

CHAPTER 6. CHARACTERISATION AND COMPARITIVE EVALUATION OF REJUVENATORS

6.1 Preamble

Recycling additives, commonly known as rejuvenators, are generally used to reverse or restore the consequence of aging on reclaimed asphalt pavement (RAP) materials, more specifically, aged binder [47,303]. Alterations in the asphalt binder's colloidal structure occur as it ages. Proportions of asphaltenes and maltenes, the basic constituents of the asphalt binder's colloids, change with aging. Maltenes portions (aromatics and resins) get converted to asphaltenes, while the saturates portion of maltenes remains more or less the same due to low reactivity [90,96]. Also, asphaltenes form agglomerations and result in colloidal instability. Largely, aging results in the binder with low maltenes content (and solvency power) and increased asphaltenes (clusters) [98,107]. Thus, rejuvenators should restore the colloidal stability by supplying the deprived maltenes content and breaking the asphaltenes clusters [84].

Various innovative products have been used in literature to reverse the effect of aging and for the successful utilization of RAP in hot mix asphalt. Four rejuvenators are used in this study and out of which two are commercial products and remaining two are waste-type (recycled) products. Commercial rejuvenators (CR) are engineered products manufactured to resemble the maltenes portion of asphalt binder. Essential ingredients for CR can be either bio-oil-based or petroleum-based. There can even be some additional components intended for specific purposes such as enhancing moisture or aging resistance etc. On the other hand, waste type rejuvenators (WR) are recycled or re-used products of petroleum or agricultural or animal-based oils. WR, being a re-used product, has an economic advantage over CR. However, the process of collection, maintaining uniformity (in terms of source), processing (required in some cases), and then integrating it into the hot mix asphalt (HMA) can be challenging.

CHAPTER 6

Other than the economic and source-related features of CR and WR, important aspects that must be assessed to recognize the best rejuvenator type are thermal stability, binder, and mixture performance. This would further help pave the way for future research on the choice of rejuvenator type in the domain of recycling. No previous study has been focused on the comparative evaluation of CR and WR. Considering the high temperatures involved in HMA, rejuvenators should have (thermal) stability after subjecting to mixing and compaction temperatures. Therefore, the RTFO test, used to mimic the short term aging (of asphalt binder) in the laboratory, is conducted on the rejuvenators. And before the further assessment of the rutting and fatigue performance of binders and mixes, optimum dosage of each rejuvenator are also evaluated.

Dosage of a rejuvenator is one of the key aspect that controls the effectiveness of recycling. In the early 90's, composition of the blend of aged binder and rejuvenator, penetration or viscosity are used to estimate the content or dosage of rejuvenator [304,305]. Penetration or viscosity methods are most preferred methods considering the simplicity of the tests. With the advancement of PG grading and uncertainties in the performance of recycled mixes (rejuvenators dosage) designed using penetration or viscosity methods, focus was shifted to PG grading of the recycled binder blends. Following this, various researchers [114,294,295,306–311] studied the suitability of the performance related specifications of binder estimated using the dynamic shear rheometer and bending beam rheometer. Parameters such as high temperature performance grade (PGH), intermediate temperature performance grade (PGI), low temperature performance grade (PGL), delta T_c (ΔT_c) parameter, Glover-Rowe (G-R) parameter, glass transition temperature, Non-recoverable creep compliance and recovery at 3.2 kPa stress ($J_{nr3.2}$ and $R_{3.2}$), crossover frequency, rheological index parameter, relaxation properties are some of the parameters that have been explored by different researchers for the calculation of quantity of rejuvenator required for the effective utilisation of RAP.

Comparative evaluation of some of the parameters have also been done in some of studies. E. Arámbula-Mercado et al. [308] proposed to use PGH to estimate the optimum dosage of rejuvenator, P. Lin, X. Liu, P. Apostolidis et al. [310] considered wide number of parameters and found that MSCR and frequency sweep tests are enough to estimate the optimum dosage (based on a SBS polymer modified binder), R.B. Ahmed et al. [311] observed that $J_{nr3.2}$ was more sensitive to the rejuvenator type and dosage and D. B. Sánchez et al. [295] suggested to estimate the optimum dosage using PGH while simultaneously verify the PGL. However, considering the variety of recognized parameters for the dosage optimisation and variables that impact the dosage such as percentage of RAP and type of rejuvenator, it is highly difficult to use a single parameter to evaluate the dosage. Therefore, a comprehensive study is conducted to identify the best suitable parameter for optimising the dosage of rejuvenator. For the combination of two RAP percentages and four rejuvenators used in this study, a total of nine parameters (as elaborated in next sections) are considered to evaluate the optimum dosage of rejuvenators.

6.2 Experimental framework

The objective of comparative evaluation of rejuvenators is done in three tasks. The first task involves the evaluation of viscosity, thermal stability and chemical composition of rejuvenators. In the second task, binder blends with different rejuvenators and RAP contents were initially prepared. The required dosages of rejuvenators were then determined based on multiple parameters, including penetration, softening point, high- and intermediate-temperature performance grading, zero shear viscosity, crossover frequency, Glover–Rowe parameter, non-recoverable creep compliance, and RILEM criteria. Subsequently, Tukey’s post-hoc analysis was carried out to examine whether statistically significant differences existed among the dosages obtained from these parameters. Finally, the performance of recycled mixes prepared at the respective dosages was evaluated to identify the optimum

rejuvenator dosage. Once the optimum dosage of rejuvenators is evaluated, mixture and binder performance are assessed in the third task. A flowchart of the methodology related to the comparative evaluation of waste and commercial rejuvenators adopted is shown in Figure 6-1.

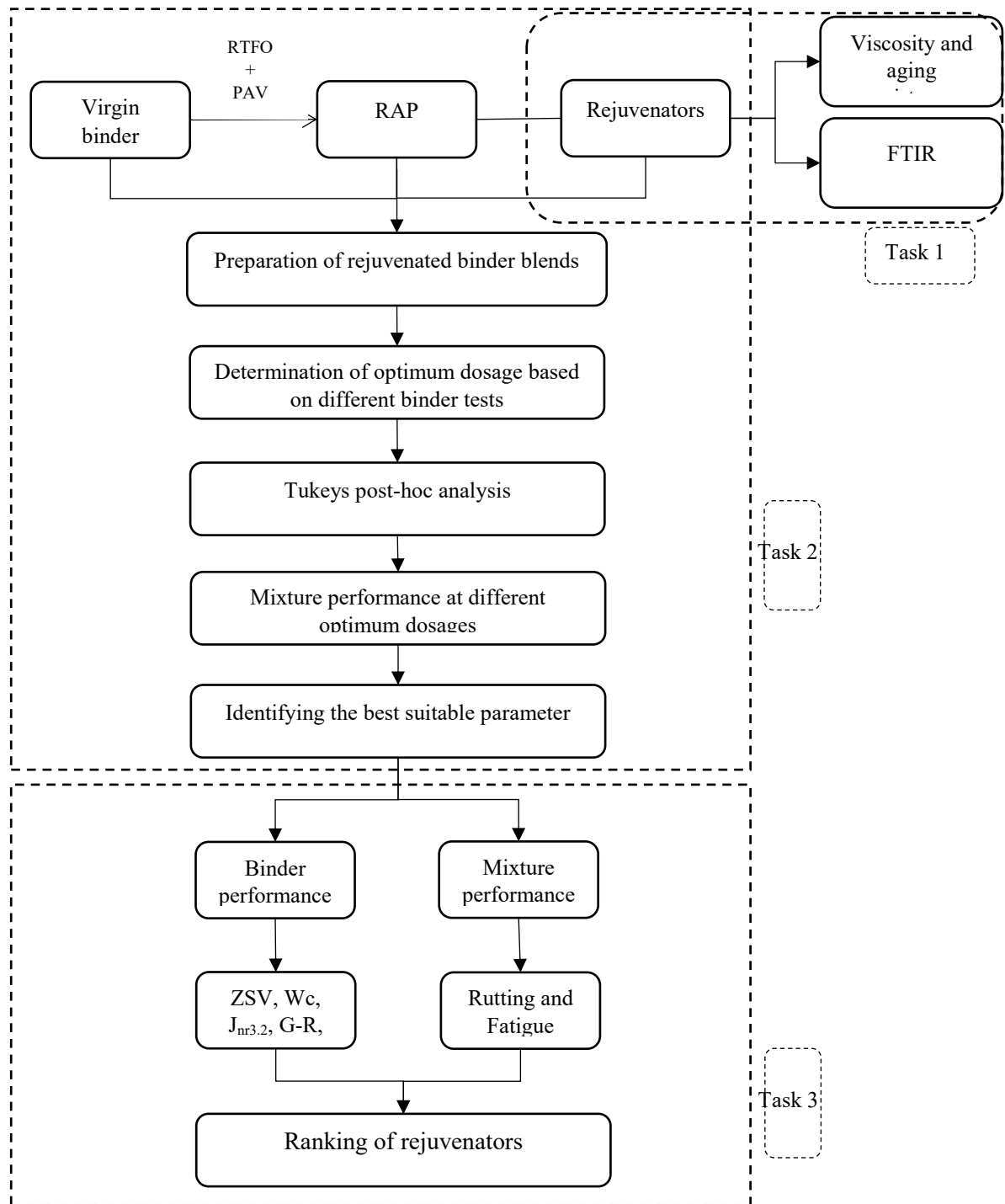


Figure 6-1 Flowchart of the experimental program

6.3 TESTS

6.3.1 *Task-1: Tests on rejuvenators*

6.3.1.1 *Viscosity and aging resistance of rejuvenators*

A concentric cylinder viscometer (Brookfield viscometer) is used to determine the viscosity of rejuvenators. The torque required to rotate a spindle at a specific shear rate (0.05 s^{-1}) inside a tube filled with a rejuvenator is used to calculate the viscosity [312]. Also, the effect of heat and air based on the change in weight and viscosity values are evaluated using a rolling thin film oven (RTFO) test as per ASTM D 2872-19 [154]. The test process involves rotating ($15 \pm 0.2 \text{ rpm}$) a thin film of rejuvenator in the oven at a temperature of $163 \pm 0.5^\circ\text{C}$ for 85 minutes while subjecting it to an airflow of $4000 \pm 200 \text{ mL/min}$.

6.3.1.2 *Fourier Transformed Infrared Radiation*

Particulars of FTIR are specified in the section 5.4.1, still some information is also provided in this section. Studying the chemical composition or constituents of matter based on the absorption of a specific band of the electromagnetic spectrum is termed spectroscopy. In Fourier Transformed Infrared Radiation (FTIR) spectroscopy, infrared radiation (especially of wavelength 0 to 4500 cm^{-1}) is used, and the absorbed or transmitted spectra are Fourier-transformed with the help of an interferometer. In a molecule, a chemical functional group constantly vibrates and absorbs infrared radiation at a specific frequency irrespective of remaining chemical bonds [198–200].

The present study uses the potassium bromide (Kbr) pellet method to recognize and classify the functional groups present in all the rejuvenators. In this approach, the rejuvenator and Kbr solution are mixed initially, and the formed pellets are placed in a dissector. A 100 kg/cm^2 pressure is applied to form a thin film, which is then placed in a transmittance chamber. The sample is then exposed to an infrared radiation beam emitted from a source. With the help of a detector, the absorbed or transmitted infrared spectrum is captured.

6.3.2 Task-2: Optimising the dosage of rejuvenator

6.3.2.1 Dosages evaluation

6.3.2.1.1 Penetration value

Penetration test is an empirical method, performed to assess the consistency of asphalt binder. Test is conducted as per IS 1203 [147], in which a standard needle of weight 100 gm is allowed to penetrate from the surface of the asphalt binder sample for 5 seconds. The depth of penetration is measured, which is reported as penetration value represents the softness or hardness of a binder. Higher the penetration softer the binder will be.



Figure 6-2 Penetration test setup

6.3.2.1.2 Softening point

Softening point is the temperature at which asphalt binder attains a certain degree of softening under specified test conditions. This is evaluated by ring and ball apparatus test and the test conditions and softening are referred to as “temperature at which a steel ball placed on a brass ring filled with asphalt binder sample starts flowing and descends a vertical distance of 2.5 cm and touch the surface of bottom plate of support”. All the test apparatus including support,

CHAPTER 6

rings, steel balls, asphalt binder sample and thermometer for temperature measurement are assembled and placed inside a glass vessel filled with water as shown in Figure 6-3. Initial temperature of waste should be 5°C and the glass vessel is placed on the top of a heating plate capable of increasing the temperature at the rate of 5°C per minute.



Figure 6-3 Test assembly for softening point test

6.3.2.1.3 Dynamic shear rheometer

Dynamic shear rheometer (Figure 6-4 (a)) is used to assess the rheological properties of the asphalt binder. Rheology is the study of the response of a material to the applied stress or strain in terms of flow or deformation. Tests are either conducted in a strain-controlled mode or stress-controlled mode. In strain-controlled mode, a sinusoidal and oscillatory strain is applied and the resulting stress is monitored, where-as in stress-controlled mode sinusoidal and oscillatory stress is applied and the resulting strain is monitored. Parallel plate geometry is used to test the asphalt binder samples, in which upper plate is oscillated at a selected frequency and angular deflection amplitudes while the lower plate is fixed. Test specimens (asphalt binder samples) of either 25 mm in diameter by 1 mm thick (PP25 (Figure 6-4 (b))) or 8 mm diameter by 2 mm thick (PP8 (Figure 6-4 (c))) are formed between parallel plates and the choice of sample dimensions varies depending on the test.



(a)



(b)



(c)

Figure 6-4 (a) Dynamic shear rheometer (b) 25 mm parallel plate geometry (c) 8 mm parallel plate geometry

The primary parameters measured using DSR are complex shear modulus (G^*) and phase angle (δ). G^* is the ratio of the absolute value of peak to peak shear stress (τ) to the absolute value of peak to peak shear strain (γ) and is defined as the total resistance to deformation to the applied shear loading. τ and γ are functions of the radius of parallel plates and the values at the periphery are calculated as shown in Equations (6-1) and (6-2),

$$\tau = \frac{2T}{\pi r^3} \quad (6-1)$$

$$\gamma = \frac{r \cdot \theta}{h} \quad (6-2)$$

where τ is the peak shear stress (N/m²), T is the torque (N/m), r is the radius of sample (mm), γ is the shear strain, θ is the deflection (radians) and h is the thickness or plate gap (mm). δ is the lag (time or phase) between applied shear stress/strain to resultant strain/stress.

6.3.2.1.3.1 High and intermediate temperature performance grading

The Superior Performance Asphalt Pavements (SUPERPAVE) specifications are developed as a result of the Strategic Highway Research Program (SHRP) in 1987. The primary objective of this research initiative was to have some enhanced and accurate binder specifications that can efficiently simulate actual pavement conditions. Performance grading (PG) can characterize the viscoelastic behaviour of asphalt binder, which cannot be described by the conventional tests such as penetration, softening point and viscosity tests.

PGH is the average seven-day maximum temperature that pavement is expected to experience in a geographical location for which the asphalt binder is anticipated to be used. PGH of the binder, as per ASTM D6373 [313], is the temperature at which $G^*/\sin\delta$ is less than 1 kPa and true fail temperature is the temperature at which $G^*/\sin\delta$ is equal to 1 kPa. True fail temperature is the actual maximum temperature that an asphalt binder under consideration is expected to work properly without resulting in excessive permanent deformation. The value of $G^*/\sin\delta$ is checked at a difference of 6°C till the criteria of 1 kPa is met at a frequency of 10 rad/s and strain of 12%.

Similarly, intermediate temperature performance grade is the temperature at which $G^* \cdot \sin\delta$ is greater than 5000 kPa and true fail temperature is the temperature at which $G^* \cdot \sin\delta$ is equal to 5000 kPa., $G^* \cdot \sin\delta$ is the stiffness parameter and is generally used as a fatigue parameter. True fail temperature is the average actual pavement temperature below which asphalt binder do not

perform satisfactorily in terms of fatigue. The value of $G^* \cdot \sin\delta$ is checked at a difference of 3°C till the criteria of 5000 kPa is met at a frequency of 10 rad/s and strain of 1%.

