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Research Article

Characterizing rheological properties and rutting risk of VG30 and PMB 40 binders with warm mix additives

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Abstract

In hot mix constructions, the paving and compaction processes must be carried out at temperatures ranging from 130°C to 150°C. Due to this, many countries restrict the paving activities to the summer months. However, the high temperatures lead to increased fuel consumption and significant environmental pollution. The emission of CO_2, a major greenhouse gas, poses a serious environmental concern. In response to rising environmental awareness and increasing energy costs, alternative paving materials have been developed that require lower operating temperatures not compromising to the performance. Warm Mix Asphalt (WMA) technology has emerged as a sustainable solution. The WMA technology allows the bituminous mixes to produce at comparatively lower mixing and laying temperatures and thus reducing the emission of greenhouse gases. The study aims at preparing mixes with two types of base binders along with warm mix additives in which six types of binders were prepared and studied the viscosity characteristics. Based on these, optimum additive content was determined. Fourier Transform Infra-Red (FTIR) tests were done to assess the variation in chemistry by the inclusion of organic and chemical warm mix additives in VG30 and PMB40 binders. Modulus values and phase angle data were determined using Dynamic Shear Rheometer (DSR) for all the binders along with the short-term aged binders and assessed the rutting potential. The rutting parameter was determined from the data obtained on the DSR and based on its relationship with temperature, VG30 and PMB40 with organic warm mix additive gave better results. Multiple Stress Creep Recovery (MSCR) tests were done to assess the rutting potential.

1. Introduction

Hot Mix Asphalt (HMA) construction is contributing to increased fuel consumption and environmental pollution in the pavement construction sector. The high temperatures required for mixing and compacting hot mix asphalt contribute to significant CO_2 emissions, which pose serious environmental concerns. However, incorporating a 1% organic warm mix additive into the base binder can reduce heat energy consumption by 2.8% and CO_2 emissions by 3.0% [1]. Increased environmental awareness and rising energy costs have driven the development of alternative paving materials that require lower operating temperatures while maintaining performance comparable to Hot Mix Asphalt (HMA). Warm mix asphalt (WMA) technology has emerged as a sustainable solution in this context [2]. This technology reduces the temperatures at which the asphalt is mixed and laid by incorporating warm mix additives into the binder prior to mixing [3]. WMA technology lowers mixing and laying temperatures significantly, resulting in reduced fuel consumption and cost, and minimizing risks [4].

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Research has shown that adding warm mix additives can lower production temperatures by over 10°C, according to the equi-viscous concept [5]. Although increasing the amount of organic warm mix additive reduces mixing and compaction temperatures, it also decreases resistance to fatigue.

Organic additives are effective in reducing viscosity and improving workability at low temperatures; also, environmentally friendly by reducing energy consumption; but having limited effect on long-term aging resistance and rutting performance. Chemical additives effective at improving binder durability over time but subjected to higher cost and complexity compared to organic additives. Foaming additives are excellent for reducing mixing temperature, leading to energy savings and lower emissions; environmentally sustainable, but may not provide significant long-term improvements in aging resistance or rutting resistance and the performance can vary depending on binder type. Experimental studies indicate that using a low viscosity binder with 1.6% organic warm mix additive can alleviate fatigue issues [6,7].

Among different WMA additives—organic, chemical, and foaming—organic warm mix additives have been found to produce the least emissions and energy consumption [8]. The optimal temperature for mixing and placing asphalt should be determined [9,10]. For improved pavement performance, polymer-modified bitumen is commonly used [11]. Evaluations of polymer-modified bitumen with organic warm mix additives, using Dynamic Shear Rheometer (DSR), showed that 3% organic warm mix additive with polymer-modified bitumen yielded the best results [12,13].

Studies comparing the rheological properties of polymer-modified bitumen with warm mix additives against short-term aged binders revealed that wax modification had a greater impact on aging [14]. Short-term performance assessments of plant-mixed warm stone mastic asphalt with chemical warm mix additives showed that pavements could be opened to traffic earlier compared to conventional mixes due to lower compaction temperatures [15]. The addition of organic WMA additives has been found to mitigate the effects of aging more effectively than chemical WMA additives [16]. Analysis of binder samples before and after aging, using conventional and DSR tests, indicated that modified binders exhibited greater property variations than base binders [17]. The influence of aging on the rheological properties and temperature susceptibility of three binder samples was analysed, with a focus on maltene content and residue viscoelastic response [18]. Penetration index values were used to assess binder response to temperature changes [19]. Evaluations of complex modulus and phase angle values in DSR showed that complex modulus is more sensitive to preheating variations than phase angle values [20].

The rheological properties of binders modified with various dosages of organic warm mix additives were analysed at different temperatures using DSR. The rutting factor decreased with increasing temperature and increased with higher additive dosage [21]. The Surface Free Energy method was used to find the rutting and fatigue resistance of nano clay modified binder and the study was conducted with four different types of aggregates. The fatigue performance was evaluated using Linear Amplitude Sweep test. The analyses of the data showed that addition of nano clay enhances the fatigue life of binder. Enhanced resistance to rutting and fatigue was observed with the addition of nanomaterials [22]. Chemical and rheological analyses of binders from two sources showed that one exhibited better aging performance based on its chemical composition [23]. FTIR spectra comparisons between base and modified binders revealed additional peaks in the modified binders [24]. FTIR was used to characterize both unmodified and modified binders [25]. Rubber-modified asphalt showed significant performance improvements at high temperatures, as evidenced by MSCR tests and statistical analysis, with a decrease in residual strain upon modification [26].

