CHAPTER 7. DURABILITY OF RECYCLED MIXES

7.1 Preamble

Over the years many innovative products, both commercial and waste type rejuvenators, have been successfully used as rejuvenators [58,108,187,195,339–341]. Literature review [24,47–49,277] on rejuvenators highlights multiple variables that should be considered to improve the applicability of rejuvenators. Aspects such as composition, optimum dosage and method of addition needs to be well thought of. Different factors such as the percentage and source (stiffness) of RAP, virgin binder grade, conditioning and mixing temperatures etc. influences the aforementioned aspects. Another important aspect that is not studied with enough rigor is the durability (aging behaviour) of the rejuvenated recycled mixes. As shown in Table 7-1, aging of rejuvenators is a major concern and needs to be studied thoroughly. Few studies highlighted that rejuvenated binders age differently and faster than virgin binders and hence are susceptible to aging. It is also observed that rejuvenated mixes are even prone to cracking at later stages despite of having better cracking resistance initially. Long-term aging performance of rejuvenated recycled mixes either needs to be better or similar to that of virgin mixes to confidently implement the rejuvenators in the field. Therefore, the final objective aims to provide insight into the durability aspect of diverse rejuvenators. This is achieved by studying the performance of recycled mixes with multiple rejuvenators and RAP percentages at different aging periods. Both aging and rate of aging of recycled mixes are compared with virgin mixes to gain better understanding.

Table 7-1 Aging performance of rejuvenators

Reference	Rejuvenator(s)	Inferences
[65]	AE 150 Mobilsol 30	Rejuvenated binders will have different long term performances and hardening rates
[67]	Aromatic oil Vegetal oil 160/220	Vegetal oil and soft binder are susceptible to aging
[66]	Rj1, Rj2, Rj3	Rejuvenated binder ages faster than virgin binder. Rejuvenated binder may not perform well in long term
[342]	Bio rejuvenator fluid (BOF) Heavy paraffinic extract (HPE) Petroleum neutral distillate (PND) Arizona pine oil (APO) Cationic water-based emulsion (CWE)	From binder tests, CWE and HPE decreased whereas BOF, PND and APO increased the rate of aging virgin binder aging rate decreases with time but constant for rejuvenated binders Although cracking resistance of rejuvenated mixes is better initially, decreased at a faster rate
[68]	R1, R2, and R3	Rejuvenators chemically change the blends of recycled asphalt blends and make them susceptible to time and temperature
[343]	A	Rejuvenated binder tend to age earlier than virgin binder

[344]	A (natural seed oil) B (cashew nut shell oil) C (tall oil)	Rejuvenators are affected differently by aging Effect of aging is vital in identifying how rejuvenators affect the RAP binder
[345]	RA 100 and RA 102	Change in properties of rejuvenator blends after aging was rapid (aging susceptible) due to high content of light fractions
[61]	Cyclogen Rapiol Waste cooking oil	Highly recommended to evaluate aging susceptibility of rejuvenators before introducing them to industry
[346]	Evoflex 3G	Compared to the virgin binder, recycled binder blends are more sensitive to aging Though rejuvenators improves cracking resistance, the long term anti-cracking property could not be guaranteed

7.2 TESTS

The rutting resistance (IDEAL-RT test), fatigue resistance (IDEAL-CT test), moisture resistance (indirect tensile strength test), and resilient modulus test were conducted as per Sections 3.8.1.3.3, 3.8.1.4, 3.8.1.5, and 3.8.1.6, respectively

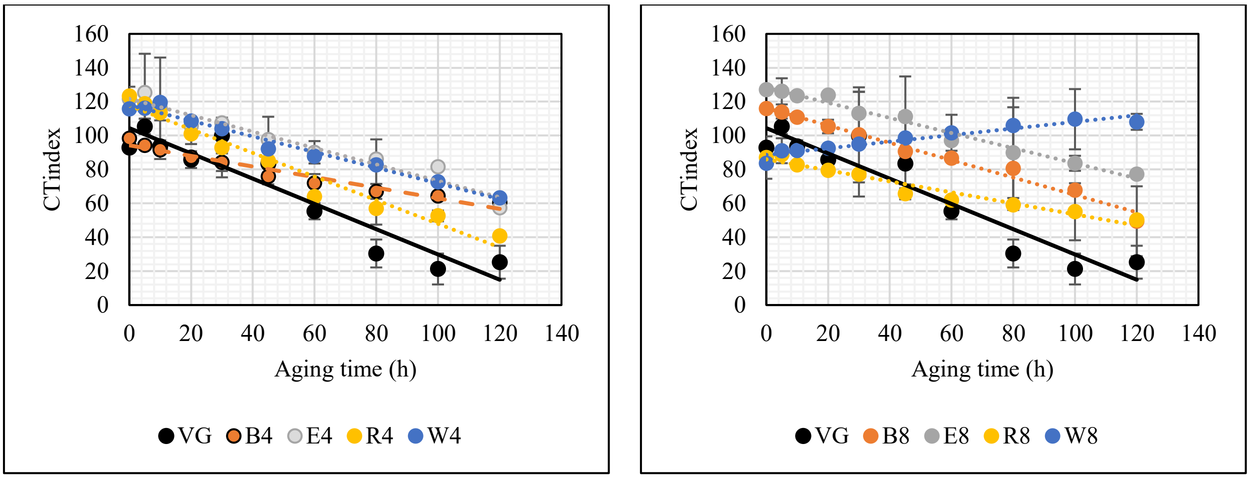
7.3 RESULTS

7.3.1 Fatigue performance

Cracking resistance of virgin mixes and recycled mixes decreased with the aging periods (except W8) as can be seen from CT_{index} values in Figure 7-1. In order to understand the underlying reason behind the trend of CT_{index}, peak load and AFR values are also studied.

