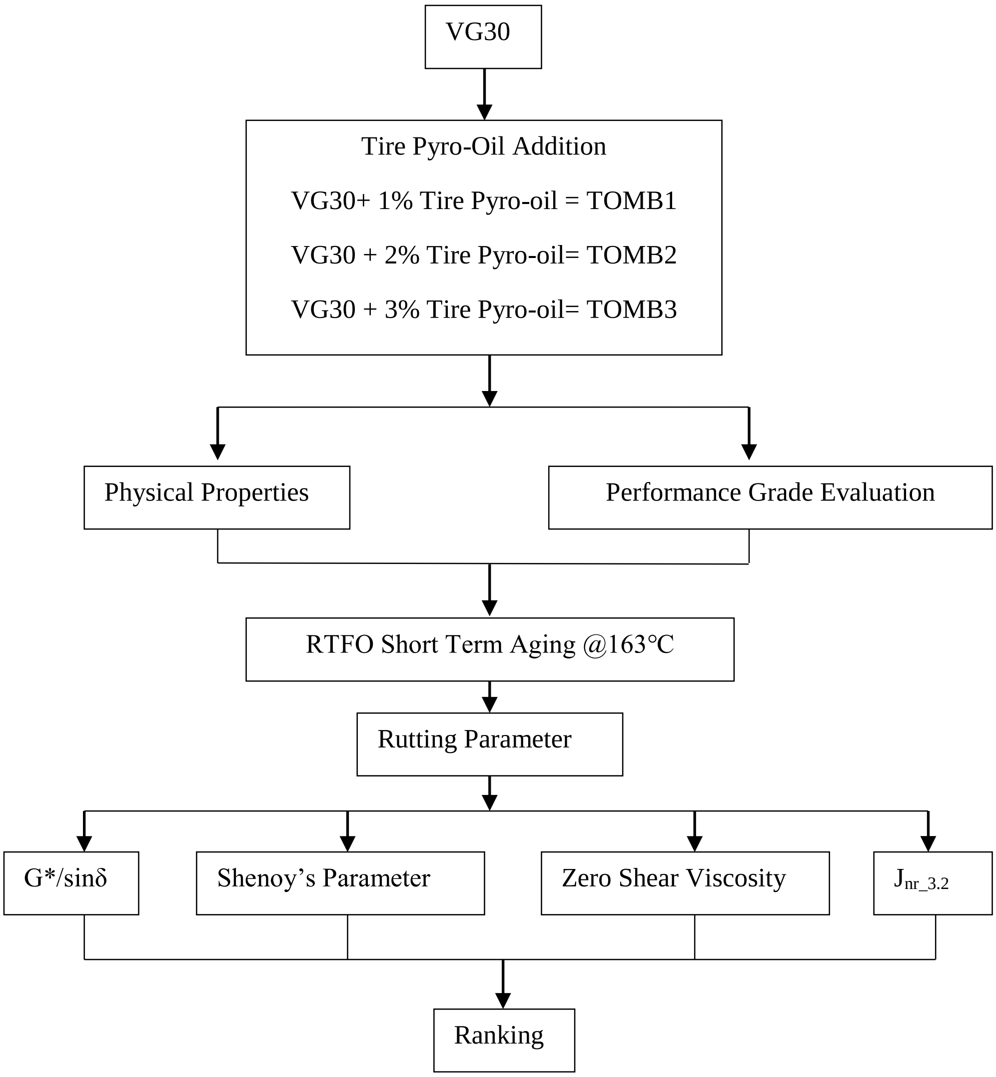


Fig. 1. Schematic Representation of Experimental Program

3. METHODOLOGY

3.1 Modification of virgin binder with tire pyro-oil (TOMB)

For modification of virgin binder was carried out at a temperature of about 145-150ºC with 3000rpm with the help of T25 digital easy clean made of IKA high shear mixer for the 15 minutes. Prior to adding tire oil, the virgin binder was heated at about 140ºC. 1%, 2% and 3% of tire-oil by weight of base binder was used to modify virgin binder, and the modified binders are abbreviated as TOMB1, TOMB2, and TOMB3.

3.2 Short term Aging

The virgin and modified binder was aged using RTFO (ASTM D 2872 [26]). The short-term ageing of virgin bitumen and pyro-oil modified bitumen was carried out at 163ºC for 85 minutes in RTFO. Schematic representation of the experimental program is shown in Fig. 1.