Remisova, E. and Holy, M. (2017) studied the changes of properties of bitumen binders by additives application. To improve the qualitative properties, four types of additives were added with the base binders and the effects of additives on penetration, softening point and viscosity were studied as per European standards. The addition of some additives changed the PI values significantly and moved the binders to less temperature susceptible, resulting an enhancement in their resilience and adaptability to varying climatic conditions. These findings provide a comparative study for understanding the modifications and highlighting the potential of additives to improve binder performance in diverse environmental scenarios [36]. Mokhtari and Nejad studied the rheological properties of binders modified with wax and SBS modified in which penetration, penetration index, softening point and ductility were measured. Also, the rate at which the consistency of the binder changes, that is temperature susceptibility was assessed based on the penetration index values [2]. Sengoz and Isikyakar evaluated the properties and microstructure of polymer modified bitumen. The results indicated that the properties and morphology are dependent on the polymer modification, which improved the conventional properties such as penetration, softening point and penetration index values. The increase in softening point values were favorable since bitumen with higher softening point values may be less susceptible to permanent deformation [38].

The literature reveals a gap in detailed comparative studies on the viscosity and rheological properties of VG30 and PMB40 binders with organic and chemical warm mix additives across various dosages. Additionally, there is insufficient exploration of how these additives interact with different binder types, particularly regarding their long-term aging and rutting potential. The primary objective of this study is to compare the viscosity and rheological properties of VG30 and PMB40 binders with the incorporation of organic and chemical warm mix additives. FTIR spectra were analyzed for binder samples with various additive dosages. Rheological properties were assessed using Dynamic Shear Rheometer data for both unaged and short-term aged samples, modified with these additives and subjected to the Rolling Thin Film Oven Test. Additionally, rutting potential was evaluated through the MSCR test.

The study aims at preparing mixes with two types of base binders, VG30 and PMB40 along with organic and chemical warm mix additives in which six types of binders were prepared and studied the viscosity characteristics. Based on these, optimum additive content was determined. FTIR tests were done to assess the variation in chemistry by the inclusion of organic and chemical warm mix additives in the base binders. The rutting parameter was determined from the rheological data obtained on the DSR and MSCR tests were done to assess the rutting potential. So the study aims at assessing the properties of base binders along with organic and chemical warm mix additives and making a comparison between them.

2. Methodology

2.1 Materials and Components

VG30 and PMB40 serve as base binders for this study, with both organic and chemical warm mix additives used. The organic warm mix additive is incorporated into the base binder once it reaches pouring consistency, while the chemical warm mix additive is blended using a Cowls' blade mechanical shaker (Fig. 1(a)). Organic warm mix additives are added in concentrations ranging from 1% to 4%, while chemical warm mix additives are used at 0.1% for unmodified binders and 0.125% for modified binders, according to manufacturer recommendations. VG30 (V) is combined with organic warm mix additives at 1% (VS1), 2% (VS2), 3% (VS3), 4% (VS4), VS with optimum organic additive, and with chemical warm mix additive (VZ). Similarly, PMB40 (P) is mixed with organic warm mix additives at 1% (PS1), 2% (PS2), 3% (PS3), 4% (PS4), PS with optimum organic additive, and with chemical warm mix additive (PZ).

The conceptual framework guiding the choice and dosage of organic and chemical warm mix additives was based on their influence on binder properties and mixture performance. Organic additives were selected for their ability to reduce the viscosity of bitumen through internal lubrication mechanisms, while chemical additives were chosen for their surfactant properties that improve coating and workability at lower temperatures. Dosages were determined through preliminary trials, aligning with manufacturer recommendations and optimized based on their compatibility with the binder and aggregate properties. These additives were assessed to ensure they met the desired performance criteria, such as reduced mixing and compaction temperatures without compromising the mechanical properties of the mix. Also, the additives must meet the specifications which may vary due to the traffic conditions and environmental factors. The maximum binder content was determined using the proposed mixes prepared with the addition of warm mix additives, following the Marshall method of mix design.

The DSR is a key rheological test that measures the viscoelastic properties of asphalt binders at different temperatures and loading conditions. It helps to assess the binder's ability to resist deformation under low and high temperatures in which the complex shear modulus (G)* and phase angle (δ) of the binder is calculated which are the critical parameters for evaluating rutting resistance. The MSCR test is a crucial tool for evaluating the rutting resistance and viscoelastic properties of binders under simulated traffic loading conditions which provides additional insights into the high-temperature behavior of binders, complementing the DSR test. The MSCR test subjects the binder to stress application and recovery cycles at high temperatures, simulating the effects of repeated traffic loading. This allows the measurement of the non-recoverable creep compliance (Jnr), which quantifies the binder's susceptibility to permanent deformation. The Jnr value measures the degree of permanent deformation after multiple loading cycles in which a lower Jnr indicates better rutting resistance. DSR primarily measures the stiffness and elasticity of the binder, while the MSCR test focuses on the deformation characteristics of the binder under repeated traffic loading.