Decrease in the flexibility (AFR) and simultaneous increase in stiffness (peak load) of the mixes (Figure 7-2) are the main reasons for the trend of CT_{index} values. This variation is observed for all the mixes except W8. Rate of decrement (slope) varied depending on the percentage of RAP and type of rejuvenator as shown in Table 7-2. It was observed that rate of decrement of recycled mixes is lower than virgin mixes, implying that CT_{index} values of recycled mixes are less effected by aging time compared to virgin mixes. Thus recycled mixes with RAP and rejuvenators are more durable than virgin mixes, in terms of fatigue performance.

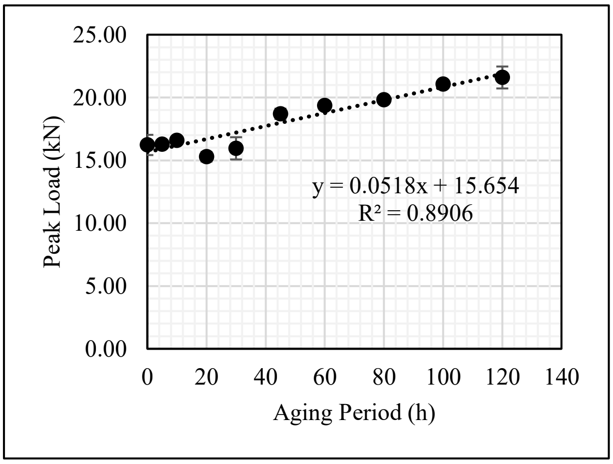
For rejuvenator B, higher CT_{index} values are observed for 80% recycled mixes at all aging periods (except at 120 h). Hence, with the increase in the recycling rate, influence of rejuvenator also increases. But rate of decrement (change) is also high for 80% recycled mixes. Durability of rejuvenator E (in terms of cracking resistance) did not dependent much on the percentage of RAP i.e. similar rate of decrement and values (almost) at both 40% and 80% RAP (except at 120 h). It can be interpreted that at optimum dosage, E performs similar at any recycling rate. In case of rejuvenator R, higher CT_{index} values are shown by 40% recycled mixes till 60 h aging period. Also high rate of decrement is shown by R4 and hence lower CT_{index} values at 80, 100 and 120 h aging periods. Thus for very high RAP contents, the influence of rejuvenator R is less and better durability is observed. It should be noted that CT_{index} of R8 mixes are lower than virgin mixes till 45 h, but showed better resistance to aging and thus higher vales from 60 h aging period. Unlike other rejuvenators, W displayed a unique and unexpected trend at 80% RAP content for which CT_{index} values increased with aging. Not much change in peak load and increase in AFR values with aging time are observed for W8 mixes. This dominance of rejuvenator and its influence on enhancing flexibility with aging needs to be explored further.



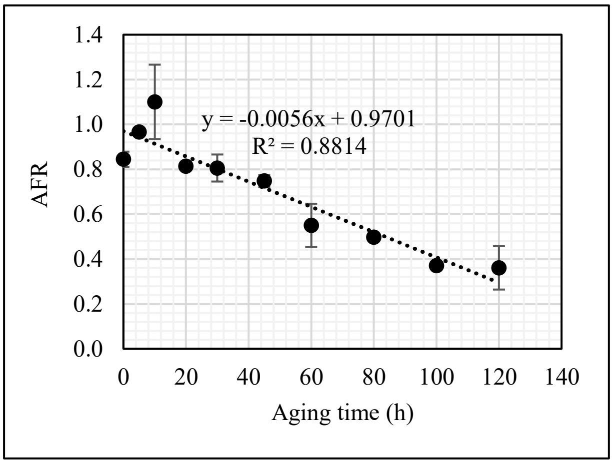
40% RAP

80% RAP

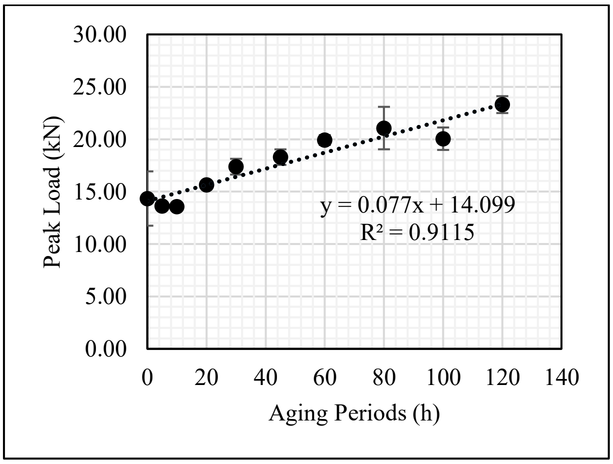
Figure 7-1 Sensitivity of Cracking Tolerance Index to aging time