6.3.2.1.3.2 Zero shear viscosity

For viscoelastic materials, (shear) viscosity varies with the shear rate and at very low shear rates, they tend to behave Newtonian and exhibit constant viscosity [314]. With the decrease in the shear rate, the viscosity value reaches a maximum value termed ZSV (at a zero shear state condition) and is a physical property of asphalt [315,316]. Cross model (Equation (6-3)) is used to calculate the ZSV from the measured viscosities (at 60°C) at different shear rates (0.1 to 100 s⁻¹) using a dynamic shear rheometer.

$$\eta_R = \frac{\eta_0}{1+(k\omega)^m} \quad (6-3)$$

where η_R is measured viscosity, η_0 is Zero Shear Viscosity, ω is shear rate, k is a material parameter of unit time,s and m is also a material parameter but dimensionless [317].

6.3.2.1.3.3 Frequency sweep test

Frequency sweep tests are used to build master curve, which is generally used to characterize the linear viscoelastic (LVE) behaviour of an asphalt binder. Master curves are a plot of complex shear modulus and reduced frequency and is a continuous curve covering wide range of reduced frequencies. It is based on time temperature superposition principle (TTSP), which explains the inter-relationship between frequencies and temperature and is used to convert the rheological measurements at multiple temperatures and frequencies to a single (reference) temperature as shown in Figure 6-5. Materials that follow TTSP are termed as thermo-rheologically simple materials. Frequency sweep tests are conducted in this study to determine the cross-over frequency and G-R parameters, which are used to estimate the dosage of rejuvenators.

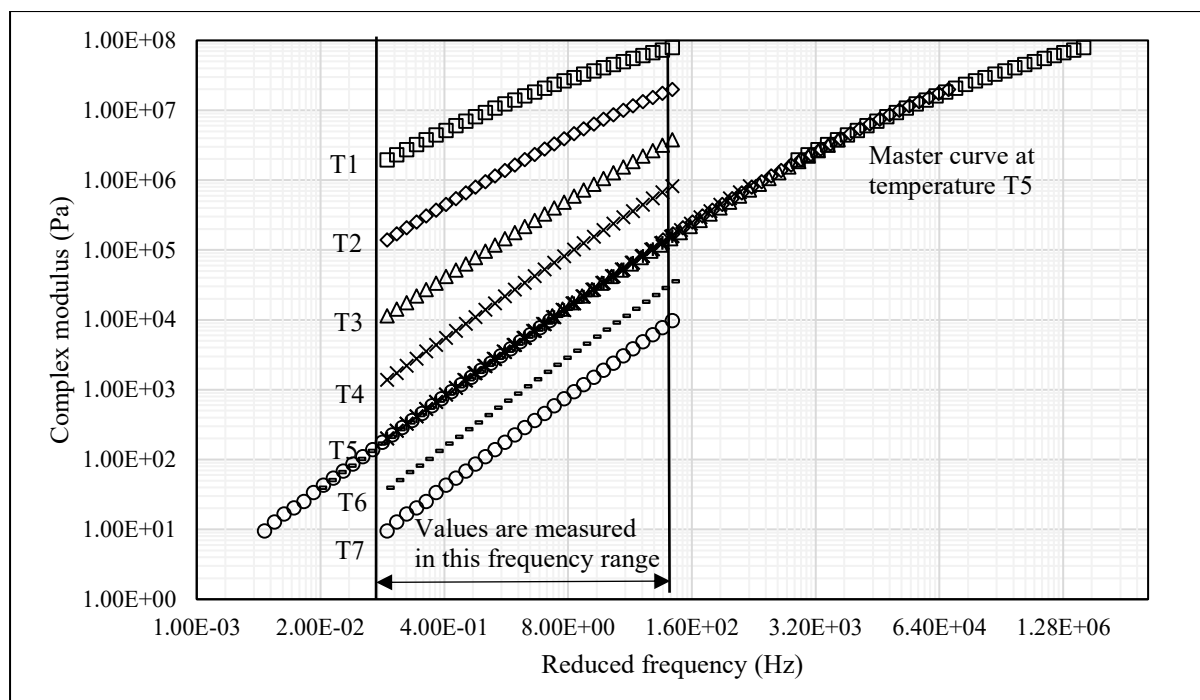


Figure 6-5 Master curve illustration

The frequency at which loss shear modulus is equal to the storage shear modulus is termed as the cross-over frequency [318]. Lower the frequency higher will be the softening point and relaxation time [319]. Frequency sweep test was conducted in linear domain (strain calculated from amplitude sweep test) by varying the frequency from 100 to 0.1 rad/s at different temperatures (10 to 70°C) with increment of 10°C. Cross-over frequency is evaluated by fitting the experimental data to the rheological or linear visco-elastic model (Christensen-Anderson [320]), formulated as Equation (6-4),

$$G^*(\omega) = G_g \left[1 + \left(\frac{\omega_c}{\omega} \right)^{\frac{\text{Log}2}{R}} \right]^{-\frac{R}{\text{Log}2}} \quad (6-4)$$

where $G^*(\omega)$ is complex shear modulus as a function of frequency, G_g is glassy modulus, ω_c is cross-over frequency, ω is the frequency, R is rheological index.

Initially developed as a surrogate parameter for ductility (15°C, 1 cm/min) and later upon further research, the G-R parameter is proposed as a cracking indicator [321–324]. G-R parameter is calculated (Equation (6-5)) based on the complex shear modulus (G^*) and phase

angle (δ) measured at a temperature of 15°C and frequency of 0.005 rad/s. Value of G-R gives the idea of aging effect on the cracking resistance based on the ductility failure planes plot in the black space [325]. Indicative values of G-R based on the field block cracking and ravelling have been suggested. Values below 180 kPa are in no cracking zone, between 180 and 450 kPa is the damage zone, and greater than 450 kPa indicates that the binder is prone to significant cracking [326]. Examples of three binders with their respective G-R values falling in different zones are illustrated in Figure 6-6.

$$G - R = \frac{G^*(\cos\delta)^2}{(\sin\delta)} \quad (6-5)$$

Where G-R is the Glover Rowe parameter, G^* is complex shear modulus and δ is the lag (time or phase) between applied shear stress/strain to resultant strain/stress.

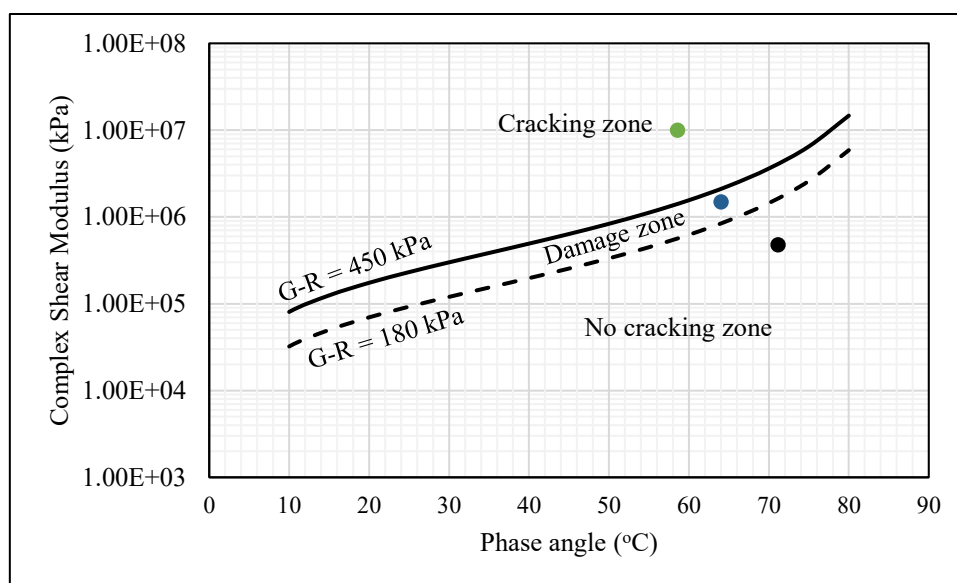


Figure 6-6 Implication of Glover Rowe parameter

6.3.2.1.3.4 Multiple stress creep recovery test

MSCR test is used to evaluate the rutting resistance of the asphalt binders and is conducted as per ASTM D7405 [327] to measure the percent recovery, R (elastic response) and non-recoverable creep compliance, J_{nr} (rutting resistance indicator). Test involves the loading and unloading pattern of 1 s creep and 9 s recovery for 10 cycles at two different stress levels, 0.1

CHAPTER 6

and 3.2 kPa. R is the percentage of recovered strain and J_{nr} is the ratio of unrecoverable strain to the applied stress. Both R and J_{nr} are averaged over all the cycles at the respective stress level.

Recovery (%) and Non-recoverable creep compliance (J_{nr}) parameters are calculated as per Equations (6-6) and (6-7), respectively, where, ε_0 is the strain value at the beginning of the creep portion, ε_c is the strain value at the end of the creep portion, ε_r is the strain value at the end of the recovery portion and σ is the stress level applied.

$$R (\%) = \frac{\varepsilon_c - \varepsilon_r}{\varepsilon_c - \varepsilon_0} \times 100 \quad (6-6)$$

$$J_{nr} = \frac{\varepsilon_r - \varepsilon_0}{\sigma} \quad (6-7)$$

6.3.2.1.3.5 RILEM criteria

RILEM (Réunion Internationale des Laboratoires et Experts des Matériaux) is an international union of laboratories and experts focused in the area of construction materials and structures. RILEM technical committee TC 264-RAP “Asphalt pavement recycling”- Task group 3 (TG 3) is mainly focused on the asphalt binder for recycled asphalt mixtures, recommended some target properties to evaluate the dosage of rejuvenators [328]. Based on the framework of the present study, the recommended target property in unaged state at intermediate temperature i.e. G^* at 28°C and 1.59 Hz using PP25 geometry is adopted.

6.3.2.2 Tukey post-hoc analysis

The Tukey test or Tukey’s honest significant difference (HSD) test is based on the studentized range distribution and is used to determine the whether there exists statistical difference between the specific groups (means) or not [329]. When the null hypothesis (all means are same) of ANOVA is rejected, then to conclude which particular means are different, post-hoc analysis is helpful for the pairwise comparisons [330]. Multiple comparisons of means help determine which means are different and also to estimate by how much they are different. Type

I error known as false positive, occurs when a true null hypothesis is rejected incorrectly, is a concern during the multiple comparisons. Techniques such as Tukey's HSD test, are most recommended for controlling the error [331]. HSD statistic is calculated as per the Equation (6-8).

$$HSD = q \cdot \sqrt{\frac{MSE}{n}} \quad (6-8)$$

Where HSD is the honest significant difference, q is the t-statistic (studentized range distribution), MSE is mean square error and n is the number of groups. When the difference between the two means is greater than HSD then it is concluded that means under comparison are different [332]. Minitab software is used to estimate the HSD, comparison of different dosages obtained using multiple parameters aforementioned and further grouping of parameters that results in same dosages.

6.3.2.3 Mixture performance

Dynamic creep compression test and Indirect tensile cracking test are conducted as per 3.8.1.3.1 and 3.8.1.4, respectively.

6.3.3 Task-3 Tests on recycled binder blends and mixtures

Recycled binder blends comprising of VG-30 (60% and 20%), RAP (40% and 80%) and rejuvenators (at optimum dosage) are prepared and tested. Rheological properties of binder blends (virgin binder, RAP and rejuvenator) such as zero shear viscosity (ZSV), cross-over frequency (w_c), non-recoverable creep compliance at stress level of 3.2 kPa ($J_{nr3.2}$), Glover-Rowe (G-R) parameter are evaluated to compare and differentiate the WR and CR. Furthermore, recycled mixes with the different binder blends are prepared and the performance (rutting and fatigue) is assessed using dynamic creep compression test and IDEAL-CT test. In the IDEAL-CT test, Fatigue index (FI) and Asphalt flexibility ratio (AFR) are used to compare

and quantify the fatigue performance. FI, as proposed by Sukhija et al. [236,237] is the ratio of fracture energy upon the peak load. As elaborated by the authors, a higher value of FI suggests that more energy can be absorbed by the asphalt mixture relative to peak load and, hence, better the fatigue resistance will be. Therefore, FI values can be applied to compare the rejuvenator's ability to impart ductile behavior. AFR is the ratio of displacement at 75% (post) peak load (l_{75}) to the slope ($|m_{75}|$) of tangential zone at 75% peak load point (N/m). It represents the flexibility of asphalt mix mainly based on the post-peak behavior.

6.3.3.1 Ranking of rejuvenators

Various tests on rejuvenators, binders, and mixes are performed in this study to compare commercial and waste-type rejuvenators. It is possible that each test outcome may not result in a similar grouping of rejuvenators. To have a specific idea about which type of rejuvenator performs superior to another, a ranking methodology proposed by Saboo et al. [333] is adopted. This ranking methodology is also effectively implemented in previous studies [334–336]. Initially, the user should prioritise different tests in the form of rank. Various tests can be assigned the same rank. After allocating rank for each test, the weightage factor (WF) for each test is calculated as,

$$WF_i = \frac{TR_i}{\sum_{i=1}^t TR_i} \quad (6-9)$$

where TR is the test rank, t is the number of tests and integer i is the test under consideration. A sum of the weightage factors is always equal to one.

In cases where a lower value of test results suggests better performance (like permanent strain), the inverse of results is used. All the test results are brought to a similar scale by normalization, as shown in Eq-6, so that different results with different units can be clubbed (addition or multiplication) together.

$$NV = \frac{R_i - \min R_i}{\max R_i - \min R_i} \quad (6-10)$$

Where NV is the normalized value and R_i is the result of a test i . Ranked value (RV) of each rejuvenator for each test is obtained using the normalized value (NV) and weightage factor (WF), as:

$$RV = \frac{NV}{WF} \quad (6-11)$$

The total ranked value (TRV) is further calculated by adding the RV of all tests. It should be understood that the rank assigned for each test (initially) depends on the user, and there can be different priorities. If the user wants to use multiple priorities, then the global total rank value (GTRV) is the sum of TRVs for each priority.

6.4 RESULTS

6.4.1 Task-1: Rejuvenator test results

6.4.1.1 Viscosity and aging resistance

Rejuvenators viscosities and RTFO test results in terms of weight change and viscosity ratio are shown in Table 6-1. Despite having similar physical properties, B-W and E-R exhibited different viscosity and aging resistance or temperature stability characteristics. Compared to B and W, the difference in viscosity between E and R is greater. In terms of aging resistance, WR are more stable than CR. As WR are already exposed to high temperatures (especially W) during their original usage, so they are expected to have more stability. On the other hand, CR are often derived from multiple chemicals or oils of diverse origins with different evaporation temperatures. Therefore, when they are exposed to high temperatures for the first time, some volatile fractions may have evaporated, resulting in excessive changes in weight and an increase in viscosity. It should be highlighted that rejuvenator R, which showed the lowest aging resistance, is developed to work as both a rejuvenator and anti-stripping additive.

Table 6-1 Viscosity and rolling thin film oven test results

Rejuvenator	Viscosity (cP)	RTFO	
		Weight change (%)	Viscosity ratio
B	25.99	0.89	1.35
W	36.81	0.38	1.04
E	68.55	0.39	1.31
R	168.2	2.05	9.9

6.4.1.2 FTIR

FTIR spectra of rejuvenators B, W, E and R are shown in Figure 6-7 to Figure 6-10 and are particularized in Table 6-2, respectively. Rather than B-W or E-R, it is observed that W-R have many similar functional groups of amines (N-H and C-N), alcohol and phenol (O-H) and alkanes (C-H). Only one additional functional group of C-H (alkane) at the wave number 1465 cm^{-1} (approximately) is identified in W. Overall, both are amine-based aliphatic (saturated) hydrocarbon additives. Although certain common functional groups are also observed in B, the presence of C=C (arenes) and C=O (esters) sets it apart from other W and R. Low viscosity and aging resistance of B compared to W can be attributed to arenes and esters. B is an aromatic (unsaturated) hydrocarbon with amines at the approximate wave numbers of 1163 and 1240 cm^{-1} . E is completely different from other rejuvenators and is just a simple aliphatic hydrocarbon with alkanes (C-H) and amine (N-H) functional groups. It should be highlighted that all rejuvenators comprise aliphatic and aromatic hydrocarbons, which are similar to the maltenes portion of asphalt.