3.3 Rheological Testing

The different rheological tests were carried out at 60°C using the dynamic shear rheometer (DSR). An oscillation frequency sweep test was conducted on the binders to evaluate the effect of frequency (loading time), in the frequency range of 0.01 to 25 Hz, on the rutting resistance of the binders. The rutting susceptibility of binders was evaluated using the multiple stress creep and recovery (MSCR) test at stress levels of 0.1 and 3.2 kPa. The different rutting parameters for binders like Superpave rutting factor (G*/sinδ), Shenoy's parameter, zero shear viscosity were determined from the oscillation frequency sweep results. The non recoverable creep compliance (J_{nr}) was determined from the MSCR test for all binders.

The difference in conditions under which the tests are conducted may cause the variance in predictions of different test results. The binder under different stress or strain levels is subjected to different loading conditions in each test. Since the response of binders is affected due to these different loading conditions, there can be significant difference in the ranking obtained from different tests.

4. RESULT AND DISCUSSION:

4.1 Superpave Rutting Factor (G*/sinδ)

Temperature sweep test was performed for binders at fixed frequency of 10rad/sec starting from 45ºC to 70 ºC with an interval of 5ºC and failure temperatures were noted with the corresponding G*/sinδ value. G*/sinδ should not be less than 1kPa and 2.2kPa for unaged and RTFO-short term aged binders respectively, as specified by Superpave specifications.

Fig. 2 shows the plot of G*/sinδ for virgin bitumen, TOMB1, TOMB2 and TOMB3 for both unaged and RTFO aged conditions. Testing results show that rutting resistance improved for TOMB1 and TOMB2 compared to virgin binder. The further addition of pyro-oil leads to decreases in rutting factor for both unaged and aged binder. It should also be noted that, though there was decrease in rutting factor for TOMB3, it shows more rutting resistance than that of virgin bitumen by 16% and 10.79% for unaged and aged condition respectively. After ageing of binders, the binder becomes stiff and which leads to increase of complex modulus (G*) of binders as shown in Table 2.

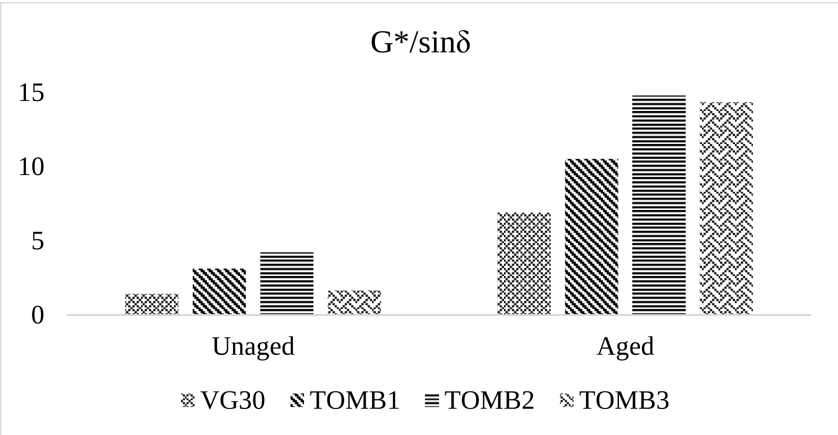


Fig 2. Values of Superpave Rutting Factor @60℃

Hence as per Superpave Rutting Factor, 2% addition of tire-oil shows maximum rutting resistance and therefore can be considered as an optimum dosage of modifier.

4.2 Shenoy's Parameter $\frac{\mathbf{G^*}}{\left(\mathbf{1-\frac{1}{\tan\delta\sin\delta}}\right)}$

Fig. 3 shows variation of $\frac{G^*}{\left(1-\frac{1}{\tan\delta\sin\delta}\right)}$ for VG30 and modified binders at 60℃. +Shenoy parameter was evaluated using temperature sweep test data at constant frequency of 10rad/sec provided that material is tested within linear viscoelastic strain limit as per guidelines provided in ASTM D7175 [27]. From the formula of

Shenoy parameter it can be observed that, complex modulus and phase angle variation plays vital role as well as if phase angle is less than 52º the unrealistic negative values of unrecoverable strain will be obtained.