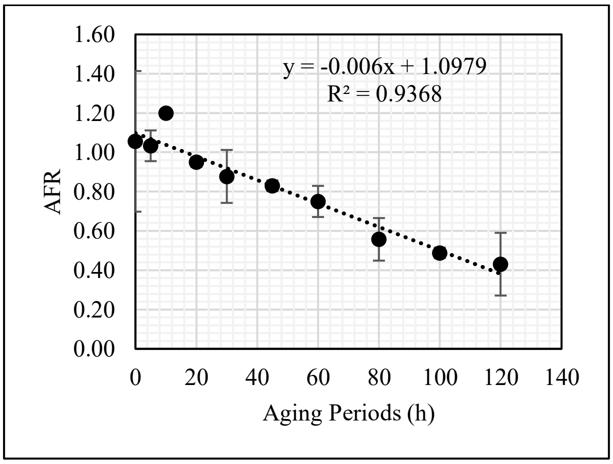
Virgin mix



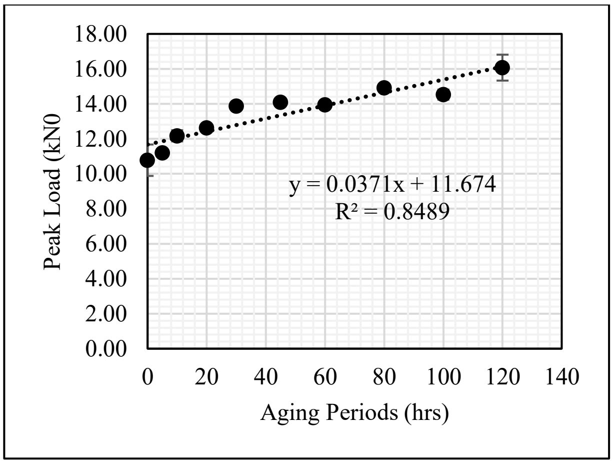
Virgin mix



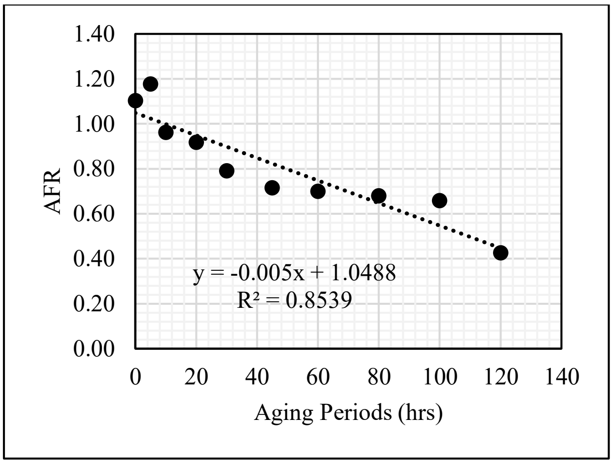
R4



R4



R8



R8

Figure 7-2 Sensitivity of peak load and Asphalt Flexibility Ratio to aging time

Table 7-2 Rate of decrement of Cracking Tolerance Index

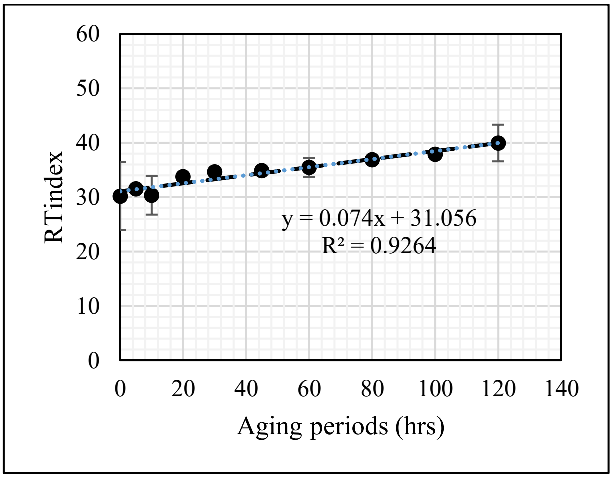
Rejuvenator	40% RAP	80% RAP	Virgin mix
B	-0.3125	-0.5125	-0.7453
E	-0.484	-0.446	
R	-0.6969	-0.325	
W	-0.4705	+0.1948	

