CHAPTER 6. PERFORMANCE OF WMA MODIFIED BINDERS

6.1 Preamble

To implement WMA technology in field, the performance of WMA technology should be satisfactory and assessed accordingly. It has been discussed in previous chapter that the performance of WMA technology is majorly influence by their mixing and compaction temperatures. This can be due to the reduced aging as result of lower mixing and compaction temperatures offered by WMA technology. The reduced aging of WMA modified asphalt binders are most repeated issues raised in the literature [37,223,261,264]. Aging is nothing but oxidation or hardening of an asphalt binder which leads to the change in behaviour of asphalt binder and mixture due to the shift in chemical composition during the construction and in-service life under different environmental conditions [220,256,257]. Aging generally occurs in two stages. The primary stage initializes at a very rapid rate during the production of the asphalt mixture. This stage is referred to as short term aging (STA). STA is caused due to the loss of volatile components present in the asphalt binder and oxidation process at elevated temperatures [263]. On the other hand, the second stage of aging is observed after the exposure of pavement to environmental oxygen and atmospheric moisture throughout its service life. The second stage mostly occurs after a certain service life of the pavement and is designated as Long term aging (LTA) [263]. Figure 6-1 shows the aging of asphalt binders at different stages. WMA technology facilitates lower production temperatures and significantly reduces the oxidative aging of the asphalt binder, which can potentially affect its structural performance [21,116,411]. Traditionally it is believed that short-term aging of asphalt binders assures stiffening which may be advantageous in terms of resistance to permanent deformation [214][412]. But, reduced aging in WMA modified asphalt binders could increase the in-service rutting potential of some WMA products [22,38]. Previous studies have indicated that the use of WMA showed lower rutting resistance as compared to HMA made of the same materials [228,413]. A recent study conducted by NCHRP Project 9-43 have shown that the WMA technology reduces PG grade by 3^{o}C with a reduction in temperature by 30^{o}C [21]. Apart from this, various researchers have reported inconsistent rutting performance as can be seen in Table 6-1. The studies conducted by various researchers indicated that the Sasobit modified asphalt binder showed better rutting performance with respect to HMA [49,101,414]. However, the use of chemical additives showed lower or equal rutting resistance [67,131,197,415,416]. To date, limited data are available to draw a firm conclusion regarding the fatigue performance of WMA modified asphalt binder. Some studies discussed in Table 6-1 have reported the better faigue performance of WMA modified asphalt binders. This may be attributed to the reduced oxidative aging, which reduces the stiffening of WMA modified asphalt binder compared to control asphalt binder (without WMA additives) [217,260]. Although the technology shows better fatigue resistance, the performance related to moisture damage remain unanswered. Due to reduction in production temperature, moisture may retain in the mineral aggregates due to incomplete drying [21,121]. This may further increase the moisture susceptibility of asphalt mixes leading to an early failure of the mixture. Many existing literatures have already cited the moisture susceptibility issue for mixes prepared using WMA [99,237,417]. It was found that the extent of moisture damage is dependent on the type of WMA technology, type of aggregates, regional climatic conditions and loading conditions [239,246,247]. Table 6-1 presents the inferences from past literatures on the performance of WMA modified asphalt binders in terms of rutting, fatigue, and moisture sensitivity. Apart from the primary distresses, such as rutting, fatigue, and moisture sensitivity, various researchers [104,260,418–421] revealed that reduced aging may also influences the low temperature performance of WMA modified asphalt binders. The authors [104,418,419] carried out low temperature testing using bending beam rheometer (BBR) and found that the difference in the stiffness and m-value (slope of master stiffness curve) was not very significant. The stiffness and m-value for WMA modified asphalt binders were found to be well within the critical limits (i.e., stiffness <300 MPa and m-value >0.3) [418,419,421]. It should be noted that the evaluation of low temperature characteristics of WMA modified asphalt binder is not considered in the scope of the present study, but it can be a potential research area to be explored in the future.

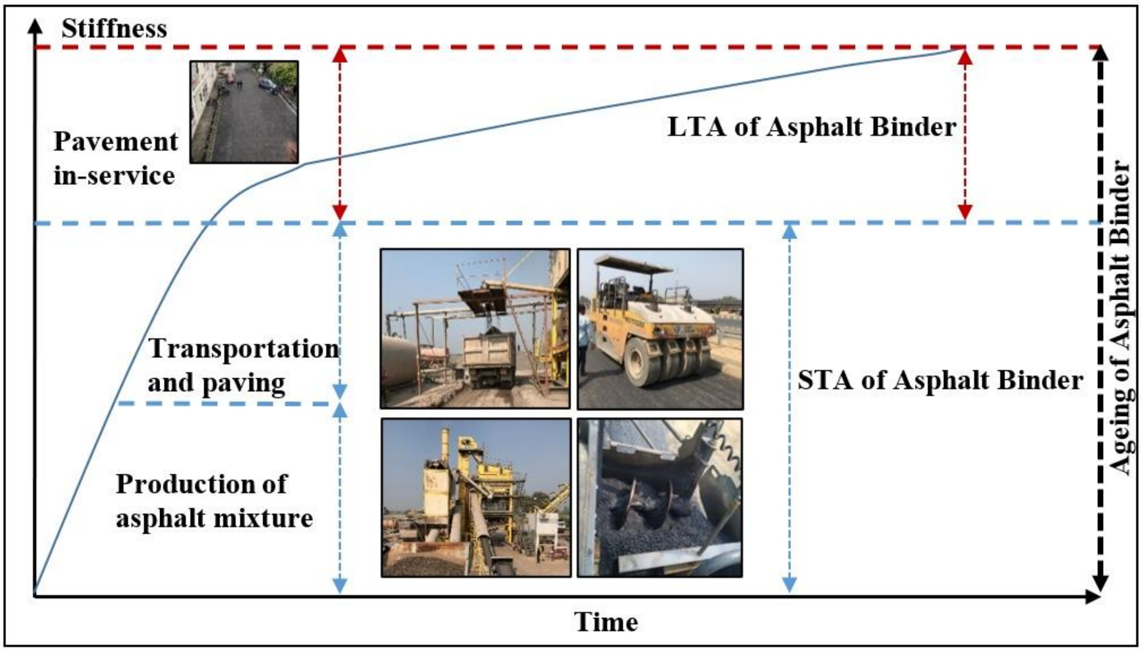


Figure 6-1. Phases of asphalt aging

Table 6-1. Results of previous studies on the effect of WMA additives on rutting, fatigue, and moisture damage performance

Author	Additives (Technology)	Performance parameter	Inferences
Rutting performance			
Xiao et al. 2012 [217]	Sasobit (Organic)	G*/sinδ Creep angle Creep Compliance	• Increased G*/sinδ and so the rutting resistance. • Sasobit modified binder showed lower creep angle and creep compliance. • At different shear strain levels, Sasobit showed the highest complex modulus and the lowest phase-angle, regardless of aging stages.

Jamshidi et al. 2015 [369]	Sasobit (Organic) Rediset (Chemical)	G*/sinδ Viscosity at 60°C	• The addition of Sasobit significantly increased the viscosity of base binders whereas the effect of Rediset not very significant. • The influence of WMA additives was found to be function of base binders.
Ragni et al. 2018 [225]	Chemical	J_{nr}	• Increase in Jnr value with the addition of chemical additives and, therefore, poor rutting performance. • The recoverable behavior of the WMA modified asphalt binders was influenced by the type of chemical additive and the short-term aging temperature.
Prakash and Suman 2023 [422]	Polyethylen Wax (Organic) Waste cooking oil (Chemical)	J_{nr}	• For initial dosages of warm mix modifiers, rutting performance was comparable. • An increase in WMA additives' dosages increased the base binder's rutting susceptibility.
Zaremotekhases et al. 2022 [423]	Sasobit (Organic) Evotherm (Chemical) Advera (Water based)	J_{nr}	• All WMA modified asphalt binders showed a lower Jnr value than the base binder. • Sasobit showed better high temperature performance than all other additive type. • There exists a strong relation between the G*/sinδ parameter, MSCR, and the outcomes of the wheel tracking test.
Fatigue Performance			
Rani et al. 2020 [230]	Chemical	G*.sinδ	• Due to reduced oxidative aging, the fatigue resistance of WMA was higher than HMA. • Fatigue performance at higher dosages (i.e., 0.75%) was found to be ineffective due to unchanged chemical composition of WMA modified asphalt binder after WMA modification.

Zaremotekhases et al. 2022 [423]	Sasobit (Organic) Evotherm (Chemical) Advera (Water based)	N_f (LAS Test)	• WMA modified asphalt binders showed better fatigue life than base binders. • The effect of chemical additives was more efficient than other WMA additives.
Kataware and Singh 2018 [34]	Sasobit (Organic) Rediset (Chemical) Advera (Water based)	N_f (LAS Test)	• WMA showed higher or equal fatigue life compared to control binder. • The improvement in fatigue life was found to be the function of WMA type and their dosages.
Behl and Satish 2021 [424]	Sasobit (Organic) Rediset (Chemical) Evotherm (Chemical)	G*.sinδ N_f (LAS Test)	• G*.sinδ showed that all WMA modified binders had better fatigue resistance than base binders. • Based on LAS fatigue life, the Evotherm and Sasobit showed higher fatigue life than the base binder, whereas Rediset showed comparable fatigue life.
Norouzi et al. 2021 [425]	Sasobit (Organic) Rheofalt LT70 (Organic) Zycotherm (Chemical)	G*.sinδ N_f (LAS Test)	• The addition of Rheofalt improved the fatigue life of the base binder followed by Sasobit. • The chemical additive, Zycotherm, failed to improve the fatigue life of the base binder. • G*.sinδ was incapable of capturing the fatigue behavior of WMA modified asphalt binder and showed a poor relationship with the beam fatigue test.
Resistance to Moisture damage			
Mogawer et al. 2011 [248]	Advera (Water based) Sasobit and Sonne warmix (Organic) Evotherm (Chemical)	Stripping Inflection Point and Bond Strength	• All WMA binders showed a reduction in bond strength after wet conditioning indicating lower resistance against moisture damage. However, this reduction relies on the type of WMA additive.

			• Among all WMA additives, Sasobit had a considerable impact on the binder's pull-out tensile strength.
Alavi et al. 2012 [247]	Water-bearing mineral (foaming) solid pelletized surfactant additive (Chemical) Viscosity Reducer (Organic)	Bond Strength and BSR	• The reduced temperature of WMA modified asphalt mixtures results in poor bonding between the aggregate and asphalt binder, thereby indicating higher moisture susceptibility. • Selection of WMA additives plays an important role in counteracting any detrimental impacts of lower production temperatures on moisture susceptibility.
Ahmed et al. 2018 [426]	Wax-based (Organic)	Bond Strength	• WMA additive showed better resistance than HMA; however, this behavior depends on the binder and aggregate type.
Habal and Singh 2021b [251]	Sasobit (Organic) Rediset (Chemical)	TSR, Energy ratio (SFE), and Bond strength ratio (BSR)	• All these parameters showed that the resistance to moisture damage deteriorated with the addition of WMA additives. • Rediset showed higher resistance to moisture damage than Sasobit.
Sukhija et al. 2023a [240]	Sasobit (Organic) Sasobit Redux (Organic) Rediset (Chemical) Cecabase (Chemical)	Bond strength ratio (BSR)	• Chemical-based WMA additives showed superior performance against moisture damage among all the additives. • The type of failure mode is a function of the type of aggregate substrate. • Calcareous aggregate showed better performance against moisture damage than siliceous aggregate.

6.2 Scope for Performance Assessment of WMA Modified Binders

Recently, a tribology-based approach was developed to determine the production temperatures (mixing and compaction temperature) of WMA modified asphalt binders. This approach indicated promising results in terms of mixing and compaction temperatures of WM asphalt mixtures. As discussed in Chapter 5, the mixing and compaction temperatures were reduced approximately by 20°C and 25°C, respectively, depending on the type of base binder, type of WMA additives and their respective dosages. This shows that WMA asphalt mixtures can be produced at lower production temperatures, and hence WMA asphalt mixtures exhibit a reduced aging effect, particularly during the construction phase [21,260]. From this perspective, it is necessary to assess the performance of WMA modified asphalt binder at a reduced aging level.

The primary objectives of the present study are:

1. Assessing the change in the chemical composition of WMA modified asphalt binders due to reduced aging effect.
2. Understanding the fatigue and rutting behaviour of WMA modified asphalt binder at a reduced aging level.
3. Evaluating the moisture sensitivity of WMA modified asphalt binder.

Figure 6-2 shows the experimental plan of this study. After preparation of WMA modified binders, the effect of WMA additives and their dosages on rheological properties of base binders were studied using various rheological models. This study adopted the tribology-based approach for the determination of mixing and compaction temperature of WMA modified asphalt binder. Following the determination of mixing and compaction temperature, the aging potential of WMA modified binder were studied using FTIR test after STA and LTA. Thereafter, the performance of WMA modified asphalt binder was determined using an MCR 102 (Anton Paar) dynamic shear rheometer (DSR). Over the years, Superpave parameters

($|G^*|/\sin\delta$ and $|G^*|\sin\delta$) has been used to understand the rutting and fatigue potential, respectively. G^* and δ refers to the complex modulus value and phase lag of the asphalt binder, respectively. It should be noted that the results of $|G^*|/\sin\delta$ and $|G^*|\sin\delta$ may not be very effective/reliable as these parameters merely depend on the stiffness of the asphalt binder [427]. It should be noted that the results of |G*|/sinδ and |G*|sinδ may not be very effective or reliable for evaluating the performance of modified binders, as these parameters are primarily stiffness-based and were originally developed for unmodified asphalt binders. Moreover, these parameters are obtained within the Linear Viscoelastic (LVE) domain and therefore fail to characterize the binder behavior in the non-linear viscoelastic regime, which is critical for understanding performance under actual field loading conditions. This limitation becomes particularly significant for modified binders and fails to characterize the modified binders. In response to the inadequacy of Superpave parameters in such cases, advanced rheological tests such as the Multiple Stress Creep and Recovery (MSCR) test and the Linear Amplitude Sweep (LAS) test were developed. These tests provide a more accurate and comprehensive evaluation of rutting and fatigue performance, respectively, by capturing the viscoelastic, stress-sensitive, and non-linear behavior of modified binders. In addition, the these test provide behaviour of binder within and outside the linear viscoelastic (LVE) domain This is the primary reason for selecting MSCR and LAS tests in this study, as they offer more realistic and reliable insights into the performance of WMA modified binders under simulated field conditions. Thus, advanced tests such as multiple stress creep and recovery (MSCR) test and linear amplitude sweep (LAS) test are recommended to clearly comprehend the rutting and fatigue behaviour of WMA modified asphalt binders. The fatigue behaviour of the WMA modified asphalt binders was assessed using the LAS test over the temperature range of 10–30◦C, while the rutting potential was evaluated through MSCR test at temperatures ranging from 40–70◦C. This study also focused on the moisture sensitivity of WMA modified asphalt binder. Recently, the bitumen bond strength (BBS) test is being used to assess the influence of moisture conditioning at the interface of asphalt binder and aggregate matrix [252,428]. As per Habal and Singh, BBS is a low-cost instrument which effectively measures the influence of moisture conditioning and provides repeatable and reproducible results [251]. In the present study, BBS test was employed to evaluate the moisture sensitivity of WMA modified asphalt matrix prepared using two sources of aggregate substrate. Further, the results of these tests were analysed to determine the effectiveness of WMA technology for asphalt pavements.

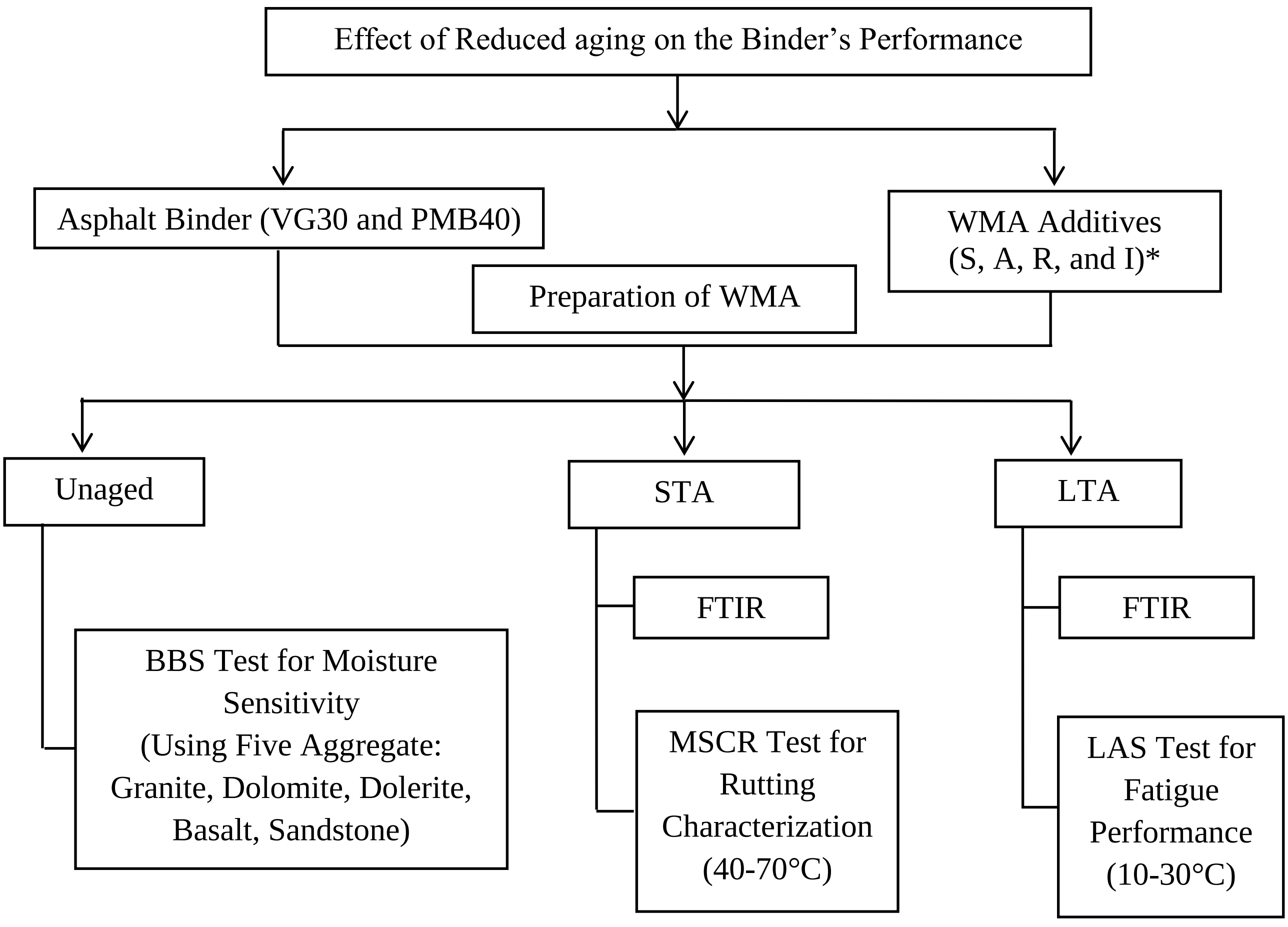


Figure 6-2. Experimental plan

*Note: * S, A, R and I are the abbreviations for Sasobit, Asphaltan A, Rediset, and Iterlow, respectively. STA and LTA are abbreviations for the short term aging and long term aging, respectively.*

6.3 Materials

A viscosity graded (VG) binder, VG-30, and a polymer modified binder, PMB-40, were used as base binder in this study to prepare WMA modified asphalt binders. These are common type of asphalt binders used for construction of flexible pavement in India. Four different warm mix additives (WMA): two organic additives and two chemical additives were selected for the research work. Organic additives selected for the study are: Sasobit and Asphaltan A. Chemical additives selected for the study are: Iterlow and Rediset. These warm mix additives were used to prepare different warm mix modified asphalt binders. The additives were mixed at different doses with VG 30 and PMB 40 binders as per the manufacturer's instructions [117]. Three basic aggregates i.e. Dolomite, Dolerite, and Basalt and two acidic aggregates i.e. Granite and Sandstone were used in this study. These various aggregate types were selected to check their effect on moisture sensitivity of WMA modified asphalt binders. The summary of materials used in the study are discussed in Chapter 3.

6.4 Experimental Investigation

6.4.1 Determination of MT and CT of WMA Modified Binders

In this study, the tribological approach was used for determination of MT and CT of WMA modified binders. The details (procedure and results) about the tribological approach have been discussed in Chapter 5. The MT and CT obtained from this approach were used for carrying out the short-term aging of WMA modified binders. Since the present study involves the application of WMA technology, wherein the asphalt mixtures are produced at lower temperatures relative to conventional HMA mixtures, it is obvious that STA of WMA binders would occur at relatively lower temperatures. Therefore, the short-term aging of WMA modified asphalt binders was carried out at the mixing temperature determined using the tribology approach.

6.4.2 Aging of WMA Modified Binders

All the WMA modified asphalt binders were short-term aged (STA) using a thin film oven as per the universal simple aging test (USAT) protocol [350]. The short-term aging of WMA modified asphalt binders was carried out at the mixing temperature determined using the workability approach. The details regarding aging are mentioned in Chapter 3. Figure 5-23 and Figure 5-25 present the MT and CT determined from tribological approach. The STA of all WMA modified binders are carried out at average MT determined from tribological approach, shown in Figure 5-23 and Figure 5-25. The long-term aging (LTA) of binders was also carried out in accordance with the USAT protocol [350]. As per the protocol, the LTA of binders was carried in the draft oven at 100°C for a duration of 40 hrs. Asphalt binders with different aging conditions (i.e., unaged, STA, and LTA) were stored separately for further investigations.