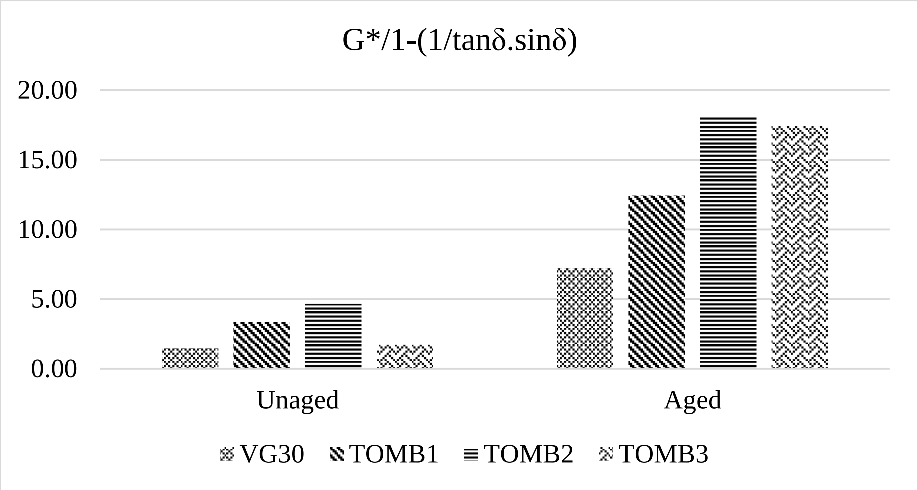


Fig. 3. Variation of Shenoy's Parameter @60℃

With increase in addition of tire pyro-oil in virgin bitumen, Shenoy parameter increases up to 2% addition of tire pyro-oil and further decreases for addition of 3% pyro-oil in virgin bitumen. This can be due to increases in stiffness of modified binder. This is due to the chemical reactions and due to formation of heavy aromatics after modification. The study related to formation of chemical compounds and its effect on rheological properties has not been included in this paper due to brevity and reported somewhere else [28]. It is also noteworthy that, the Shenoy rutting parameter is on higher side when compared to Superpave rutting factor and hence it can be inferred that Superpave rutting factor gives conservative results compared to Shenoy parameter.

4.3 Zero Shear Viscosity (ZSV)

Frequency sweep test was performed for virgin and modified binder with 0.01 to 25Hz at an increment of 0.1Hz within linear viscoelastic limit. The test was performed at 45, 50, 55, 60, 65 and 70℃. However, zero shear viscosity at 60℃ is considered as a better alternative to Superpave rutting factor, as it has a good potential to correlate well the viscosity of modified binder with the field performance [16]. Hence the master curve at 60℃, was constructed using WLF equation [29]. The data from master curve was used to calculate ZSV. Further, the Cross-Sybilski model has been used fit the data and to calculate ZSV. Master curve variation indicates a pseudoplastic system over a broader range of frequency and shear rate.

ZSV for virgin and modified binders are presented in Fig. 4. TOMB2 has highest value of ZSV whereas lowest for VG30. However, the variation in results of ZSV also indicates the relation between G* and phase angle in terms of elastic response for aged conditions. For example, TOMB2 has a higher G*, lower phase angle, which implies better elastic properties than other binders and better rutting resistance. It was noted that, modified binders attain steady state and hence it can be concluded that ZSV parameter results into accurate rutting behaviour.

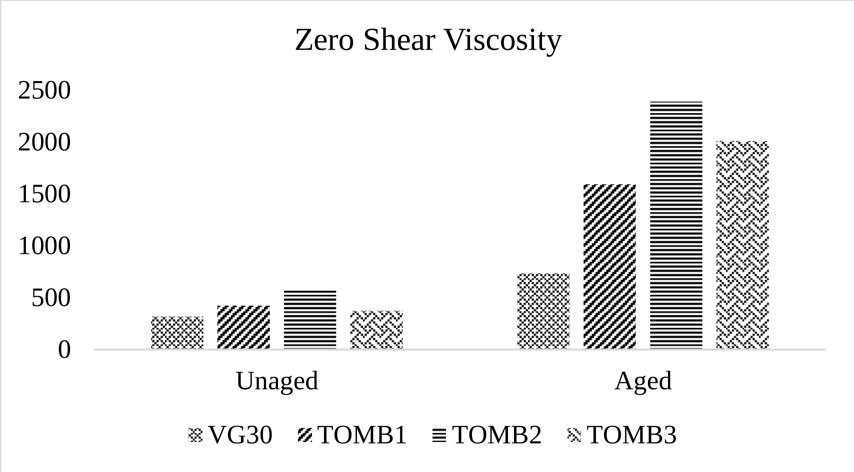


Fig. 4. Zero Shear Viscosity for virgin and modified binders @60℃

4.4 $J_{nr\_3.2}$ Rutting Parameter

Rutting performance of virgin and modified binder was evaluated using MSCR test as per ASTM D7405[21] and AASHTO T 350[30]; which was performed on RTFO aged samples at temperatures of 60 °C. Fig. 5 presents variation of J_{nr} at 3.2 kPa at 60°C. Higher value of J_{nr} indicates lower rutting resistance of the binder. The percentage decrease in J_{nr} was observed with increase in percentage of tire pyro-oil. Minimum $J_{nr\_3.2}$ was noted for TOMB2, hence shows maximum rut resistance. Similar trend was observed in other rutting parameters like Superpave rutting factor, Shenoy rutting parameter and ZSV. From this observation it can be concluded that addition of tire oil to the virgin binder will lead to improvement in recovery during unloading period.

