

CHAPTER 4. SUITABILITY OF EXISTING AGING PROTOCOL

4.1 Preface

Hot-mix asphalt (HMA), commonly used in the surface course (upper layer) of flexible pavements, is comprised of bitumen (asphalt) and aggregates (of different sizes). Asphalt is a viscoelastic and thermoplastic material, which implies that the behaviour depends not only on the amount of load but also on the rate of load and temperature. Another important factor that influences the asphalt properties is age. During the construction process, aggregates and bitumen are heated and mixed at a specific temperature (depending on the grade of bitumen) in a hot mix plant, transported to the construction area, spread and laid. A particular change in the properties (termed short-term aging) occurs in bitumen from heating to laying. Aging which happens during the in-service condition of the pavement is denoted as the long-term aging. Various mechanisms through which aging occurs in bitumen are - evaporation of volatile fractions, oxidation, syneresis, time-dependent thixotropy property, photo-oxidation in case of the surface layers, dissociation, isomerization, fragmentation, polymerization etc. [70,79,83,88,89]. The extent of aging is affected by the climatic conditions it is exposed to and volumetric properties of the mixes [92]. Aging leads to increase in stiffness and reduction in flexibility of the asphalt mix [72,252,253].

Field aging of asphalt mixture can be simulated in the laboratory using a forced draft oven. Loose asphalt mixtures are first kept in oven at compaction temperature for 4 hours to simulate short-term aging. After compaction, the sample is conditioned at 85°C for 120 hours. This protocol or procedure is envisioned to simulate 7 to 10 years (approximately) of field aging of HMA [254–256]. In the field, aging takes place due to multiple factors, and it causes the properties to vary continuously with time. At any certain point of time (over its service life), the extent to which aging takes place dictates the behaviour (performance). So, the general

CHAPTER 4

practice of assessing the performance at a particular aging level would not provide the complete idea about the performance variation with time in the field. Hence the rate at which the performance changes with time would be a better approach to understand the effect of aging on performance. Approach would not only be able to mimic the field performance evolution but also helps identify the aging sensitive parameter of the mix considered.

Few studies have tried to study the performance at different aging levels, as shown in Table 4-1. Either limited parameters at multiple aging levels or different performance parameters at limited aging periods were evaluated in previous studies. A study on the in-detail performance of HMA at diverse aging times, considering different or uniform aging rates, is not available in the literature. This forms the motivation of the present objective. The present chapter is mainly focused on assessing the effect of aging (different times and rates) on the performance of HMA and thereby study whether the AASHTO R 30 aging protocol is sensitive to aging or not. It should be noted that aging levels used in this study are not correlated with field aging and do not represent a specific age (in field). Rather, the present long-term aging protocol (5 days at 85°C) of AASHTO R 30 is used, and the variation in performance with increase in aging time is studied. This approach is further used in the last objective to assess the durability of rejuvenators in comparison with virgin mixes. In addition, having correlation of field aging with laboratory aging would even help in scheduling the maintenance activity of asphalt layer of flexible pavement. Thus the suitability of the aging protocol is evaluated based on the sensitivity of performance of virgin mixes to aging periods.

Table 4-1 Performance of mixes at different aging periods

Reference	Aging levels	Performance studied	Inferences
Baek et al (2012)	Short-term aging (STA) at 135°C for 4 hr Long-term aging (LTA) at 85°C for 2, 4 and 8 days	Linear viscosity elastic response and damage characteristics of mixes	Fatigue failure is a function of temperature and aging level
Sarsam and Adbulmajeed (2023)	STA at 135°C for 4 and 8 hrs LTA at 85°C for 2 and 5 days	Marshall stability, indirect tensile strength, resilient modulus and permanent deformation	<ul style="list-style-type: none"> • Marshall stability, indirect tensile strength, resilient modulus and rutting resistance increased • 8 hr STA and 2 days LTA had same effect
Gao et al. (2017)	At 163°C for 2, 4, 6, 8, 16 and 24 hrs	Elastic modulus at different aging periods and fatigue loads	<ul style="list-style-type: none"> • Aging had more impact than fatigue loading on elastic modulus • Modulus increased with aging time
Sirin et al. (2019)	STA at 125°C, 135°C, and	Dynamic modulus	Parameters of prony series were only affected by short-