Table 6-2 Functional groups identified for each rejuvenator

Rejuvenator	Peaks at wave number (approximate values, cm ⁻¹)	Corresponding functional group	Overall description
B	722	C-H rocking	Aromatic (unsaturated) hydrocarbon of amine- based
	1163	C-N (stretching vibration)	
	1240		
	1462	C-H (bending Vibration)	
	1636	C=C (stretching vibration)	
	1746	C=O (stretching vibration)	
	2854	C-H (stretching vibration)	
	2925		
	3009		
3434	O-H (stretching vibration)		
W	697	N-H wagging	Amine-based aliphatic (saturated) hydrocarbon
	912		
	998	C-N (Stretching vibration)	
	1152		
	1320	O-H bending	
	1465	C-H deformation	

	1587	N-H Scissoring	
	2854	C-H (Stretching vibration)	
	2926		
	3009		
	3362	O-H (stretching vibration)	
E	1376	C-H (Bending vibration)	Aliphatic hydrocarbon of amine-based
	1458		
	2853	C-H (Stretching vibration)	
	2924		
	3432	N-H (stretching vibration)	
R	602	N-H (Wagging)	Amine based aliphatic (saturated) hydrocarbon
	720		
	818		
	879		
	1058	C-N (stretching vibration)	
	1127		
	1316	O-H (bending)	
	1467		
	1570	N-H (scissoring)	
	2852	C-H (stretching vibration)	
	2923		

	3385	O-H (stretching vibration)	
--	------	-------------------------------	--

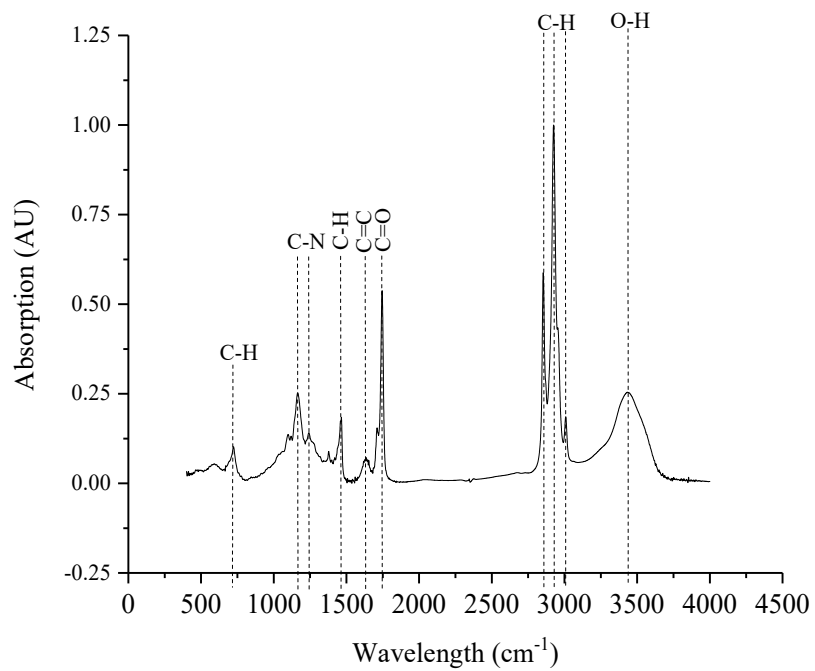


Figure 6-7 FTIR Spectra of Rejuvenator B

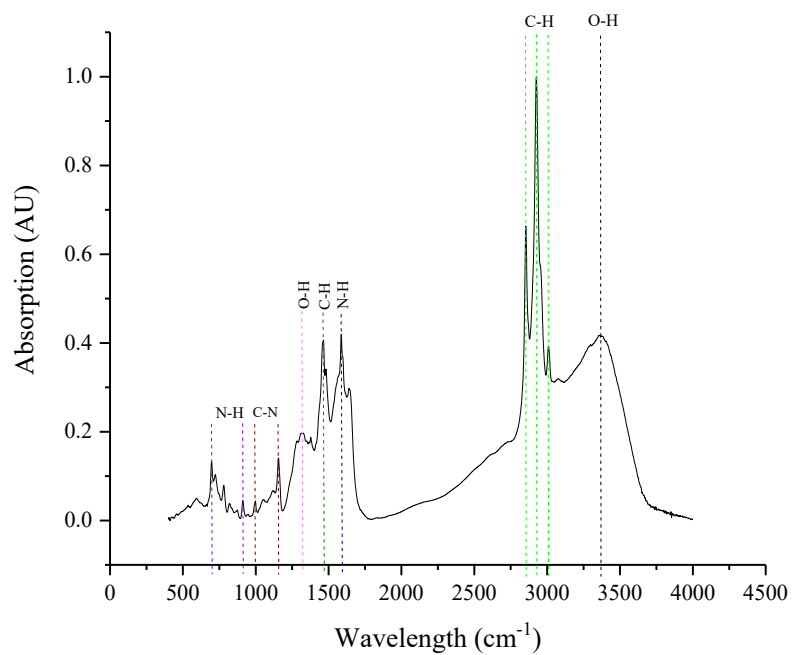


Figure 6-8 FTIR Spectra of Rejuvenator W

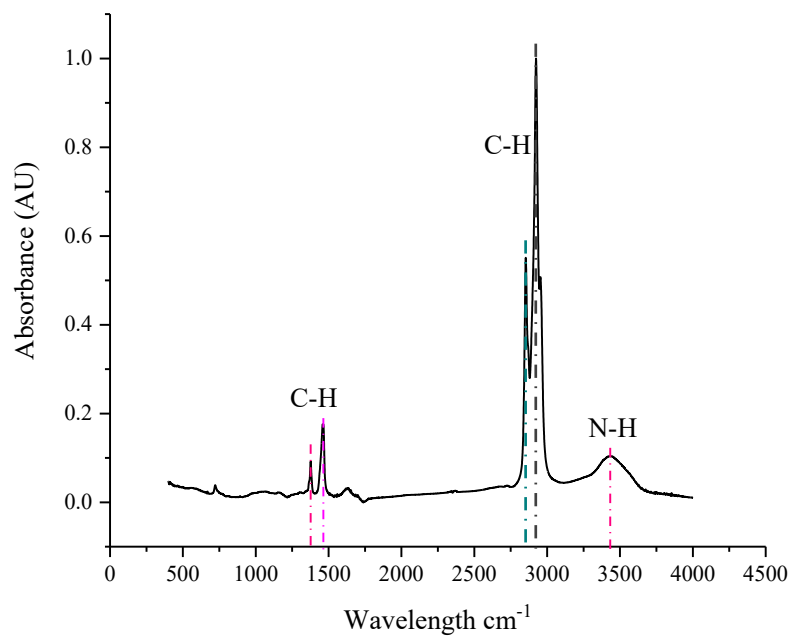


Figure 6-9 FTIR Spectra of Rejuvenator E

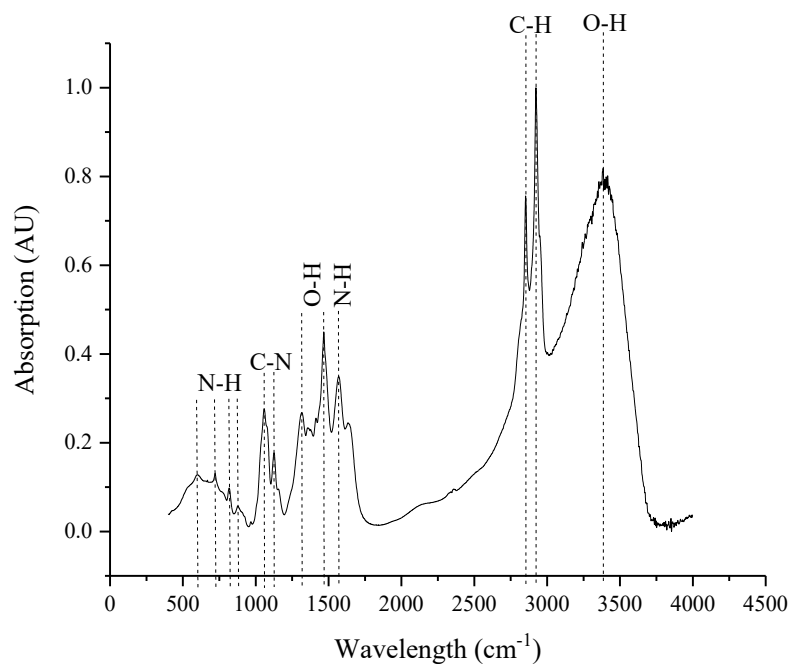


Figure 6-10 FTIR Spectra of Rejuvenator R

6.4.2 Task-2: Optimising the dosage of rejuvenator

6.4.2.1 Dosages evaluation

The percentage of rejuvenator at which the blend (virgin binder + rejuvenator + RAP binder) property (parameter under consideration) will be same as that of virgin binder (VG-30), is generally considered as optimum dosage. Since numerous parameters are considered, quantity (percentage) of rejuvenator corresponding to each parameter is termed as dosage only. Optimum dosage is then evaluated from all the dosages (corresponding to all parameters) at the end of this task (Task 2) after Tukey's post-hoc analysis and from mixes performance (rutting and fatigue).

From all the test results, it is recognized that all rejuvenators considered in this study are capable of restoring all the parameters, but at dosages slightly different from one parameter to another. Addition of rejuvenators (increasing dosage) reduced stiffness at both high temperatures (softening point, PGH, ZSV, $J_{nr3.2}$) and intermediate temperatures (penetration,

CHAPTER 6

PGI, G-R, G^* at 28°C). Also, not only rheological properties of binder blends, empirical properties (such as penetration and softening point) are also influenced by rejuvenators. Penetration, crossover frequency and non-recoverable creep compliance at 3.2 kPa ($J_{nr3.2}$) values increased (linearly) with the increase in the dosage of rejuvenators, as shown in Figure 6-11 to Figure 6-18. Whereas softening point, PGH, PGI, ZSV, G-R and G^* (at 28°C) values decreased (linearly) with the increase in the dosage of rejuvenators, as shown in in Figure 6-11 to Figure 6-18. This trend is observed for both 40% and 80% RAP contents. This is anticipated (as already elaborated in chapter 2), since addition of rejuvenators increases the maltenes phase and breaks the clusters of asphaltenes, which would result in the reduction in the stiffness of binder.

For all the parameters, it is observed that the rate of change in the value with the increase in dosage is higher for 80% RAP contents compared to 40% RAP blends. Percentage of rejuvenators mentioned in this study i.e. 4%, 8% and 12% are by the weight of RAP binder. Thus for the same weight ratio of rejuvenator, the properties of binders with high RAP percentage are more sensitive to the dosage of rejuvenator. This can be attributed to the low virgin binder content and the constituents (Asphaltene and Maltenes) of RAP binder being highly influenced by the dosage of rejuvenators.

Among the four rejuvenators and from all the parameters considered, rejuvenator B is most sensitive (highest slope) to the increase in dosage and rejuvenator E is least sensitive (lowest slope), at both 40% and 80% RAP contents. Also, W showed similar or somewhat lesser rate of change than B, whereas R have shown similar or somewhat higher rate of change compared to E. It can be inferred that bio-oil based rejuvenators (B and W) imparts highest change in the binder properties i.e. dosage of bio-oil based rejuvenators is more delicate compared to petroleum based (E) and compound (R) rejuvenators.

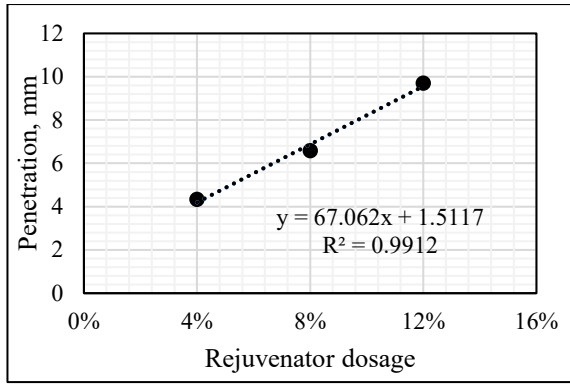
CHAPTER 6

Penetration value and $J_{nr3.2}$ have similar sensitivity to rejuvenator dosages, especially for the binder blends B8, E4, R8 and W8 and comparable rate of change for remaining blends. Penetration value signifies the stiffness of a binder and generally stiff binders tend to have high rut resistance, low $J_{nr3.2}$ values. On the other hand, PGH and softening point, that also indicates the stiffness of the binder and often used for rutting resistance (especially PGH) have similar rate of change but completely different to that of penetration value and $J_{nr3.2}$. It can be attributed to the test temperatures and principals involved. In PGH and softening point tests, temperature is increased gradually (5°C per min in case of softening point and measurements at every 6°C increment in case of PGH) till a specific softness is achieved (ball touches the bottom plate in softening point and $G^*/\sin.\delta$ value of 1 kPa is reached). In MSCR test, multiple cycles of load and recovery takes place (which is basically resistance to deformation) and in Penetration test, binder resists the penetration of freely falling needle. Thus PGH and softening point can be used as indicators of stiffness and both would give similar idea of sensitivity to the increase in dosage of rejuvenator. And Penetration test would provide insights into the sensitivity of rutting resistance of binder blends to the rejuvenator dosage as that of $J_{nr3.2}$.

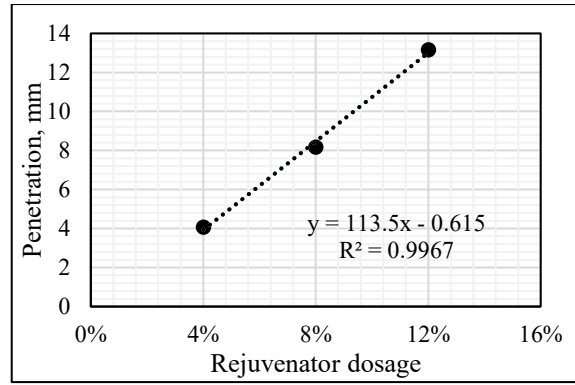
Cross-over frequency of the binder blends increased with the increase in dosage, for every rejuvenator at both the RAP contents. Thus adding more rejuvenator results in the binder with reduced elastic behaviour and increased flowability (viscous). As specified in section 6.3.2.1.3.3, higher crossover frequencies translates to binders with lower softening points and relaxation times i.e. softer binders. Thus binder blends with less relaxation times tend to have high cracking resistance, as can also be seen by PGI and G-R values. The rate of change of PGI and G-R is different and G-R values are more sensitive to the dosage than PGI. Thus with the increase in the dosage of rejuvenators, G-R values decreased linearly signifying delay in the onset of cracking. Similarly, ZSV and G^* at 28°C, that suggests the stiffness also decreased

CHAPTER 6

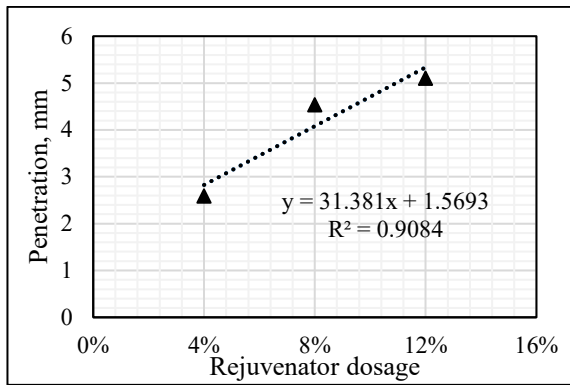
with the addition and increasing the dosage of rejuvenators. The final dosages corresponding to every parameter are illustrated in the Table 6-3.