FTIR spectroscopy is a tool for characterizing functional groups and chemical bonds in materials, making it an ideal method for analyzing the chemical changes in binders, especially when modified with warm mix additives. The basic reason for using FTIR can be such that it provides detailed information about the chemical structure of the binder and also can detect the minor changes in the functional groups that may be induced by the additives.

2.2 Experimental Setup

VG30 and PMB40, used as base binders, are tested to determine physical properties such as specific gravity, penetration, softening point, ductility, and viscosity. The physical properties of binders modified with organic and chemical warm mix additives are also evaluated. The effects of these modifications are analyzed using FTIR spectra. Viscosity is measured with a Brookfield Viscometer, short-term aging is assessed using the Rolling Thin Film Oven Test, complex modulus and phase angle are obtained from a DSR (Fig. 1(b)), and rutting potential is evaluated through the MSCR test.

(a)

(b)

Fig. 1(a). Cowls' blade mechanical shaker and (b) Dynamic Shear Rheometer (DSR)

3. Results and Discussions

3.1 Physical Properties of Binders

Physical properties of VG30 and VG30 modified with organic and chemical warm mix additives; and PMB40 and PMB40 modified with organic and chemical warm mix additives are given in Table1.

Table1. Physical properties of binders

Bitumen	Penetration, 1/10 of a mm	Softening point, °C	Ductility, cm	Elastic recovery, %	Specific Gravity	Penetration Index
V	58	51	83	63	1.01	-0.61
VS1	55	56.5	>75	64	1.01	0.54

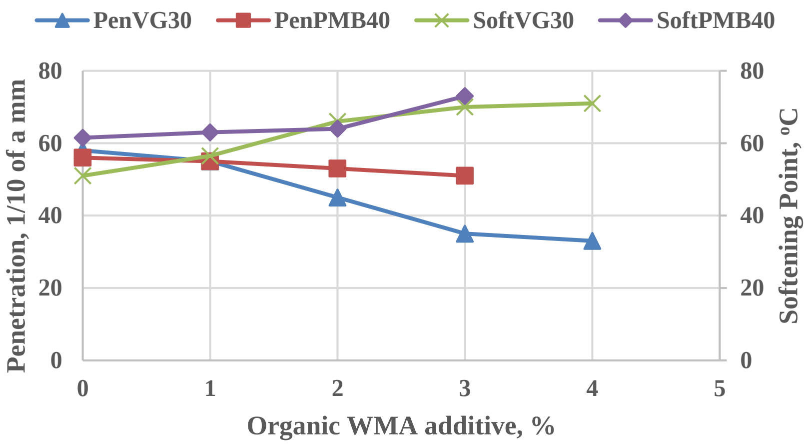
VS2	45	66	>75	68	1.01	1.88
VS3	35	70	>75	69	1.02	1.95
VS4	33	71	>75	68	1.02	1.97
VZ	41	71	>75	68	1.02	2.49
P	56	61.5	>75	71	1.02	1.62
PS1	55	63	>75	68	1.02	1.86
PS2	53	64	>75	71	1.02	1.94
PS3	51	73	>75	70	1.01	3.36
PZ	46	75	>75	68	1.01	3.39

3.2 Temperature Susceptibility Based on Penetration Index Values

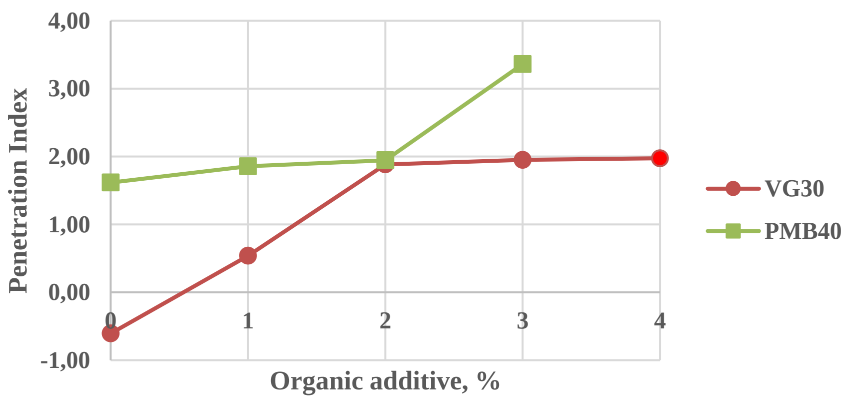
The basic characterization of the binders was performed through penetration tests at 25°C and softening point tests. Temperature susceptibility was evaluated by calculating the penetration index (PI) values, which assess how the binder's properties change with temperature. PI values for all binder samples were determined following the methodology outlined in the Shell Bitumen Handbook [27] as described in Eq (1):

$$PI = \frac{1952 - 500 * log(Pen25) - 20 * SP}{50 * log(Pen25) - SP - 120} \quad (1)$$

Where, Pen25 is the penetration at 25°C and SP is the softening point temperature. Penetration and softening point values of binders modified with varying dosages of organic warm mix additives are given in Fig. 2(a).