6.4.3 Fourier Transform Infrared Spectroscopy (FTIR) Test

In this study, the FTIR test was done using the KBr pellet method and a detailed procedure can be found in Chapter 3. The process includes measurement of absorbance in a range of wavenumbers between 400 cm^{-1} to 4000 cm^{-1}. FTIR is often used to assess the variations in the chemical composition of asphalt binders after STA and LTA [352]. It is well known that the most significant functional groups affected by aging are the carbonyl group (C=O), and the sulfoxide group (S=O) [41]. As per the literatures [41,216] carbonyl and sulfoxide indices, as given in Equation 6.1 and 6.2, provide an estimation of aging effect in the asphalt binder. Thus, an attempt has been made to determine these indices for different WMA modified asphalt binders and compare them with the results of base asphalt binder. The area between the 1350 cm^{-1} and 1525 cm^{-1} wavelength range, is considered a reference area that remains stable during aging [356]. In addition, the effect of aging on presence of polymeric network in PMB40 can be studied through transbutadiene index. Generally, for polymer modified binders, peaks at 700 and 965 cm^{-1} correspond to polystyrene and butadiene, respectively. The effect of aging on this peak has been evaluated in this study for PMB40 binders. The Equation 6.3 used for calculation of transbutadiene index. Based on the area below the absorbance spectrum about the peaks of functional groups, the following indices were calculated for analysis.

$$Carbonyl\ Index\ (I_{\mathrm{C=O}}) = \frac{A_{\mathrm{C=O}}}{A_{\mathrm{Ref}}} \tag{6-1}$$

$$Sulfoxide\ Index\ (I_{\mathrm{S=O}}) = \frac{A_{\mathrm{S=O}}}{A_{\mathrm{Ref}}} \tag{6-2}$$

$$Transbutadiene\ Index\ (I_{\mathrm{SBS}}) = \frac{A_{\mathrm{SBS}}}{A_{\mathrm{Ref}}} \tag{6-3}$$

Where,

$A_{C=O}$= area around carbonyl group (Area around 1700 cm^{-1})

$A_{S=O}$= area around sulfoxide group (Area around 1030 cm^{-1})

A_{SBS}= area around transbutadiene group (Area around 968 cm^{-1})

A_{Ref}= area around the aliphatic group (Area between 1350 cm^{-1} and 1525 cm^{-1})

6.4.4 Performance Test on WMA Modified Binders

In this study, various performance tests have been carried out on warm mix modified binders to check their suitability. The selection of particular type of warm mix additive for different type of distresses was made based on these performance tests. The performance tests were carried out on warm mix modified binders are described in Table 6-2.

Table 6-2. Performance test used for WMA modified binders

Performance Test	**Characterization of Distress**	**Performance Parameter**	**Equipment**	**Procedure**	**Specifications or Reference**
Multiple Stress Creep and Recovery (MSCR) Test	Rutting	J_{nr} and %R	Dynamic shear rheometer (DSR)	On STA* binder Temperature: 40-70°C Stress level: 0.1 and 3.2 kPa	[357]
Linear Amplitude Sweep (LAS) Test	Fatigue Cracking	Failure strain and N_F (fatigue life) at 2.5% and 5% strain level	Dynamic shear rheometer (DSR	On LTA* binder Temperature: 10-30°C Frequency sweep: frequency varies from 0.2 Hz to 30 Hz at strain of 0.1% followed by Amplitude sweep: Strain amplitude varies from 0.1 % to 30% in 300 secs at a frequency level of 10 Hz	[359]
Bitumen Bond Strength Test	Moisture Damage	Dry bond Strength, Wet bond Strength, Bond strength ratio	Pneumatic Adhesion Tester (PAT)	On unaged binder Loading: 100 psi/s Aggregate used: Basalt, Dolerite, Dolomite, Granite, and Sandstone	[365]

Note: STA and LTA referred to as Short Term Aged and Long Term aged. The FS and AS are abbreviations for the frequency sweep and amplitude sweep.

6.5 Results and Discussion

6.5.1 Aging Resistance of WMA Modified Binders Using FTIR test

Figure 6-3 to Figure 6-6 show the Carbonyl and Sulfoxide indices for different combination of base binders and WMA additives corresponding to STA and LTA conditions. As obvious, both indices showed an increment with the change in aging condition from STA to LTA, irrespective of the binder type. This is attributed to the simultaneous oxidation, dehydrogenation, and crosslinking reactions [215]. Higher values of indices indicate higher oxidation of asphalt binders and vice-versa [256]. As can be seen in Figure 6-3 to Figure 6-6, WMA modified asphalt binders exhibit lower carbonyl and sulfoxide indices as compared to base asphalt binders. The reason behind the lower value of indices of WMA modified asphalt binders is attributed to their lower mixing temperatures (aging temperature), resulting in improved aging resistance. In addition, it can be seen that the polymer modified binder PMB40 showed lower carbonyl and sulfoxide indices as compared to VG30 binders. However, the WMA modification in PMB40 showed higher value of these indices as compared to WMA modified in VG30. This can be due to the higher temperatures of polymer modified binders as compared to WMA modified binders (in case of VG30). From Figure 6-6 to Figure 6-8, it can also be observed that the carbonyl and sulfoxide indices found to be decreases with increase in dosages of warm mix additives. This can be due to increase in reduction of mixing temperatures with dosages of WMA additives. Among the WMA additives, chemical additives showed higher aging resistance (or lower indices) than organic additives. However, the rate of improvement in aging resistance is influenced by the type of base binder, WMA type, additive dosage, and aging level (i.e., STA and LTA). In this study, binders were compared after undergoing STA and LTA to assess the overall effect of WMA additives on aging resistance. Overall, the results showed that the addition of WMA additives to both the base binders improved the aging resistance of the binders. As per the previous literatures [36,216,264], reduced aging inevitably affect the rutting and fatigue performance of asphalt binders. Thus, in the present study, the effect of reduced aging on the performance of asphalt binder was determined, and the results are discussed in subsequent sections.

In this study, the efforts were made to evaluate the effect of aging on polymeric network of polymer modified binders. This was done by evaluating transbutadiene peak which occurred around wavelength of 968 cm^{-1} [412]. From the literature, it can found that the reduction in this peak value after aging indicates the degradation of polymeric network due to excessive aging [256,412]. It is desirable that the values should not change significantly after aging to ensure better polymer network. Figure 6-7 shows the effect of STA and LTA on transbutadiene index of polymer modified binders. It can be seen that the transbutadiene index reduced after change in aging condition from STA to LTA. This can be due to the fact that the during the aging process of SBS, oxidation occurs, leading to the generation of free radicals. These free radicals, in turn, initiate reactions within the polymer structure. Specifically, they target the double bonds situated in the unsaturated midblock of polybutadiene, a component of SBS. This oxidative reaction can result in degraded chain segments of butadiene in SBS [429]. The addition of both the WMA additives did not show significant change in transbutadiene index indicating presence of better polymer network in WMA modified binders. This can be due to the reduced production temperature of PMB40 due to WMA additives. No specific trend was observed with dosages of WMA additives. Overall, these results showed that WMA additives do not disturb the polymeric network of PMB40 binder.

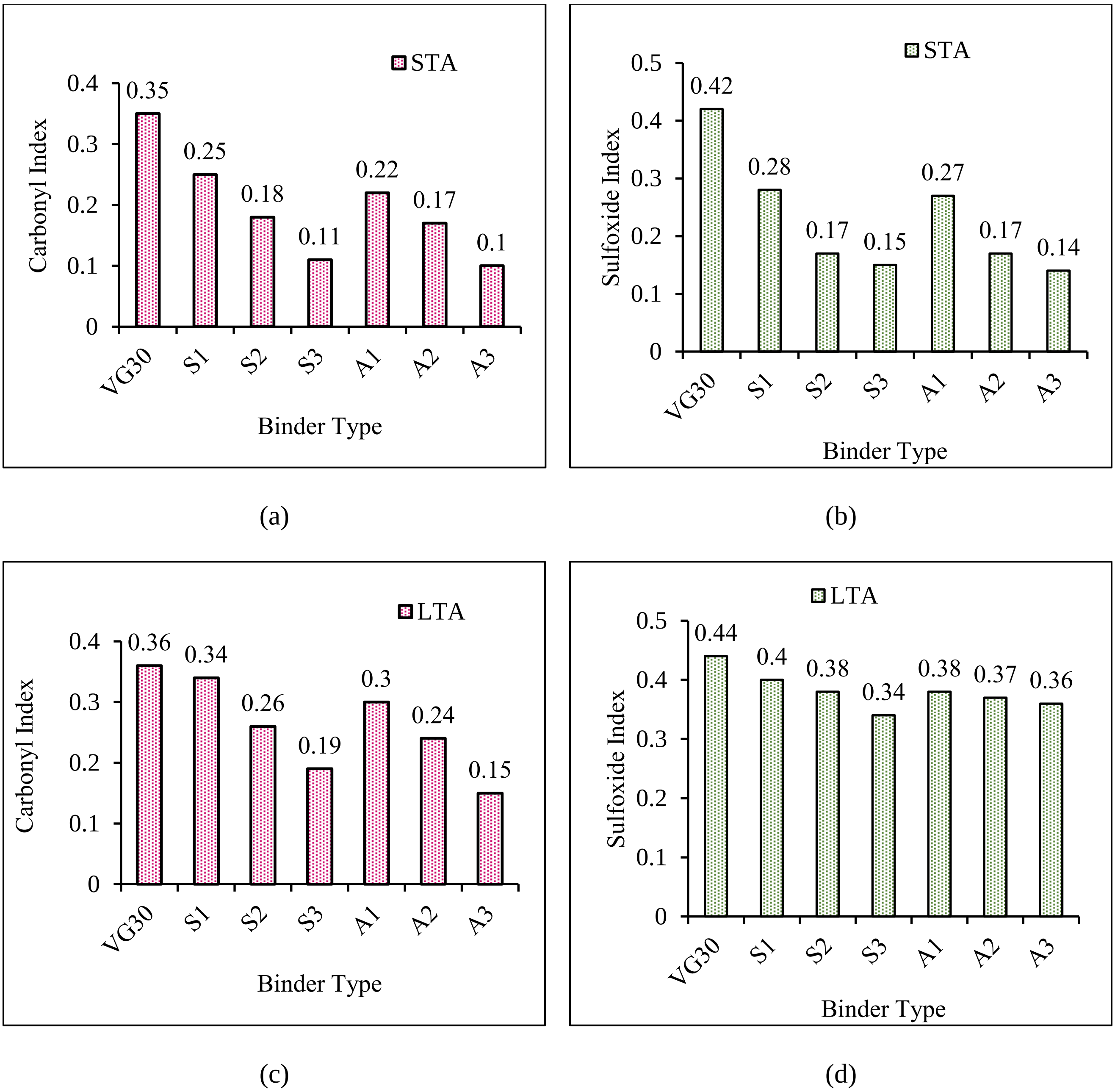
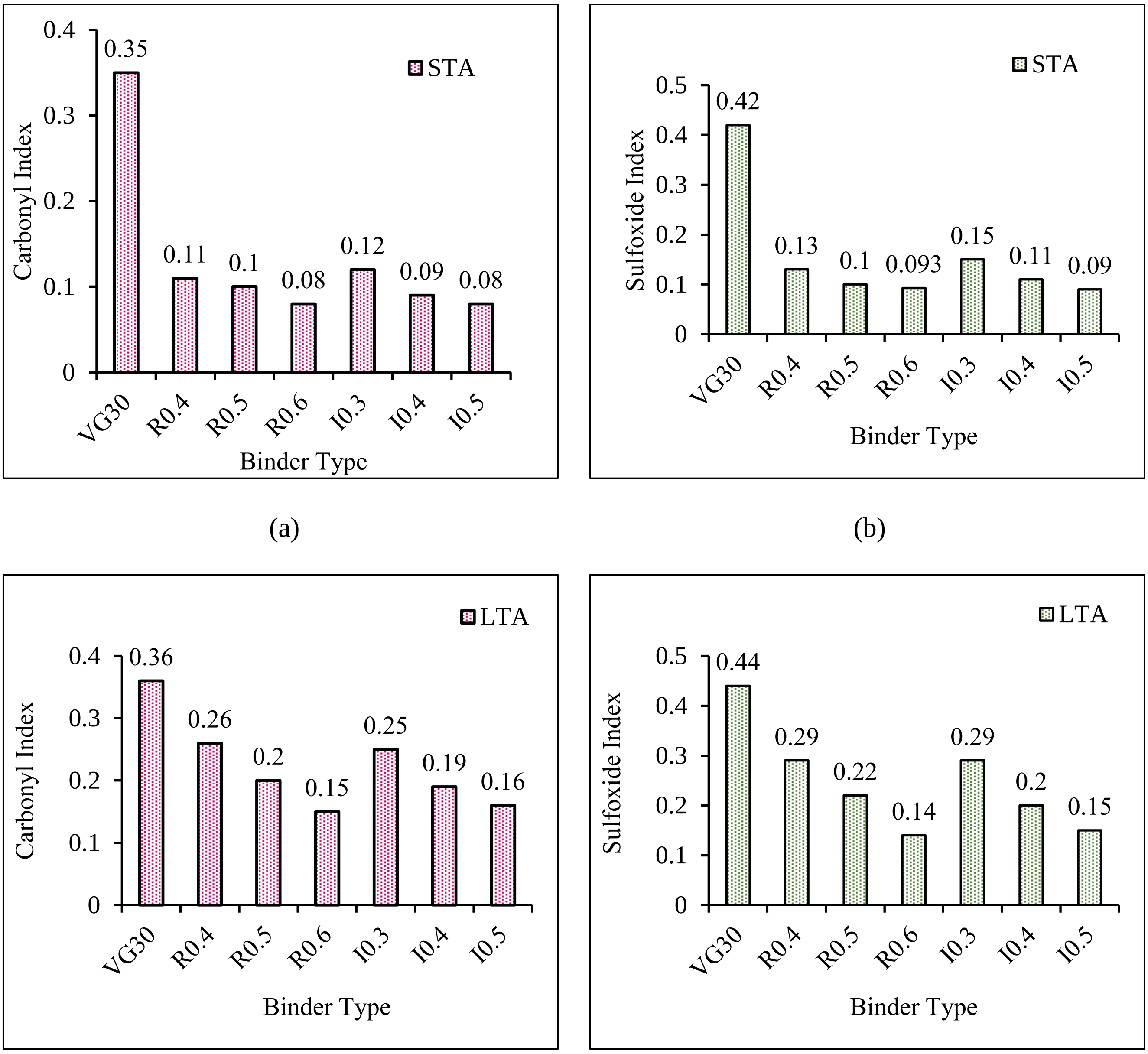
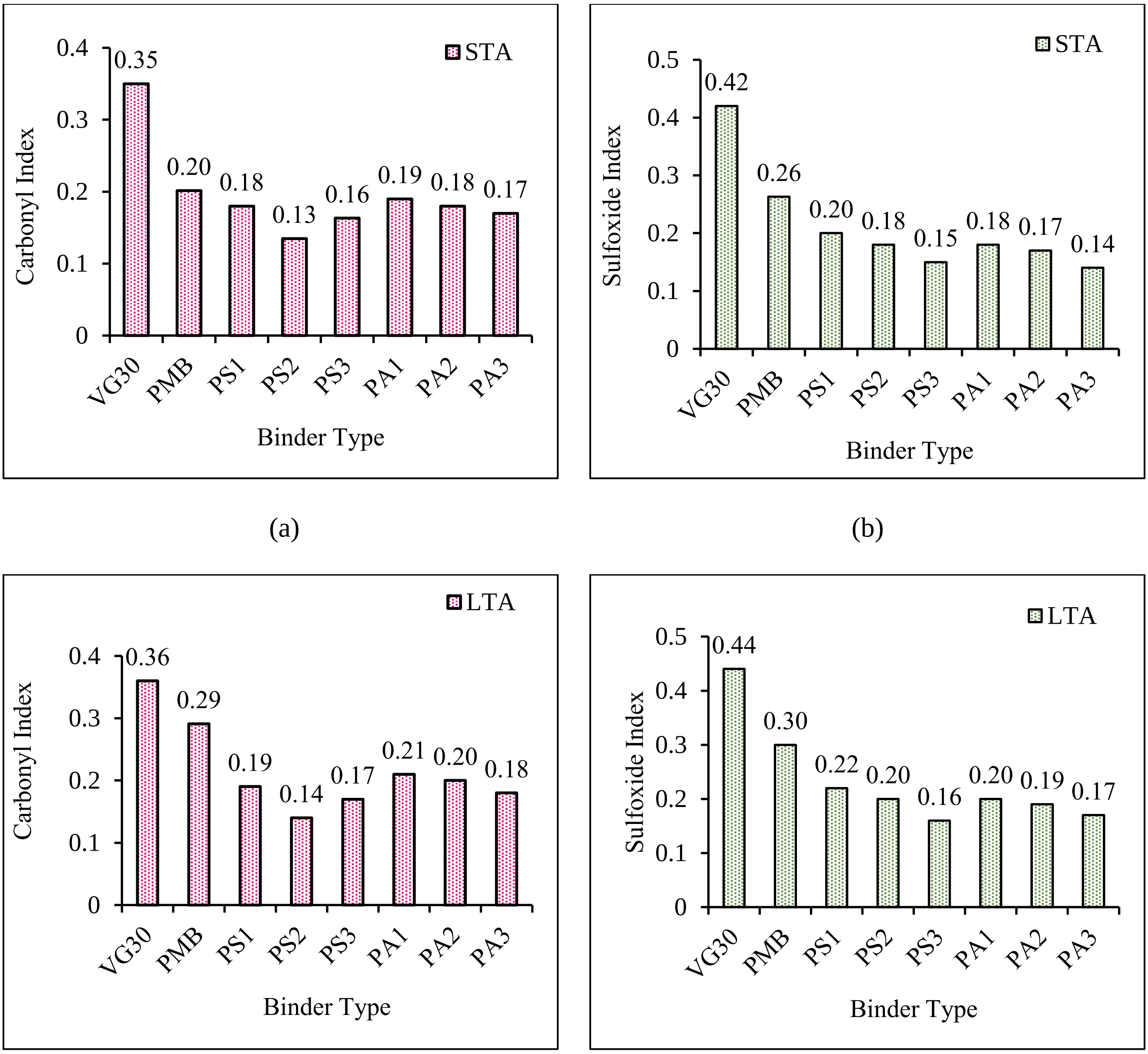


Figure 6-3. Aging indices for organic additives in VG30 as base binder (a) Carbonyl index after STA (b) Sulfoxide index after STA (c) Carbonyl index after LTA (d) Sulfoxide index after LTA



(c) (d)

Figure 6-4. Aging indices for chemical additives in VG30 as base binder (a) Carbonyl index after STA (b) Sulfoxide index after STA (c) Carbonyl index after LTA (d) Sulfoxide index after LTA



(a) (b)

(c) (d)

Figure 6-5. Aging indices for organic additives in PMB40 as base binder (a) Carbonyl index after STA (b) Sulfoxide index after STA (c) Carbonyl index after LTA (d) Sulfoxide index after LTA

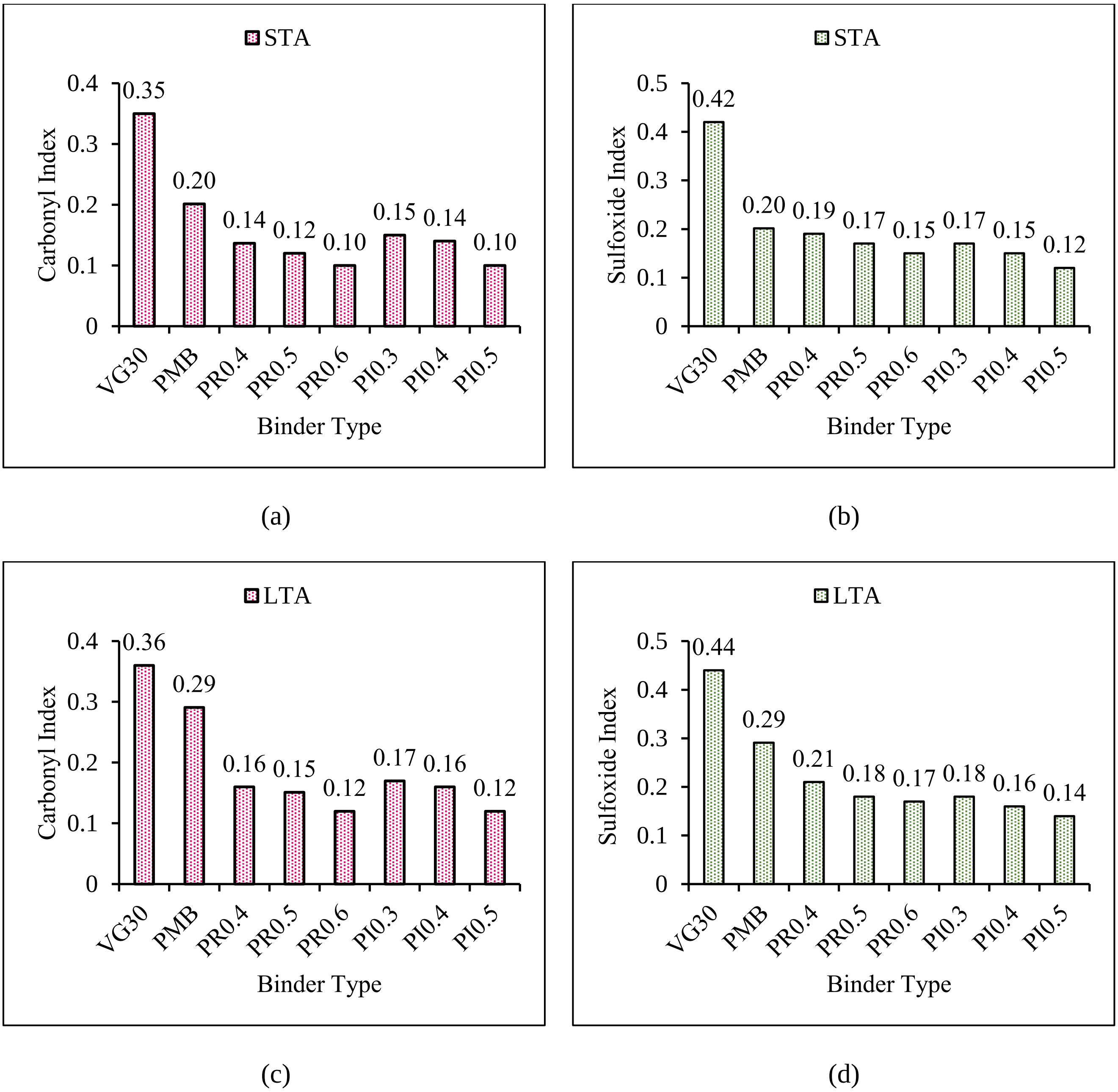
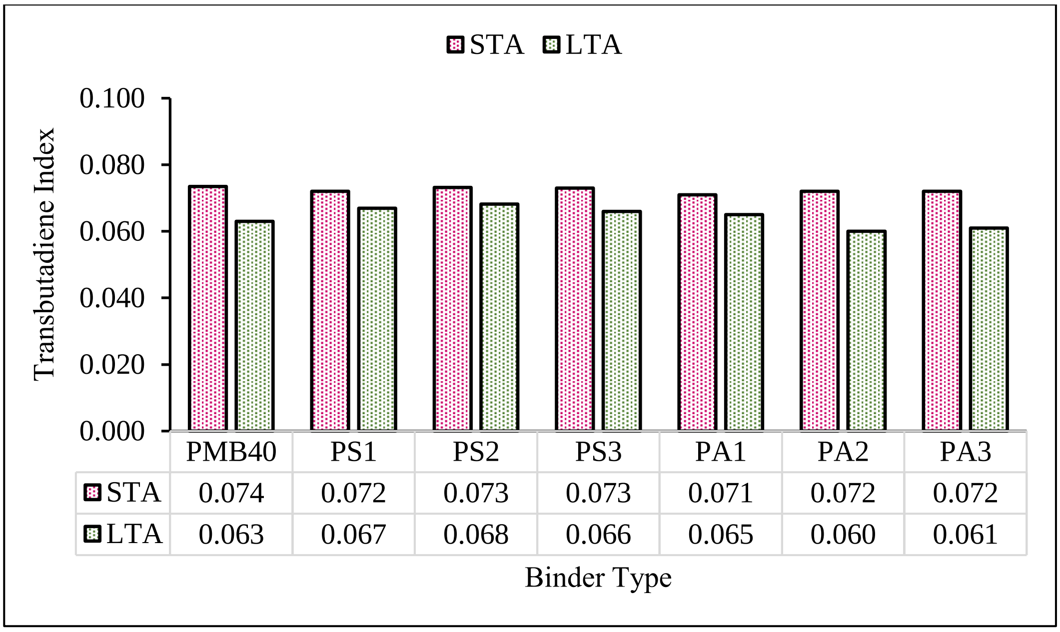
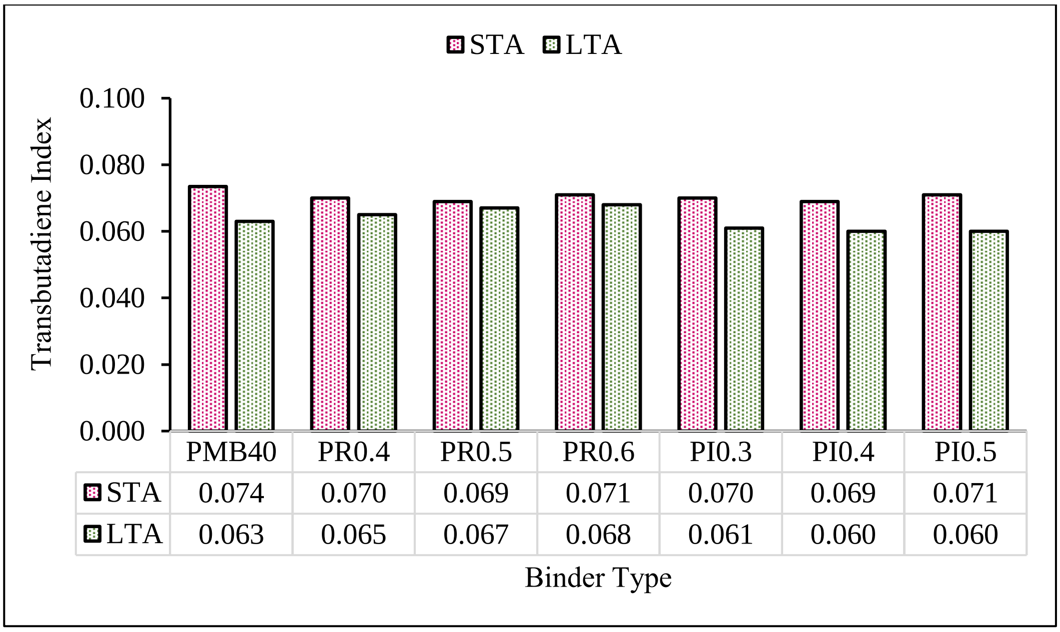