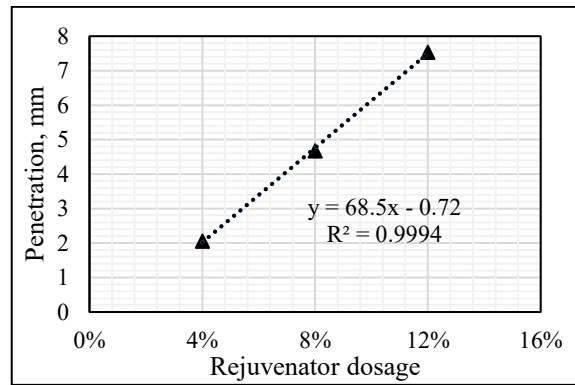
B4



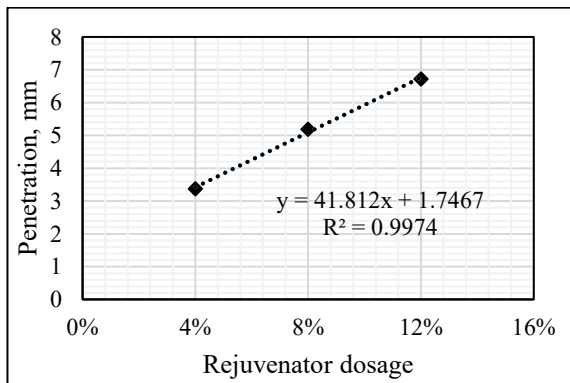
B8



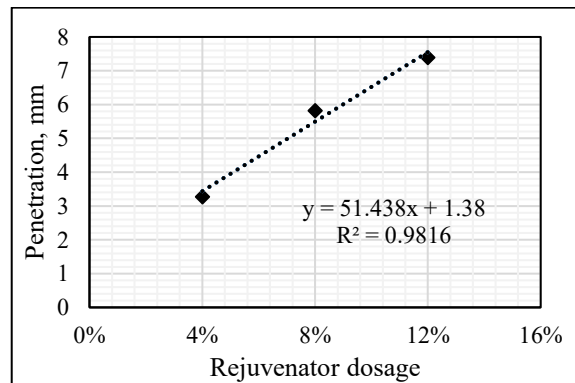
E4



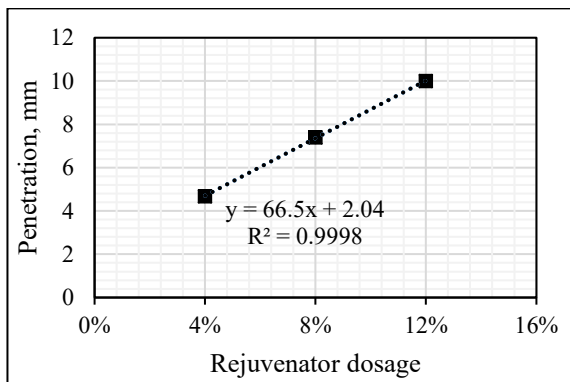
E8



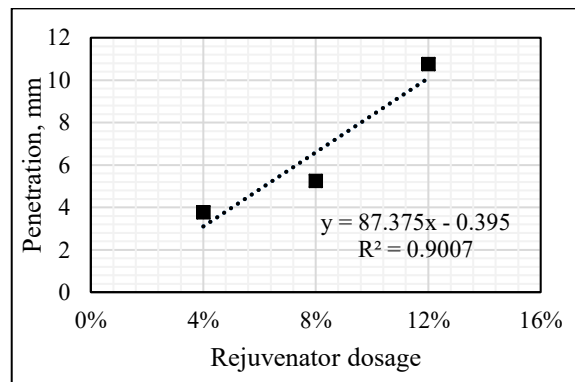
R4



R8

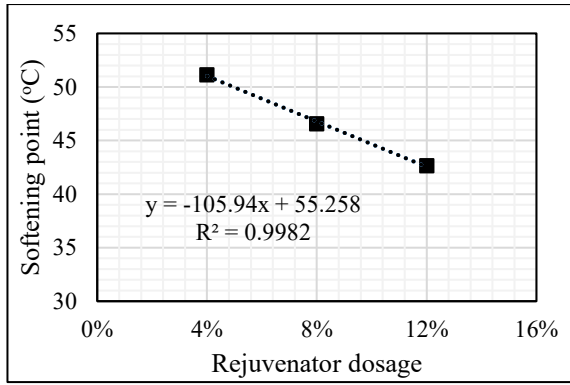


W4

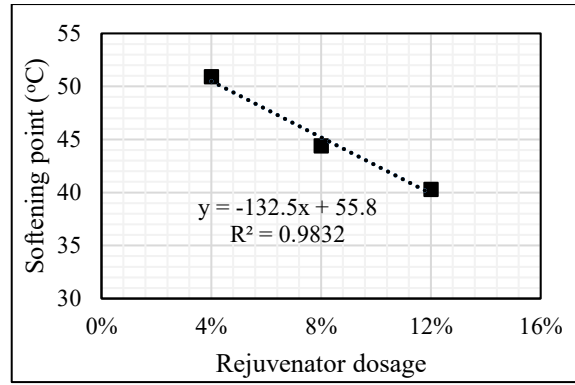


W8

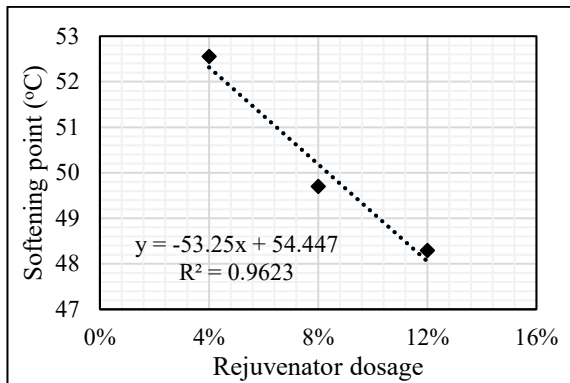
Figure 6-11 Penetration trend with rejuvenator dose



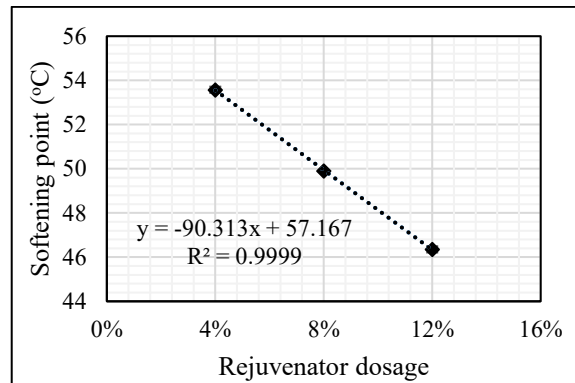
B4



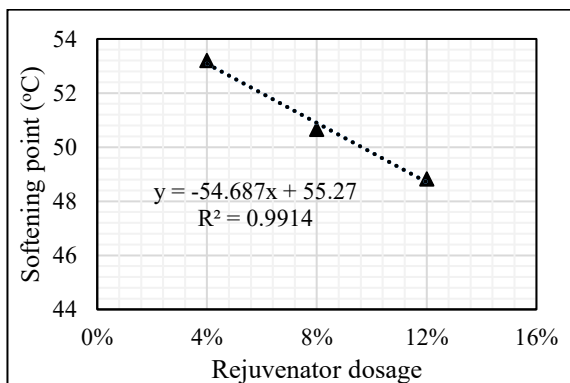
B8



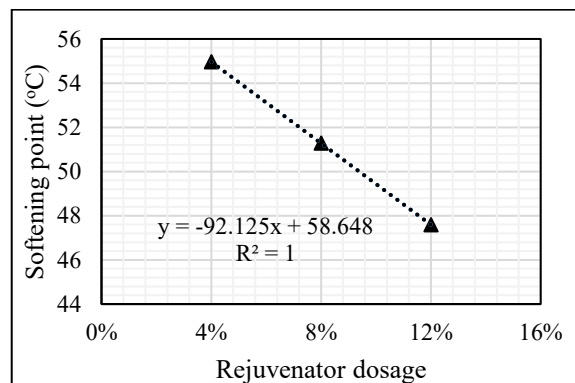
E4



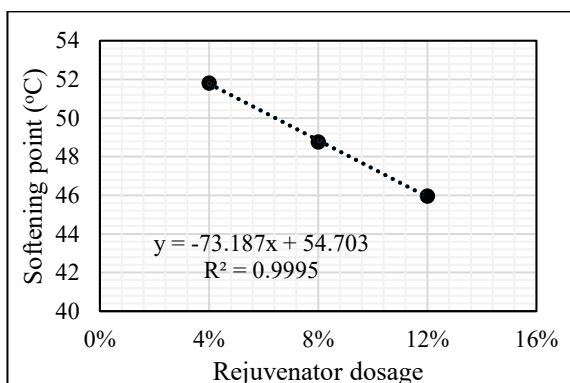
E8



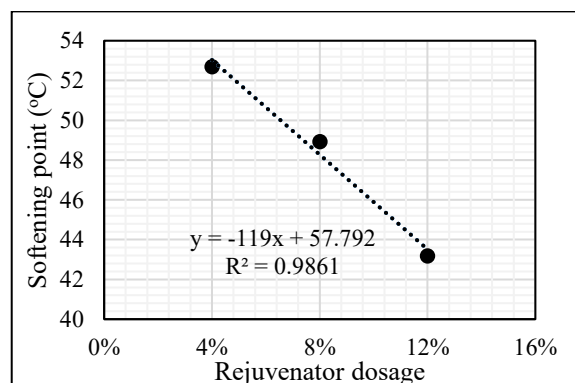
R4



R8

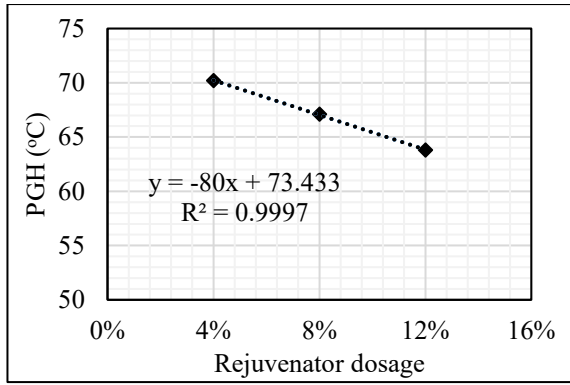


W4

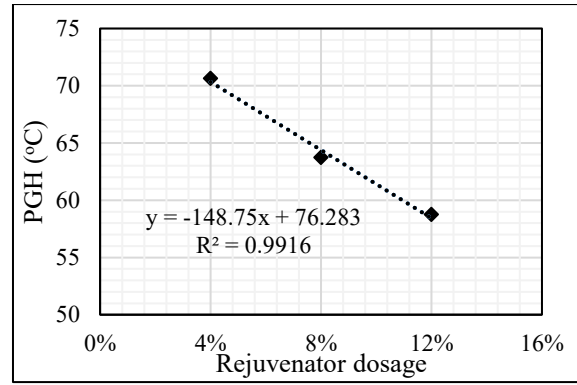


W8

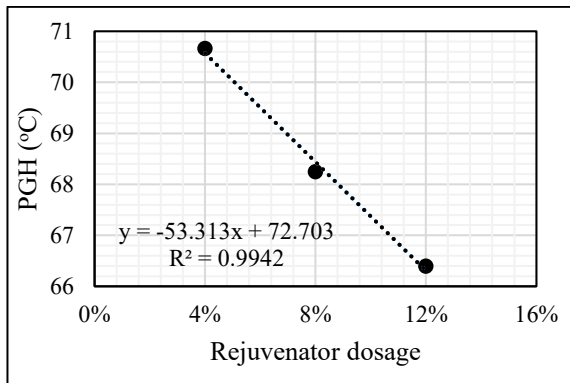
Figure 6-12 Softening point trend with rejuvenator dose



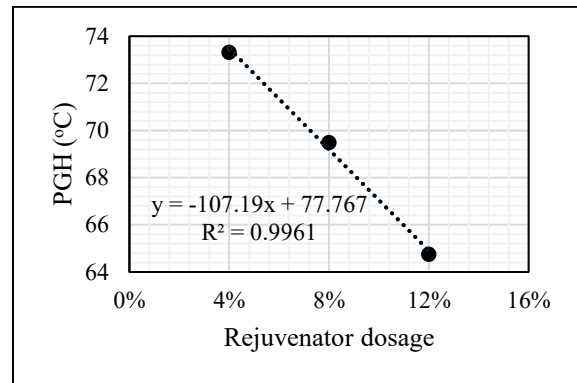
B4



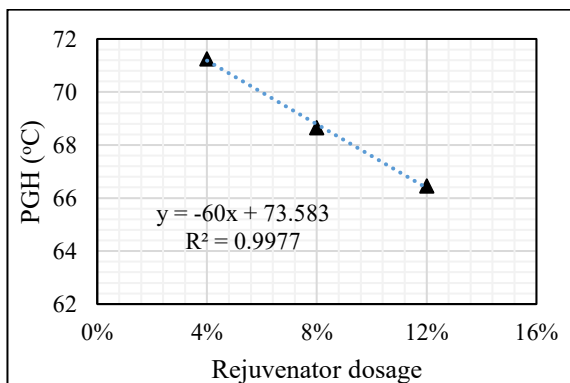
B8



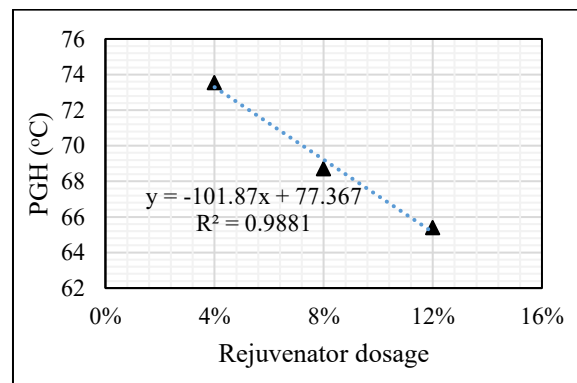
E4



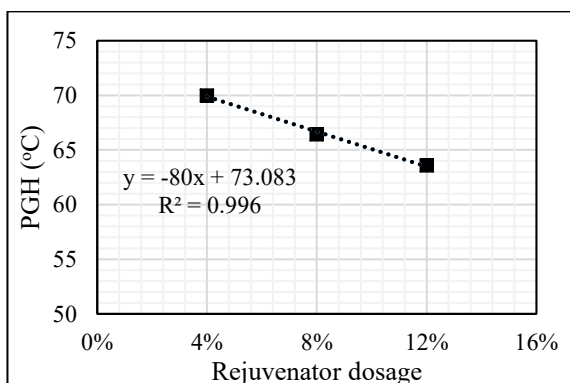
E8



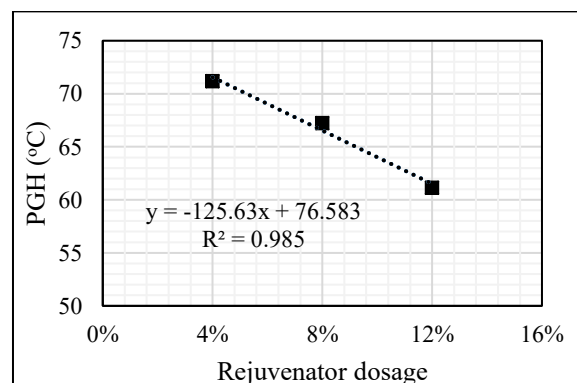
R4



R8

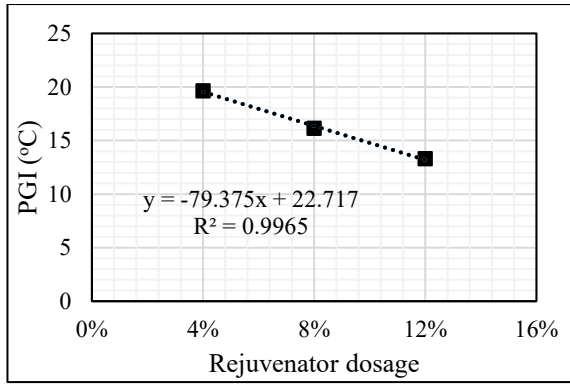


W4

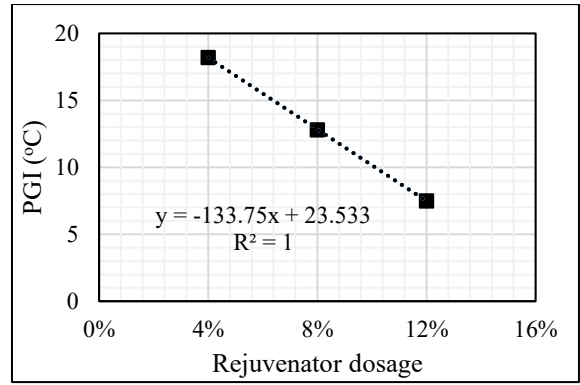


W8

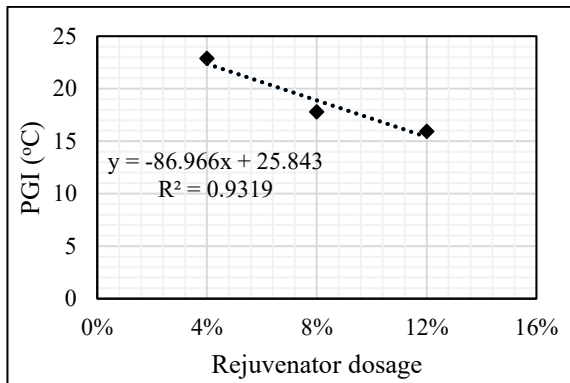
Figure 6-13 High temperature Performance Grade trend with rejuvenator dose