	145°C for 2, 4, 6 and 8 hrs LTA at 75°C, 85°C and 95°C for 0, 2, 4, 6, 8 and 10 days		term aging time and temperature
Sahebzamani et al. (2020)	Aging loose mix at 95°C for 3 and 7 days	Dynamic modulus and thermal cracking tests (semi-circular bending and indirect tensile strength)	<ul style="list-style-type: none"> Elastic modulus increased, relaxing potential and fracture energy reduced with aging More the binder content, the lesser will be increase in stiffness

4.2 Aging of asphalt mixes

Initially, aggregates and asphalt binder are heated in the oven at mixing temperature (158°C) for 2 hours. After heating, aggregates and asphalt binder are mixed and spread uniformly to a thin layer (thickness not more than the maximum aggregate size) in a pan. The mixture is then placed in the oven at compaction temperature (150°C) for 4 hours to simulate short-term aging, which accounts for the binder aging and absorption (by aggregates). Following the short term aging, samples are compacted by giving 75 blows on either side for 4% air voids (34 blows in case of 7% air voids) at optimum binder content. Compacted samples are placed in the oven at 85°C for the long-term aging of asphalt mixes for 120 hours (5 days). Variation in the performance of asphalt mixes with time is evaluated by dividing the aging time into different intervals, as shown in the Table 4-2. It is assumed that in the initial stage of aging (long-term

CHAPTER 4

here), the properties of asphalt mix change rapidly and then gradually at later stages. Different aging times and increments are chosen based on the above assumption. A minimum of two equal increments are selected to capture the deviation in the trend of asphalt mixture performance for a similar aging rate.

It should be noted that previous studies have identified a few drawbacks of the AASHTO R30 aging protocol: inability to mimic long-term field aging, imparting oxidation gradient (both in radial and vertical directions) in the samples, change in the sample geometry (due to self – weight) etc. [262–264]. Although the AASHTO R 30 long-term oven aging protocol does not produce uniform aging across all climates, but under certain environmental conditions, the oxidative hardening produced by this procedure can approximate the degree of binder aging typically observed in the surface layer of pavements after about 7–10 years of field service. It is important to note, however, that this equivalence is an empirical correlation, highly dependent on climate, solar radiation, and pavement conditions. Also as specified earlier, aging levels used in this study are not intended to correlate with a specific field age. But instead to assess the variation in the performance with the increase in aging periods. Only samples without any distortion and air voids within the targeted range were considered. As the current research is a comparative study, all the samples are expected to have similar oxidation gradients. Also, considering the simplicity of the procedure, aging the compacted samples in the oven at 85°C was adopted in this study.

Table 4-2 Aging periods implemented in the present study

<i>Aging time (h)</i>	0	5	10	20	30	45	60	80	100	120
<i>Increment (h)</i>		← 5	← 5	← 10	← 10	← 15	← 15	← 20	← 20	← 20

4.3 Tests

The Marshall stability test, rutting resistance (dynamic creep compression test), fatigue resistance (IDEAL-CT test), moisture resistance (indirect tensile strength test), and resilient modulus test were conducted as per Sections 3.8.1.2, 3.8.1.3.1, 3.8.1.4, 3.8.1.5, and 3.8.1.6, respectively.

4.4 Results

4.4.1 Marshall stability

Variation in the values of MS with the aging time is shown in Figure 4-1. Neither values change considerably nor specific trend was observed with the aging time. This unanticipated result can be either due to the incapability of the current aging procedure (or protocol) to impart any change in the binder or the insensitivity of MS values to the aging level of the asphalt mix. From the performance of the mixes (discussed in the next sections) it is noticeable that aging protocol does bring changes in the binder stiffness. Thus, it can be stated that MS cannot signify or take account of the material property variation accompanied by different environmental conditions (aging levels and the resultant stiff binder here).