Figure 6-6. Aging indices for chemical additives in PMB40 as base binder (a) Carbonyl index after STA (b) Sulfoxide index after STA (c) Carbonyl index after LTA (d) Sulfoxide index after LTA



(a)



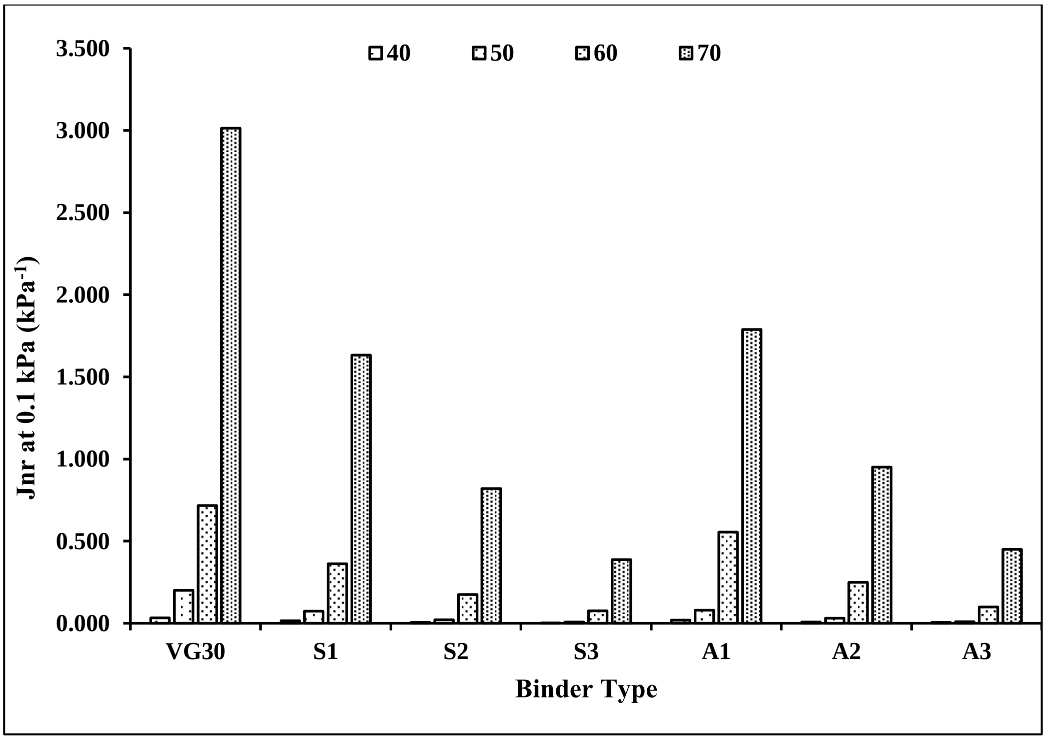
(b)

Figure 6-7. Effect of aging on polymeric network (transbutadiene index) of PMB40 a) organic additives b) chemical additives

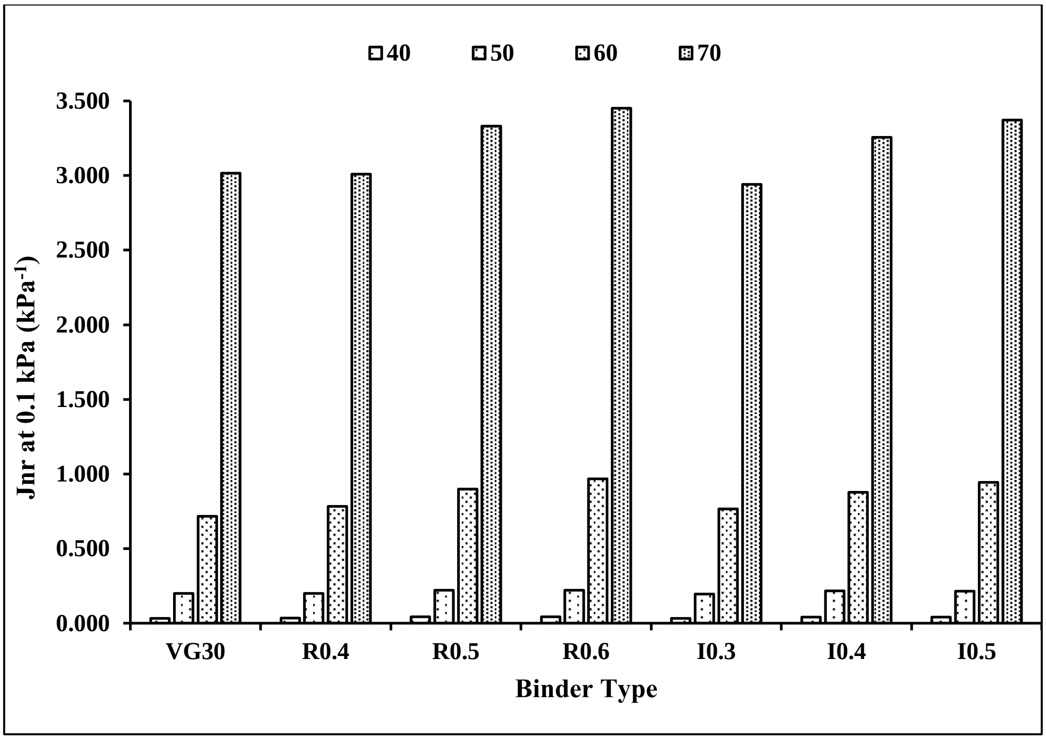
6.6 MSCR Results

6.6.1 J_{nr} of WMA Modified Asphalt Binders

Figure 6-8 to Figure 6-11 shows the non-recoverable creep compliance (J_{nr}) determined at a stress level of 0.1 kPa and 3.2 kPa for various combination of WMA additives and base binders. The results at 0.1 kPa stress level was expected in linear viscoelastic range whereas the results at 3.2 kPa stress level was supposed to fall within non-linear viscoelastic range [430]. The non-recoverable creep compliance values at 3.2 kPa stress level was higher than at 0.1 kPa stress level, irrespective of type of binder, WMA type, and temperatures. This can due to the fact that at higher stress levels, the binder behavior transitions from the linear viscoelastic to the non-linear viscoelastic regime resulting in more pronounced and less recoverable deformation. From Figure 6-8 to Figure 6-11, it can be seen that the polymer modified binders showed lower values of J_{nr} as compared to VG30 binders. The same has been true for WMA modification in PMB40 as compared to VG30. This can be attributed to higher stiffness of polymer modified binders due to the presence of polymeric network in their structure. Regardless of the test temperature, and type of base binder, the value of J_{nr} decreased with the increase in dosage of Sasobit and Asphaltan A at both stress levels. For example, at 70^{o}C, the J_{nr} value of the VG30 at 3.2 kPa stress level was found to be 3.64 kPa^{-1}, which decreased to 2.62 kPa^{-1}, 1.48 kPa^{-1}, and 1.67 kPa^{-1} with the addition of 1%, 2%, and 3% Sasobit, respectively. The same trend was observed for Asphaltan A modified binder. This is attributed to the crystalline (lattice) structure of organic additives which improves the rutting resistance of asphalt binders. However, the Asphaltan A modified binder showed slightly higher J_{nr} values as compared to Sasobit modified binders. This can be due to the lower congealing point of Asphaltan A as compared to Sasobit. Similar kind of observations were made for polymer modified binders. On the other hand, although adding Rediset and Iterlow reduced the production temperature, it affected the rutting behaviour of base asphalt binders, as inferred from MSCR results. For example, the J_{nr} values of 0.4%, 0.5% and 0.6% Rediset modified asphalt binder at 70°C and 3.2 kPa stress level were 3.57 kPa^{-1}, 4.0 kPa^{-1}, and 4.22 kPa^{-1}, which is almost similar or higher than the VG30 binder (i.e., 3.64 kPa^{-1}). The same trends were observed for polymer modified binders. This is because the increase in dosage of Rediset and Iterlow reduced the aging temperature, which restricts the oxidation in Rediset and Iterlow modified asphalt binders, resulting in lower stiffness as compared to base asphalt binders and relatively lower rutting resistance. These attributions are in line with previous studies that observed lower rutting resistance with the use of Rediset, especially at higher dosages [35,270,431]. However, the addition of Iterlow to the both base binders showed lower values of J_{nr} as compared to Rediset.



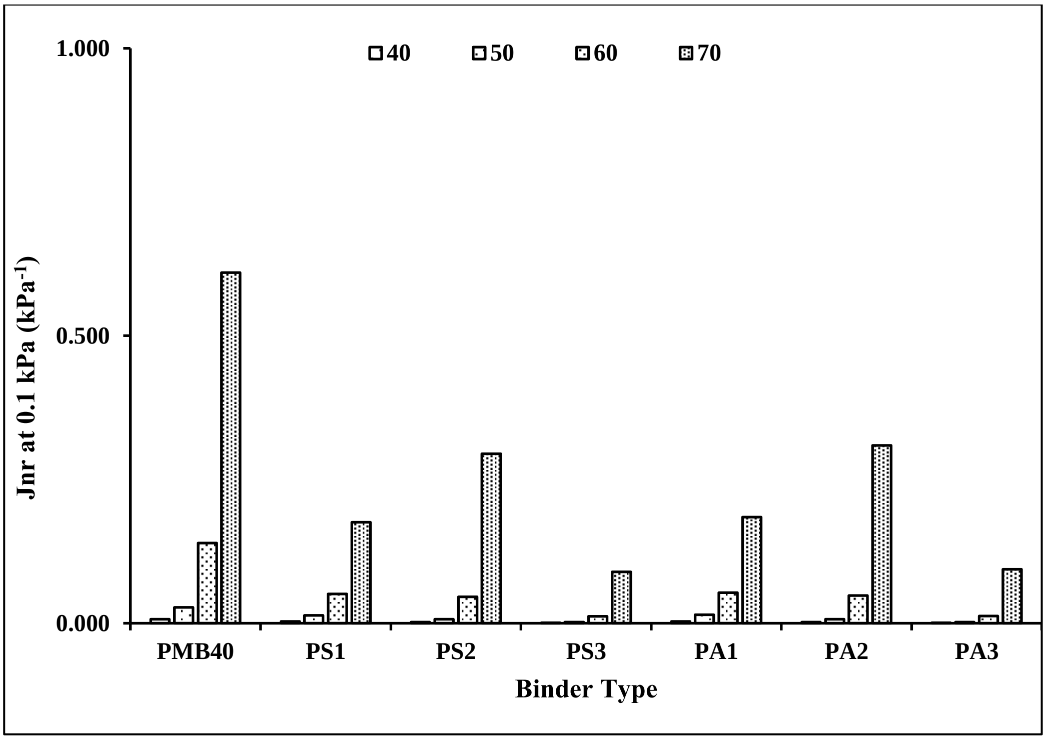
(a)



(b)

Figure 6-8. Non-recoverable creep compliance (J_{nr}) for VG30 as base binder at 0.1 kPa

a) organic additives b) chemical additives



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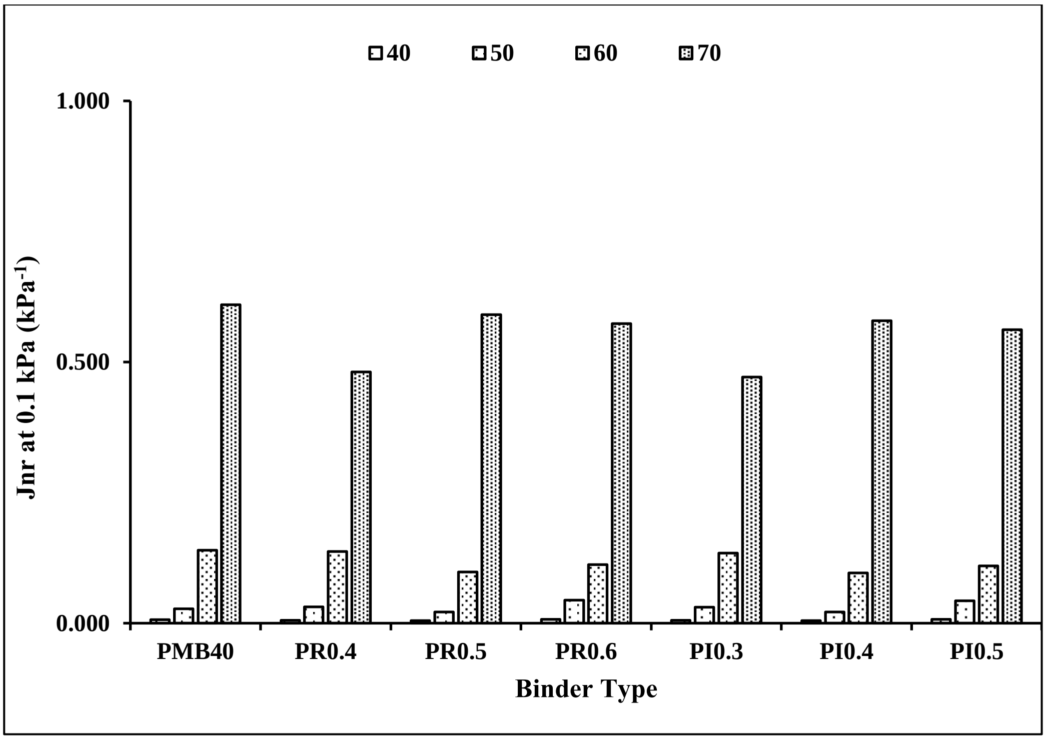
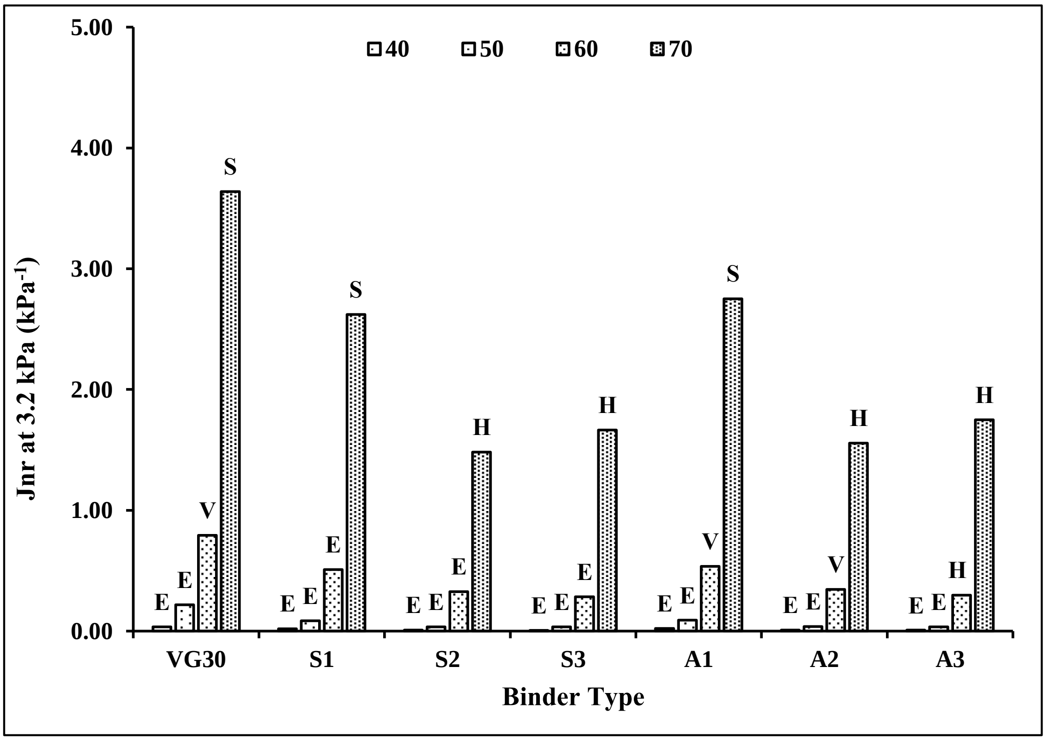


(b)

Figure 6-9. Non-recoverable creep compliance (J_{nr}) for PMB40 as base binder at 0.1 kPa a) organic additives b) chemical additives



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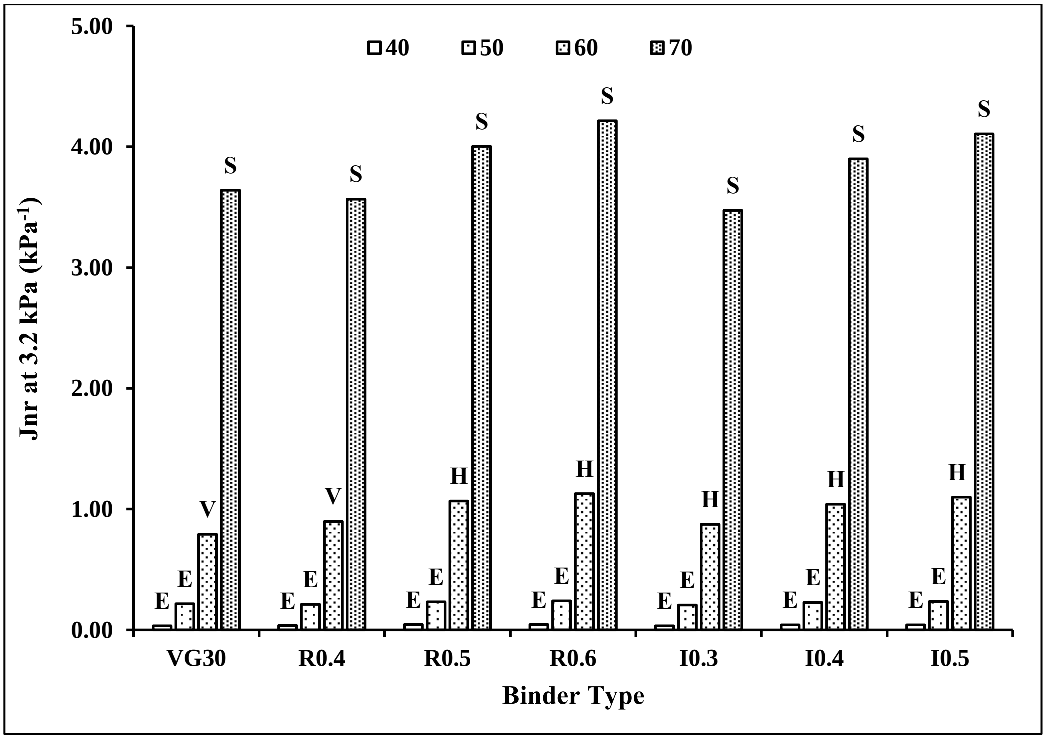
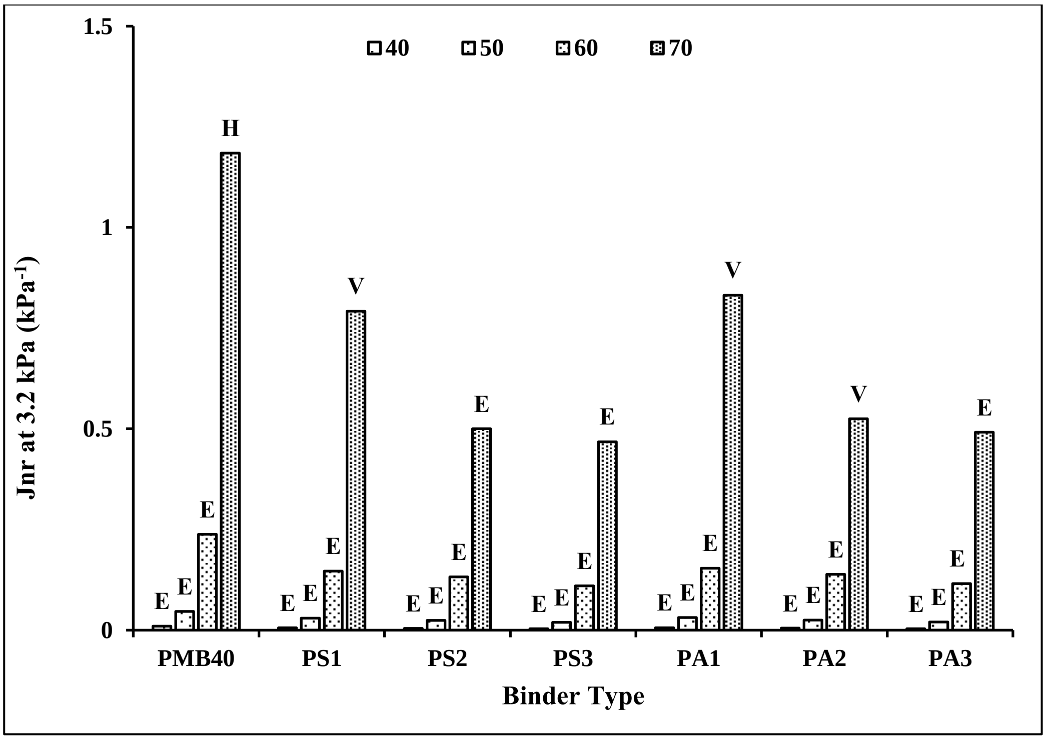