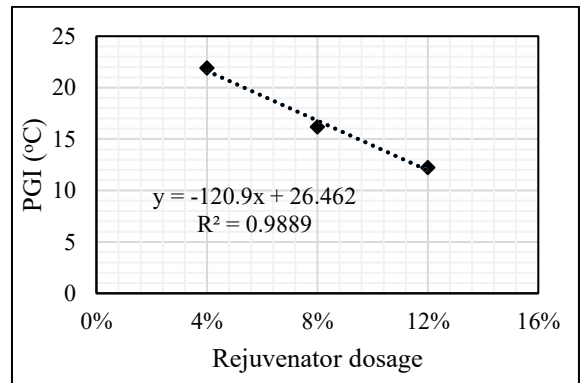
B4



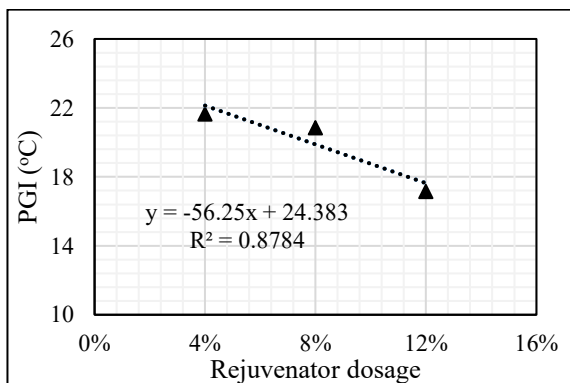
B8



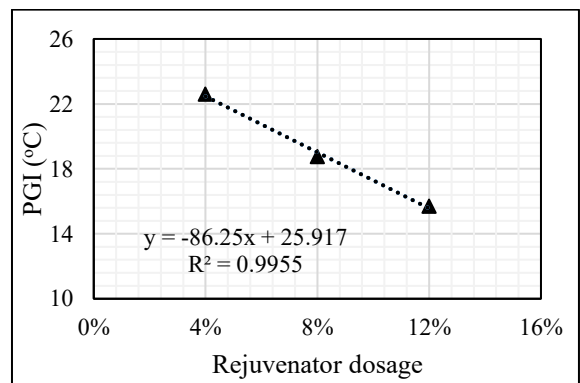
E4



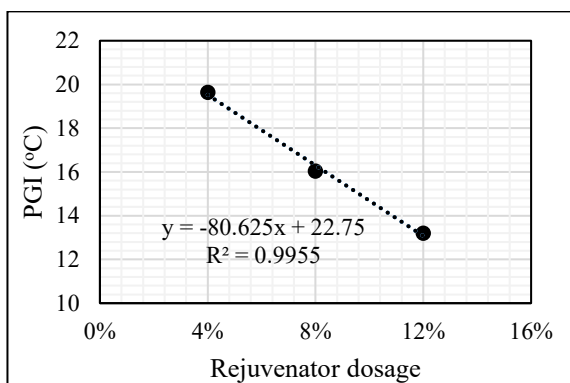
E8



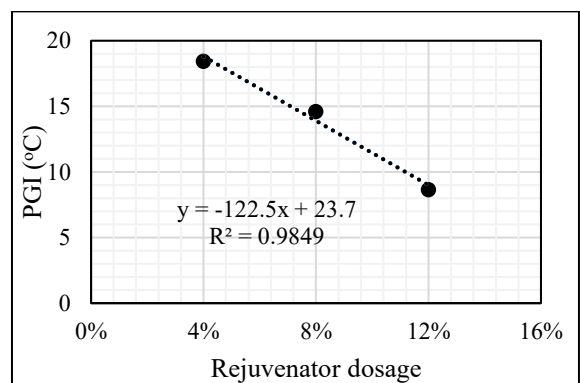
R4



R8

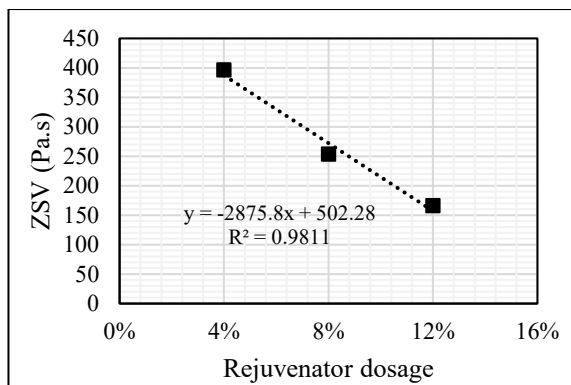


W4

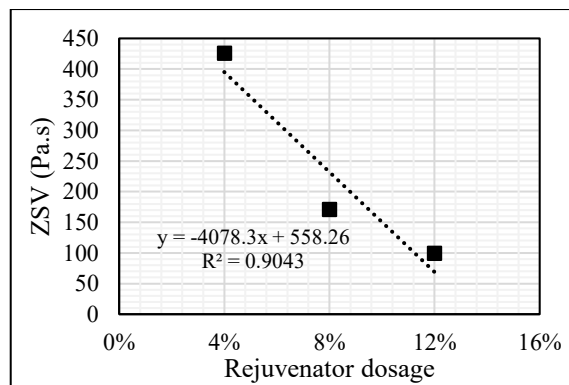


W8

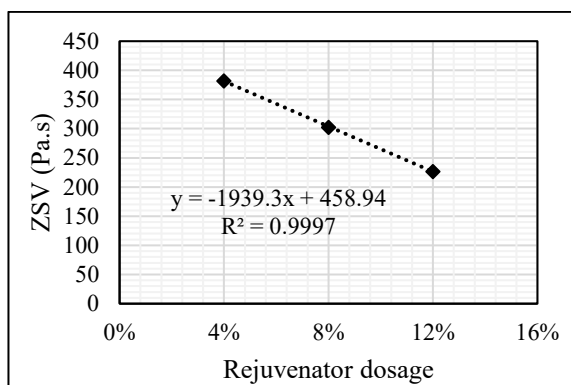
Figure 6-14 Intermediate temperature Performance Grade trend with rejuvenator dose



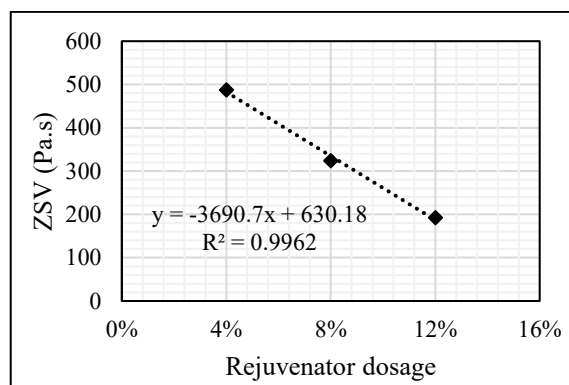
B4



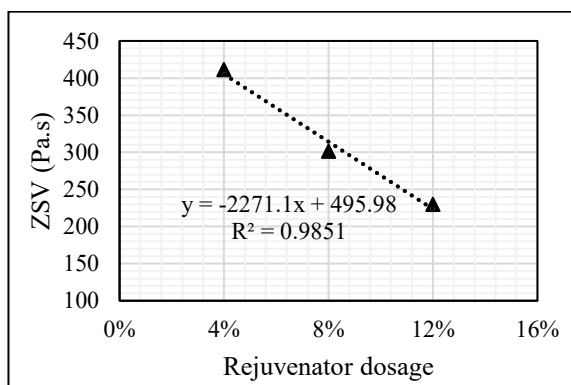
B8



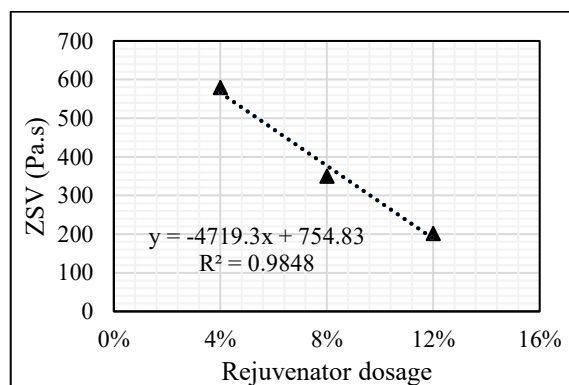
E4



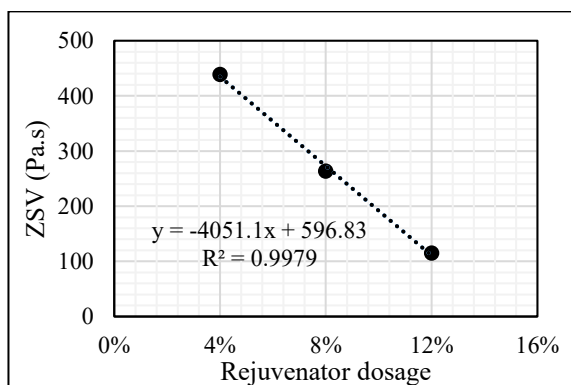
E8



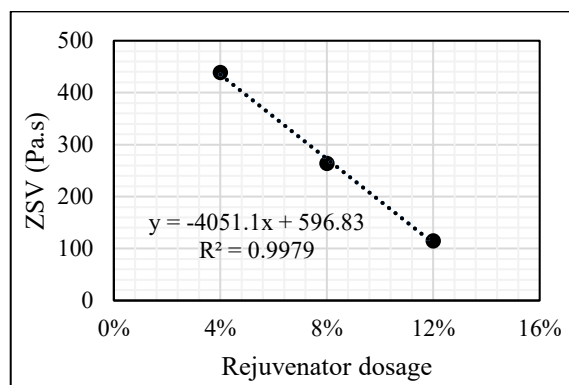
R4



R8

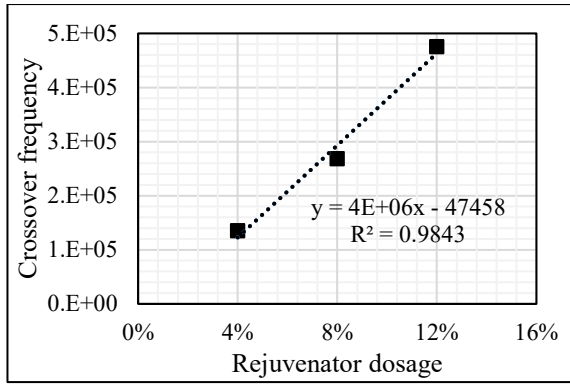


W4

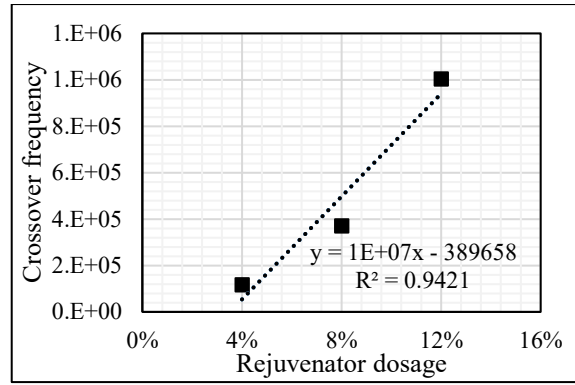


W8

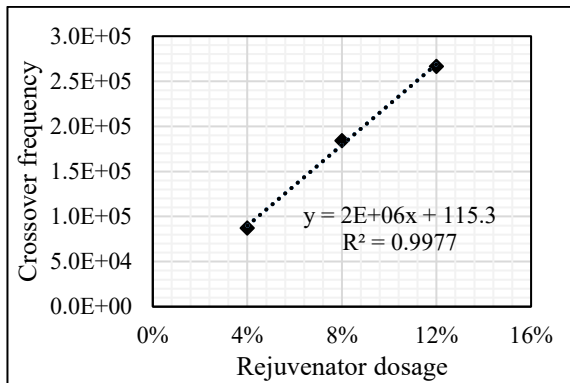
Figure 6-15 Zero Shear Viscosity trend with rejuvenator dose