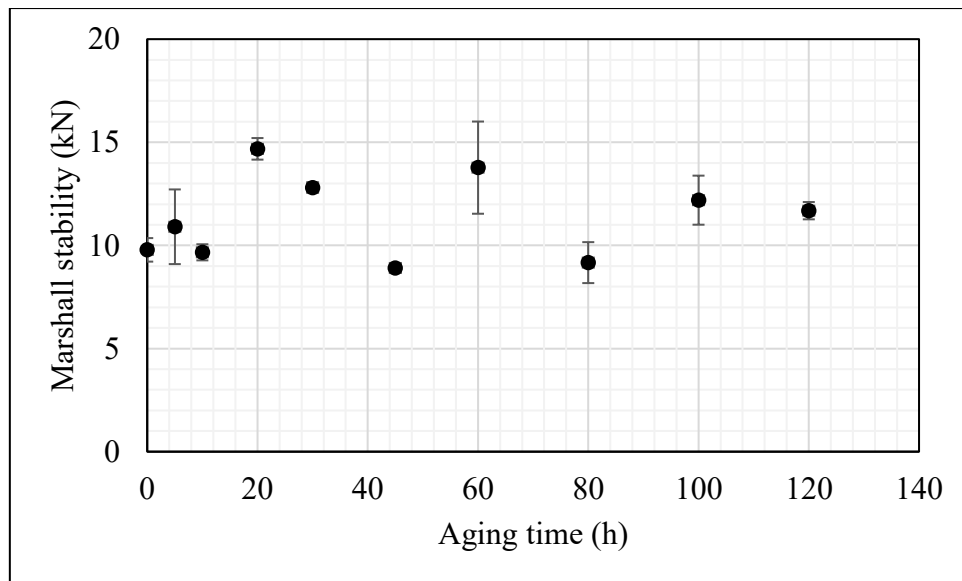


Figure 4-1 Variation in Marshall Stability with aging

4.4.2 Rutting resistance

Figure 4-2 shows the sensitivity of the permanent strain values to the aging time. Unlike MS, permanent strain decreased linearly with the aging time, which can be attributed to the increased binder stiffness. Till 30 h of aging, strain values did not change much (considering standard deviation), instead resulted in slightly higher strain at 5 and 10 h. Keeping the compacted samples in the oven at 85°C for 30 h does not change the rutting performance. The effect of aging (on binder stiffness) was mainly observed from 45 h and further, as can be seen from Table 4-3 and Figure 4-2. The decrease in permanent strain values indicates that with the increase in aging time, mixes tend to have high recoverable and less irrecoverable strains.

The percentage decrease in strain values with the increase in aging time is shown in Table 4-3. It was observed that variation (% decrease) in the strain value is approximately the same for a particular rate of aging. 21% (approximately) decrease for 15 h aging time gap (30 to 45 h and 45 to 60 h) and almost 31% reduction for 20 h increment (60 to 80 h and 80 to 100 h). The longer the aging time gap, more is the percent change in the permanent strain value. However, a further increase in the aging time (to 120 h) did not impart much variation in the strain value. Most of the impact of long-term aging on the binder stiffness took place in the time zone of 45 hr to 100 h. Therefore, the present protocol of 120 h aging is sufficient to bring appreciable change in the mix, considering rutting performance.