As per IS 15462 (2019) and AASHTO M332[31], the suitability of virgin and tire pyro-oil modified binder for varying traffic loading conditions was assessed based on J_{nr} value at 3.2 kPa. According to Table 3 taken from AASHTO M332[31], VG30 binder at 60°C was designated 'S' which corresponds to standard traffic loading. While at 60℃ TOMB1 and TOMB3 are designated as ‘V’, whereas TOMB2 is designated as ‘E’. The value of J_{nr} at 60°C for stress level of 3.2 kPa falls by 83%, 78% and 73% compared to VG30 for TOMB2, TOMB3 and TOMB1 respectively. It was observed that J_{nr} value for TOMB3 decreases with addition of tire oil but found to be less than

that of TOMB1. Hence $J_{nr\_3.2}$ rutting criteria also conclude 2% addition of pyro-oil as optimum dose as a modifier.

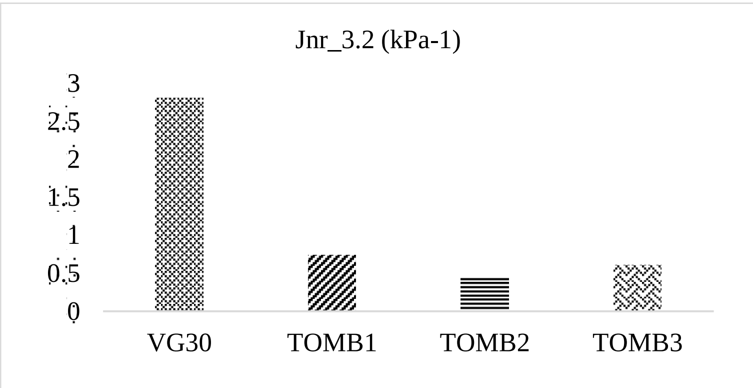


Fig.5. Non recoverable creep compliance for virgin and modified binders @60℃

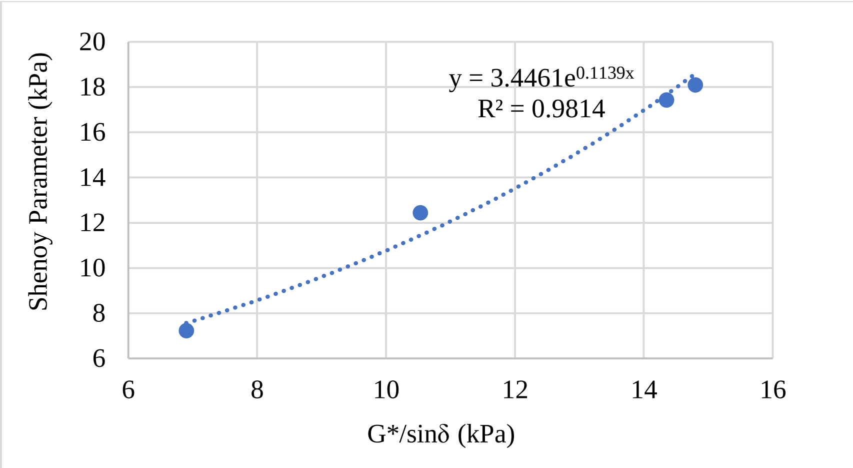
Since the MSCR test takes into consideration the loading and unloading conditions and has a potential to record the behaviour of the binders under these realistic test conditions, the J_{nr} may be considered as the most reliable rutting parameters of all.