(b)

Figure 6-10. Non-recoverable creep compliance (J_{nr}) for VG30 as base binder at 3.2 kPa a) organic additives b) chemical additives



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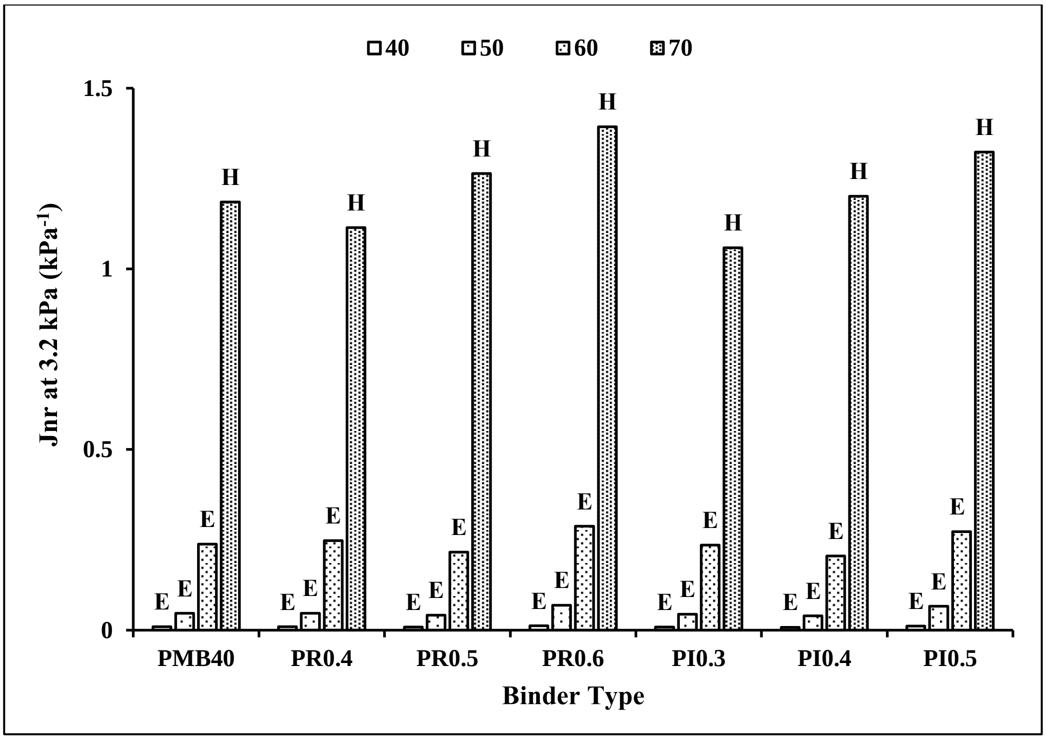


(b)

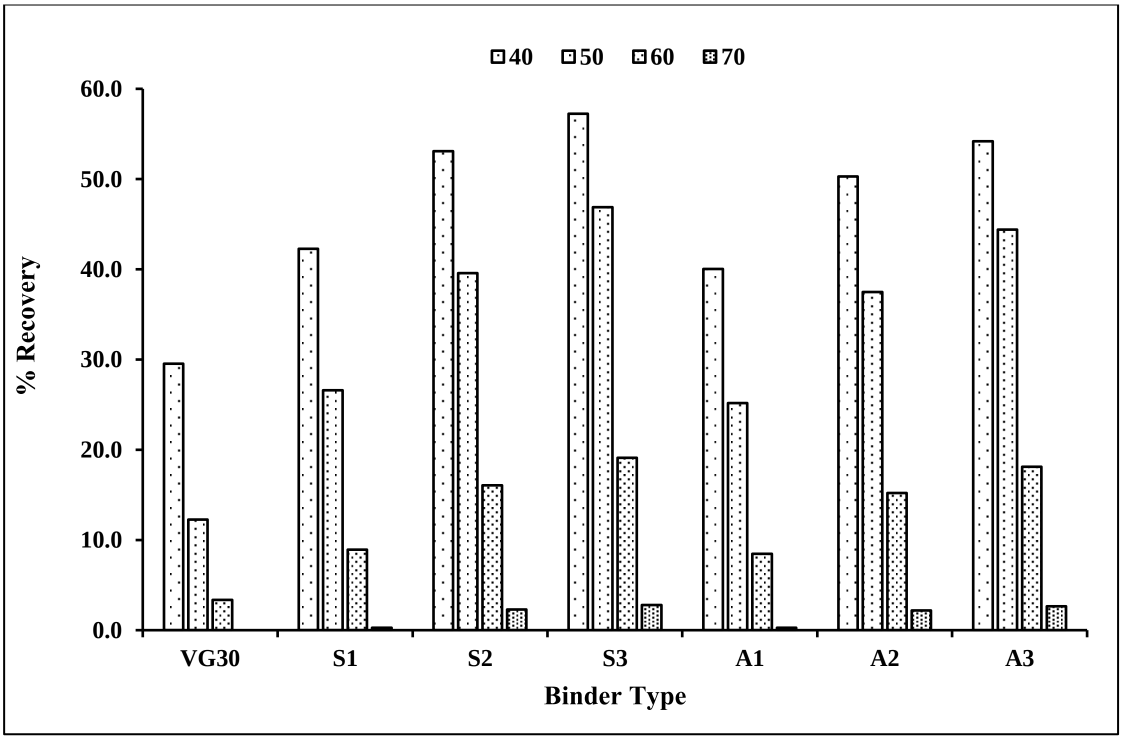
Figure 6-11. Non-recoverable creep compliance (J_{nr}) for PMB40 as base binder at 3.2 kPa a) organic additives b) chemical additives

6.6.2 Percent Recovery of WMA Modified Binders

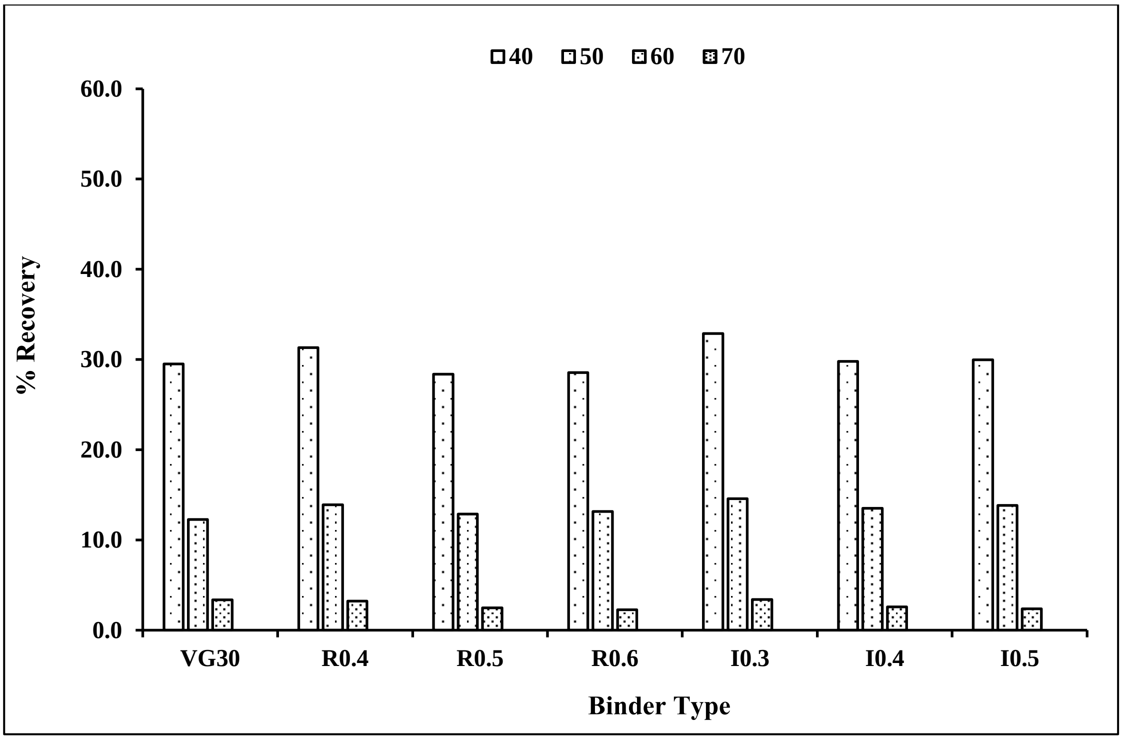
Figure 6-12 and Figure 6-13 shows the percent recovery (%R) of WMA modified asphalt binders determined at a stress level of 0.1 kPa and 3.2 kPa for VG30 and PMB40, respectively. As can be seen, with the increase in dosage of organic additives (Sasobit and Asphaltan A), there is an increase in elasticity, as indicated by the higher %R values. It implies that organic modified asphalt binder can restore a fraction of its total strain more efficiently than the base asphalt binders. This effect of organic additive dosages was consistent regardless of the test temperatures and stress levels. Similar trends were obtained for the polymer modified binder as can be seen in Figure 6-13. The value of % R were higher for WMA modification in the PMB40 than VG30 asphalt binder. This can be due to the better restoring capacity of total strain due to the presence of elastomers in the polymer modified binders. On the other hand, the recovery values of Rediset and Iterlow modified asphalt binders were almost similar to the base asphalt binders, especially at lower dosages. At higher dosages and higher test temperatures (>50°C), the recovery of Rediset was either equivalent or slightly lower than the base asphalt binders. It may be attributed to the lower stiffness (due to reduced aging temperatures) of Rediset and Iterlow modified asphalt binder at higher dosages. However, the addition of chemical additives to polymer modified binders showed improved recovery behaviour as compared to VG30 binder.

6.6.3 Grading of WMA Modified Binders

The grading of WMA modified asphalt binder based on the J_{nr} value at 3.2 kPa is shown in Figure 6-10 and Figure 6-11. All the asphalt binders at 40°C and 50°C were graded as 'E', indicating the suitability of the asphalt binder for extremely heavy traffic conditions. As can be seen in Figure 6-10 (a), at 60°C and 70°C, the VG30 was graded as 'V' and 'S', indicating very high and standing traffic conditions, respectively. Interestingly, the addition of Sasobit and Asphaltan A in VG30 binder shifted the grade of neat asphalt binder from 'V' to 'E' and 'S' to 'H' at 60°C and 70°C, respectively. This showed that the addition of organic additives improved the suitability of base asphalt binder against rutting. The same trend has been observed for polymer modified binder. As can be seen from Figure 6-11 (a), the PMB40 was graded as 'E' and 'H' at 60°C and 70°C, indicating extremely heavy traffic conditions and heavy traffic conditions, respectively. The addition of organic additives to PMB40 binder do not influence its grade at 60°C whereas they improved the grade to 'V' at 70°C indicating improved suitability of PMB40 against rutting. On the other hand, Rediset and Iterlow modified asphalt binder indicated a similar or lesser rank as that of the base asphalt binders at higher temperatures (60°C and 70°C). The change in traffic grade was found to be highly influenced with the change in the dosage of Rediset and Iterlow. For example, 0.4% Rediset in VG30 was found to be suitable for the 'V' grade at 60°C, whereas the grade shifted to 'H' for 0.5% and 0.6% Rediset modified asphalt binder. The same has been observed in case of Iterlow modified binders for VG30. This showed that the addition of chemical additives lowered the suitability of VG30 binder. However, this effect is depending on the dosages of chemical additives. As can be seen from Figure 6-11 (b), the addition of chemical additives to PMB40 binder do not influence its grade of PMB 40 i.e. all chemical modified binders were graded as E' and 'H' at 60°C and 70°C, indicating extremely heavy traffic conditions and heavy traffic conditions, respectively. From the result, it can also be found that all the WMA binders perform similar or even better than base asphalt binders. Attributable to the difference in interaction, the impact of WMA additives was observed to be more favorable for VG30 than PMB40. Based on the result of MSCR test, it can be concluded that the priority should be given to organic additives wherever rutting is predominating type of distress. However, the priority of chemical additives depends on the type of base binder and the priority might be given to chemical additives when base binder is polymer modified binder.

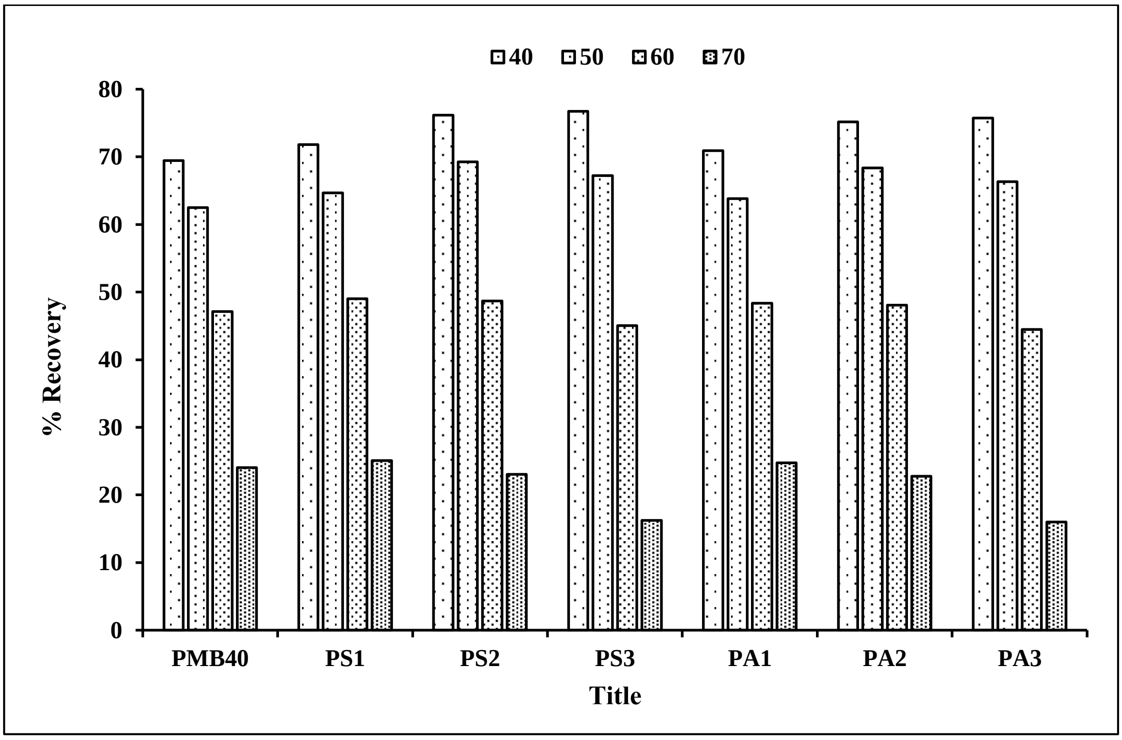


(a)

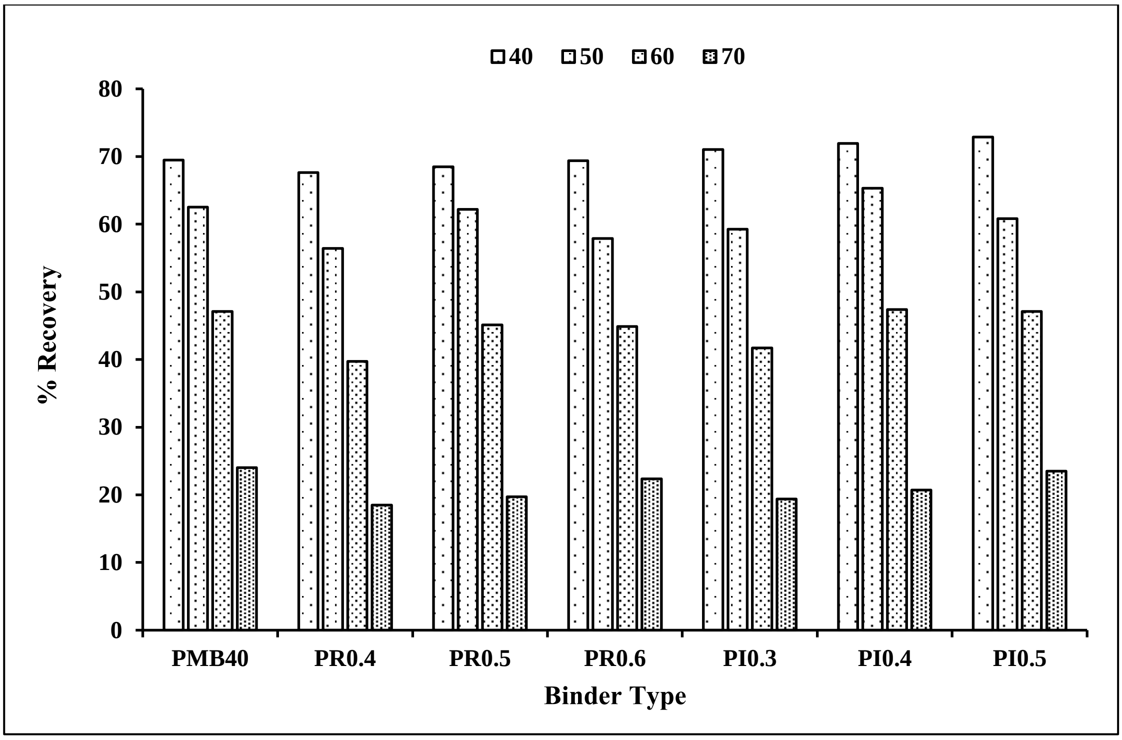


(b)

Figure 6-12. Percent recovery (%R) for VG30 as base binder at 3.2 kPa a) organic additives b) chemical additives



(a)



(b)

Figure 6-13. Percent recovery (%R) for PMB40 as base binder at 3.2 kPa a) organic additives b) chemical additives

6.7 LAS Results

6.7.1 Strain Response Curve

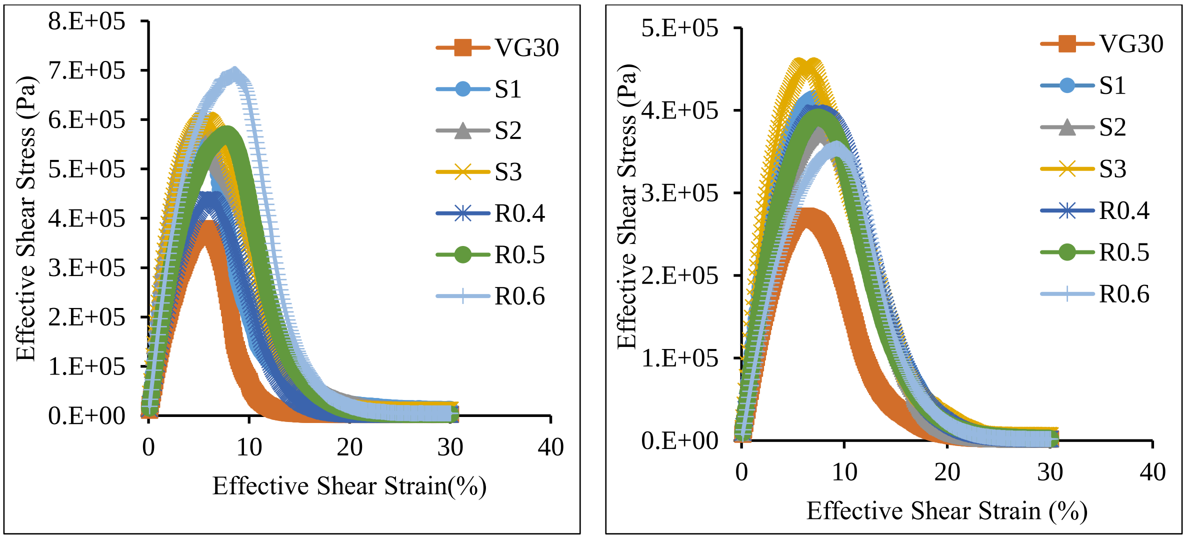
The effect of WMA additives on the stress-strain behaviour of the asphalt binder was assessed at three different temperatures (10, 20, and 30 °C), as shown in Figure 6-14. The plot represents the variation of effective shear stress with respect to different amplitude of effective strain applied during amplitude sweep test. This curve indicates the strain dependency of asphalt binder [360]. The stress response of VG30 and WMA modified asphalt binders increases with an increase in strain amplitude up to a certain level, and beyond a point of strain, the stress decreases. The reduction in stress response after a critical point indicates the damage initiation in the asphalt binder, and the corresponding strain represents the failure strain [361]. The curve with broader peak indicates less strain dependency of asphalt binder whereas sharper peaks represent higher dependency on applied strain. It can be observed that the Sasobit-modified asphalt binder showed sharper peaks as compared to the neat binder, indicating higher strain dependency. The same trend has been observed for the Asphaltan A, not shown here for brevity. These observations are independent of the temperatures and type of base binder chosen in this study. This is attributed to the formation of wax particles' crystallization lattice structure, which increases stiffness of asphalt binder [38]. On the other hand, irrespective of type of base binder, the addition of Rediset broadens the peaks, except for R0.6 at 10^{o}C. This could be due to unaltered stiffness of asphalt binder after addition of Rediset [201]. This shows that the extent of variation in the stress-strain response is a function of the WMA additive and the temperature conditions. The Iterlow modified binders showed similar trend as that of Rediset modified binders. Figure 6-14 (d) shows the variation of strain response curve with temperature for VG 30 asphalt binder. It can be seen that the higher temperature exhibits the broader peaks. This is due to the softening of asphalt binder with increase in temperature. Similar results were obtained for WMA modified asphalt binder and results are not shown for brevity. Figure 6-14 (e) shows the variation of stress response curve for the PMB40 and VG30 binder at 20^{o}C. It can be seen that the polymer modified binder showed boarder peaks as compared to the VG30 binder, indicating better behaviour against fatigue cracking up to higher failure strain. In addition, it also indicates the less strain sensitivity of PMB40 as compared to VG30. This can be due to the better elasticity of polymer modified binder due to the presence of polymeric network in it. The effect of WMA additives on PMB40 was found to be similar as that of VG30 but strain response curve showed boarder peaks as compared to the WMA modification in VG30, results are not shown here for brevity.