Table 4-3 Percentage variation in strain values with corresponding increase in aging periods

Aging time (h)	% Change
45	-20.12 (compared with 30 h)
60	-22.56 (compared with 45 h)
80	-31.13 (compared with 60 h)
100	-29.53 (compared with 100 h)

120	-6.79 (compared with 120 h)
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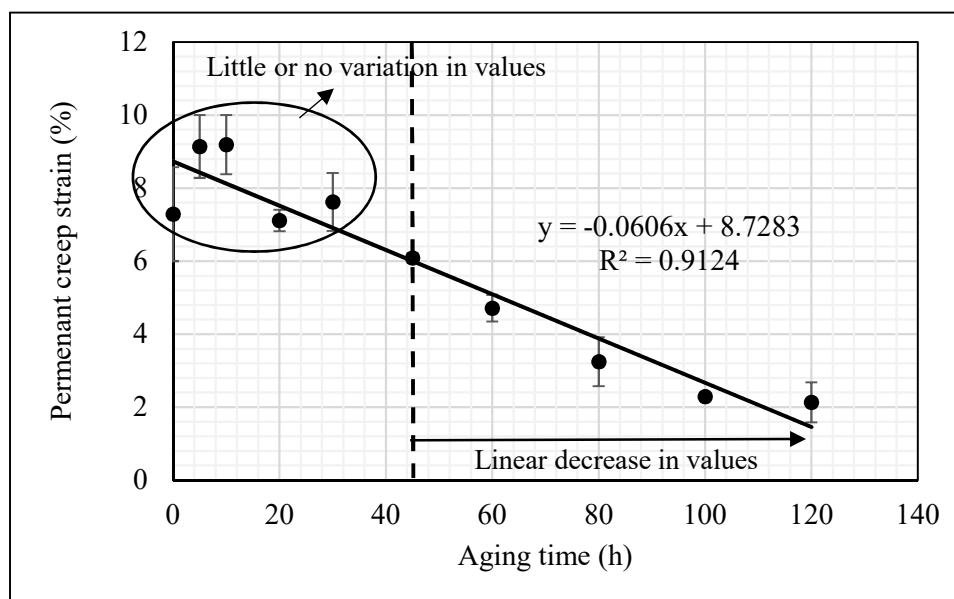


Figure 4-2 Permanent strain variation with aging periods

4.4.3 Fatigue resistance

The sensitivity of CT_{index} and AFR along with Peak load with time are shown in Figure 4-3 and Figure 4-4, respectively. From AFR values, it can be said that the flexibility of the mix decreased with time. The decrease in flexibility of the mix is due to an increase in binder stiffness, as can be observed from peak load values (Figure 4-4). Thus, the reduction in the CT_{index} values can be attributed to the changes in the binder stiffness due to aging. Like permanent strain values, aging effect on CT_{index} was also mainly detected from 45 h. However, the effect of the rate of aging, i.e. change in CT_{index} value for the same increment in aging time, is not constant (Table 4-4) as seen in the case of permanent strain values. Instead, the percentage change (decrease) continuously increases with age, till 80 h. Even the change is appreciable at 100 h, but further increment did not result in any variation (considering standard deviation). Although overall trend appears linear, some deviations are observed in the early aging data (specifically 5 and 30 h aging periods). Therefore, based on the CT_{index} , it can be

stated that most aging happened from 45 to 100 h aging period. The present aging protocol is also sufficient to bring appreciable change in the mix in terms of cracking resistance also.