Table 3. Designation based on $J_{nr\_3.2}$ value

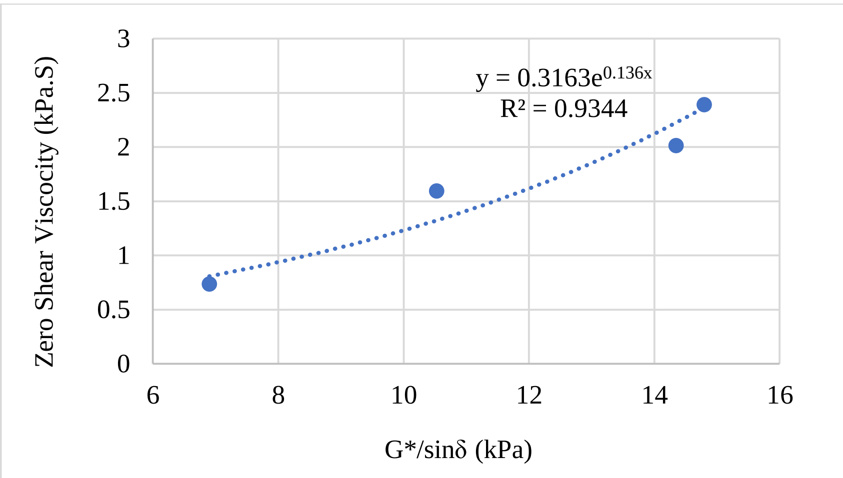
Traffic Level (ESALs) and load rate	Designation	Meaning	$J_{nr\_3.2}$ value (kPa^{-1})
>30 million and <20 km/h	E	Extremely high traffic loading	0.0 - 0.5
>30 million or <20 km/h	V	Very high traffic loading	0.5 - 1.0
10-30 million or 20-70 km/h	H	High traffic loading	1.0 – 2.0
<10 million and >70 km/h	S	Standard traffic loading	2.0 – 4.0

4.5 Relationship between the rutting parameters

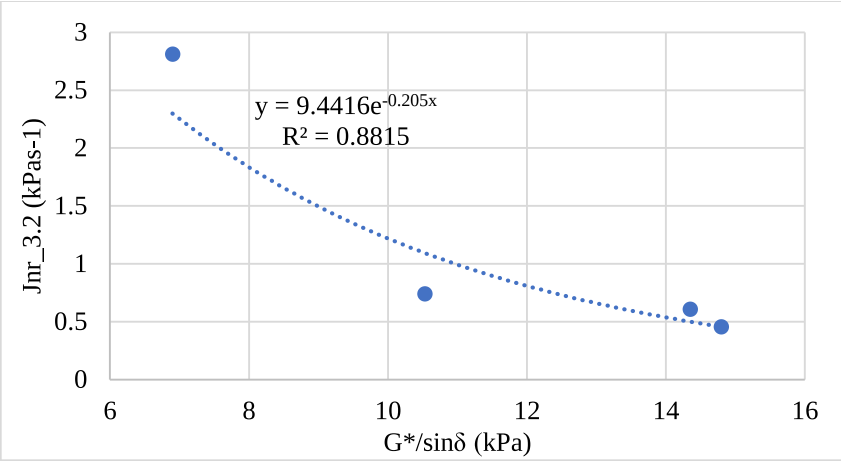
The correlation between Superpave rutting factor with Shenoy parameter, zero shear viscosity and non recoverable creep compliance is presented in Fig. 6 (i) – (iii). The trendline that best fitted to the data was selected for the correlation. It can be seen that the Shenoy parameter and zero shear viscosity increases with increase in G*/sinδ, while the increase in G*/sinδ resulted in a decrease in values. This was expected as higher values of G*/sinδ indicates more stiff binders.



(i)



(ii)



(iii)

Fig. 6 Correlation between (i) G*/sinδ and Shenoy's Parameter, (ii) G*/sinδ and ZSV and (iii) G*/sinδ and Jnr_3.2.

The critical values for Shenoy parameter, zero shear viscosity and non recoverable creep compliance corresponding to the limiting value of Superpave rutting factor (G*/sinδ) are 4.43 kPa, 0.42 kPa and 6.01 kPa-1 respectively. These correlations may be important in terms of helpfulness for estimating non recoverable creep compliance if one of the other parameters are known.

5. CONCLUSIONS

The study was aimed to characterise rutting resistance of VG30 bitumen containing tire pyro oil as modifiers in different percentages, using the Superpave rutting parameter (G*/sinδ), Shenoy parameter (G*/(1-(1/tanδ.sinδ))), zero shear viscosity and non recoverable creep compliance. The following conclusions are drawn from results of the study:

- Similar trend of rutting resistance of binder was given by Superpave rutting factor and Shenoy parameter. The Shenoy parameter overestimates the rutting resistance than the Superpave rutting factor.
- All the four parameters showed that addition of tire oil helps improve the rutting resistance of the VG30.
- 2% tire pyro-oil by weight of binder is found to be the optimum dosage for modification based on all the four rutting parameters.
- VG30 and VG30 +2% tire pyro-oil are found to be the least rut resistant and most rut resistant respectively based on the rheological parameters.
- A fine correlation was found between G*/sinδ and the remaining three rutting parameters. Alternative rutting parameters can be estimated using these correlations in absence of others.

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