7.3.2 Rutting performance

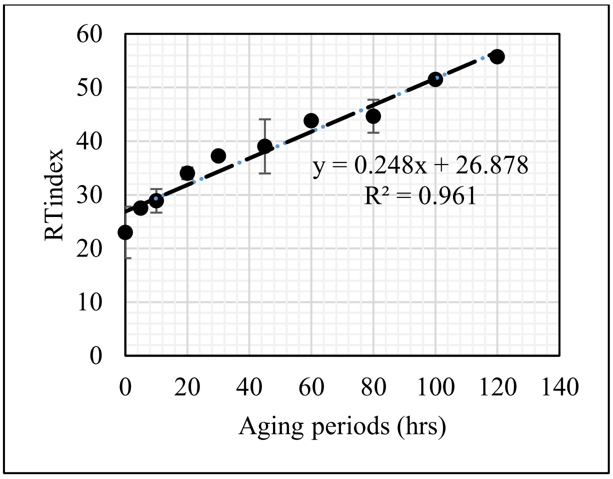
As mentioned earlier, shear failure is induced in the sample in IDEAL-RT test. Higher the value of RT_{index} higher will be the shear strength and hence more load is required to induce the shear failure. Since aggregate gradation and air voids are kept constant in the present study, change in the RT_{index} value is mainly due to the binder only. RT_{index} of all the mixes (virgin and recycled) increased with the increase in the aging period (see Figure 7-3). When the mixes are conditioned for higher aging periods, quantity of load required to fail the sample in shear increased, which resulted in high RT_{index} values. But the rate of increment is binder specific as illustrated in Table 7-3. E4 and R8 mixes exhibited almost similar values and same rate of increment as that of virgin mixes. For remaining recycled mixes, both values and rate of increment differed from virgin mixes (dependent on the percentage of RAP and rejuvenators).

Almost all the recycled mixes exhibited high rate of increments than virgin mixes. Although rutting performance of recycled mixes is more sensitive to aging, it improves with time.

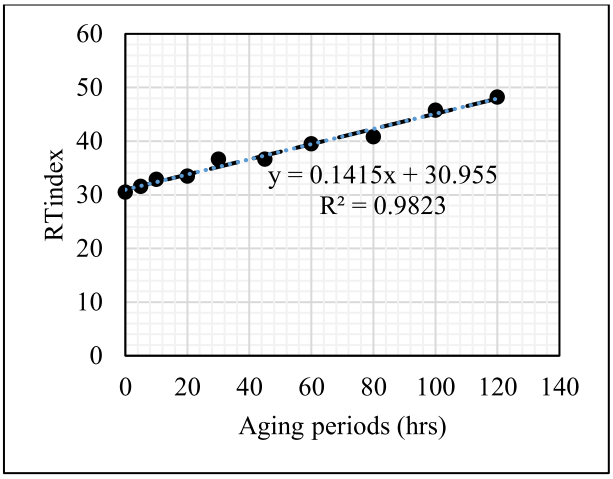
For rejuvenator B, higher RT_{index} values are observed for 80% recycled mixes at 0, 5 and 10 h aging periods. But B4 displayed high RT_{index} values from 20 h aging time due to high rate of aging. Similar trend of high rate of aging and high values after 45 h aging time was also observed in case of W8. A general custom of increase in rutting resistance with increase in percentage of RAP is observed for rejuvenator E, E8 mixes have high RT_{index} values at all aging periods. In case of rejuvenator R, a reverse trend decrease in rutting resistance with the increase in RAP percentage is observed due to the dominance of rejuvenator, R4 have high RT_{index} values at all aging periods.