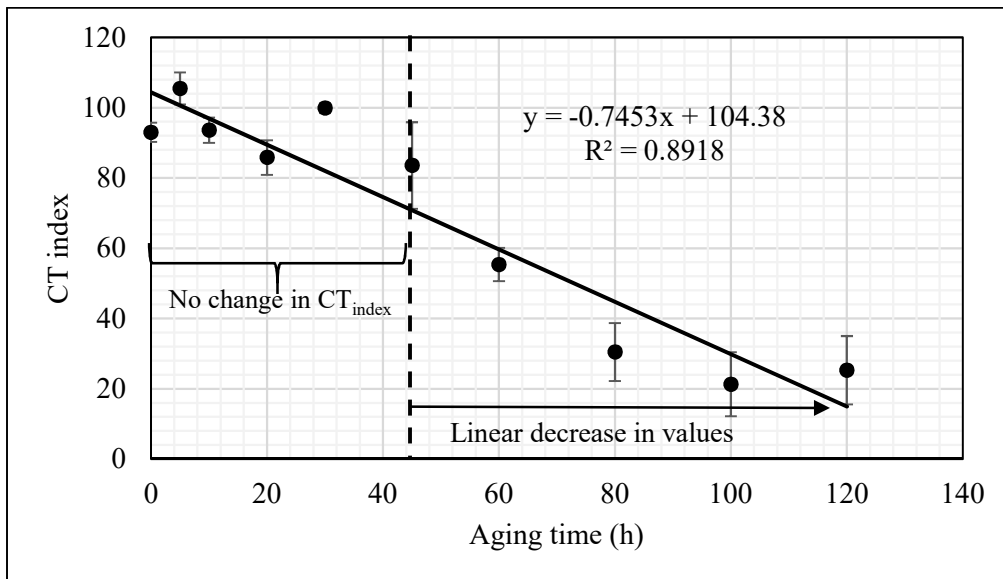


Figure 4-3 Cracking Tolerance index variation with time

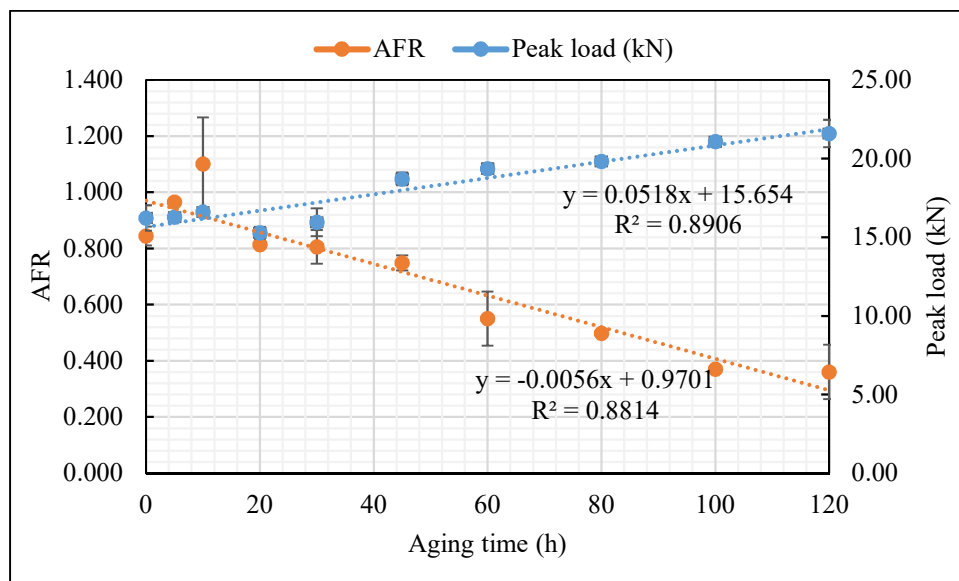


Figure 4-4 AFR and Peak load variation with time

Table 4-4 Percentage variation in cracking tolerance index values with corresponding increase in aging periods

Aging time (hrs)	% Change
45	-16.36 (compared with 30 h)
60	-33.76 (compared with 45 h)
80	-45.01 (compared with 60 h)
100	-30.08 (compared with 100 h)
120	+18.82 (compared with 120 h)