(a)



(b)

Fig. 2. (a) Penetration and softening point values of binders modified with varying dosages of organic warm mix additive, (b) Penetration index values of binders modified with organic warm mix additive

For VG30, increasing the dosage of organic warm mix additives from 0% to 4% results in a 43% decrease in penetration values, while the reduction with chemical warm mix additives is 29%. For PMB40, increasing the dosage of organic warm mix additives from 0% to 3% leads to a 9% decrease in penetration values, whereas the reduction with chemical warm mix additives is 18%. This reduction in penetration values may be attributed to the binder hardening caused by the addition of warm mix additives at intermediate temperatures. Regarding the softening point, for VG30, increasing the organic warm mix additive dosage from 0% to 4% results in a 39% increase, with a similar 39% increase observed when using chemical warm mix additives. For PMB40, increasing the organic warm mix additive dosage from 0% to 3% leads to a 19% increase in the softening point, while the increment with chemical warm mix additives is 22%. The increase in softening point values may be due to binder hardening caused by the warm mix additives at higher temperatures. This hardening could potentially enhance rutting resistance. The penetration index (PI) values for the base binders and those modified with warm mix additives are presented in Fig. 2(b). For paving bitumen, the penetration index (PI) values should fall between -2 and +2. A lower PI indicates that the binder's consistency changes more rapidly with temperature fluctuations, demonstrating greater temperature sensitivity. For VG30, when modified with organic warm mix additives, the PI values remain within this range, but with chemical warm mix additives, the PI values slightly increase. For PMB40, the PI values remain within the range when modified with up to 2% organic warm mix additive, but increase slightly with 3% organic warm mix additive and chemical warm mix additives. Consequently, the temperature susceptibility of all mixes, except those with chemical warm mix additives, is improved. VG30 and PMB40 with chemical warm mix additives, and PMB40 with 3% organic warm mix additive, show higher temperature susceptibility compared to other binders.

3.3 Viscosity Analysis Using Brookfield Viscometer

Viscosity tests were performed using a Brookfield viscometer, which assesses dynamic viscosity through a rotating spindle. The mixing and compacting temperatures for both the base binders and those modified with warm mix additives were determined according to the equi-viscous concept. The results are summarized in Table 2.

Table 2. Mixing and compacting temperatures for VG30 & PMB40 with warm mix additives

Binder	Mixing Temperature, °C	Compacting Temperature, °C
V	155-160	145-150
VS1	150-155	140-145
VS2	137-142	133-138
VS3	135-140	130-135
VZ	135-140	125-130
P	165-170	155-160
PS1	160-165	150-155
PS2	145-150	130-135
PS3	140-145	133-138
PZ	140-145	128-132

The addition of organic warm mix additives lowers the mixing and compaction temperatures for all samples. For VG30, a 1% organic warm mix additive reduces the mixing temperature by 3.2% compared to the base binder, while 2-4% reduces it by 10%. The corresponding reductions in compaction temperatures are 3.4% and 7%, respectively. In contrast, the addition of a chemical additive lowers the mixing temperature by 16% and the compaction temperature by 17%. For PMB40, a 1% organic warm mix additive reduces the mixing temperature by 3% compared to the base binder, with 2-4% reducing it by 12%. The corresponding reductions in compaction temperatures are 3.2% and 11%, respectively. The chemical additive reduces the mixing temperature by 15% and the compaction temperature by 16%.

Dynamic viscosity measurements from the Brookfield viscometer for all binder types with organic and chemical warm mix additives are shown in Fig. 3. Both types of additives significantly reduce the mixing temperatures of the binders. The desired viscosity for proper mixing is 0.17 ± 0.02 Pa·s. Compared to the base binders; viscosity decreases considerably with increasing temperature due to the addition of warm mix additives.

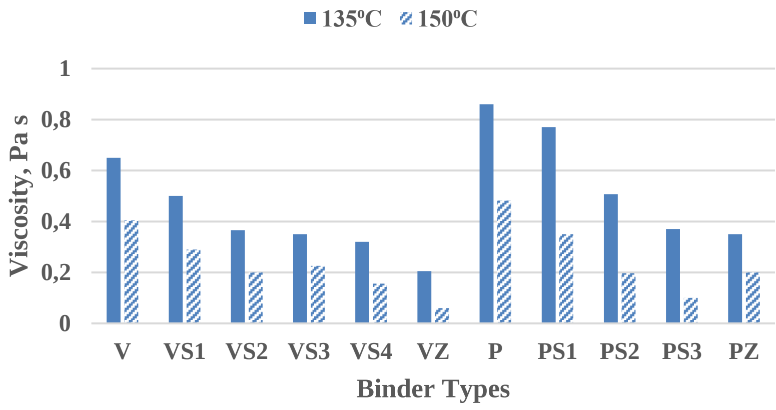
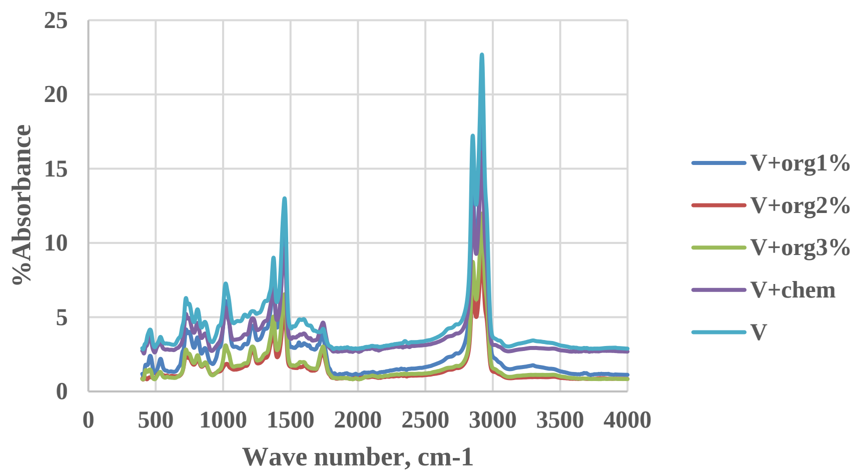