Generally, a higher value of failure strain is desirable for better resistance against fatigue damage. Table 6-3 shows the failure strain of all the tested asphalt binders. As can be seen, failure strain increases with an increase in temperature, indicating higher fatigue resistance of asphalt binders at relatively higher temperatures. It was found that the addition of chemical additives (Rediset and Iterlow) exhibits a higher failure strain than organic additives (Sasobit and Asphaltan A) for both the base binders. This observation was found to be consistent at all the test temperatures. This implied that the addition of organic additives caused an early initiation of fatigue damage compared to chemical-modified asphalt binders. However, the failure strain values for organic additives-modified binders were comparable with the base asphalt binders. From the Table 6-3, it can be observed that the polymer modified binder exhibited higher failure strain as compared to VG30 binders. The same has been true for WMA modification in PMB40 as compared to VG30. This can be due to the better elasticity of PMB40 as compared to VG30. Overall, the stress-strain curve revealed that chemical additives positively influence fatigue performance compared to organic-modified asphalt binders. This can be attributed to lower stiffness offered by chemical WMA modification in intermediate temperature zone, so binder can dissipate energy without undergoing severe cracking. In addition, this better fatigue performance could be due to less aging and low stiffness offered by WMA modification. Similar observations were reported in a previous study [432].

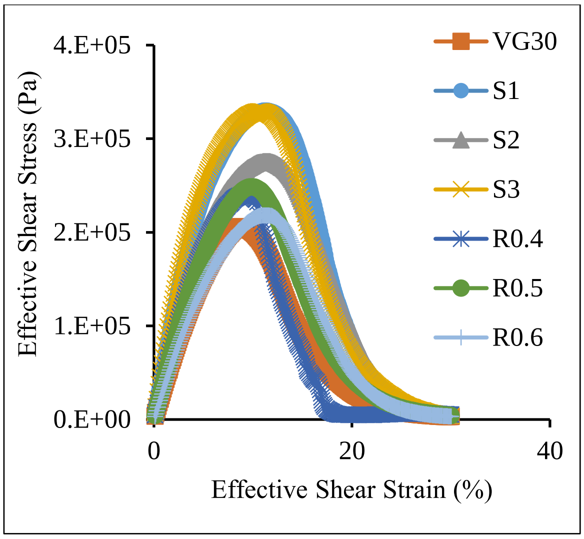
Table 6-3. Failure strains for WMA modified binders for both the base binders at different temperatures

Binder Type	**Failure Strain (%)**		
	10°C	20°C	30°C
VG30	5.64	6.14	8.84
S1	5.425	7.035	11.235
S2	5.32	7.64	11.33
S3	5.63	6.23	10.73
A1	5.48	7.31	11.7
A2	5.37	8.25	11.4
A3	6.1	6.9	11.9
R0.4	5.84	7.14	9.23

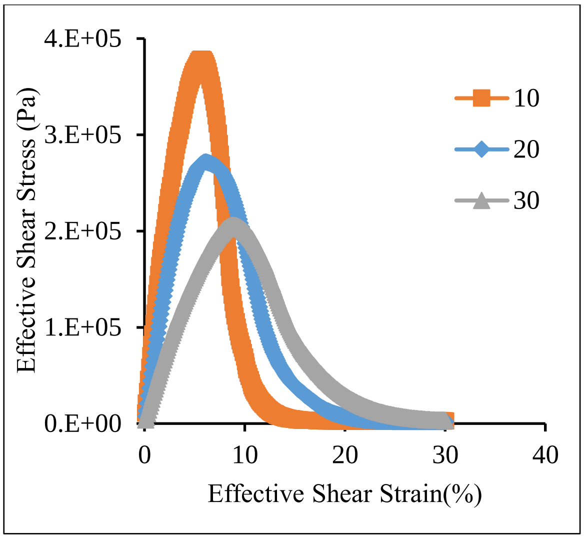
R0.5	7.83	7.43	9.93
R0.6	8.54	9.23	11.035
I0.3	5.9	7.24	9.4
I0.4	8.0	7.4	10.1
I0.5	8.2	9.64	11.1
PMB40	6.53	8.83	14.53
PS1	5.73	7.93	9.3
PS2	5.6	6.63	13.3
PS3	3.61	5.7	7.24
PA1	5.7	8.9	9.58
PA2	5.65	6.4	13.70
PA3	4.2	5.91	7.46
PR0.4	6.57	8.71	14.61
PR0.5	6.6	9.21	14.68
PR0.6	6.84	9.3	14.7
PI0.3	6.8	9.06	15.1
PI0.4	6.9	9.5	15.2
PI0.5	7.11	9.6	15.3



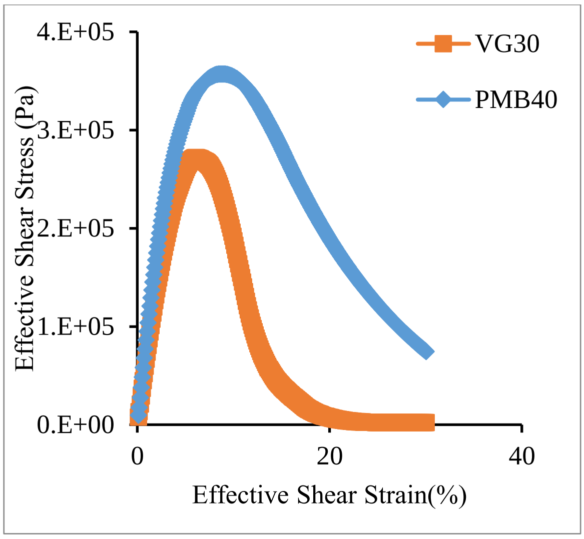
(a) (b)



(c)



(d)

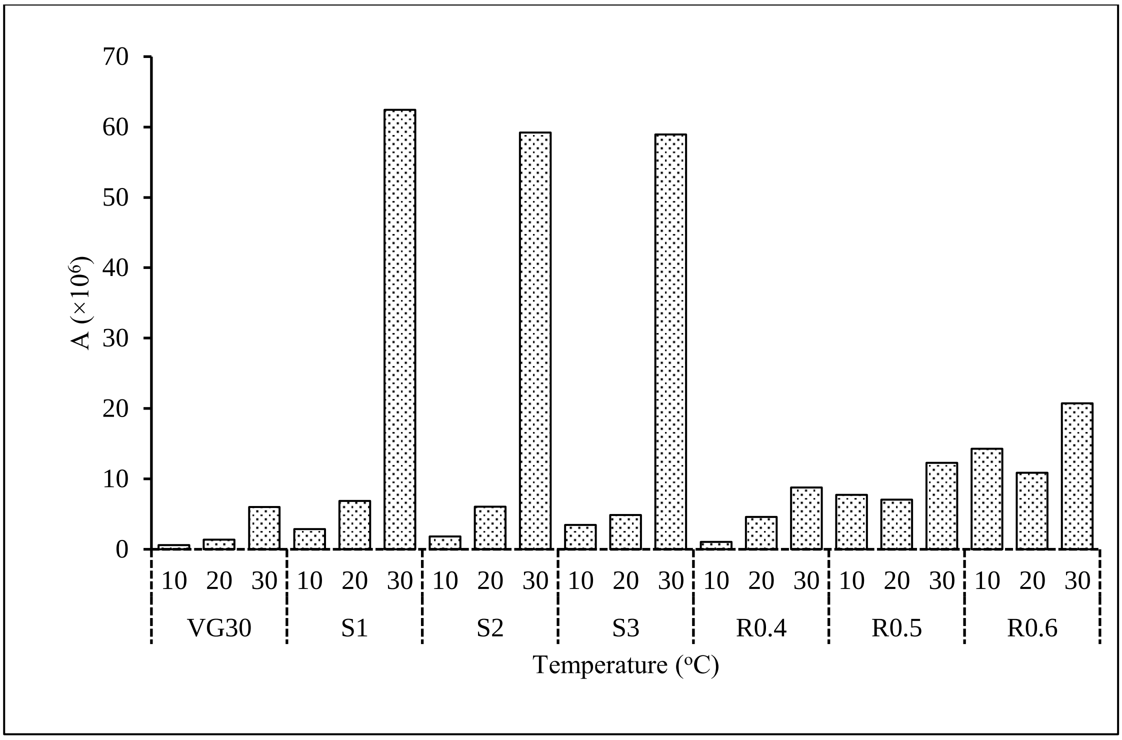


(e)

Figure 6-14. Strain response curve for Sasobit and Rediset for VG30 as base binder a) at 10°C, b) at 20°C, c) at 30°C, d) Variation of strain response with temperature, e) Variation of strain response with binder type

6.7.2 Fatigue Law Parameters and Fatigue Life

Figure 6-15 shows the fatigue law parameters (A and B) for WMA modified binders for VG30 as base binder. Parameter A represents the damaged integrity against accumulated damage, while B indicates the strain sensitivity of asphalt binders. The higher value of A and subsequently the lower value of B lead to the better capability of asphalt binder to sustain fatigue damage. It can be observed that addition of Sasobit and Rediset offered a higher A value as compared to neat binders. A general trend, indicating an increase in A value with the increase in temperature, was observed for all the asphalt binders. Values of parameter A was found to be increased with the increase in the dosage of WMA additives. On the other hand, Rediset modified asphalt binders exhibit lower B values in comparison to base and Sasobit modified asphalt binders, as shown in Figure 6-15 (b). Notably, similar B values were observed for VG30 and Sasobit modified asphalt binder, indicating lower strain sensitivity. In addition, no definite trend was reflected with the increase in the dosage of WMA additives. Interestingly, the influence of WMA on the value of B was not much significant. The similar kind of trend was observed with Asphaltan A and Iterlow modified binders for both the base binders, not shown here for brevity. Figure 6-16 shows the fatigue law parameters (A and B) for base binders. It can be seen that the values of parameter were found to be higher for PMB40 as compared to VG30 for all the test temperatures indicating better integrity of polymer modified binder as compared to VG30. On the other hand, values of parameter B for PMB40 were found lower than VG30 indicating better capacity to sustain fatigue damage. Similar trend was observed with WMA modification in PMB40 as that of VG30, but values of parameters A and B were found better as compared to VG30. The value of A and B were further analysed to evaluate the variation in fatigue life of WMA modified asphalt binders with the change in strain amplitudes. This is discussed in the next section.



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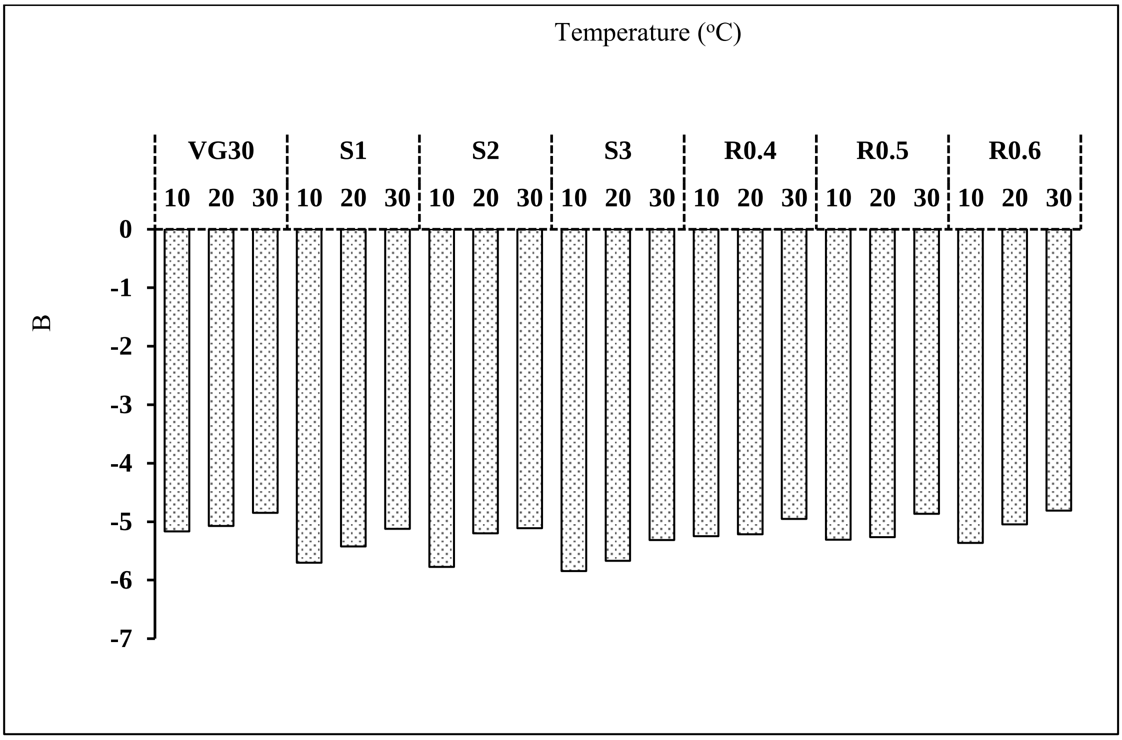
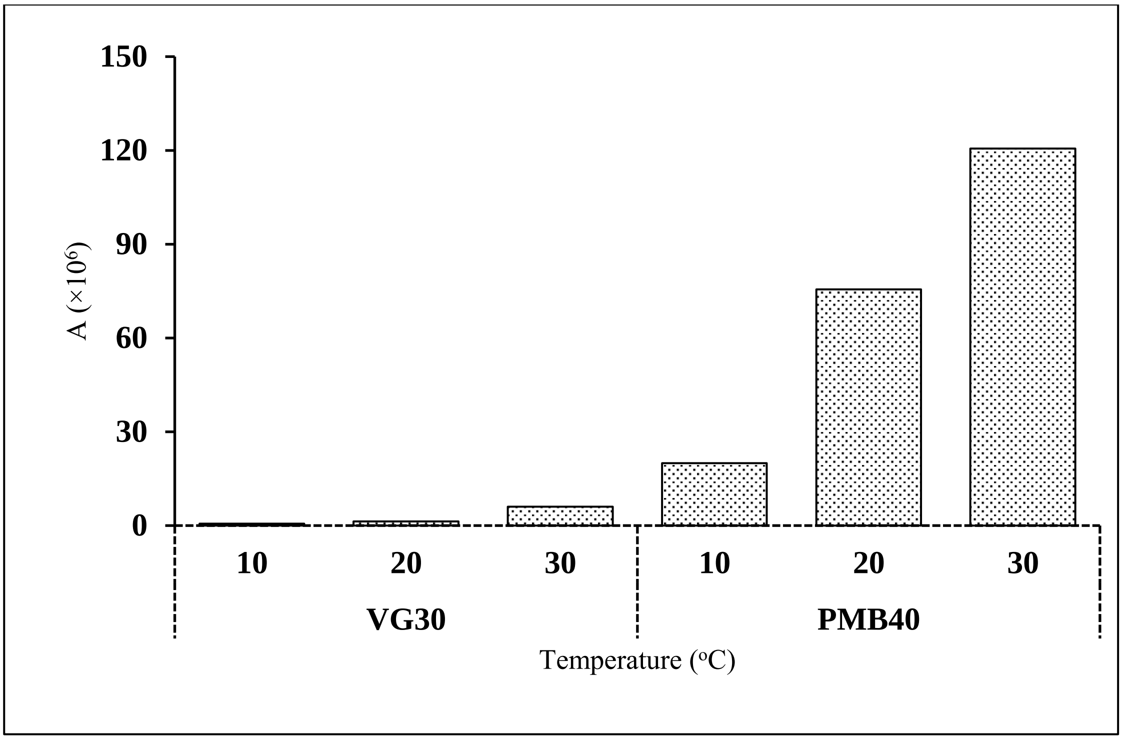


(b)

Figure 6-15. Fatigue law parameter for different WMA modified asphalt binders a) Parameter A and b) Parameter B



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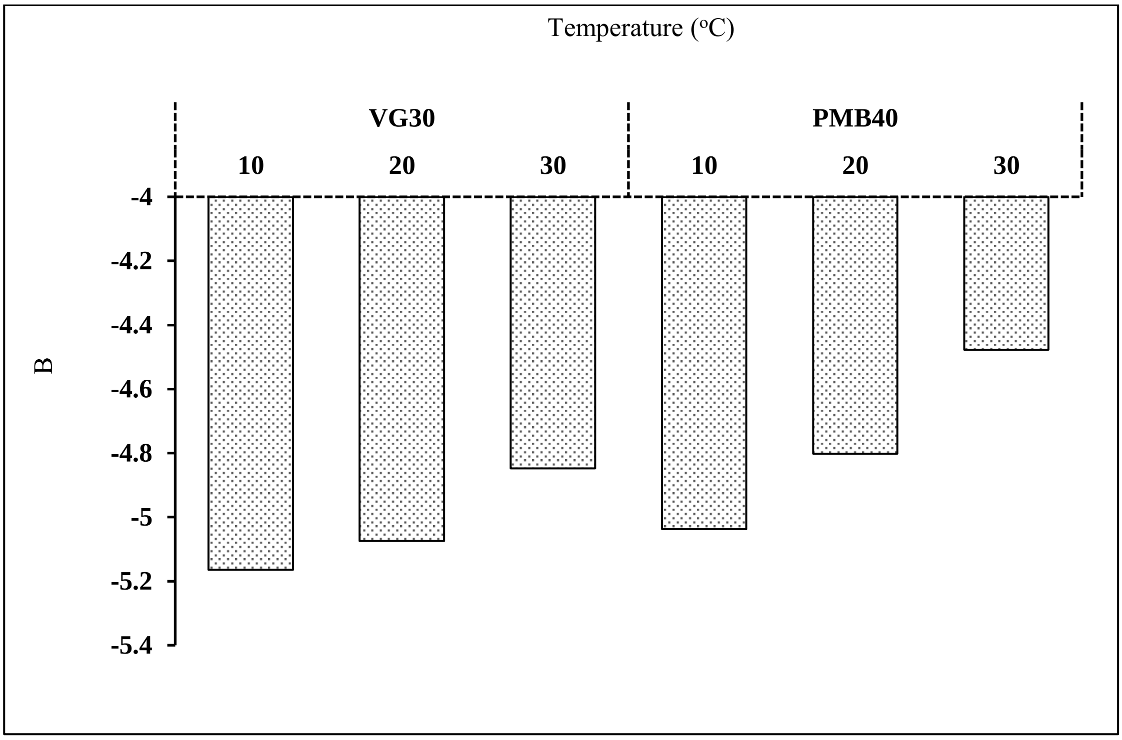


(b)

Figure 6-16. Fatigue law parameter for different base asphalt binders a) Parameter A b) Parameter B

Figure 6-17 (a-c) and Figure 6-18 (a-c) present the variation of fatigue life with shear strain at 10°C, 20°C, and 30°C for Sasobit modified and Rediset modified asphalt binder (for VG30 as base binder), respectively. The addition of Sasobit and Rediset indicates similar or even improved fatigue life as compared to neat asphalt binder, irrespective of the strain range. This is due to the lower aging (due to reduced aging temperature) of WMA modified asphalt binders. In addition, the rate of improvement was found to increase with increase in dosages of WMA additives. In addition to Sasobit and Rediset, the effect of Asphaltan A and Iterlow on fatigue life of base binder has also been evaluated in this study. Although additives were different, the trend (rate of improvement) of organic additives (Asphaltan A and Sasobit) was similar and also chemical additives (Rediset and Iterlow) showed similar trend. Hence, results for Asphaltan A and Iterlow are not provided here for brevity. Figure 6-19 shows the variation of fatigue life with shear strain for both the base binder at 20°C. It can be seen that the rate of reduction in fatigue life with shear strain was lower for polymer modified binder as compared to VG30 binder. This showed that better performance of polymer modified binder against fatigue cracking was due to presence of polymeric network in its structure. In addition, WMA modification in PMB40 showed better fatigue behaviour as compared to WMA modification in VG30. However, the trends (for WMA-PMB) were found to be similar with WMA-VG30 binder, not shown here for brevity. Overall, it can be stated that the rate of improvement is a function of base binder type, WMA type, dosage, and test temperatures. The improvement is observed to be greater with the increase in temperature in the case of organic additives however, chemical additives showed improvement at lower temperatures. This is attributed to reduction in the stiffness of asphalt binder with the increase in temperature.