4.4.4 Moisture resistance

Compared to rutting and cracking performance, the sensitivity of moisture resistance to aging time is not considerable (Figure 4-5). Nevertheless, TSR values decreased linearly with aging time. Since mix design and aggregate type are constant in this study, the reduction in TSR values can be attributed to the variation in binder properties [265,266]. This can be explained by the concept of chemical disbonding and displacement [267]. In this regard, chemical compound change is one of the main aspects that occur in binders due to aging. It is well established that oxygen-containing functional groups (carbonyls and sulfoxides) increase in the asphalt binder due to aging [268]. These compounds (mainly carboxylic acids and anhydrides) get strongly absorbed by the aggregate and also have a high affinity to water (through hydrogen bonding) [269,270]. Therefore, with the increase in the aging time, the amount of the carbonyl compounds increased in the binder and are absorbed on the aggregate surface. When these mixes are conditioned in water, absorbed compounds got displaced by water and resulted in lower TSR values. Another reason for the reduction in TSR values could be the weakening of the binder or, more precisely, the mastic phase. However, this is highly unlikely since the stiffness of the binder only increases with the aging time, and failure in the mastic film is unlikely.

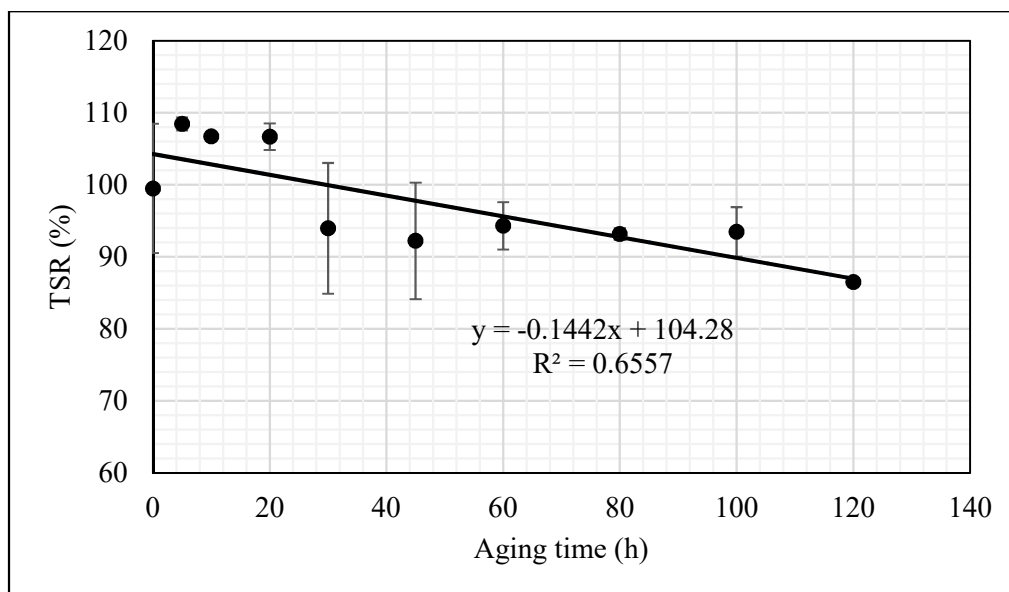


Figure 4-5 TSR variation with time

4.4.5 Resilient modulus

Resilient modulus is measured at two different positions (0° and 90°) on the same sample and is the average of two measured values (for a sample). Excellent repeatability was observed at the two positions and between the samples (maximum coefficient of variation being 13.59). Like rutting and fatigue resistance, the resilient modulus is also sensitive to time and increases with aging time, as shown in Figure 4-6. The load applied (10% of tensile strength) during the testing increased as tensile strength increased with the aging time. Also recoverable (vertical) strain decreased with the aging time as shown in Figure 4-7. Thus higher tensile loads resulted in lower (recoverable) strains and the combined effect led to greater resilient modulus values. This effect of aging was reflected in the resilient modulus values from the aging time of 60 h and above. Almost 35% increase in the value was observed with the increase in aging time from 45 to 60 h. Only a 10% (approximately) increase was observed at 80 and 120 h.