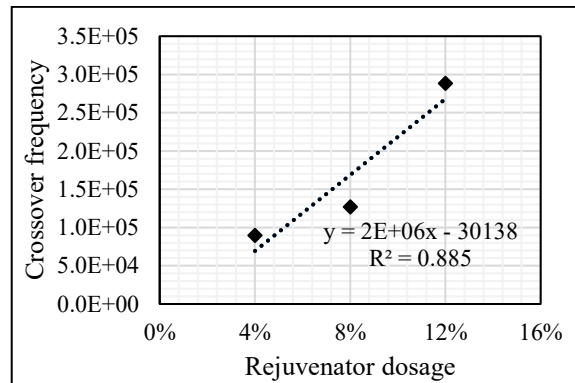
B4



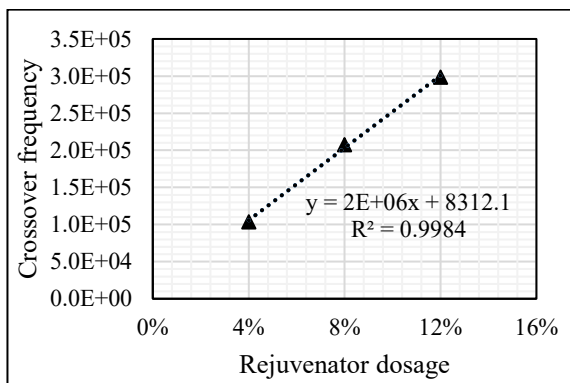
B8



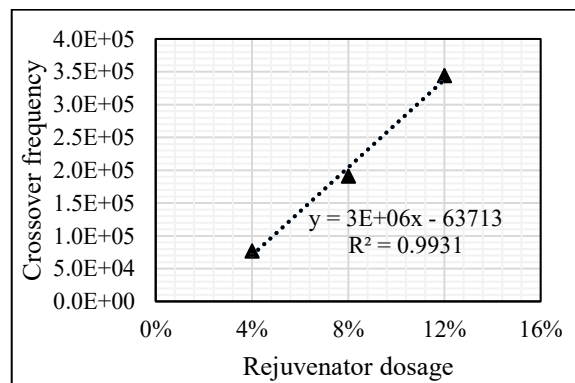
E4



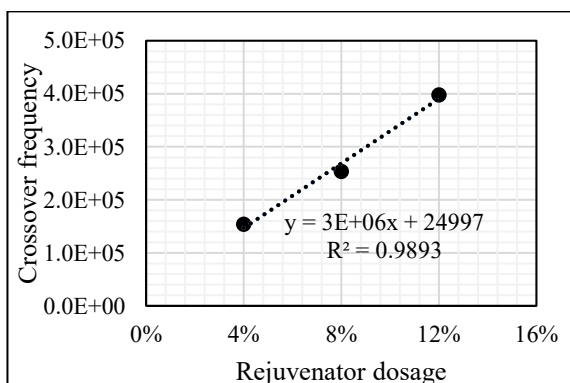
E8



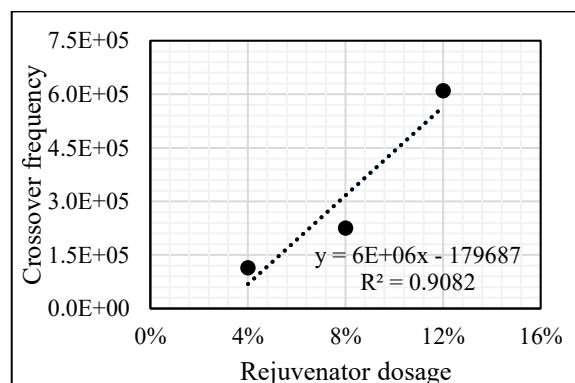
R4



R8

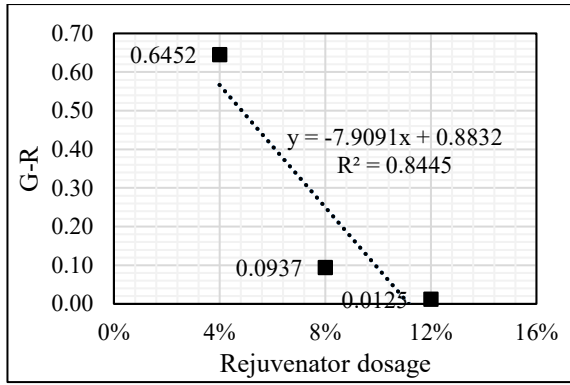


W4

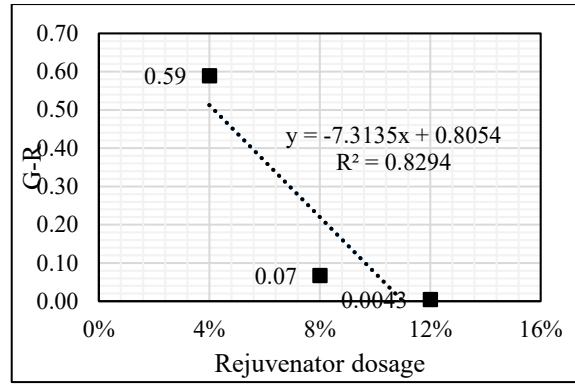


W8

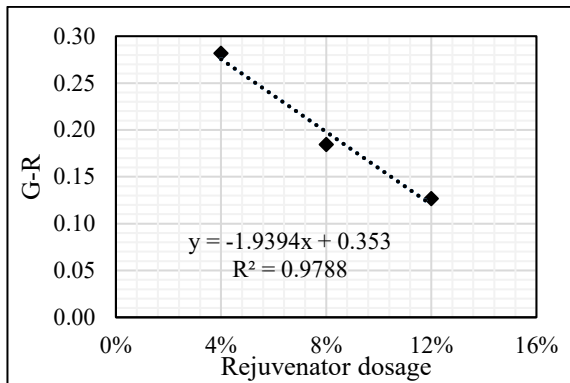
Figure 6-16 Crossover frequency trend with rejuvenator dose



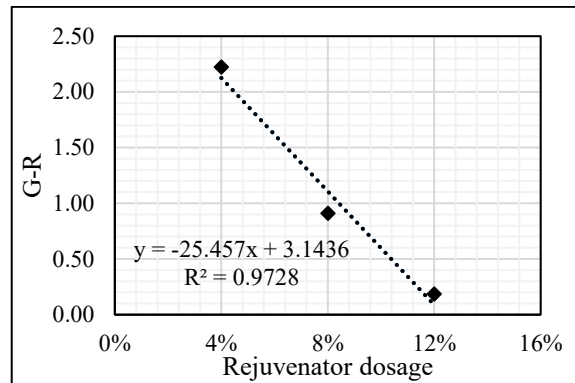
B4



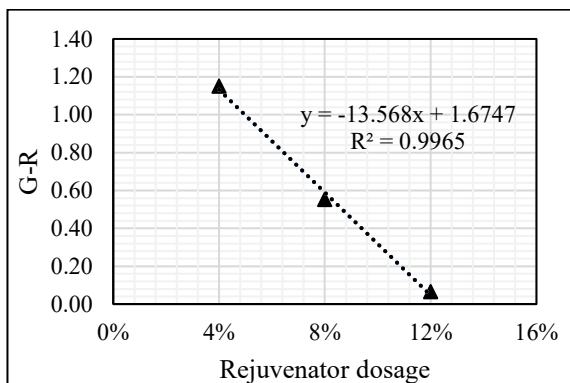
B8



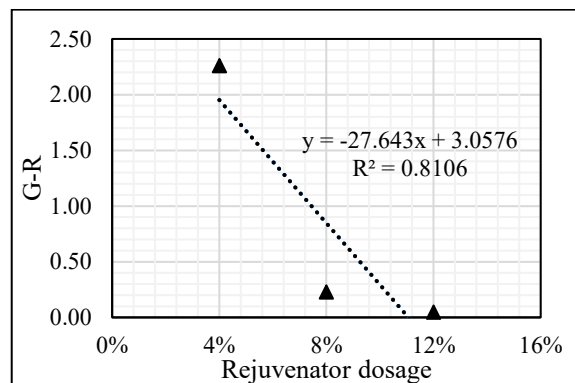
E4



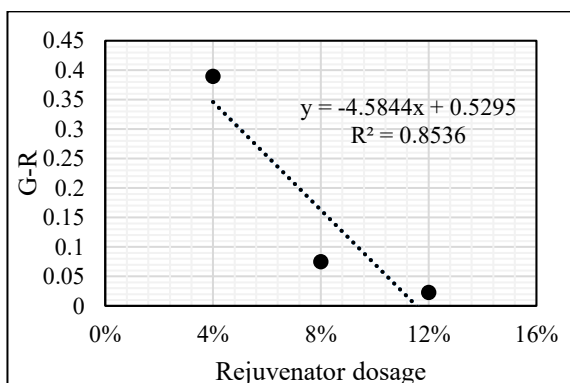
E8



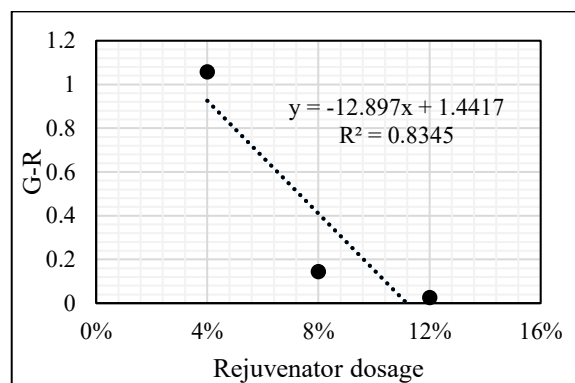
R4



R8

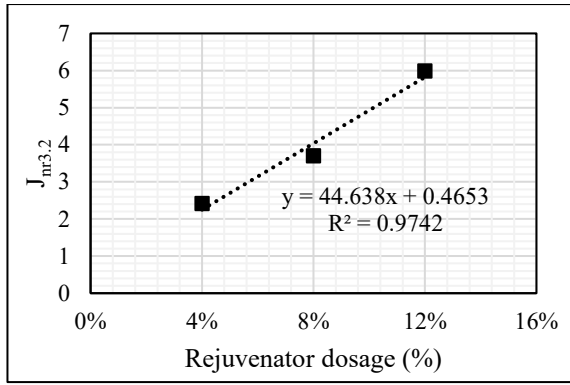


W4

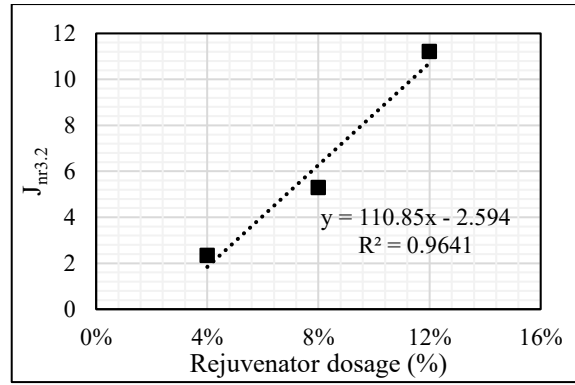


W8

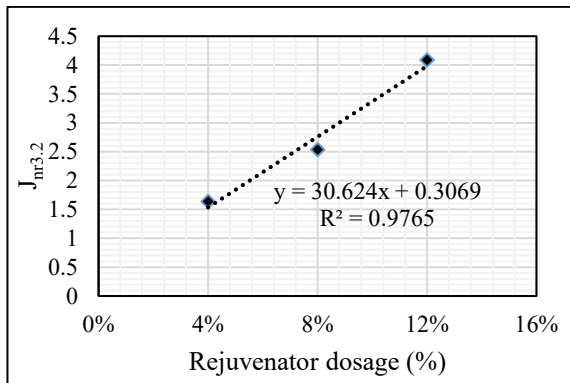
Figure 6-17 Glover Rowe parameter trend with rejuvenator dose



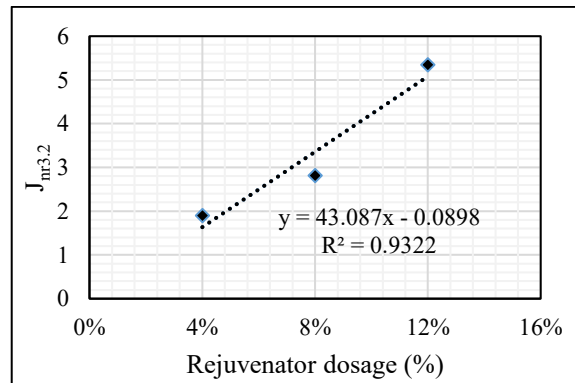
B4



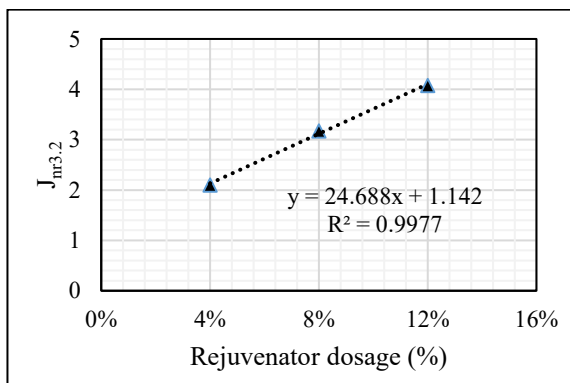
B8



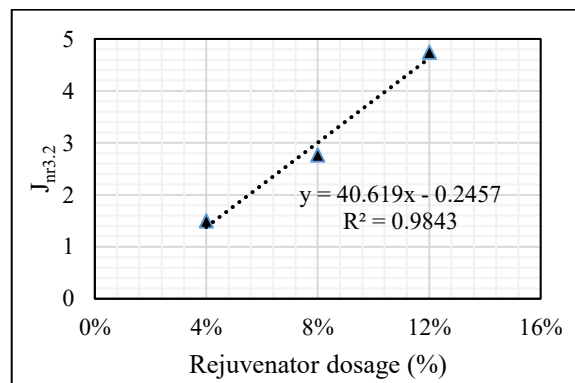
E4



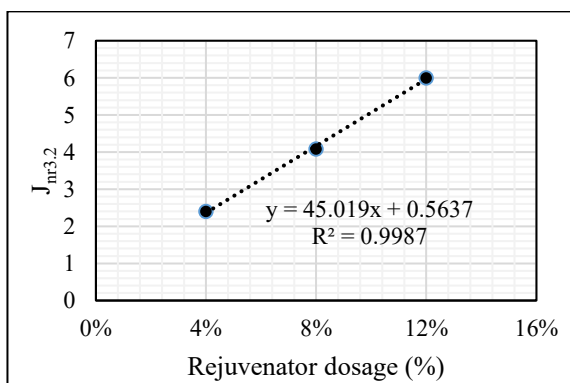
E8



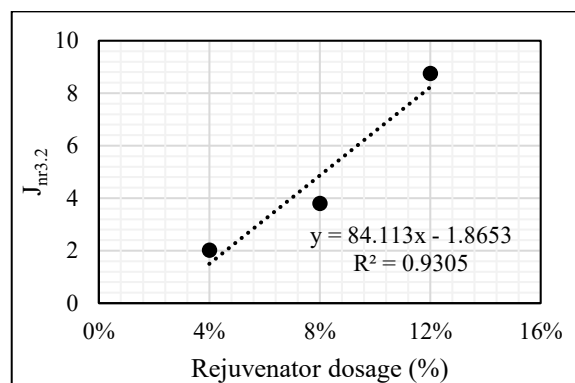
R4



R8

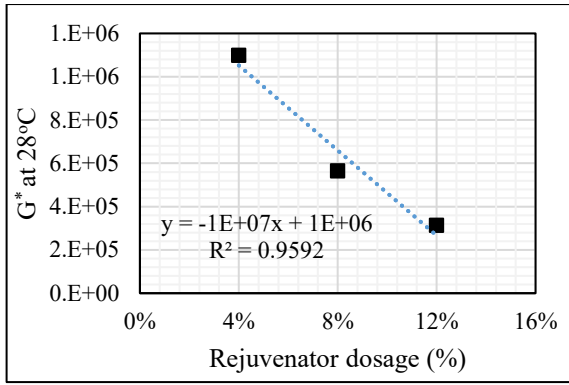


W4

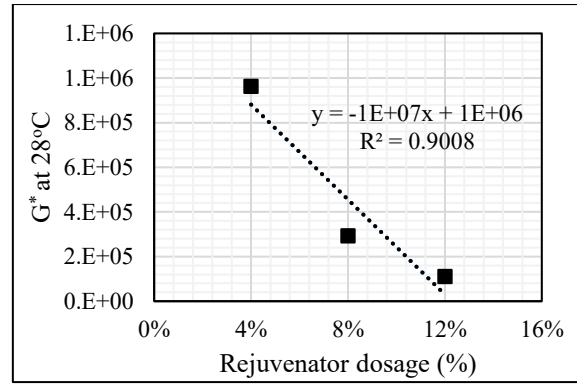


W8

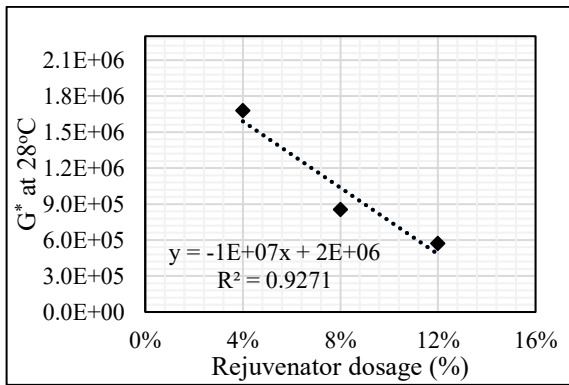
Figure 6-18 Non-recoverable creep compliance trend with rejuvenator dose