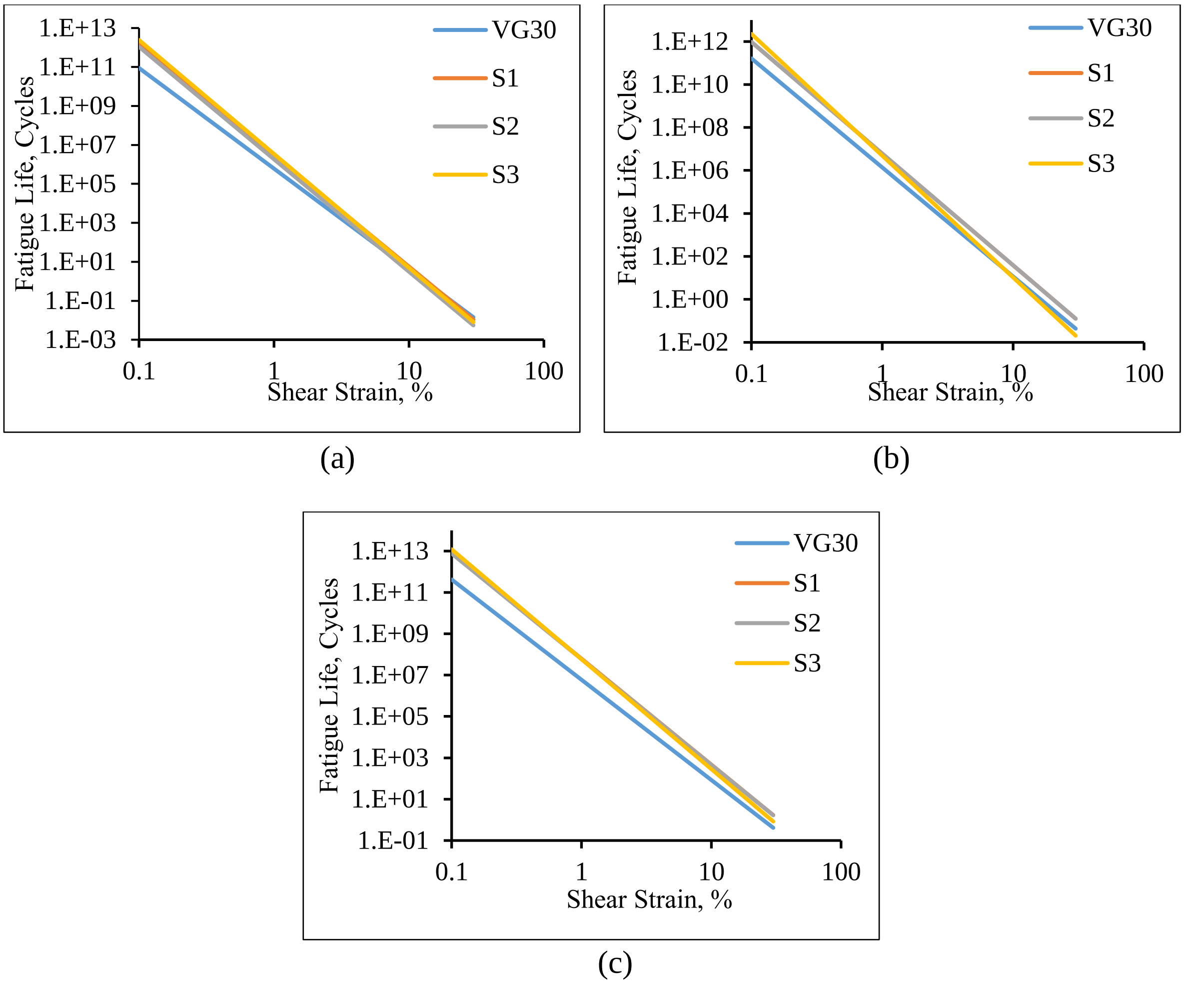
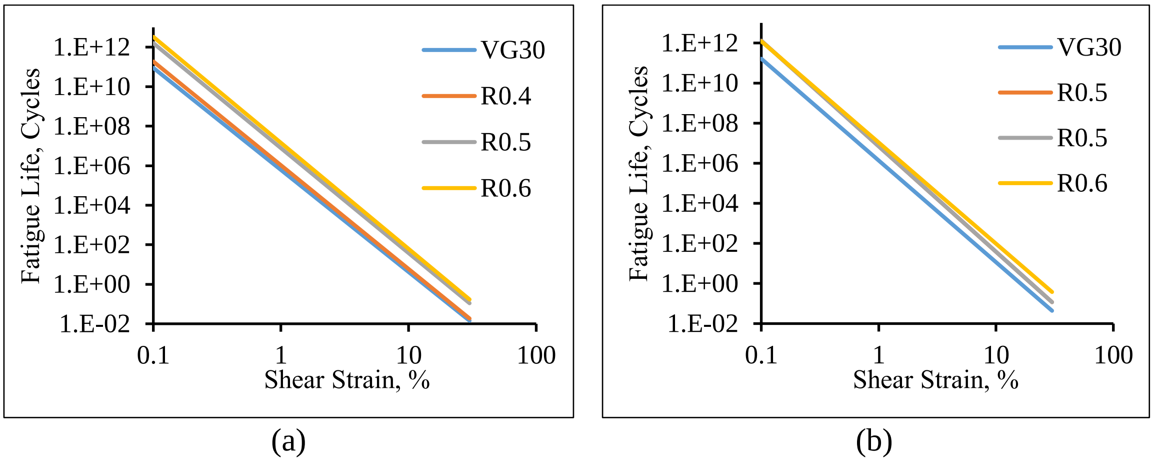
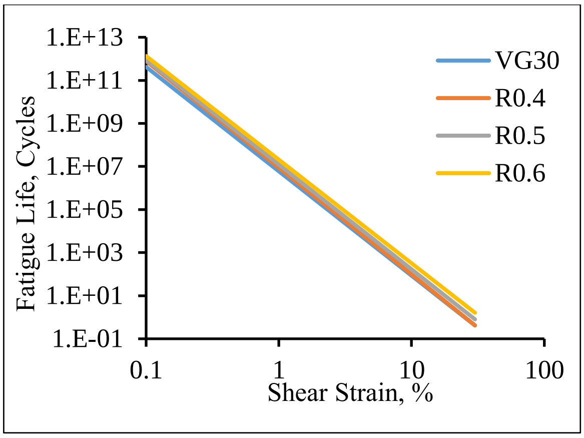


Figure 6-17. Variation of fatigue life for Sasobit modified asphalt binder with strain at (a) 10°C; (b) 20°C; and (c) 30°C





(c)

Figure 6-18. Variation of fatigue life for Rediset modified asphalt binder with strain at (a) 10°C; (b) 20°C; and (c) 30°C.

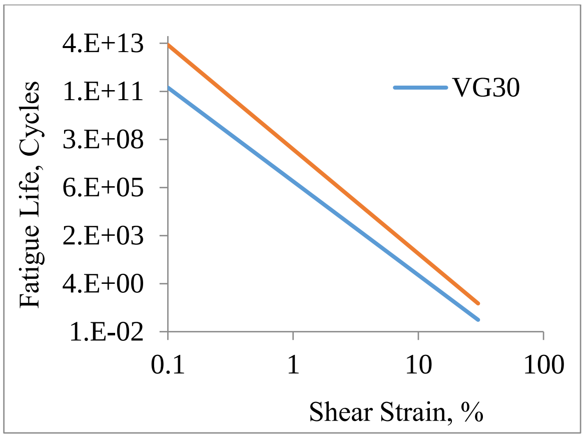


Figure 6-19. Variation of fatigue life for both asphalt binder at 20°C.

Figure 6-20 and Figure 6-21 shows the effect of WMA on the fatigue life for VG30 and PMB40 with varying strain levels at different test temperatures, respectively. The two strain levels i.e., 2.5% and 5% were selected to compare the fatigue life of all WMA modified asphalt binders. The strain level at 2.5% represents the peak strain in the binder corresponding to the thick pavement, whereas the 5% strain level indicates the peak strain corresponding to thin pavement [433,434]. Irrespective of the strain levels, WMA modified asphalt binders resulted in similar or even higher fatigue life than base asphalt binders. Although the increase in dosage of Sasobit lowered the number of cycles to failure, the effect of WMA modified binders was still appreciable as the cycles to failure were more than base binders at all the test conditions.

Chemical additives (Rediset and Iterlow) delivered higher fatigue life at lower temperatures (10°C and 20°C), whereas the effect of Sasobit was found to be more prominent at 30°C. This implies that both the type (organic and chemical additives) of WMA modified asphalt binders may perform differently based on their viscoelastic nature under different time and temperature conditions. In the present study, the higher fatigue life of chemical additives could be due to the softening of asphalt binder as result of lower aging and emulsifying action of these additives. In case of organic additives at lower temperature i.e. 10^{o}C and 20^{o}C, the lower fatigue life of organic additives is attributed to the creation of crystalline lattice network, which imparts brittle viscoelastic nature to the asphalt binder. The effect was found to be more pronounced if temperature drops to 10^{o}C. In line to the same context, the study conducted by Wang et al (2020) showed that the wax components form a crystallized structure at 20^{o}C within the binder matrix, which makes the binder stiffer, resulting in higher stresses at a certain strain level, and vulnerable to fatigue damage [79]. As temperature increased to 30^{o}C, the behaviour of organic modified binder was shifted from brittle viscoelastic material to viscoelastic liquid. This might be the reason for higher fatigue life of Sasobit modified asphalt binder at 30^{o}C. The previous study has also reported that the behaviour of organic modified asphalt binder improves with increase in intermediate temperature (shift in temperature from 20^{o}C to 30^{o}C). The similar kind of observations were seen for effect of WMA additives on PMB40. But fatigue life of polymer modified binders were higher as compared to VG30. This can be due to delay or prevent of the micro-cracks formation under fatigue loading as result of better elasticity imparted by SBS (polymeric network) present in the structure of PMB40 [435]. The results of LAS test showed that the variation in fatigue life was dependent on the type of base binders, WMA additive, dosage, and test temperatures. Overall, it is anticipated that the lower aging temperature of WMA modified asphalt binder may be the probable reason for the improvement in fatigue life at all temperatures.

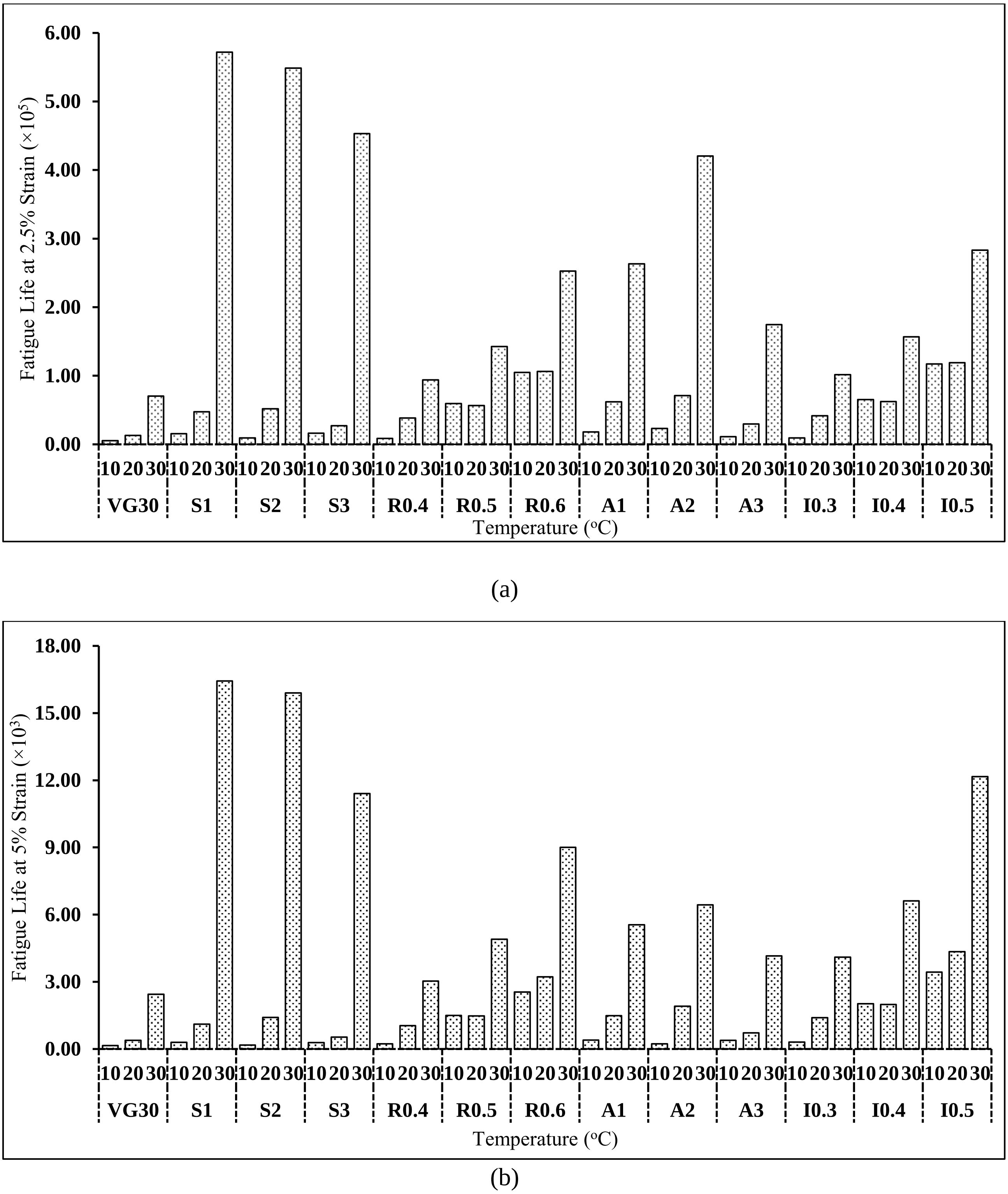


Figure 6-20. Fatigue life (N_f) for WMA additives in VG30 at a) 2.5% strain level; b) 5% strain level

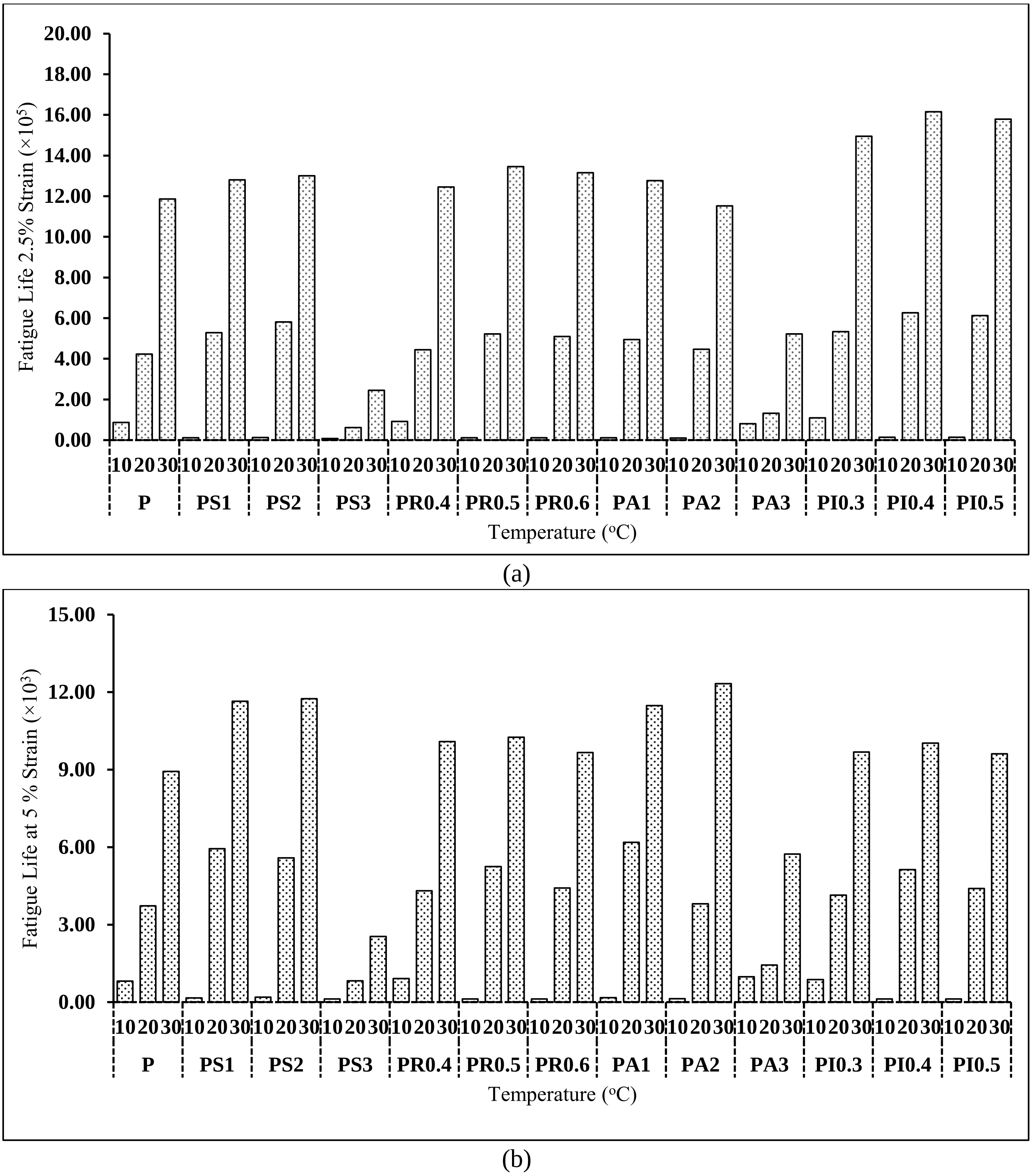


Figure 6-21. Fatigue life (N_f) for WMA additives in PMB40 at a) 2.5% strain level; b) 5% strain level.

6.8 BBS Test Results

Testing was performed on all the BBS test samples after a conditioning period of 24 hours, irrespective of the conditioning process (dry and wet). The samples were assessed based on bond strength and manner of failure. Figure 6-22 shows the POTS value for VG 30 and PMB

40 binders with different aggregates (Basalt, Dolomite, Dolerite, Granite, and Sandstone). It was found that the bond strength between asphalt binder and aggregates is a function of several factors, such as, binder type, WMA type, aggregate type, and moisture conditioning. Based on the results, the effect of these parameters on the bond strength (POTS) and bond strength ratio (BSR) are discussed in the following sections:

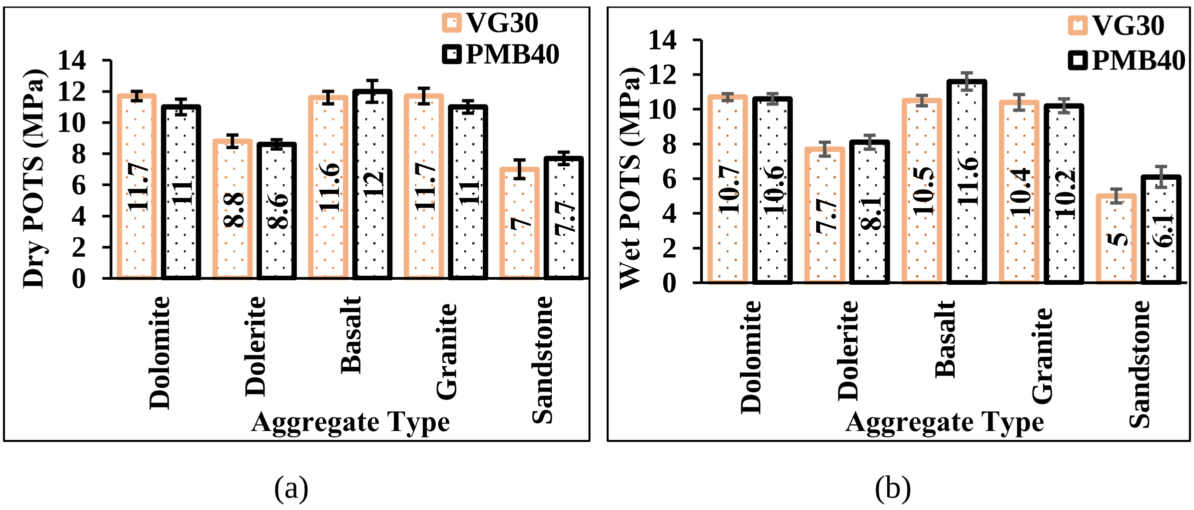
6.8.1 Effect of Base Binder and Aggregate Source on POTS and BSR

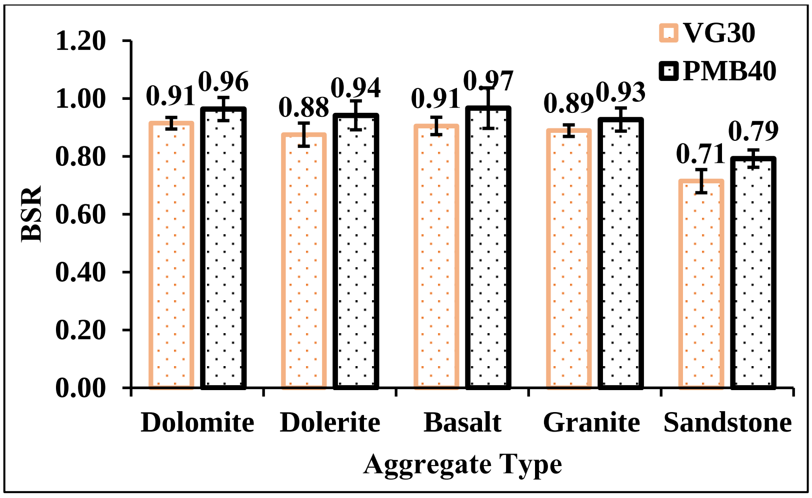
Figure 6-22 (a) and (b) present the effect of aggregate type and base binder on POTS value in dry and wet conditions, respectively. A minimal difference was observed between the POTS values of VG30 and PMB40 in both wet and dry conditions, irrespective of aggregate type. This was also confirmed using the analysis of variance, where the p-value was found to be greater than the chosen significance value (0.05). The dry POTS value for VG30 ranged from 11.7 MPa to 7 MPa, whereas it ranged from 12 MPa to 7.7 MPa in the case of PMB40. As expected, the value of POTS in dry condition is higher than wet conditioned samples for both the base binders. In wet conditions, the POTS value ranged from 11.6 MPa to 5 MPa (10.7 MPa - 5 MPa for VG 30 and 11.6 MPa - 6.1 MPa for PMB40). This is attributed to the weakening of the bond at the interface of aggregate and asphalt binder owing to the presence of water [239].

The extent of increase or decrease in POTS values depends upon the aggregate type. The POTS values of VG30 were higher than PMB40 in the case of Dolomite and Granite, whereas the trend was quite the opposite in the case of Basalt and Sandstone, which resulted in higher POTS for PMB40 than VG30. Surprisingly, no specific trend was observed for the asphalt-aggregate combination prepared using Dolerite. This variation in wet and dry POTS values might be associated with the different mineral compositions of aggregates. Regarding the aggregate type, Sandstone resulted in lower POTS values in wet and dry conditions than the other aggregates.

This behaviour was found to be consistent for both the base binders. This lower POTS value can be attributed to the acidic nature of Sandstone, which leads to poor bonding with acidic asphalt binder [333,428]. The other probable reason may be the presence of SiO_2 (around 44.1%) in the Sandstone, which is hydrolytically unstable in water. In general, silica weakens the bond between asphalt binder and siliceous aggregates by releasing H^+ ions and lowering p^H.