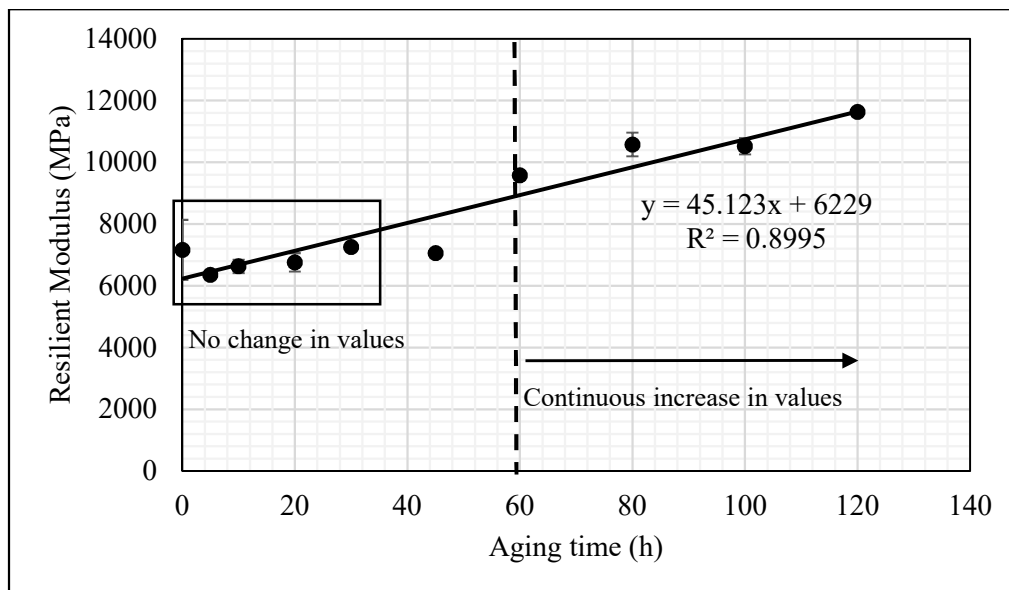


Figure 4-6 Resilient Modulus variation with time

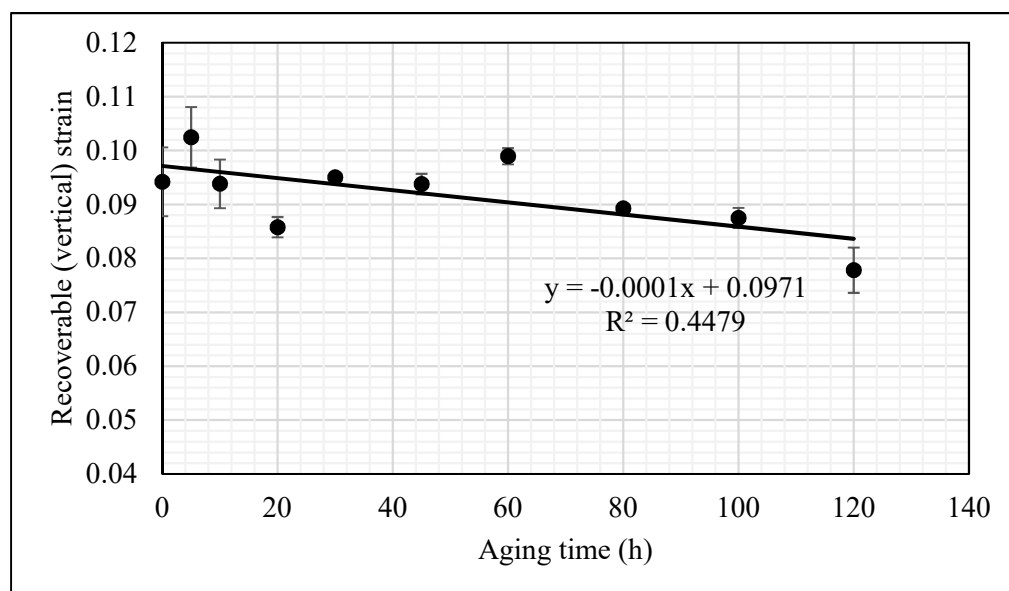


Figure 4-7 Recoverable strain variation with time

4.5 Discussion

Although results showed that aging periods influence the performance of asphalt mixes, statistical analysis was also conducted to verify whether the effect is significant or not. The results of one-way Analysis of Variance (ANOVA), performed using Minitab software, are presented in Table 4-5. A variable can influence the measured parameter when the p-value is less than 0.05 (for a 95% confidence interval). The statistical analysis concluded that aging