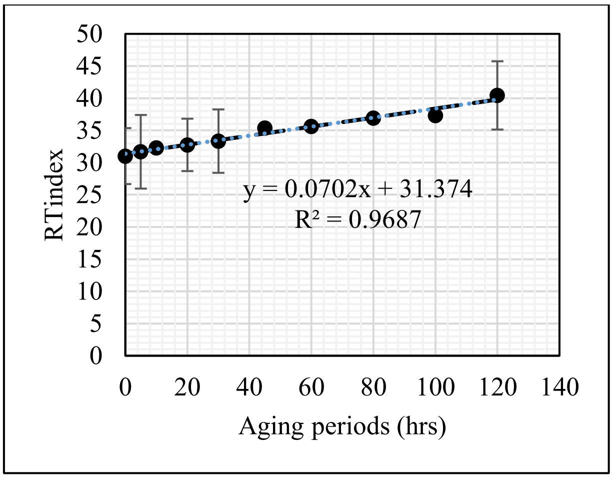
Virgin mix



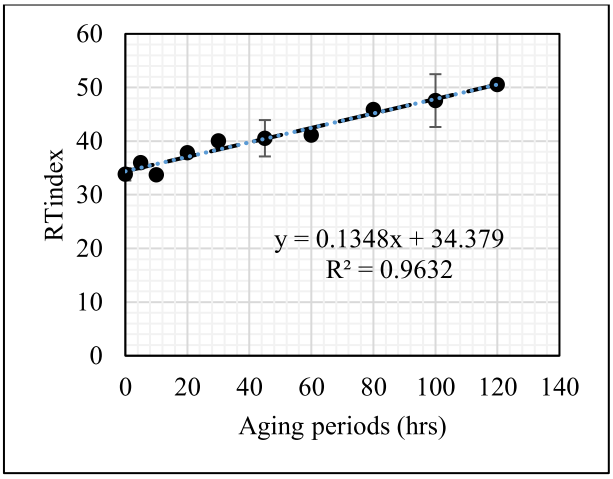
B4



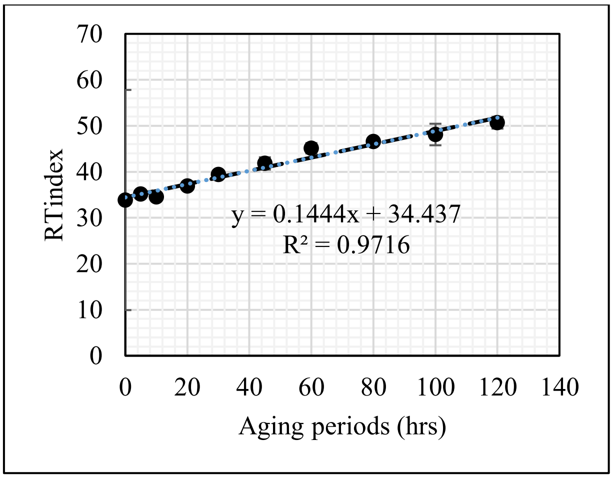
B8



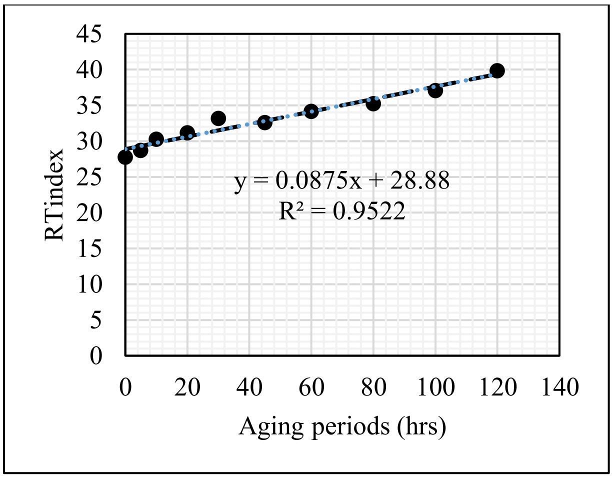
E4



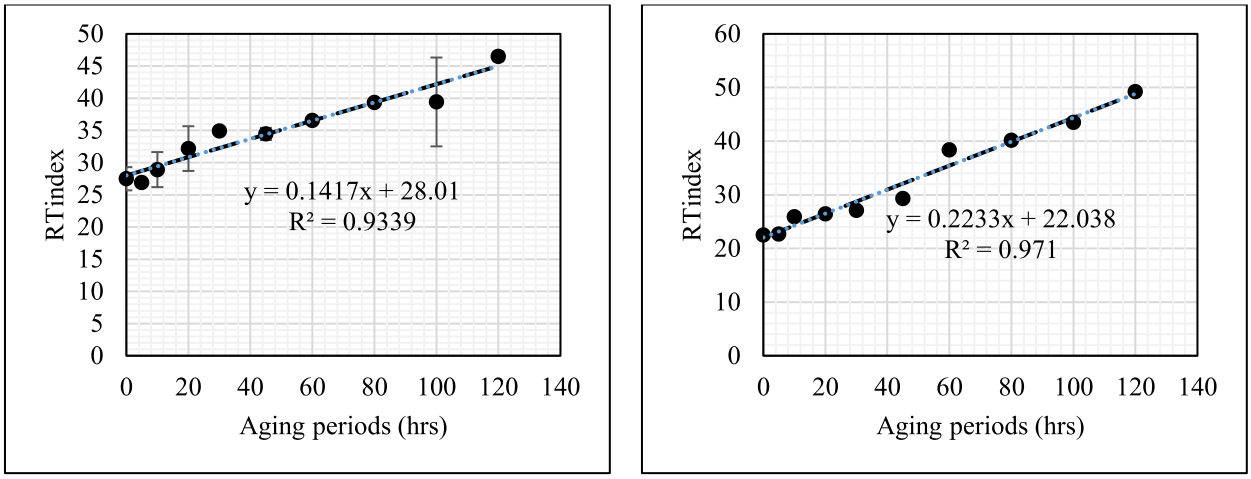
E8



R4



R8



W4 W8

Figure 7-3 Sensitivity of Rutting Tolerance index to aging time

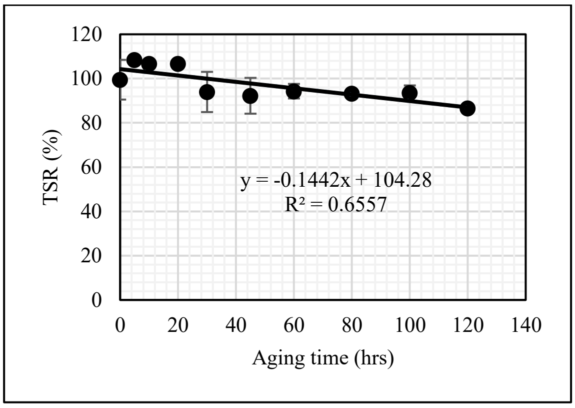
Table 7-3 Rate of increment of Rutting Tolerance index