To determine the effect of moisture, BSR was evaluated using the POTS values in dry and wet conditions, as shown in Figure 6-22 (c). The BSR for the VG30 (ranging from 0.91 to 0.71) was lower than PMB40 (0.97 to 0.79), indicating better performance of PMB40 against moisture damage. In other words, it can be stated that PMB40 requires higher stresses to strip off the binder from the aggregate surface in the presence of moisture [334]. However, similar to bond strength, the extent of bond strength loss depends on the aggregate type. The combination with Dolomite aggregate performed better against moisture damage, followed by Basalt, Granite, Dolerite, and Sandstone. Irrespective of the base binder, their combination with all the aggregates resulted in a BSR close to 0.9, except for Sandstone. This shows that the mineralogy of the aggregates plays an imperative role in characterizing the behaviour of asphalt mixtures in the presence of moisture; thus, it should be chosen sensibly.





(c)

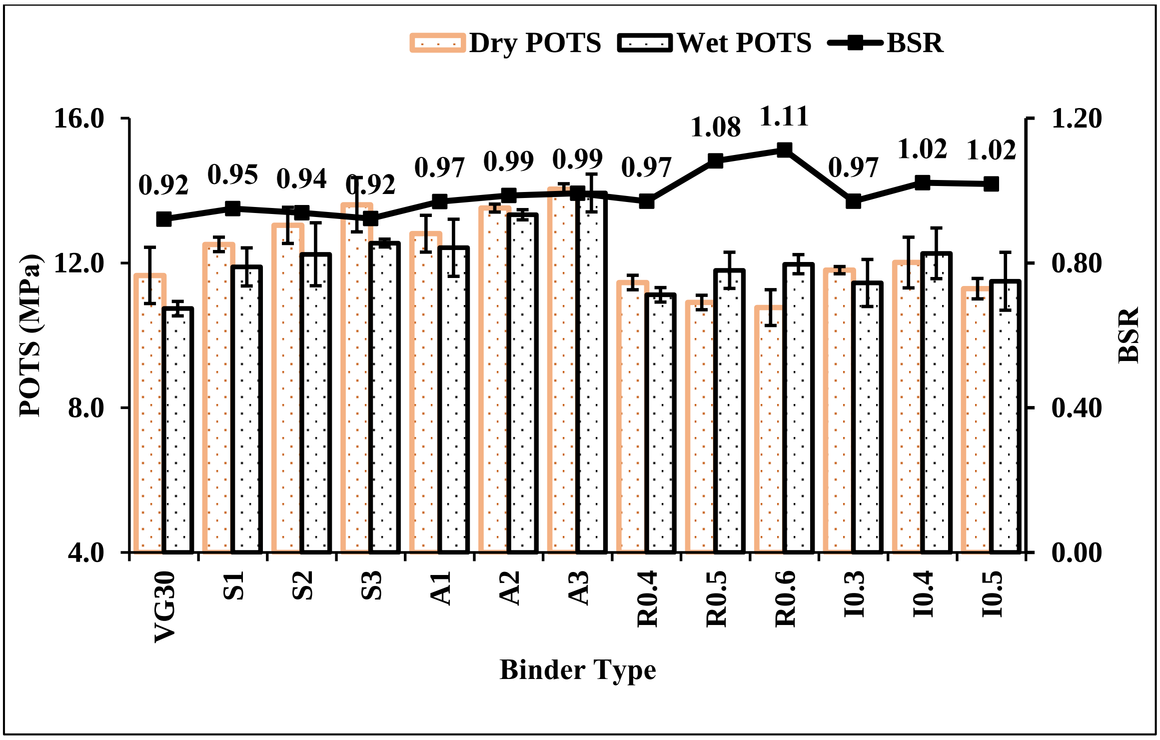
Figure 6-22. Effect of aggregate type and binder type on POTS a) Dry POTS b) Wet POTS (c) BSR

6.8.2 Effect of Warm Mix Additive on POTS and BSR

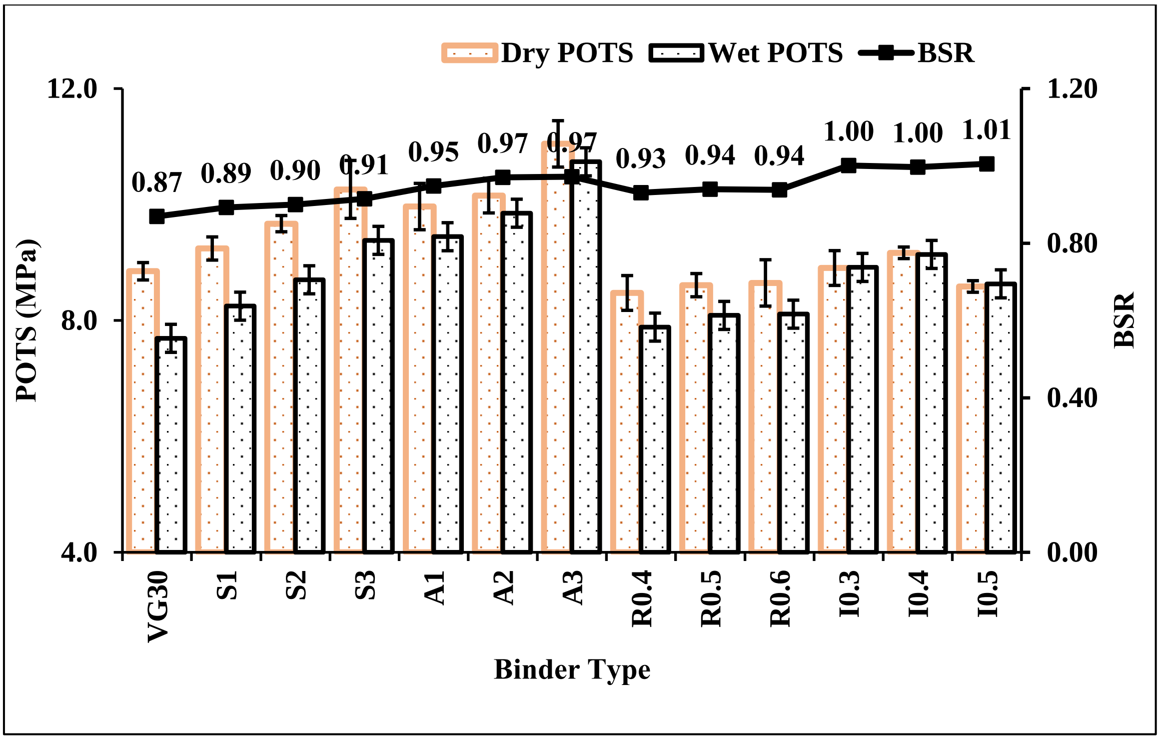
Figure 6-23 and Figure 6-24 shows the effect of WMA additive on POTS and BSR values of VG30 and PMB40 binder, respectively. It is desirable that the WMA modification in the base binder should improve the bonding behaviour between aggregate and asphalt binder. Adding organic additives (Sasobit and Asphaltan A) increased the POTS values of base binder in both wet and dry conditions. This can be due to the crystallization effect imparted by wax in the organic additives. This phenomenon causes the binder to stiffen in a way that is similar to fibre-reinforced materials [436]. Additionally, these waxes reduce the binder's viscosity, allowing more binder to diffuse into the aggregate and enhance the bonding properties. In contrast, adding chemical additives (Rediset and Iterlow) in base binders lowered the POTS values. The lowering of POTS might be due to the softening and emulsifying (due to chemical additive) of the asphalt binder with the incorporation of chemical additives [243]. It was also observed that WMA modification's effect on bond strength relies on the base binders. For example, Sasobit showed a predominant effect in the VG30 binder, while Asphaltan A indicated higher POTS with the PMB40 binder. Considering the WMA additive dosage, POTS values increase with an increase in the dosage of organic additives, whereas the dosage effect was not very significant in the case of chemical-based WMA additives. Among organic additives, Asphaltan A showed higher POTS values as compared to Sasobit in both wet and dry condition. This can be due to the presence of Amine in the structure of Asphaltan A which impart better bonding between aggregate and asphalt binder. On the other hand, chemical additives showed approximately similar bonding behaviour.

Irrespective of the base binder and aggregate type, all WMA additives showed higher BSR values than base binders. The values of BSR indicated that the chemical additives and Asphaltan A outperformed against moisture damage as loss in bond strength was minimal. For instance, most combinations prepared with chemical additives yield a BSR close to 1. Higher BSR for chemical additives and Asphaltan A is due to the presence of amine and silane groups in the Asphaltan A, Rediset, and Iterlow, which imparts antistripping characteristics [9,58,361,437]. In addition, chemical additives help reduce the surface tension of the binder, thereby improving the coating of asphalt binder over the aggregates [436]. The proper coating acts as a potential barrier preventing the water from finding a direct path to the aggregate surface, significantly improving the moisture resistance of asphalt mixtures. Like POTS values, BSR does not show any specific trend with a change in WMA additive dosage, regardless of WMA type. Overall, the analysis showed the potential of WMA additives in lowering the production temperatures of asphalt mixtures without conceding their moisture susceptibility. The extent of variation in BSR was found to be the function of base binder, WMA type, their dosages and aggregate type, as the BSR values were different for different aggregate-asphalt binder combinations.

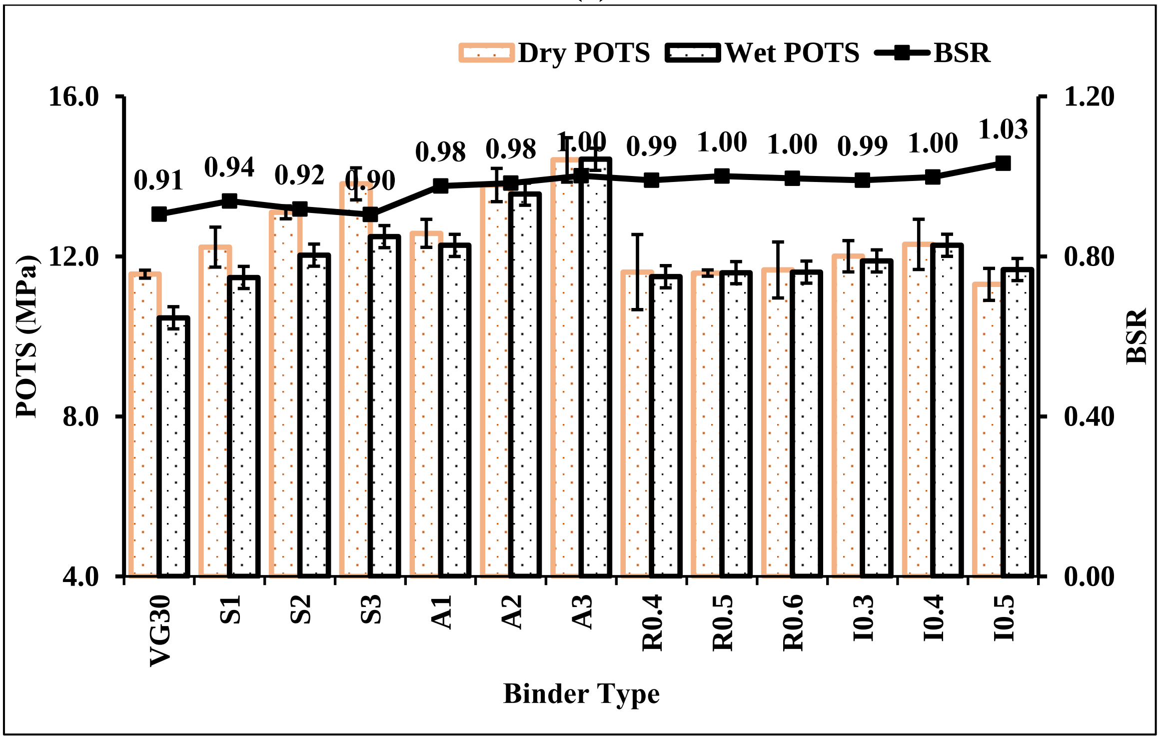
Figure 6-25 shows the failure pattern for different binder aggregate combinations. These failure patterns can help in understanding the bonding characteristics between binder and aggregate in presence of water. The failure pattern is anticipated to be cohesive if 50% of asphalt binder remains on the aggregate surface, else it is adhesive in nature [243,246]. From Figure 6-25, it can be observed that all WMA modified asphalt binder showed cohesive failure for both aggregate type under dry and wet condition. This indicate that the adhesive strength between aggregate and binder is higher than cohesive strength. The higher adhesive strength at interface of binder and aggregate is a favourable condition to resist moisture damage. The few combinations of WMA binders with Sandstone showed adhesive failure. This can be due to formation of weaker bond between Sandstone and WMA modified binders due to presence of high silica in it. The study conducted by Annaya et al. suggested that the cohesive failure is always better from moisture damage point of view [243]. Overall, it can be stated that the all WMA modified asphalt binder showed similar or better resistance to moisture damage as compared to base binder.



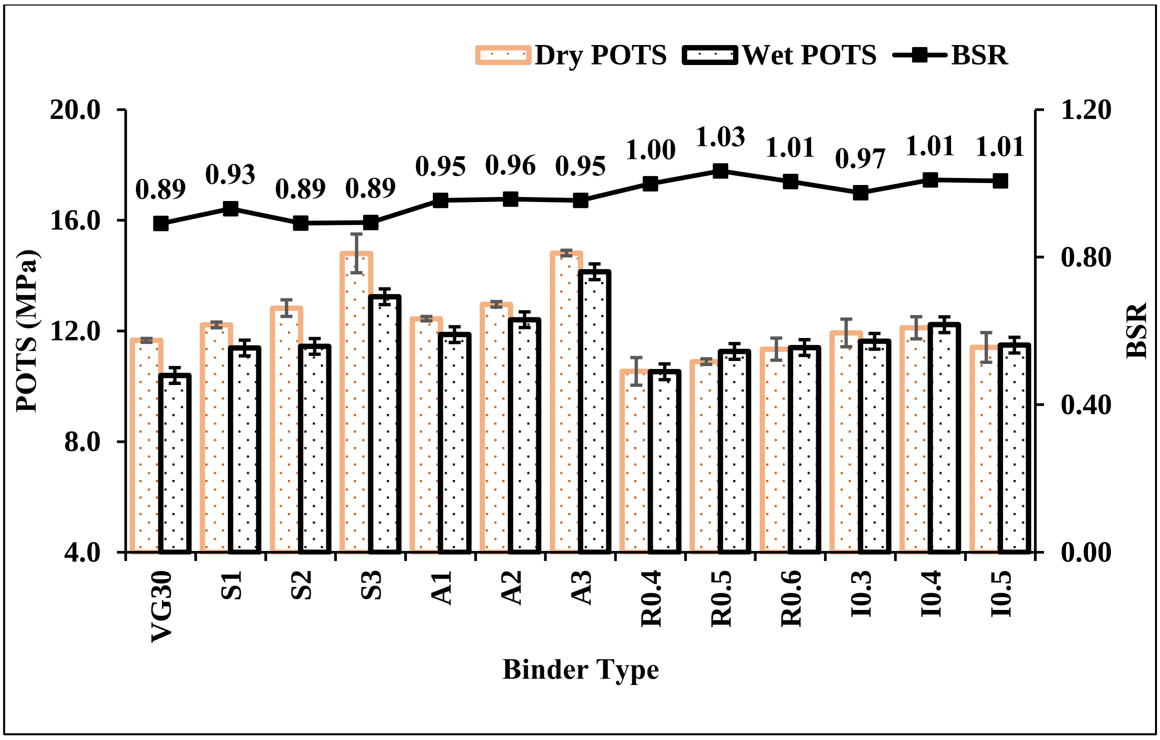
(a)


Dry POTS
Wet POTS
BSR
12.0
8.0
4.0
1.20
0.80
0.40
0.00
POTS (MPa)
BSR
0.87
0.89
0.90
0.91
0.95
0.97
0.97
0.93
0.94
0.94
1.00
1.00
1.01
VG30
S1
S2
S3
A1
A2
A3
R0.4
R0.5
R0.6
I0.3
I0.4
I0.5
Binder Type

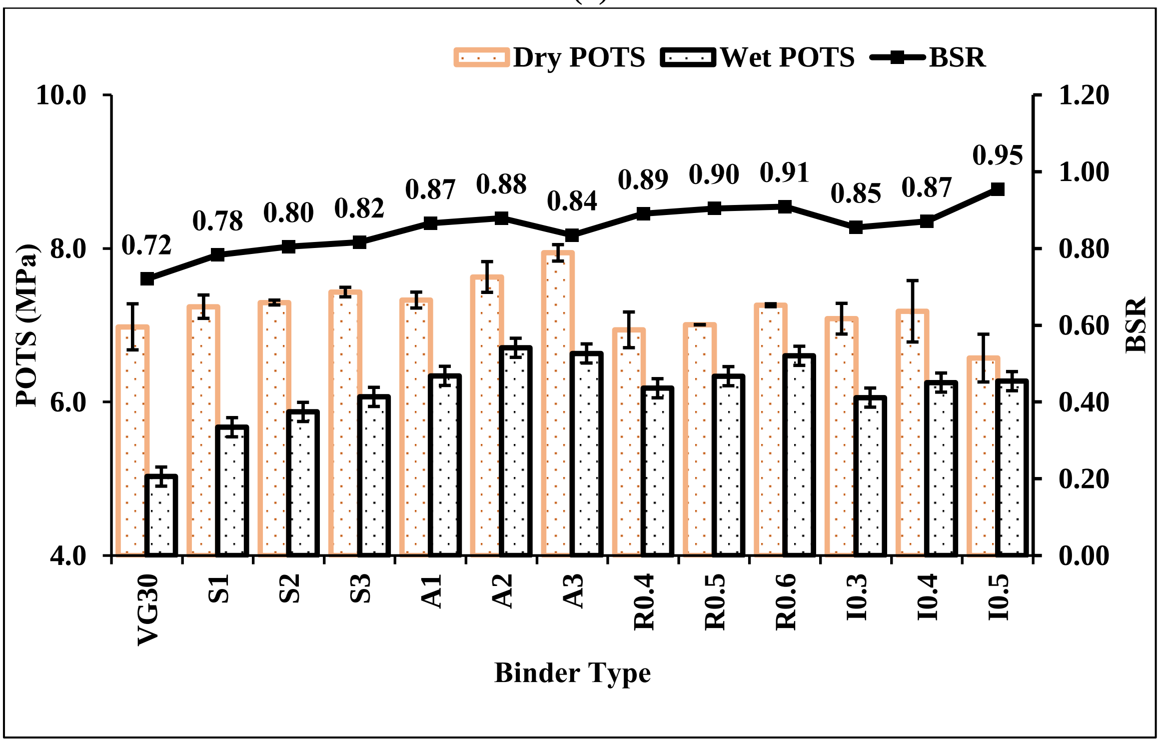
(b)


Dry POTS
Wet POTS
BSR
16.0
12.0
8.0
4.0
1.20
0.80
0.40
0.00
POTS (MPa)
BSR
0.91
0.94
0.92
0.90
0.98
0.98
1.00
0.99
1.00
1.00
0.99
1.00
1.03
VG30
S1
S2
S3
A1
A2
A3
R0.4
R0.5
R0.6
I0.3
I0.4
I0.5
Binder Type

(c)

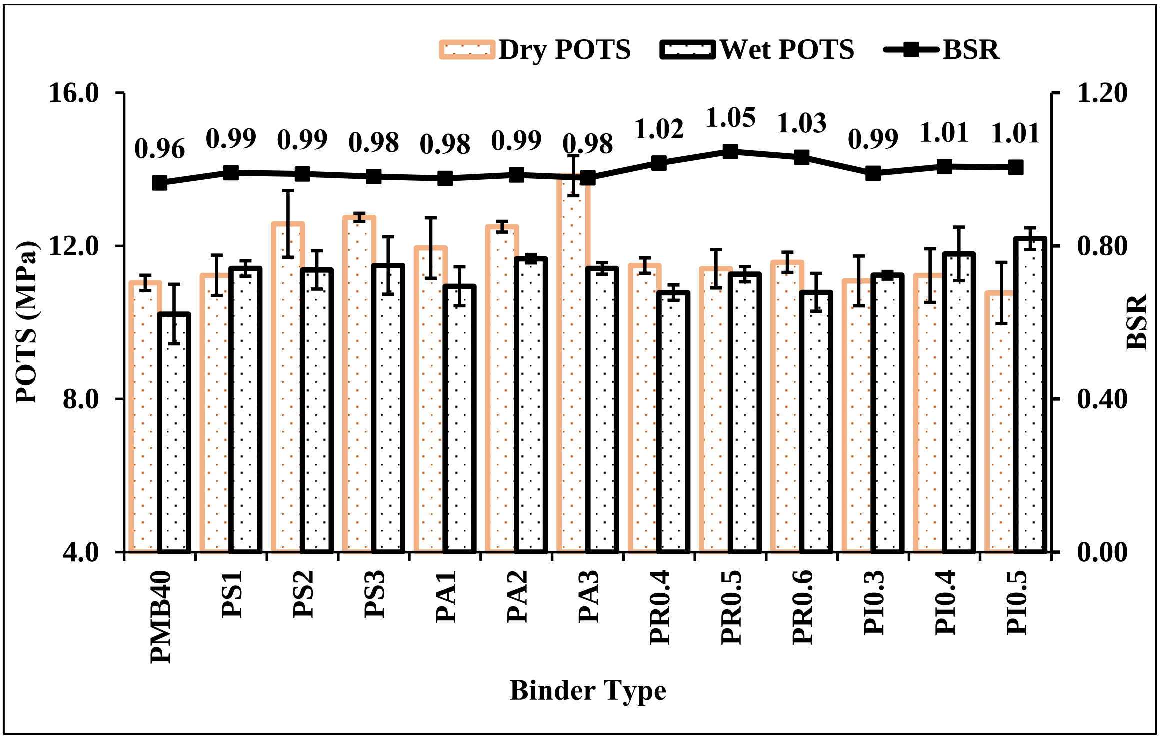


(d)