CHAPTER 4

time significantly affected the rutting resistance, fatigue resistance and resilient modulus. Moisture resistance is not as sensitive as other performance parameters to aging time.

Table 4-5 One-way ANOVA results

Parameter	Source of variation	SS	df	MS	F _{calculated}	P-value
Permanent strain	Aging time	126.811	9	14.09	15.07	0
CT _{index}		19634.3		2181.59	22.39	0
Mr		67803894		7533766	27.92	0
TSR		999		111	2.17	0.122

Additionally, to estimate which performance type had a greater impact, Aging Index (AI) was considered. AI is the ratio of the property (value) after aging to the value before aging. It should be highlighted that resilient modulus increased with aging, but permanent strain and CT_{index} values decreased after aging. So, to compare all parameters, AI for permanent strain and CT_{index} are the inverse of the definition mentioned earlier. AI's are calculated from the aging time 45 h and above (see Table 4-6), since this is the time zone where aging most affects performance. AI's at all aging times were evaluated by comparing with the value at 0 aging time. CT_{index} was the most affected parameter, followed by permanent strain and resilient modulus. Therefore, the effect of aging (time and rate) varies depending on the performance type considered.

For the asphalt binder and gradation used in this study, fatigue and rutting performance are affected (by aging) the most, followed by resilient modulus. Since aging benefits rutting (permanent strain values decreased with aging time), the main focus should be on improving the fatigue properties and resilient modulus. Correlating the laboratory aging times with field aging will help schedule the pavement maintenance. Also, we would have the idea of specific distress to be tackled beforehand.

Table 4-6 Aging index at different aging times

Aging time (h)	Permanent strain	CT_{index}	Mr
45	1.197	1.113	0.985
60	1.546	1.680	1.337
80	2.245	3.055	1.477
100	3.185	4.370	1.469
120	3.417	3.677	1.624

4.6 Conclusions

The effect of aging times and different aging rates on the performance of asphalt mixes are evaluated in this study. Various tests such as Marshall stability, dynamic creep, IDEAL-CT, resilient modulus and indirect tensile strength tests are conducted. Based on the different tests, the following conclusions can be drawn: With increasing aging periods, the asphalt mixes exhibited notable changes in performance. Marshall stability, being empirical, showed minimal variation and could not capture the material property changes due to aging. In contrast, rutting resistance improved as permanent strain decreased with stiffer binders, while IDEAL-CT results indicated reduced flexibility and fatigue resistance alongside increased stiffness. Moisture resistance (TSR) was less sensitive to aging but still decreased due to oxygenated compounds with higher water affinity. Finally, both resilient modulus and tensile strength increased significantly with aging, as stiffer binders contributed to lower recoverable strains and higher stiffness in the mixes.

The present study's findings highlight that aging affects the performance of the mixes in the time zone of 45 to 100 h. From the statistical analysis and aging index, CT_{index} was the most affected parameter, followed by the permanent strain and resilient modulus. The present AASHTO R30 aging protocol proved adequate for changing the performance of asphalt mixes. The effect of aging (time and rate) varies depending on the performance type considered. Thus

CHAPTER 4

AASHTO R 30 aging protocol are further used to assess the durability of rejuvenators selected in this study. Although, 45 to 100 h is the aging zone where performance of virgin mixes varied mostly, all aging periods are considered for recycled mixes. This is to assess whether similar effect of aging will be observed in the recycled mixes with different rejuvenators and RAP contents.