Rejuvenator	**40% RAP**	**80% RAP**	**Virgin mix**
B	+0.248	+0.1415	+0.074
E	+0.0702	+0.1348	
R	+0.1444	+0.0875	
W	+0.1417	+0.2233	

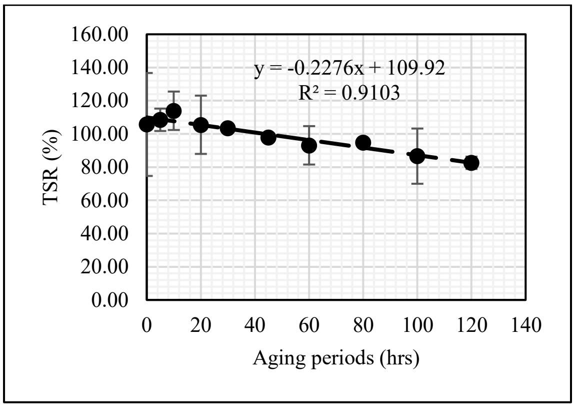
7.3.3 Moisture resistance

For virgin mixes, the sensitivity of moisture resistance to aging time is not substantial, but a trend of linear decrease with aging time is observed (Figure 7-4). This is due to the fact that functional groups that results due to aging such as carbonyls and sulfoxides, tend to have high affinity to water [267–270]. Therefore, when the mixes exposed to higher aging time are conditioned in water, these compounds forms hydrogen bond and leads to low TSR values. Similar trend is also seen in B4, E4, W4 and E8 recycled mixes also (Figure 7-4). Unlike virgin mixes, a very good correlation exists between TSR values and aging time for recycled mixes.

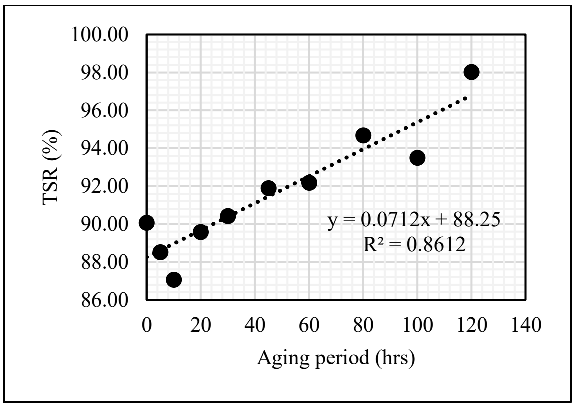
R4, B8, R8 and W8 recycled mixes showed a reverse trend of linear increase of TSR values with aging periods (Figure 7-4). TSR values at 0 conditioning period suggest the influence of rejuvenator is more than the RAP binder. To have more understanding about the chemical groups that make-up the rejuvenators, FTIR test is conducted. High amount of amine functional groups (N-H) in rejuvenators R and W and also traces of C-N and N-H functional groups in rejuvenators B and E are detected, respectively. It should be pointed out that amines imparts antioxidant behavior [83,297] and are also part of the cationic liquid anti-stripping additives [300,347,348]. As an anti-stripping agent, it improves the adhesion between aggregate and binder by forming covalent and hydrogen bods [349]. With the aging, asphaltenes and resins portions of binder increases and amines reacts with acids groups and the liberated polar components forms bond with aggregates. Thus with the increase in aging periods the bond strength increases and as a result TSR values increased.