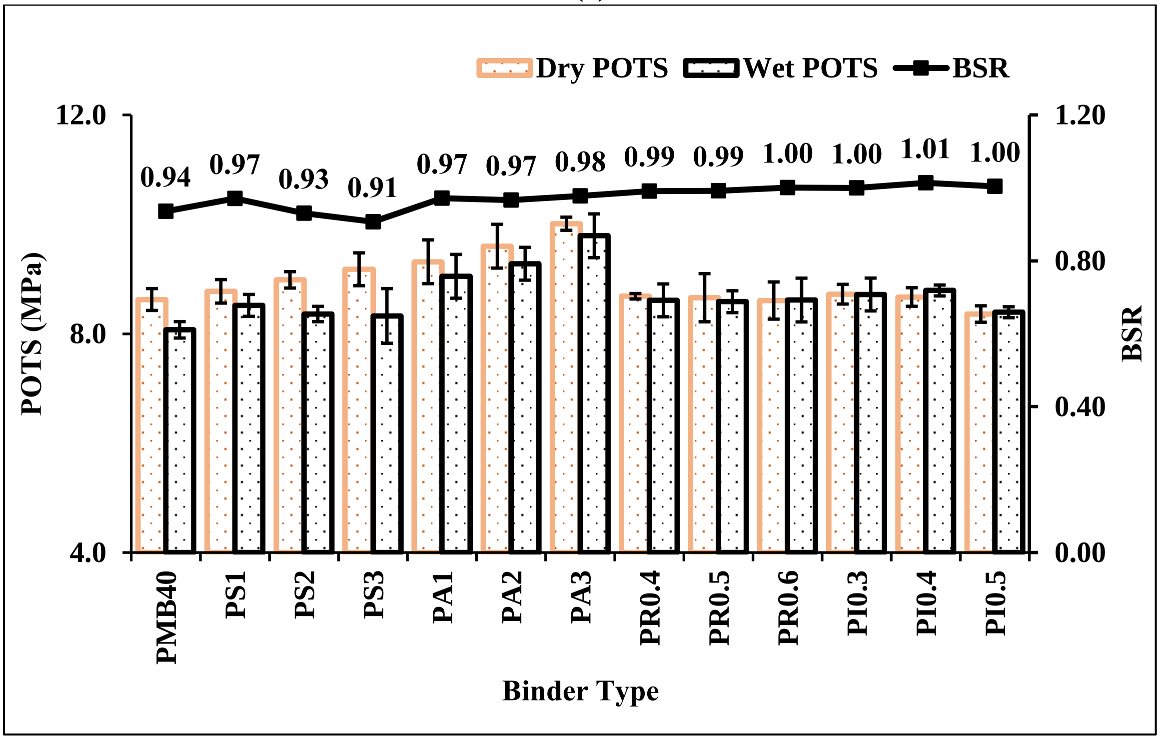


(e)

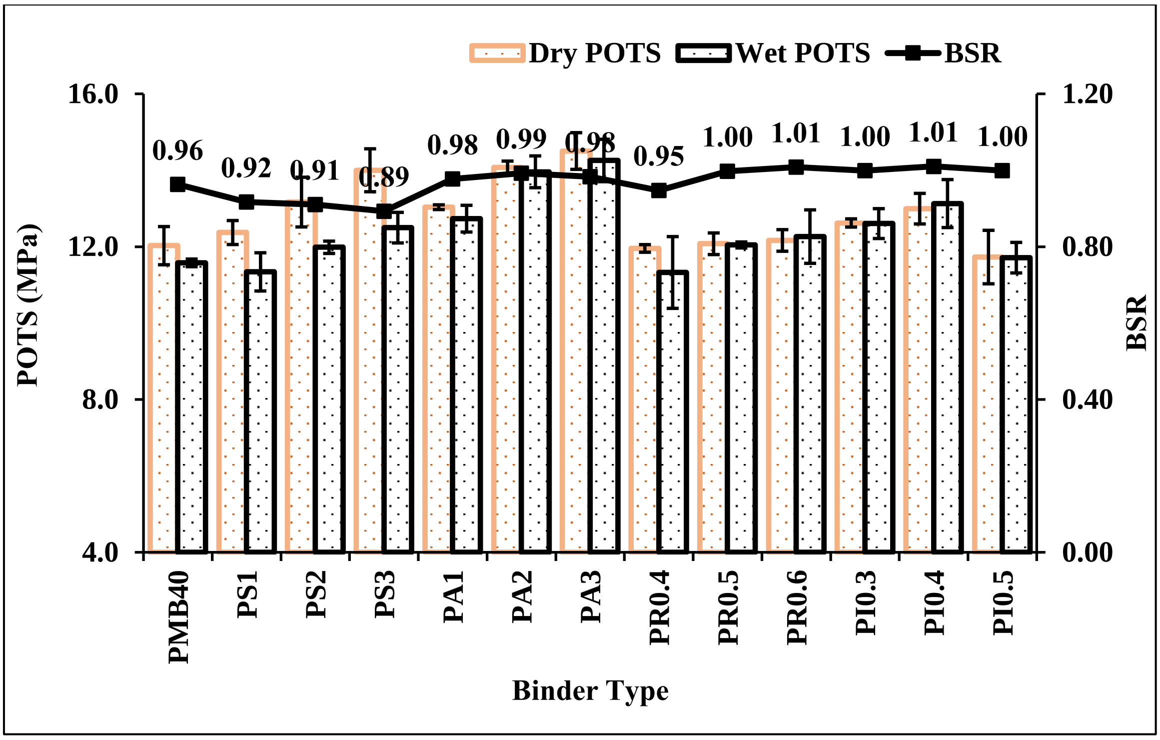
Figure 6-23. Effect of WMA additives on POTS and BSR value for VG30 as base binder a) Dolomite b) Dolerite c) Basalt d) Granite e) Sandstone


Dry POTS
Wet POTS
BSR
POTS (MPa)
BSR
16.0
12.0
8.0
4.0
1.20
0.80
0.40
0.00
0.96
0.99
0.99
0.98
0.98
0.99
0.98
1.02
1.05
1.03
0.99
1.01
1.01
PMB40
PS1
PS2
PS3
PA1
PA2
PA3
PR0.4
PR0.5
PR0.6
PI0.3
PI0.4
PI0.5
Binder Type

(a)

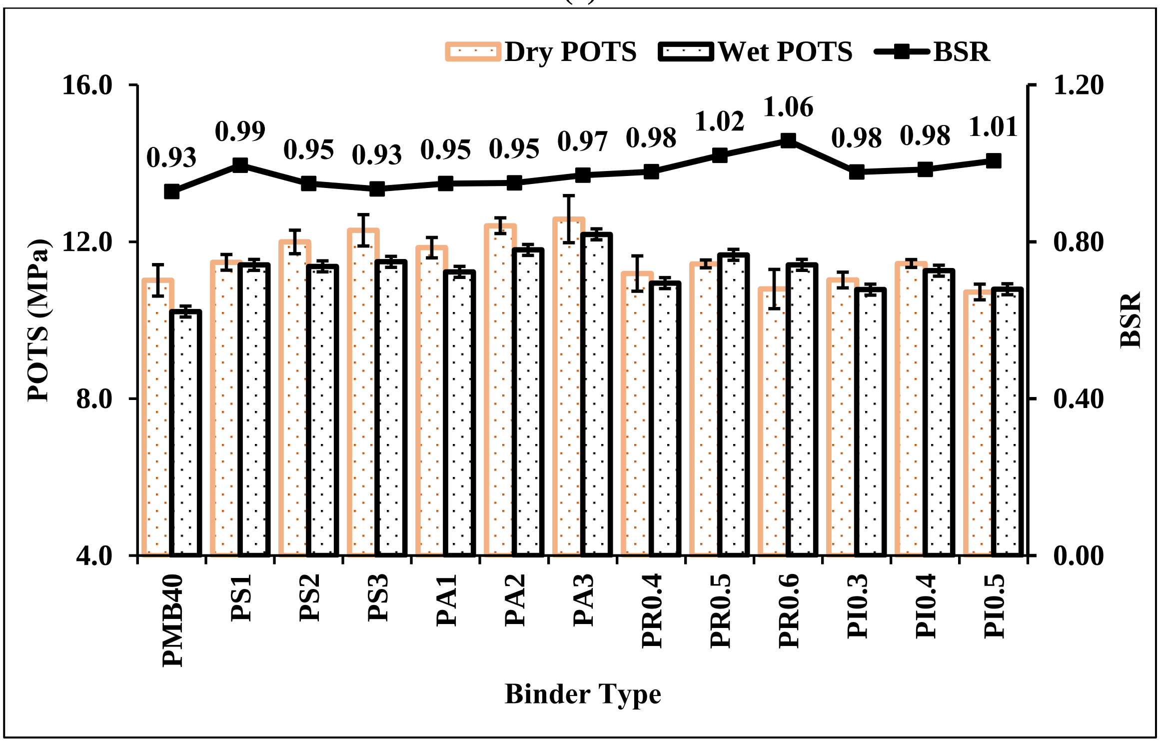

Dry POTS
Wet POTS
BSR
POTS (MPa)
BSR
12.0
8.0
4.0
1.20
0.80
0.40
0.00
0.94
0.97
0.93
0.91
0.97
0.97
0.98
0.99
0.99
1.00
1.00
1.01
1.00
PMB40
PS1
PS2
PS3
PA1
PA2
PA3
PR0.4
PR0.5
PR0.6
PI0.3
PI0.4
PI0.5
Binder Type

(b)



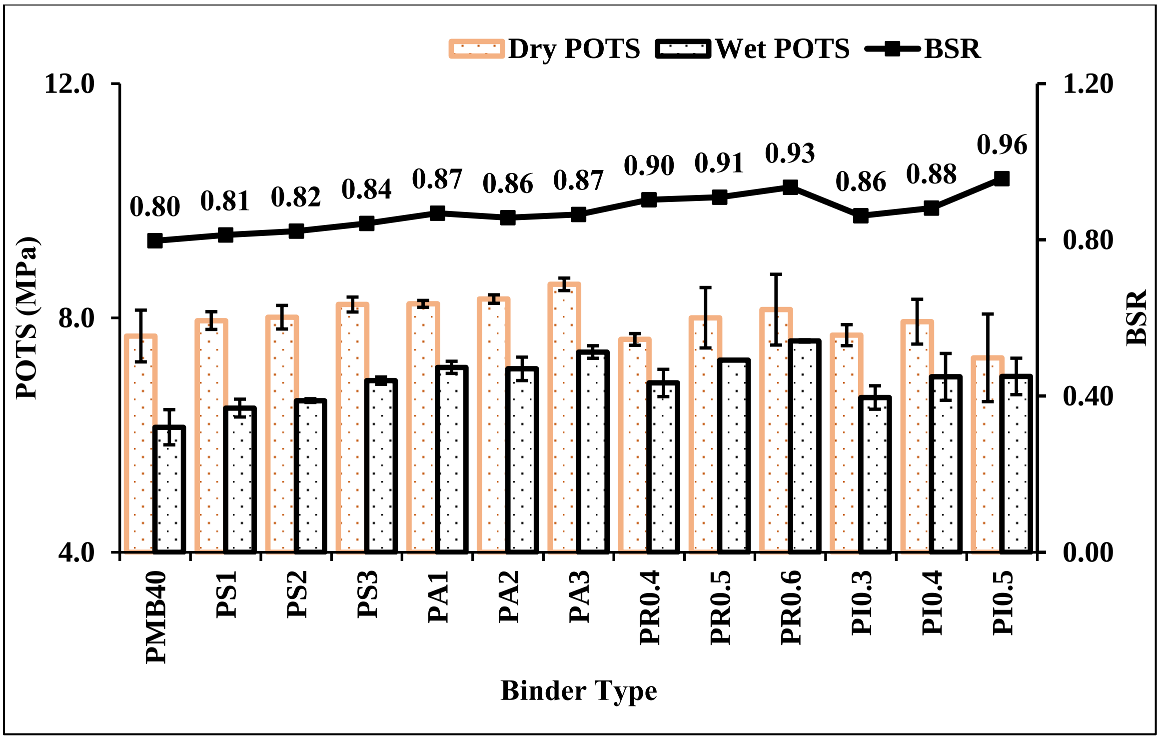
Dry POTS
Wet POTS
BSR
POTS (MPa)
BSR
16.0
12.0
8.0
4.0
1.20
0.80
0.40
0.00
0.96
0.92
0.91
0.89
0.98
0.99
0.98
0.95
1.00
1.01
1.00
1.01
1.00
PMB40
PS1
PS2
PS3
PA1
PA2
PA3
PR0.4
PR0.5
PR0.6
PI0.3
PI0.4
PI0.5
Binder Type

(c)



Dry POTS
Wet POTS
BSR
POTS (MPa)
BSR
16.0
12.0
8.0
4.0
1.20
0.80
0.40
0.00
0.93
0.99
0.95
0.93
0.95
0.95
0.97
0.98
1.02
1.06
0.98
0.98
1.01
PMB40
PS1
PS2
PS3
PA1
PA2
PA3
PR0.4
PR0.5
PR0.6
PI0.3
PI0.4
PI0.5
Binder Type

(d)



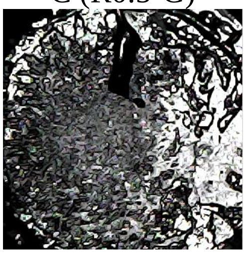
(e)

Figure 6-24. Effect of WMA additives on POTS and BSR value for PMB40 as base binder a) Dolomite b) Dolerite c) Basalt d) Granite e) Sandstone

After dry conditioning

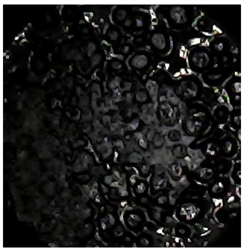
C (S2-D)

C (R0.5-G)



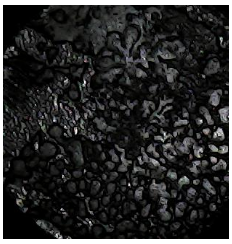
C (PS2-B)

After wet conditioning



C (S2-D)

C(R0.5-G)



C (PS2-B)

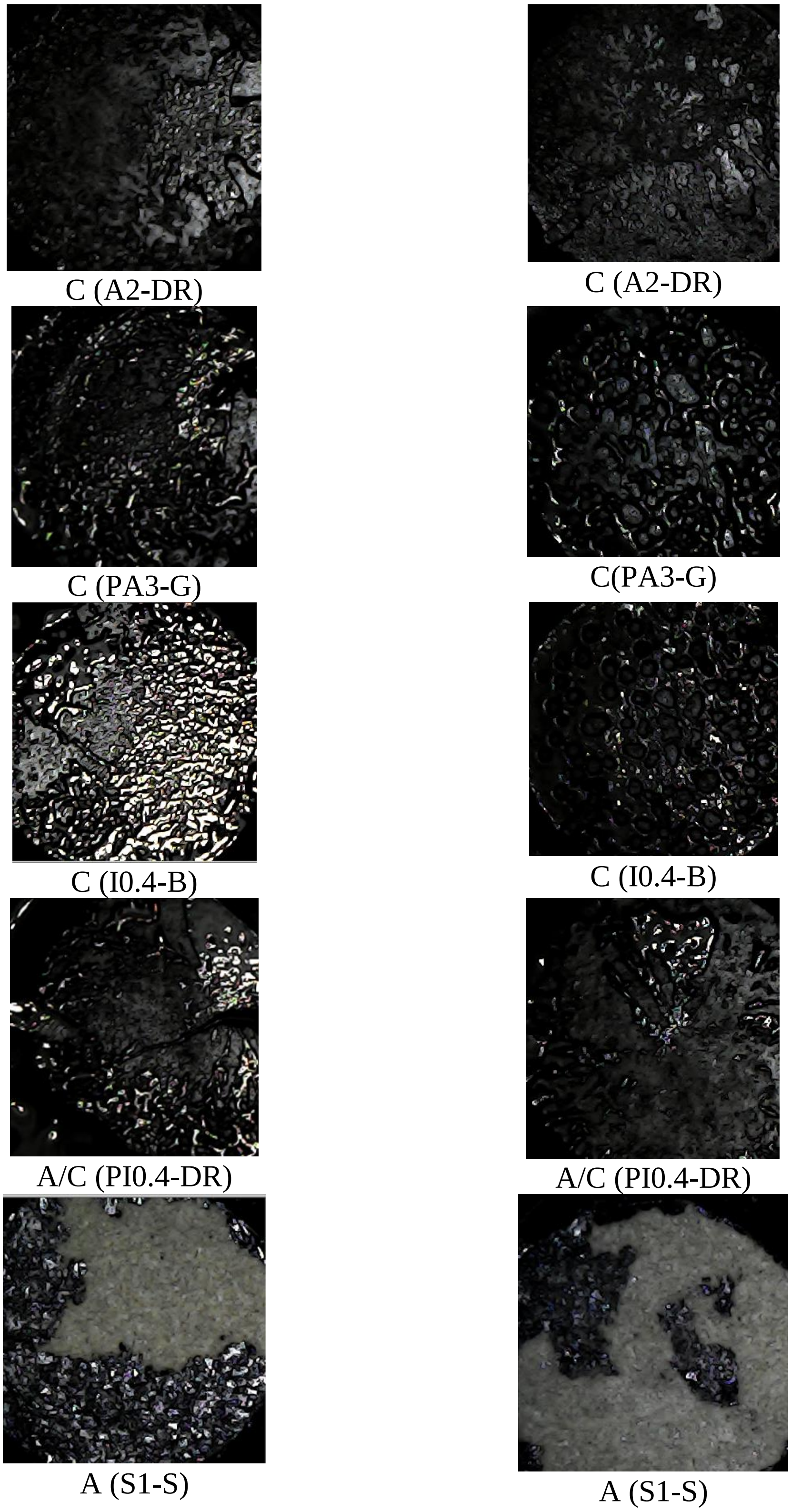


Figure 6-25. Failure patterns for different aggregate-binder combinations

Note: A: Adhesive Failure C: Cohesive Failure, A/C: Adhesive-Cohesive Failure. The term in round bracket indicates WMA binder-aggregate combination where B: Basalt, D: Dolomite, DR: Dolerite, G: Granite, and S: Sandstone.

6.8.3 Establishing Threshold Limit for BSR:

The phenomenon of moisture damage can be effectively studied through bond strength ratio (BSR) which is ratio of dry bond strength and wet bond strength. BSR is mainly dependent on the type of aggregate and asphalt binder. To check suitability and compatibility of the aggregate type and asphalt binder against moisture damage, it is necessary to have threshold value for BSR. The threshold can be a pass or fail criteria for the moisture damage in terms of bond strength. Additionally, the BBS test is still in its early stages of development. Although AASHTO T361 has published a testing protocol standard, the threshold limit has not yet been established, and few studies have reported threshold values for the BBS method. However, these values were obtained from fewer data points and dependent upon specific aggregates [240,251]. In this study, the threshold determination was based on tensile strength ratio (TSR). TSR is a well-established parameter for evaluation of the moisture sensitivity of the asphalt mixture, and defined as the ratio of wet to dry tensile strength of asphalt mixture [438,439]. The limiting value for TSR as per the standard is 0.8 and the mixture which exhibits values below this threshold can be considered more prone to moisture damage [251]. For this purpose, TSR test was performed on 35 asphalt mixtures in accordance to AASHTO-T283. From the 35 asphalt mixtures, it was found that the TSR follows the normal distribution and had mean and standard deviation of 0.91 and 0.072, respectively. Considering this mean and standard deviation, the Monte Carlo simulation was performed to generate random data set of 1000 samples (considering the normal distribution) and reliability of TSR threshold (0.8) were evaluated. It was found that the TSR threshold had reliability of 93.2 %. This reliability level was considered during determination of the threshold for BSR parameter. The same concept of simulation was applied for BSR based on 130 data points; the threshold value was found to be 0.82 corresponding to 93.2 % reliability. Table 6-4 shows the threshold value for BSR based on reliability level. This implies that the threshold of 0.8 (corresponding to TSR) and threshold of 0.82 (corresponding to BSR) exhibit same level of reliability. From the study, it can be concluded that the BSR threshold of 0.82 can be applicable to most of the aggregate-binder combinations and can be used as pass/fail criteria for bond strength against moisture damage.

Table 6-4. Threshold value of BSR based on reliability level

Parameter	Mean	Standard deviation	Random samples	Threshold criteria	Reliability
TSR	0.915	0.0723	1000	0.8	93.2
BSR	0.93	0.0694	1000	0.82	93.3

6.9 Summary

Warm mix asphalt technology has proved to be a substitute for the production of asphalt pavements, due to its lower mixing and compaction temperatures. However, one of the concerns associated with WMA technology is the effect of reduced aging on the performance of asphalt binders. Therefore, the performance of WMA modified binders at reduced aging has been evaluated in this chapter. This chapter aimed to conduct an extensive investigation on the performance of WMA modified binders against rutting, fatigue, and moisture failure. Also, different test variables such as aggregate source, base asphalt binder, and WMA technology were chosen to comprehensively examine and compare the performance of WMA modified binder with base binders. In this chapter, the performance of various WMA modified binders at reduced aging level using various performance tests such as FTIR, MSCR, and LAS test has been evaluated. In addition, suitability of the WMA additives against moisture damage using various aggregates has also been discussed in this Chapter. Based on results of these tests, the following conclusions are drawn:

- FTIR results showed that all WMA modified asphalt binders exhibit lower carbonyl and sulfoxide indices due to reduced mixing and compaction temperatures, leading to higher aging resistance. PMB40 showed higher aging resistance as compared to VG30 binder.

- The response of stress-strain curve of the organic-modified asphalt binders were sharper than those of the neat binder, indicating a stronger strain dependency. Conversely, chemical additives showed a lower strain dependency as indicated by broader peaks.
- Incorporating organic additives in both the binders reduced the non-recoverable creep compliance (J_{nr}) and enhanced the recovery of asphalt binder. This trend was inverse in the case of chemical-modified asphalt binders, especially at higher dosages. Despite reduced aging temperatures, all the WMA modified asphalt binders were suitable for extremely heavy traffic conditions at 40ºC and 50ºC, equivalent to the grading of base asphalt binder. Among all binders, the combination of PMB 40 and WMA technology ensures the enhanced rutting performance.
- The LAS test results showed that the inclusion of chemical additives enhanced fatigue performance compared to organic additives. Although the increase in dosage of organic additives lowered the fatigue life, its application was still worthwhile as the cycles to failure were more than VG30 at all the test conditions. It is believed that better fatigue life of the WMA modified asphalt binders is due to their lower aging temperature.
- The dry POTS of organic-modified asphalt binders was higher than chemical additives and base binders, indicating higher bond strength for organic-modified asphalt binder. On the other hand, the use of chemical additives and Asphaltan A showed higher POTS in wet conditions for both aggregate types, thereby leading to higher BSR and moisture resistance. Among all the WMA additives, chemical additives and Asphaltan A showed better performance against moisture damage (as BSR value close to 1 in most of the cases) due their antistripping behaviour. Considering the aggregate type, Dolomite showed higher bond strength whereas Sandstone showed lower bond strength due to the higher amount of silica. The threshold of BSR was found to be 0.82 corresponding to 93.2% reliability. This value can be used as pass/fail criteria for moisture damage assessment at binder level.

- Overall, it was observed that the performance of WMA modified binder was found to be function of aggregate type, base binder, WMA additive and its dosages.