Fig. 3. Viscosity data for the binders

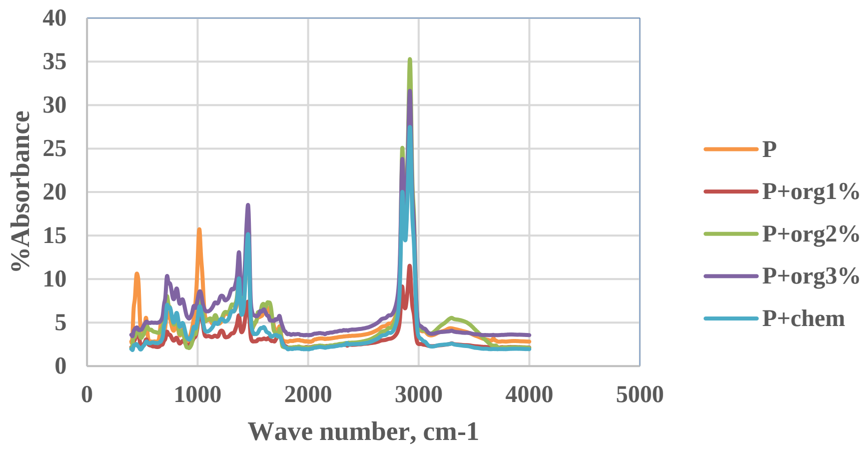
3.4 FTIR Analysis of Binder Modifications with Warm Mix Additives

The spectroscopic technique utilizes infrared light to study the interaction between radiation in the infrared region and molecules. Infrared radiation is absorbed by the sample, causing bonds to stretch, a process known as vibrational transition, which can be identified from the spectrum. The infrared spectrum is recorded by passing a beam of infrared light through the sample. Absorption occurs when the frequency of the infrared light matches the vibrational frequency of a bond or group of bonds. The transmitted light is analyzed to determine how much energy was absorbed at each frequency (or wavelength). Adding warm mix additives can alter the chemistry and rheology of binders, and FTIR is used to identify the functional groups. FTIR spectra for VG30 and PMB40 modified with 1%, 2%, and 3% organic and chemical warm mix additives are shown in Fig. 4(a) and Fig. 4(b).

For PMB40, the peak values in the range of 3000 to 3500 cm^{-1} also correspond to the strong O-H stretching bonds of carboxylic acids. The percentage absorption for PMB40 mixed with 2% organic warm mix additive is higher compared to the base binder. The broad peak in the range of 2850 to 2920 cm^{-1} reflects the C-H stretch of alkanes, indicating a higher saturate content in PMB40 binders with 2% organic warm mix additive.



(a)



(b)

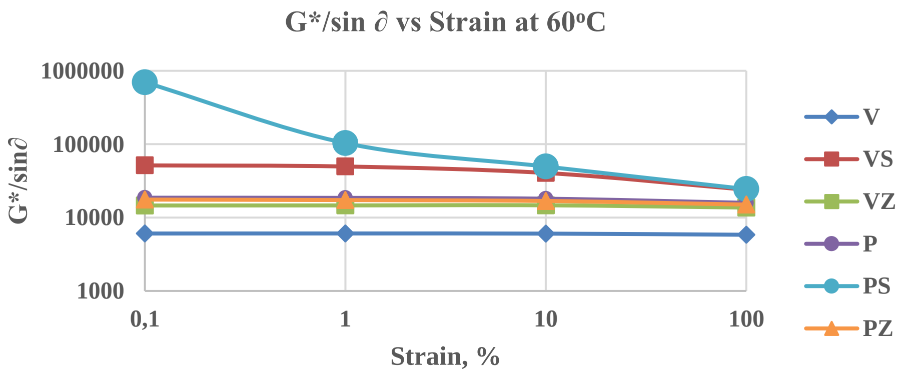
Fig. 4. (a) FTIR spectra of VG30 with varying % of organic WMA additive and chemical WMA additive and (b) FTIR spectra of PMB40 with varying % of organic WMA additive and chemical WMA additive

The reduction in viscosity at lower temperatures may be attributed to this increased saturate content. The peak at 1650 cm^{-1} denotes the C=C stretch of alkenes, with PMB40 mixed with 2% organic warm mix additive showing higher absorption compared to the base binder. The peak at 1456 cm^{-1}, representing the bending of CH_2 and CH_3, shows higher absorption for PMB40 mixed with 2% and 3% organic warm mix additives, indicating more aromatic compounds or asphaltenes. Similarly, the peak at 1378 cm^{-1} shows increased absorption for PMB40 with 2% and 3% organic warm mix additives compared to the base binder. The peak at 1230 cm^{-1} represents the C-O bond in carboxylic acids, with higher absorption observed for PMB40 mixed with 2% and 3% organic warm mix additives. The optimum content of organic warm mix additive was determined to be 2% based on the equi-viscous concept and FTIR analysis, which is also confirmed by temperature susceptibility studies based on PI values.