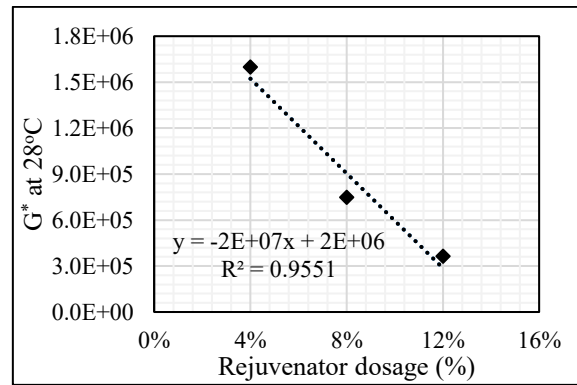
B4



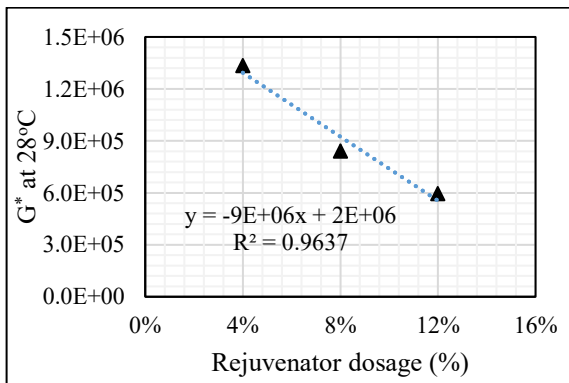
B8



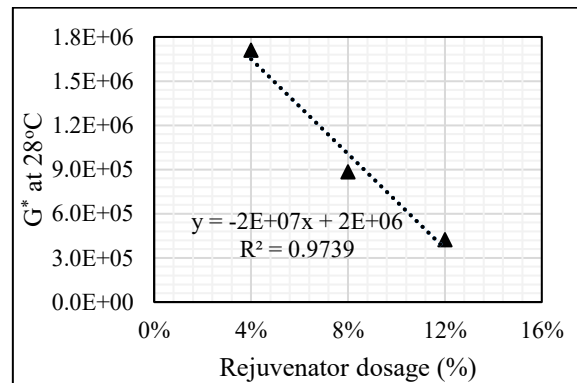
E4



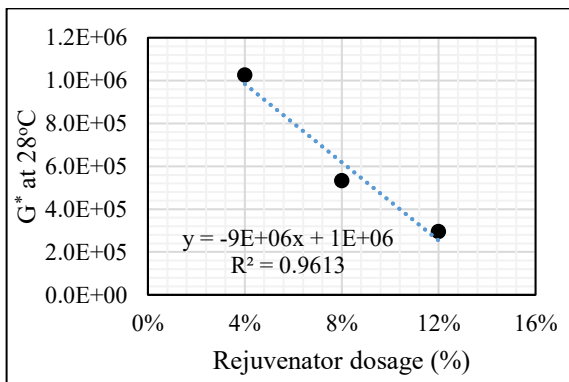
E8



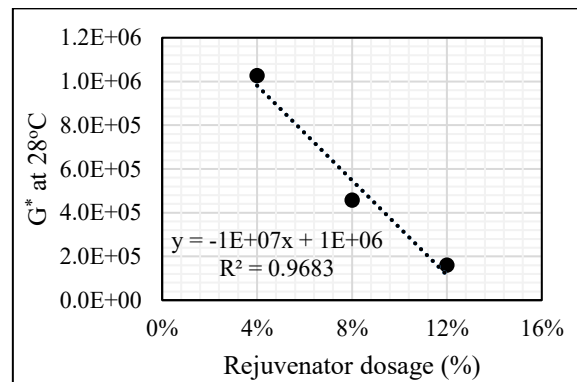
R4



R8



W4



W8

Figure 6-19 RILEM criteria trend with rejuvenator dose

Table 6-3 Rejuvenator dosages corresponding to different parameters

Binder	Penetration	PGH	PGI	SP	CV	G-R	RILEM	Jnr3.2	W_c
E4	13.46	13.18	8.12	6.97	6.10	12.80	14.95	11.07	4.13
E8	10.57	10.92	6.46	7.25	6.68	11.59	11.64	9.48	6.60
W4	6.96	9.56	6.20	4.21	3.00	9.53	11.10	7.04	2.41
W8	8.09	8.66	4.86	5.18	4.47	10.46	10.00	6.39	4.80
B4	7.69	9.92	6.26	4.74	2.72	10.92	11.27	7.11	3.62
B8	6.11	7.25	4.32	4.38	4.13	9.74	7.81	5.70	4.87
R4	11.77	13.47	11.79	6.67	5.3	11.66	14.25	10.68	4.44
R8	10.28	11.65	9.47	7.62	7.29	10.73	10.71	9.62	5.36

6.4.2.2 Tukey post-hoc analysis

Test results showed that dosages varied depending on the parameter selected, rejuvenator type and percentage of RAP. But upon careful observation, it is discovered that, for a particular rejuvenator and RAP content combination, some parameters resulted in similar or comparable dosages. So Tukey post-hoc statistical analysis is conducted to understand which dosages are similar or different. Minitab software is used to perform the analysis. First, HSD statistic is calculated and if the difference between two dosages is greater than HSD then those dosages are different and are placed in a different group (cluster). If difference is less than HSD then they are considered same and clubbed together in same group (cluster). Analysis is performed for different combinations such as considering all the binder blends (all rejuvenators and RAP contents) or only single RAP (40% or 80%) contents and all rejuvenators or single rejuvenator and both RAP contents. Considering all the combinations, clusters are made as shown in Table 6-4.

CHAPTER 6

From the literature, it is recognized that parameters related to high temperature properties such as PGH gives maximum dosage and parameters related to intermediate temperature properties such as PGI gives minimum dosage. In most of the cases, RILEM parameter (G^* at 28°C) and PGH offered maximum dosages. Whereas crossover frequency provided minimum dosage. $J_{nr3.2}$ and penetration parameters provided dosages slightly lower than RILEM and PGH, in most of the cases. From the clusters, it can be seen that some parameters such as softening point and ZSV (related to high temperature performance) and G-R (related to intermediate temperature performance) resulted in erroneous dosages. It highlights the inadequacy of the mentioned parameters for the evaluation of dosages, despite of the test results observed in 1.4.1.1. Nonetheless, optimum dosage for each rejuvenator and RAP content is finally decided based on the performance of the mixes as evaluated in the following section.

Table 6-4 Clusters and corresponding dosages for all binder blends

Binder blend	Cluster designation	Parameters	Dosage (%)
B4	<i>B41</i>	<i>RILEM, PGH and G-R</i>	10.92
	<i>B42</i>	<i>Jnr3.2 and Penetration</i>	7.40
	<i>B43</i>	<i>Softening Point and PGI</i>	5.50
	<i>B44</i>	<i>Crossover frequency and ZSV</i>	3.17
B8	<i>B81</i>	<i>RILEM, PGH and G-R</i>	7.81
	<i>B82</i>	<i>Jnr3.2 and Penetration</i>	5.90
	<i>B83</i>	<i>Softening Point, PGI, ZSV and Crossover frequency</i>	4.35
E4	<i>E41</i>	<i>RILEM, PGH, G-R and Penetration</i>	13.32
	<i>E42</i>	<i>Jnr3.2 and PGI</i>	9.6

	<i>E43</i>	<i>Softening Point and ZSV</i>	6.53
	<i>E44</i>	<i>Crossover frequency</i>	4.13
E8	<i>E81</i>	<i>RILEM, PGH, G-R and Penetration</i>	11.26
	<i>E82</i>	<i>Jnr3.2 and PGI</i>	7.97
	<i>E83</i>	<i>Softening Point, ZSV and Crossover frequency</i>	6.68
R4	<i>R41</i>	<i>RILEM and PGH</i>	13.86
	<i>R42</i>	<i>Jnr3.2, Penetration, PGI and G-R</i>	11.72
	<i>R43</i>	<i>Softening Point</i>	6.67
	<i>R44</i>	<i>Crossover frequency and ZSV</i>	4.87
R8	<i>R81</i>	<i>Penetration, PGH, G-R and RILEM</i>	10.72
	<i>R82</i>	<i>Jnr3.2 and PGI</i>	9.54
	<i>R83</i>	<i>Softening Point and ZSV</i>	7.46
	<i>R84</i>	<i>Crossover frequency</i>	5.36
W4	<i>W41</i>	<i>RILEM, PGH and G-R</i>	9.56
	<i>W42</i>	<i>Penetration, Jnr3.2 and PGI</i>	6.96
	<i>W43</i>	<i>Softening Point</i>	4.21
	<i>W44</i>	<i>Crossover frequency and ZSV</i>	2.71
W8	<i>W81</i>	<i>RILEM and G-R</i>	10.07
	<i>W82</i>	<i>Penetration and PGH</i>	8.37
	<i>W83</i>	<i>Jnr3.2 and Softening Point</i>	5.78
	<i>W84</i>	<i>PGI, Crossover frequency and ZSV</i>	4.80

6.4.2.3 Balance rutting and fatigue mix performance to select the optimum dosage

From the binder tests, it is found that different parameters offered different dosages that would result in the binder blend similar to VG-30. Hence to assess whether these dosages (clusters) will provide same performance as that VG-30, performance (rutting and fatigue resistance) of recycled mixes is evaluated. Lower the permanent strain value better the rutting resistance will be and higher the CT_{index} better the cracking resistance will be. As the rejuvenators dosage is shifted from maximum to minimum, permanent strain values decreased and CT_{index} values increased as shown in Figure 6-20, suggesting the increase in the stiffness and decrease in the flexibility of binder blends.

The cluster that provides similar or better performance in terms of both rutting resistance (permanent strain) and fatigue resistance (CT_{index}) is considered as optimum dosage for the binder blend under consideration. If multiple clusters resulted in better performance considering both rutting and fatigue, then cluster of lowest dosage is selected. From Table 6-4, it can be seen that in case of B4, all clusters resulted in better rutting resistance and cluster B41 and B42 have higher CT_{index} than VG-30. Although both B41 and B42 offered balanced optimised performance, cluster B42 is selected as the optimum dosage credited to the low dosage compared to B41. Similarly, all other optimum dosages are selected and are shown in Table 6-5. Considering all the binder blends with four rejuvenators and two different RAP percentages, the optimum dosage lies in the range of $PGI \pm 3.75\%$.

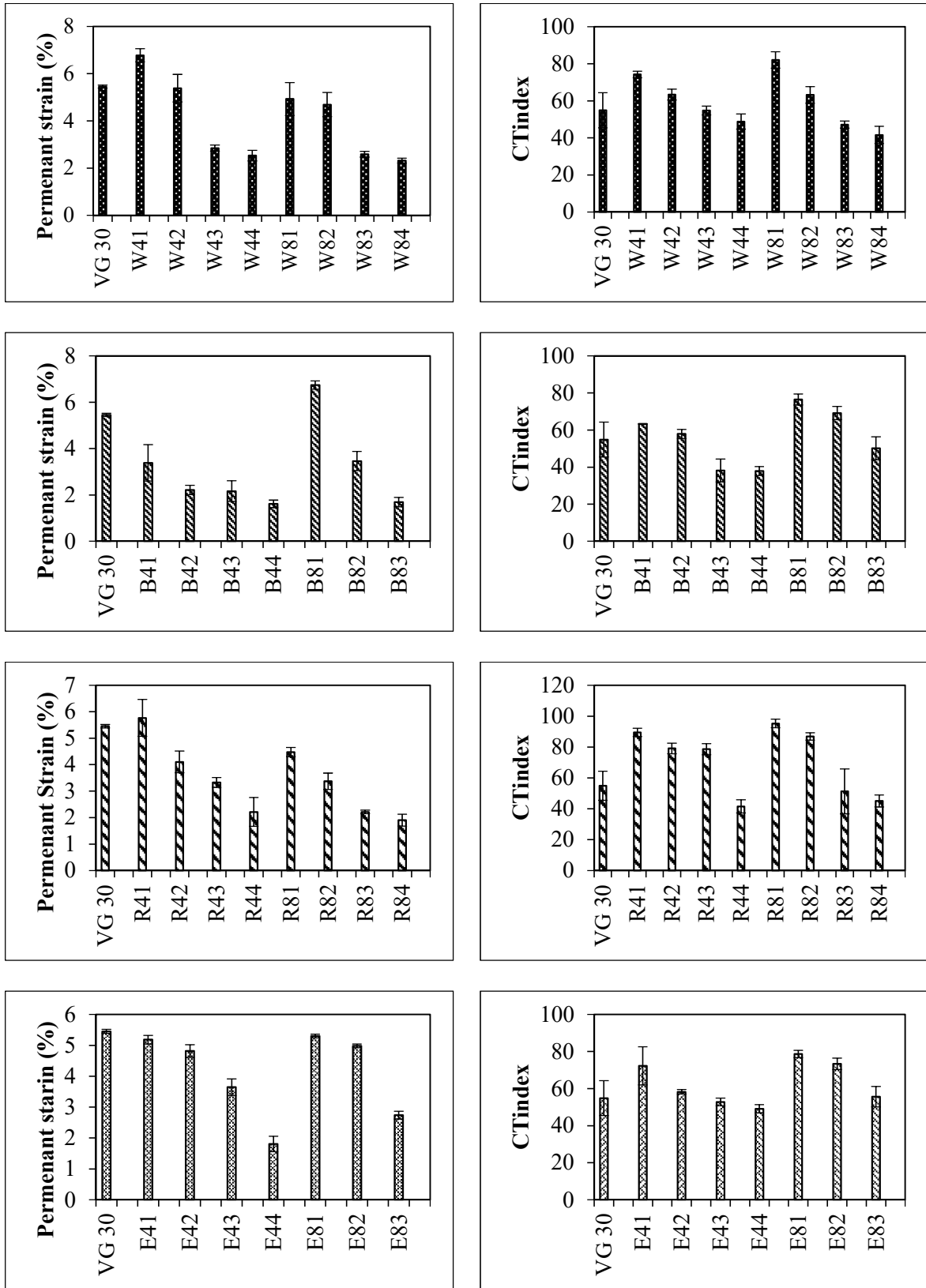


Figure 6-20 Rutting and fatigue performance results of different clusters

Table 6-5 Selection of optimum dosage cluster

	40% RAP		80% RAP	
	DC	IDCT	DC	IDCT
W	<u>W42</u> , W43, W44	W41, <u>W42</u>	W81, <u>W82</u> , W83, W84	W81, <u>W82</u>
E	E41, <u>E42</u> , E43, E44	E41, <u>E42</u>	E81, E82, <u>E83</u>	E81, E82, <u>E83</u>
R	R42, <u>R43</u> , R44	R41, R42, <u>R43</u>	R81, <u>R82</u> , R83, R84	R81, <u>R82</u>
B	B41, B42, B43, <u>B44</u>	B41, B42, B43, <u>B44</u>	<u>B82</u> , B83	B81, <u>B82</u>

6.4.3 Task-3: Recycled binder and mixture test results

6.4.3.1 Binder test results

As stated in section 6.2, ω_c represents the hardness of the binder and it is revealed that ω_c decreases with an increase in aging time or temperature (basically viscosity) [337,338]. It makes sense, as the stiffer the binder is, the lower the frequency (higher temperature) at which the storage modulus will be the same as the loss modulus. Hence, ω_c and ZSV are presented in the same graph in Figure 6-21 (a) and (b). For 40% RAP, W and E (WR) showed lower ZSV and higher ω_c values than B and R (CR). Also, WR have comparable ZSV and ω_c at 40% RAP. But at 80% RAP, E have the highest ZSV and, hence, the lowest ω_c . Rejuvenators W and R, which have many similar functional groups, behaved similarly in terms of ω_c at 80% RAP. Alkane functional group made W softer (compared to R) and the impact on ZSV and ω_c can be clearly observed at 40% RAP but only ZSV is able to capture the influence at 80% RAP. ZSV and ω_c have a good (linear) correlation with R^2 value of 0.842. Considering less test time and more straightforward calculation, the ZSV parameter is enough to have a comparative idea about the impact of rejuvenators on the linear viscoelastic response of RAP.

Softer binders (low ZSV values) usually tend to have higher non-recoverable strains (higher J_{nr} values) and, thus, lesser rutting resistance. The expected trend is observed at both RAP contents

CHAPTER 6

as can be seen from Figure 6-21 (c) and (d), except R at 80% RAP have better rutting resistance (lower J_{nr} value) than B value despite of being softer. CR performed better than WR in rutting (except E at 80% RAP). On the other hand, G-R parameter signifies the onset of cracking; the lower the value, the higher the scope for the binder to avoid cracking. Since it is a cracking parameter, softer binders (low ZSV and J_{nr} values) are anticipated to perform better. Thus WR performed better than commercial rejuvenators in cracking, except E at 80% RAP. Rejuvenator B performed better than R in rutting and cracking at 40% RAP and comparable rutting and better-cracking resistance at 80% RAP. This can be attributed to the arenes and ester functional groups in the rejuvenator B. Presence of one additional C-H (alkane) functional group made W softer than R. Overall, WR resulted in softer binders (except E at 80% RAP) and thus are beneficial in improving cracking resistance.