Virgin Mixes



B4



B8

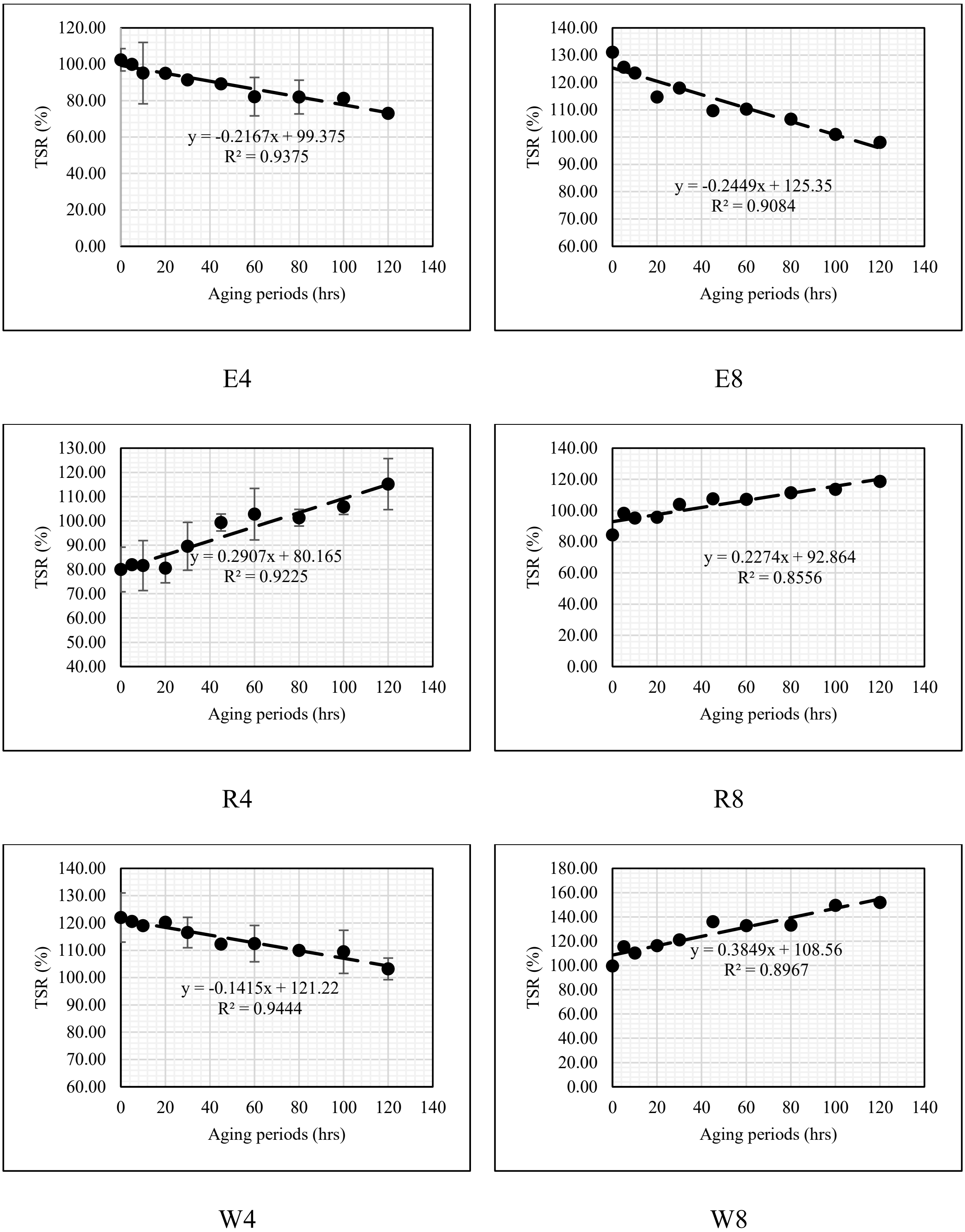
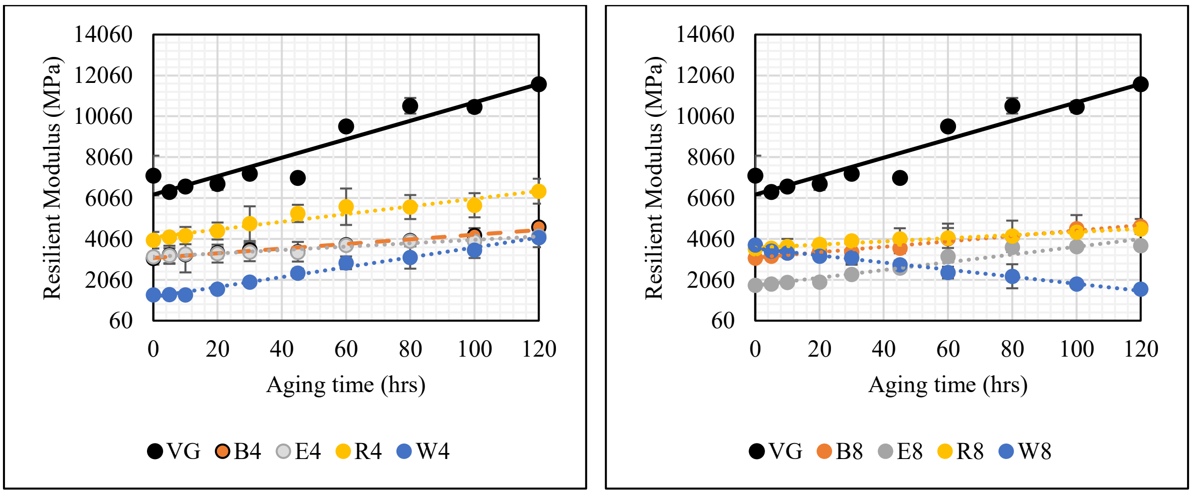


Figure 7-4 Sensitivity of Tensile Strength Ratio to aging time

7.3.4 Resilient Modulus

Resilient modulus (M_R) values and its trend with aging time for virgin mixes and recycled mixes are shown in Figure 7-5. M_R of all mixes (except W8) increased with aging time. Increase in load accompanied with less recoverable deformation are the primary factors. It can be seen that M_R values of recycled mixes are very less than virgin mixes. Compared to virgin mixes, load applied during the test (10% of ITS) is less for recycled mixes and also recoverable deformation for recycled mixes is considerably high.

The rate of change is quite different (low) for recycled mixes compared to virgin mixes (Table 7-4). Similar to CT_{index}, recycled mixes with RAP and rejuvenators are more durable than virgin mixes in terms of resilient modulus. As seen in the case of fatigue performance, a reverse trend of decrease in M_R values with aging time was observed for W8. Again this dominance of rejuvenator and its influence on enhancing recoverable deformation with aging needs to be explored further.