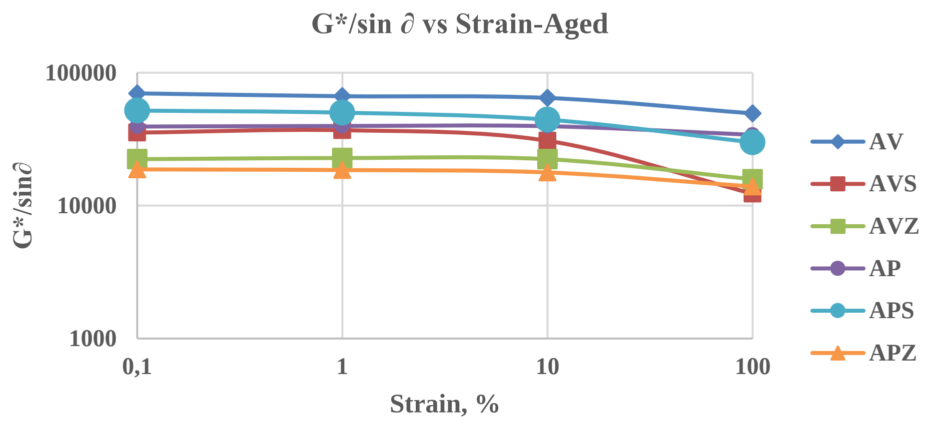
3.5 Comparative Analysis of Rutting Factor Using DSR

Total resistance to deformation can be measured by complex modulus, G*. Complex modulus and phase angle data will give an idea about how the material behave under traffic conditions at specified temperature. The test was conducted at 10rad/sec. An increase in the value of $G^*/\sin\partial$ indicates better rutting potential than in the case of base binders for various strain levels. A drastic increase such as 4 to 7 times in rutting factor is observed in VG30 modified with organic warm mix additives. Also, an increase of 2 times in rutting factor is observed in VG30 modified with chemical warm mix additives. An increase in trend is also observed in rutting factor in PMB40 modified with organic warm mix additives but a slightly decreasing trend is observed in PMB40 modified with chemical warm mix additives. Both the base binders modified with organic warm mix additives are showing more rutting potential as compared to the other mixes.

Variation of rutting factor with different strain values at 60°C for the unaged and aged binders are given in Fig. 5(a) and Fig. 5(b) respectively. After the binders are aged by RTFOT method, the base binder VG30 and PMB40 mixed with organic warm mix additive are showing good results to rutting potential. Aged PMB40 and aged VG30 with organic warm mix additive are showing similar results. Both the base binders mixed with chemical warm mix additive are showing least results in the form of rutting potential after ageing. At 60°C, $G^*/\sin\partial$ should be greater than 1.0kPa and for all the samples the values are more than that. Also, for the aged specimens, the value should be more than 2.2kPa [28].



(a)

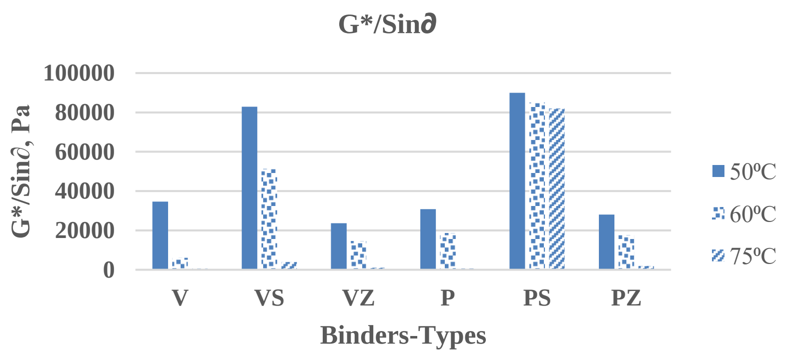


(b)

Fig. 5. (a) Variation of rutting factor for the unaged binders and (b) Variation of rutting factor for the aged binders

3.6 Variation of Rutting Parameter with Temperature

Variation of rutting factor at high temperatures for the base binders and for the base binders modified with warm mix additives are shown in Fig. 6(a); and for the RTFOT samples are shown in Fig. 6(b). For all the samples, the rutting factor is more than the standard value of 2.2kPa after RTFO test method. Increasing trend of rutting factor indicates improvement in rutting potential in the case of PMB40 and VG30 & PMB40 modified with organic warm mix additives.