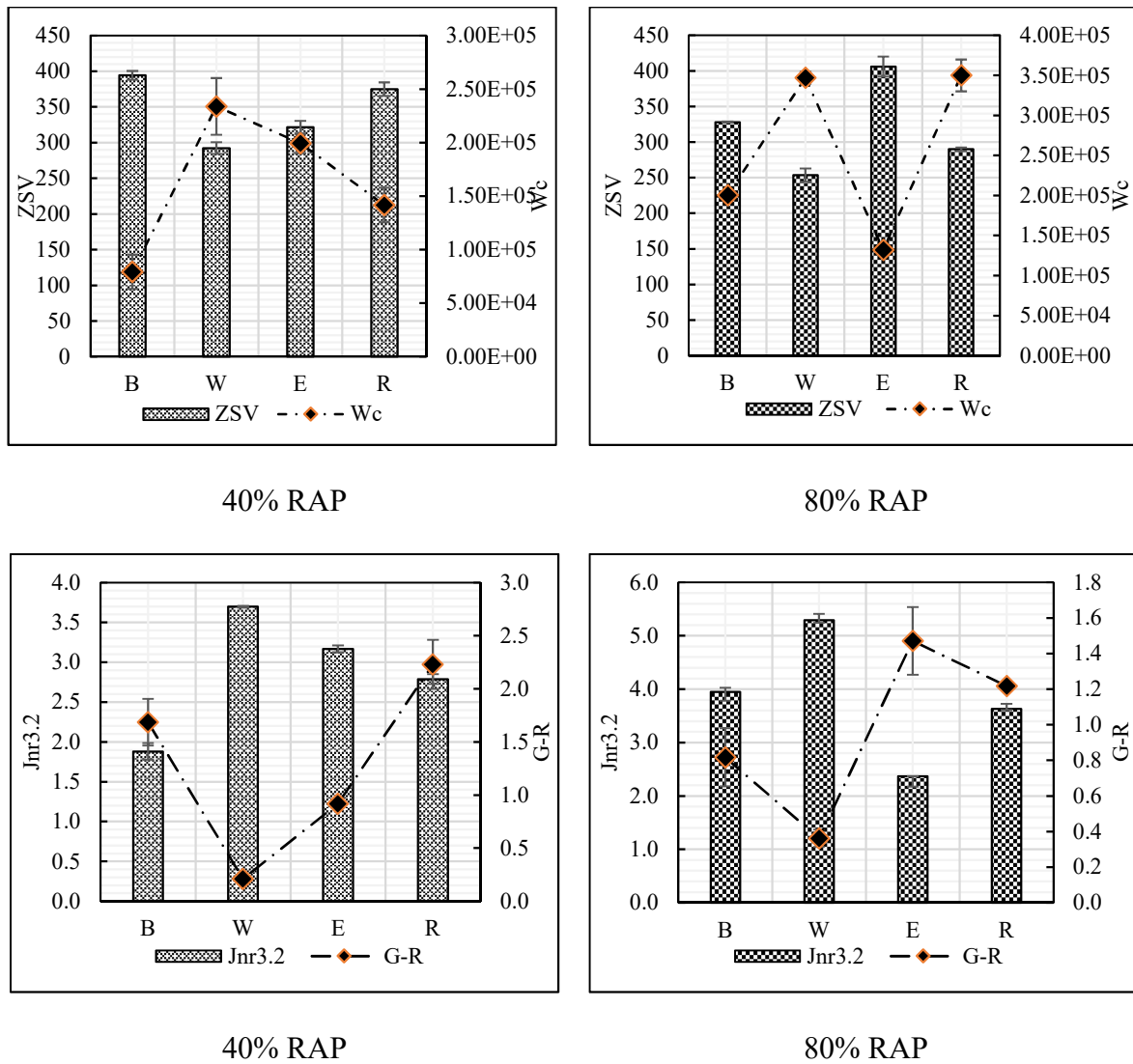


Figure 6-21 Rheological properties of recycled binders with different rejuvenators

6.4.3.2 Mixture performance

The total (cumulative) permanent strain is the result of time-dependent and independent strains, and higher values suggest the proneness of the binder (rejuvenator) to undergo high irrecoverable strains (less rutting resistance). Similar to MSCR results, WR showed higher irrecoverable strains than CR, except E at 80% RAP. Rejuvenator B at 40% RAP and rejuvenator E at 80% RAP showed the highest rutting resistance (less irrecoverable strains) compared to other mixes at respective RAP percentages. AFR showed a better correlation with permanent strain than FI at 40% and 80% RAP, considering standard deviation as shown in Figure 6-22 (a) to (d). This can be due to the fact that AFR is a deformation-based parameter,

whereas FI is a load-related parameter. Also, AFR can capture or differentiate the influence of rejuvenators on fatigue performance rather than FI. CR, on top of performing well in rutting, also showed better (R) or comparable (B) fatigue performance (both FI and AFR) at 40% RAP. On the other hand, at 80% RAP, E displayed balance performance, comparable AFR to that of CR and the lowest irrecoverable strain. MSCR and uniaxial cyclic compression tests resulted in a similar ranking of rejuvenators, but G-R parameter and IDEAL CT results (in terms of FI and AFR) did not correlate well.

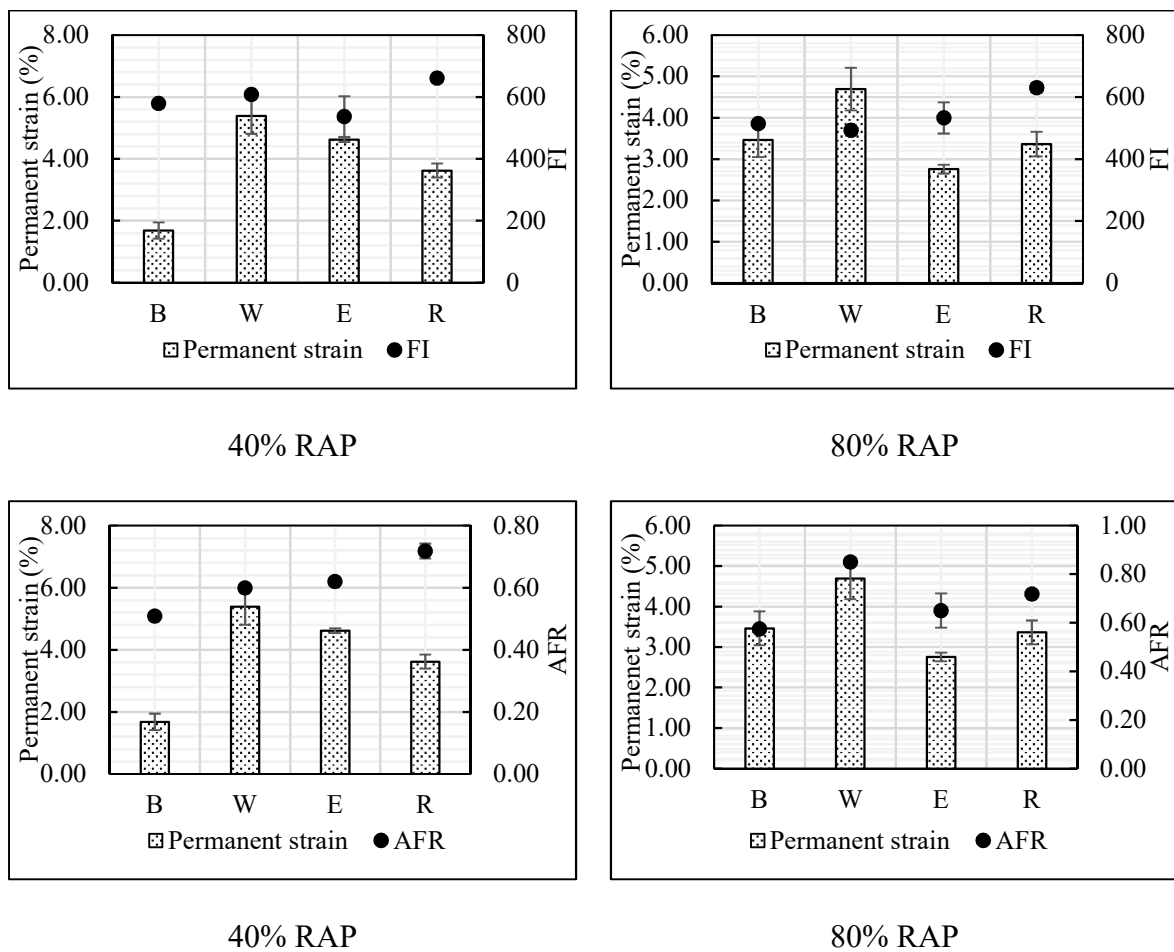


Figure 6-22 Rutting and Fatigue Performance of recycled mixes with different rejuvenators

6.4.4 Ranking of rejuvenators

Tests on rejuvenators are given high priority followed by mixes and binder's performance and then rheological parameters. Generally, rejuvenators are used to improve the cracking resistance of recycled mixes. However, there will also be a simultaneous decrease in rutting

CHAPTER 6

resistance. Therefore, two cases are considered when assigning rank to the performance tests. In case 1, rutting is given a better rank than fatigue, and in case 2, fatigue is given a preference over rutting. Both binder and mix rutting and fatigue tests are assigned the same rank. Ranks assigned for each test in both cases for 40% RAP are shown in Table 6-6. The same has also been followed for 80% of RAP.

Inverse values of RTFO results (weight change and viscosity ratio), Jnr, G-R and permanent strain (PS) are considered for both cases. Also, in case 2, inverse viscosity values are implemented, as low viscous rejuvenators benefit fatigue performance. From Table 6-8, the TRV of B is somewhat comparable to E, at 40% RAP, but the difference amplified at 80% RAP. W ranked highest at 40% RAP in case 1 and performed even better when preference was given to fatigue performance (case 2). Rejuvenators with similar physical characteristics (B-W and E-R) have very different rankings and, thus, performance. From the TRV values, it can be decided that WR outperformed CR at both 40% and 80% RAP contents and, in both cases, considered. Overall, GTRV values also suggested the same, with W ranking the highest, followed by E, B and R. Weight change from the RTFO test correlated well with the GTRV rather than the viscosity ratio or viscosity values of rejuvenators. Therefore, if one needs to select a better performing rejuvenator from multiple options, it is recommended to conduct RTFO test on rejuvenators and select the one with the lowest weight change.

Table 6-6 Ranking approaches for 40% RAP

	Viscosity	RTFO	ZSV	ω_c	J_{nr}	G-R	PS	AFR	
<u>Case-1</u>									
Rank	2	1	1	5	5	3	4	3	4
WF	0.0071	0.0036	0.0036	0.179	0.179	0.107	0.143	0.107	0.143
<i>Ranked values</i>									
B	0.00	20.82	8.30	5.60	0.00	9.33	0.24	9.33	0.00
W	1.07	28.00	28.00	0.00	5.60	0.00	7.00	0.00	3.04
E	4.19	21.55	27.12	1.60	4.35	1.61	1.05	0.71	3.71
R	14.00	0.00	0.00	4.54	2.26	3.15	0.00	2.07	7.00
<u>Case-2</u>									
Rank	2	1	1	5	5	4	3	4	3
WF	0.0071	0.0036	0.0036	0.179	0.179	0.143	0.107	0.143	0.107
<i>Ranked values</i>									
B	14.00	20.82	8.30	5.60	0.00	7.00	0.31	7.00	0.00
W	9.13	28.00	28.00	0.00	5.60	0.00	9.33	0.00	4.05
E	3.72	21.55	27.12	1.60	4.35	1.21	1.39	0.53	4.95
R	0.00	0.00	0.00	4.54	2.26	2.36	0.00	1.55	9.33

Table 6-7 Ranking approaches for 80% RAP

	Viscosity	RTFO	ZSV	ω_c	J_{nr}	G-R	PS	AFR	
<u>Case-1</u>									
Rank	2	1	1	5	5	3	4	3	4
WF	0.0071	0.0036	0.0036	0.179	0.179	0.107	0.143	0.107	0.143
<i>Ranked values</i>									

CHAPTER 6

B	0.00	20.82	8.30	2.73	1.76	2.57	1.83	4.71	0.00
W	1.07	28.00	28.00	0.00	5.52	0.00	7.00	0.00	7.00
E	4.19	21.55	27.12	5.60	0.00	9.33	0.00	9.33	1.90
R	14.00	0.00	0.00	1.34	5.60	3.46	0.48	5.25	3.66
<u>Case-2</u>									
Rank	2	1	1	5	5	4	3	4	3
WF	0.0071	0.0036	0.0036	0.179	0.179	0.143	0.107	0.143	0.107
<i>Ranked values</i>									
B	14.00	20.82	8.30	2.73	1.76	1.92	2.44	3.53	0.00
W	9.13	28.00	28.00	0.00	5.52	0.00	9.33	0.00	9.33
E	3.72	21.55	27.12	5.60	0.00	7.00	0.00	7.00	2.53
R	0.00	0.00	0.00	1.34	5.60	2.59	0.64	3.94	4.88

Table 6-8 Final ranking of Rejuvenators

	TRV				GTRV	Rank
	<u>Case-1</u>		<u>Case-2</u>			
	40% RAP	80% RAP	40% RAP	80% RAP		
B	53.62	42.72	63.03	55.51	214.88	3
W	72.70	76.59	84.12	89.32	322.74	1
E	65.88	79.03	66.42	74.52	285.85	2
R	33.02	33.78	20.04	18.98	105.83	4

6.5 CONCLUSIONS

In this chapter, characterisation and comparative evaluation of different rejuvenators (used in this study) is carried out in three tasks. In the first task, RTFO and FTIR tests on rejuvenators, rutting and fatigue performance on recycled binder blends and mixes, and rheological

CHAPTER 6

parameters of binders are assessed. The optimum dosage of rejuvenators using multiple parameters is done in the second task. In the last task, mixture and binder performance are assessed at the optimum dosages obtained in the second task.

Despite having similar physical properties, the rejuvenators B-W and E-R showed differences in viscosity, aging resistance, and chemical characteristics. R was the most viscous, followed by E, W, and B, with WR offering better aging stability than CR. Chemically, W and R are amine-based aliphatic hydrocarbons while B is aromatic, and E is a simple aliphatic type. All rejuvenators, however, contained both aliphatic and aromatic hydrocarbons resembling the maltenes fraction of asphalt. Their effectiveness in restoring binder properties was dosage-dependent, with parameters varying linearly as dosage increased. Blends with 80% RAP were more sensitive to rejuvenator dosage than those with 40% RAP, and bio-oil-based rejuvenators (B and W) required more precise dosages compared to petroleum-based (E) and compound (R) rejuvenators. While parameters such as softening point, ZSV, and G-R gave inconsistent results for dosage determination, the optimum dosage across all rejuvenators and RAP levels was found to be within $\text{PGI} \pm 3.75\%$.

In terms of performance, WR rejuvenators generally produced softer binders, better cracking resistance, and higher rutting susceptibility than CR rejuvenators, except for E at 80% RAP. At 40% RAP, W and E exhibited lower ZSV and higher ω_c compared to B and R, while at 80% RAP, E had the highest ZSV and lowest ω_c . Mix performance reflected binder behaviour, with WR mixes showing higher irrecoverable strains than CR mixes, except for E at 80% RAP. CR rejuvenators performed better in rutting resistance and showed either better (R) or comparable (B) fatigue performance at 40% RAP. At 80% RAP, E balanced rutting and fatigue, yielding the lowest irrecoverable strain. Based on global total rank values (GTRV), WR outperformed CR, with W ranking the highest, followed by E, B, and R. Furthermore, RTFO weight change

CHAPTER 6

correlated strongly with GTRV, suggesting that rejuvenators with the lowest RTFO weight change can be selected for better performance.