40% RAP 80% RAP

Figure 7-5 Sensitivity of resilient modulus to aging time

Table 7-4 Rate of increment of Resilient Modulus

Rejuvenator	40% RAP	80% RAP	Virgin mix
B	+11.376	+13.244	
E	+8.3121	+18.967	+45.1236
R	+18.843	+7.7757	

W	+24.184	-17.318	

7.4 DISCUSSION

Although RT_{index} values of recycled mixes changed rapidly (with aging time) than virgin mixes, it should be noted that aging only improves rutting performance. But values during early aging periods should be better or comparable with virgin mixes. Considering this, B4, W4, R8 and W8 mixes had low RT_{index} values than virgin mixes and hence measures (such as decreasing binder content or modifying with polymer) should be taken to enhance rutting performance. The aspect of durability is crucial from fatigue performance point of view and all rejuvenators performed better than virgin mixes at almost all aging periods. Therefore, high RAP percentages can be implemented with proper use of rejuvenators. In case of moisture resistance, TSR values of B4 and W4 are lower than virgin mixes and are susceptible to moisture damage with the further increase in the aging (W4 have failed the TSR criteria of 80% at 120 h aging period). Since rejuvenators already contain amine functional groups, increasing the dosage may help in tackling this problem. But this would compromise rutting performance and hence another alternative of using solid anti-stripping agents will be beneficial. All recycled mixes had lower M_R values and even the rate of change is also better than virgin mixes. So in terms of stiffness or recoverable strain, recycled mixes perform superior.

Based on the summation of percentage error at all aging periods (in comparison with virgin mixes), ranking of rejuvenators based on each performance parameter is shown in Table 7-5. Except in case of resilient modulus, ranking of rejuvenators varied with the RAP percentage. Also excluding 40% RAP (RT_{index}), it is perceived that commercial rejuvenators (B and R) performed similarly to virgin mixes. This does not mean that recycled rejuvenators did not perform well. In fact, for recycled rejuvenators CT_{index} and TSR values and rate of change are better than virgin mixes. However, the objective of this study is to analyze the durability of recycled mixes vis-à-vis virgin mixes. Overall, rejuvenator B with 40% RAP (except RT_{index}

and M_R) and R with 80% RAP are better performing rejuvenators based on the durability of recycled mixes.

Table 7-5 Ranking of rejuvenators corresponding to each performance parameter

RT_{index}		CT_{index}		TSR		M_R	
40% RAP	80% RAP	40% RAP	80% RAP	40% RAP	80% RAP	40% RAP	80% RAP
E	*R*	*B*	*R*	*B*	*R*	*R*	*R*
W	*B*	*R*	*W*	*R*	*B*	*B*	*B*
B	*W*	*W*	*B*	*E*	*E*	*E*	*E*
R	*E*	*E*	*E*	*W*	*W*	*W*	*W*

7.5 CONCLUSIONS

The main objective of this study is to assess the durability of the recycled mixes in comparison with virgin mixes. Two high RAP percentages (40% and 80%) and four different rejuvenators, of which two commercial (B and R) and two recycled (W and E) products are considered. Recycled and virgin mixes of dense bituminous macadam (DBM) gradation are fabricated and studied. Cracking resistance (CT_{index}) decreased with aging for both virgin and recycled mixes, except W8, with recycled mixes showing a steeper decline. This was mainly due to reduced AFR and increased peak load, indicating that recycled mixes were less affected by aging compared to virgin mixes. Rutting resistance, measured by RT_{index}, increased with aging as shear load at failure rose. While E4 and R8 behaved similarly to virgin mixes, most recycled mixes showed a higher rate of increase, suggesting that rutting performance of recycled mixes is more sensitive to aging.

Moisture resistance trends varied: virgin mixes and some recycled mixes (B4, E4, W4, E8) showed a linear decrease in TSR with aging due to increased water-affinitive functional groups, whereas others (R4, B8, R8, W8) displayed an increase, likely due to rejuvenator dominance and amine-based antioxidant and anti-stripping effects. Resilient modulus (MR) values were generally lower in recycled mixes than virgin mixes, but most (except W8) increased with aging as higher loads and lower recoverable deformations developed. The slower rate of change in recycled mixes indicated better durability of RAP–rejuvenator blends compared to virgin mixes.

From the durability study, it is evident that rate of change of RT_{index} of recycled mixes is more sensitive to aging compared to other performance parameters. Since, at the same time the CT_{index} values of recycled mixes are better than virgin mixes, it should not be a major concern. In initial aging periods, the RT_{index} values of B4, W4, R8 and W8 mixes are lower than virgin mix and measures should be taken to enhance the values. B4 and W4 are susceptible to moisture damage with the further increase in the aging and using a solid-type antistripping agent may help in tackling this problem. Overall, rejuvenator B with 40% RAP and R with 80% RAP are better performing rejuvenators based on the durability of recycled mixes. In case of W8, the dominance of rejuvenator and its influence on enhancing cracking resistance and recoverable deformations with aging needs to be studied further.