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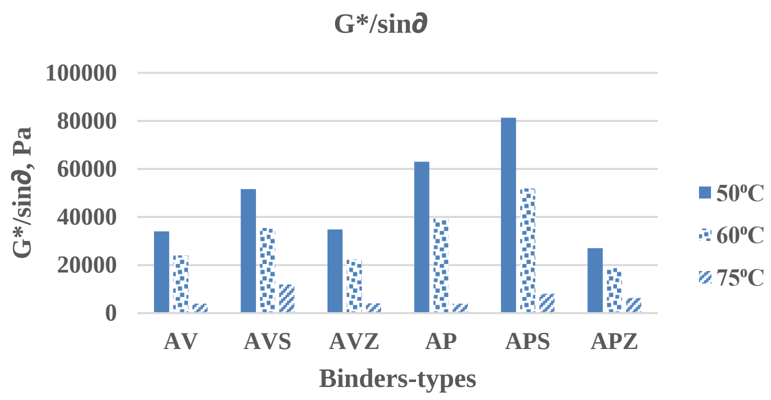

(b)

Fig. 6. (a) Variation of rutting factor at high temperatures and (b) Variation of rutting factor at high temperatures for RTFOT samples

The increase in rutting factor in VG30 with organic and chemical warm mix additives as compared to the base binder are 51% and 2.2% respectively. The change in rutting factor in PMB40 with organic and chemical warm mix additives as compared to the base binder are 29% and -57% respectively. Also, the rutting potential is decreasing at the increase of temperature. There is no improvement in rutting potential as compared to the other binders can be seen in PMB40 modified with chemical warm mix additive.

3.7 Influence of RTFOT Ageing on Binder Temperature Susceptibility

In dynamic mechanical analysis, the temperature susceptibility of binders may be calculated by measuring storage and loss moduli and complex modulus at different temperatures [29] as per the Eq (2):

$$G^*TS = (\log\log G1^* - \log\log G2^*)/(\log T2 - \log T1) \qquad (2)$$

where, G_1^* is the complex modulus at T_1, G_2^* is the complex modulus at T_2, and T_1 & T_2 temperature in Kelvin. Also, G*TS is the temperature susceptibility due to complex modulus.

Ageing of binders can be evaluated by calculating ageing index, which is obtained by taking the ratio of the rheological parameter of the aged binder to that of the unaged binder. Table 3 compares the values of the temperature susceptibility obtained using the complex modulus values at 50°C and 60°C; and also, the ageing index values.

Table 3. Temperature susceptibility in terms of complex modulus; and ageing index values

	G*TS 50°C to 60°C		Ageing Index	
Binder	Before RTFOT	After RTFOT	At 50°C	At 60°C
V	5.90	1.87	1.87	3.58
VS	1.53	1.09	0.59	0.70
VZ	1.66	1.52	1.39	1.43
P	1.64	1.51	2.11	2.12
PS	0.60	1.38	0.29	0.23
PZ	1.40	1.27	0.96	1.00

Base binder VG30 is less temperature susceptible compared to the other binder combinations. From 50°C and 60°C, the aged specimens also have not much reduction in temperature susceptibility and this may be due to the increased values of complex modulus after ageing by RTFOT method. At 60°C, for the base binders VG30 and PMB40 and VG30 with chemical warm mix additive, high value of the ageing index is showing which indicates high degree of binder hardening. Also, the same trend is seen in the case of 50^{o}C.

3.8 MSCR Test for Assessing the Rutting Potential

The MSCR test in binders uses the concept of creep and recovery to evaluate the potential for permanent deformation. After the one second load is removed, the sample is allowed to recover for 9 seconds for the low and high stress levels of 0.1kPa and 3.2kPa respectively. Sometimes the G*/sin∂ data obtained does not exactly serve the ability of some polymer modified binders to resist rutting as low levels of stress and strain are used in the test procedure. But in MSCR test, higher levels of stress and strain are applied to the binder which represents the actual condition of the pavement. Non recoverable creep compliance (Jnr) values from MSCR test for all the binder samples for the stress levels of 0.1kPa and 3.2kPa are given in Fig. 7.

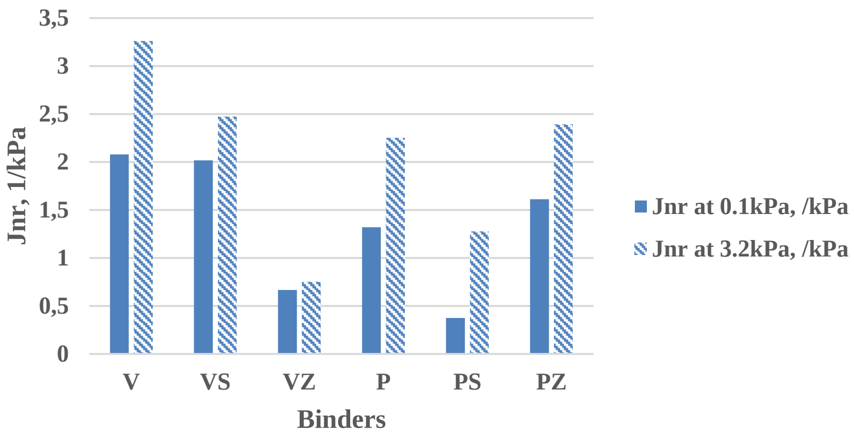

Fig. 7. Variation of Non recoverable creep compliance values (Jnr) for the binders

The influence of additives on rutting resistance was evaluated through non-recoverable creep compliance (Jnr) values under repeated load testing at different stress levels. Based on the Jnr values, for standard traffic loading, the base binders VG30 and PMB40; and VG30 with organic additive and PMB40 with chemical additive gave better rutting potential. For heavy traffic loading, VG30 with chemical additive and PMB40 with organic additive gave better rutting potential. At lower stress level, the non-recoverable creep compliance values under repeated load for the binder samples of VG30, VG30 with organic additive, PMB40 and PMB40 with chemical additive are higher as compared to the samples of VG30 with chemical additive and PMB40 with organic additive. The same trend is observed at higher stress level also for the same samples under repeated load. The difference between the values at the lower and higher stress levels for the same sample is low in VG30 with chemical additive indicating its superior performance and suitability for applications involving heavy traffic loading. This behavior underscores the ability of chemical additives to enhance binder stiffness and improve rutting resistance across varying stress conditions.

4. Conclusions

The study demonstrates that the addition of organic and chemical warm mix additives to VG30 and PMB40 binders significantly impacts their physical and performance characteristics. Notably, VG30 and PMB40 show substantial reductions in penetration values when mixed with these additives, with the most pronounced effects observed at 2-3% organic additive content. This results in similar trends in softening point values, indicating that both types of warm mix additives increase the binder's resistance to temperature variations. This reduction in penetration values may be attributed to the binder hardening caused by the addition of warm mix additives. As PI indicates binder's ability to change with temperature fluctuations, the results of the samples with organic warm mix additives showed better temperature susceptibility properties as compared to the chemical additives. Increasing the organic warm mix additive dosage from 0% to 4% results in a 39% increase, with a similar 39% increase observed when using chemical warm mix additives. For

PMB40, increasing the organic warm mix additive dosage from 0% to 3% leads to a 19% increase in the softening point, while the increment with chemical warm mix additives is 22%.

The equi-viscous concept applied to viscosity studies reveals that both organic and chemical warm mix additives lower the mixing and compacting temperatures of the binders. This adjustment in temperature contributes to improved rutting potential as measured by the $G^*/\sin\delta$ parameter, except for PMB40 with chemical warm mix additive, which does not meet the standard specifications at 60°C. VG30 and PMB40 binders, particularly with organic additives, show enhanced rutting performance for both unaged and aged samples, comparing with the rutting performance of the samples with the chemical additives. Studies using DSR revealed a drastic increase such as 4 to 7 times in rutting factor in VG30 modified with organic warm mix additives. Also, an increase of 2 times in rutting factor is observed in VG30 modified with chemical warm mix additives. An increase in trend is also observed in rutting factor in PMB40 modified with organic warm mix additives but a slightly decreasing trend is observed in PMB40 modified with chemical warm mix additives. Both the base binders modified with organic warm mix additives are showing more rutting potential as compared to the other mixes.

After the binders are aged by RTFOT method, the base binder VG30 and PMB40 mixed with organic warm mix additive are showing good results to rutting potential.

In the FTIR analysis, the peak values in the range of 3000 to 3500 cm^{-1} represent the strong O-H stretching bonds associated with carboxylic acids. The percentage absorption of both the binders mixed with organic and chemical warm mix additives is higher compared to the base binders. A broad peak in the range of 2850 to 3000 cm^{-1} corresponds to the C-H stretch of alkanes, which are long-chain hydrocarbons. Among VG30 binders, those with 2% and 3% organic warm mix additives show higher saturate content. The reduction in viscosity at lower temperatures for VG30 with 2% organic warm mix additive may be due to the increased saturates content.

Ageing assessments using the ageing index indicate a higher degree of binder hardening at 50°C and 60°C for VG30, PMB40, and VG30 with chemical warm mix additives. The MSCR test results highlight that VG30 and PMB40 base binders, along with VG30 with organic additives and PMB40 with chemical additives, exhibit better rutting potential under standard traffic loading conditions. For heavy traffic loading, VG30 with chemical additives and PMB40 with organic additives provide superior rutting resistance.

In the laboratory, temperatures during mixing and compaction were measured manually, which differs from field practices where automated temperature controllers and monitoring systems are typically employed to ensure consistent thermal conditions. While the manual method provided adequate control for experimental purposes, it may not fully replicate the precision achievable in actual field scenarios. To address this limitation, future studies could incorporate advanced temperature control systems during mixing and compaction to better simulate real-world conditions and improve the reliability of lab-to-field performance correlations. Predicting the exact temperature in the mixing plant is challenging, but the development of a suitable temperature control system could be achieved by adopting an interdisciplinary approach in collaboration with researchers from other fields, which could greatly benefit the Transportation Engineering sector. As the additives used in this study are present in very small quantities, determining their precise environmental impact is complex. Additionally, the long-term effects of these additives on environmental balance could be explored in future research, including any cumulative impacts that might emerge over time. Future research could build on these findings by focusing on real-world testing at mixing plants, conducting life cycle assessments of additives, and exploring their long-term environmental consequences. Such studies would provide a more comprehensive understanding of the sustainability and practical implications of using warm mix additives in bituminous binders.

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