



Performance Evaluation of Fatigue and Fracture Resistance of WMA Containing High Percentages of RAP

Saad Tayyab ^{1*}, Arshad Hussain ¹, Fazal Haq ², Afaq Khattak ³

¹ School of Civil and Environmental Engineering (SCEE), National University of Sciences and Technology (NUST) Islamabad, Pakistan.

² National Institute of Transportation (NIT), Military College of Engineering NUST Risalpur, Pakistan.

³ Department of Civil Engineering, International Islamic University Islamabad (IIUI), Pakistan.

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Abstract

Sustainability and durability are the key requirements of pavement structure. Sustainability of asphalt pavement structure involves utilization of Warm Mix Asphalt (WMA) technologies with the addition of Reclaimed Asphalt Pavement (RAP), where durability of asphalt involves performance parameters like fatigue and fracture resistance properties etc. Utilizing the RAP content in asphalt mix increases the mixing and compaction temperature which may degrade the performance of asphalt. Hence, numerous studies have recommended different WMA technologies to decrease mixing and compaction temperature of asphalt mix containing RAP. The present research work evaluates the fatigue and fracture performance of WMA and Hot Mix Asphalt (HMA) with varying percentages of RAP and Sasobit. Different mixes of WMA and HMA were designed with varying percentages of RAP (0, 20, 40 and 60%) through Marshall Mix design. Sasobit (organic/wax-based additive) was used as WMA technology to prepare WMA at varying percentages (0, 2, 4 and 6%). The fatigue behavior of asphalt was evaluated using four-point bending test, where fracture resistance of asphalt was determined using Semi Circular Bending (SCB) test in the laboratory. Fatigue and fracture resistance of WMA were improved with the increase in percentages of Sasobit and RAP content, while the addition of RAP in HMA showed a decreasing trend of fatigue and fracture resistance due to the stiffer nature of RAP. Furthermore, WMA was identified as economical for construction besides other benefits like improved properties and environment friendly asphalt mix.

Keywords: Warm Mix Asphalt (WMA); Hot Mix Asphalt (HMA); Fracture Resistance; Fatigue Cracking; Reclaimed Asphalt Pavement (RAP); Sasobit.

1. Introduction

Production asphalt mixes with WMA technologies and RAP materials are emerging technologies and gaining popularity to deal with the concern related to energy consumption and global warming throughout the world. WMA technologies permit 10-30 °C lower mixing and compacting temperatures than conventional HMA. The conventional HMA are compacted at 145-150 °C and mixed at 150-155 °C [1]. The reduction in mixing and compacting temperature during mix production will in turn lead to less fuel costs in production and laying of asphalt mix. In addition to cost saving, less fuel consumption leads to lower greenhouse gases and fumes emission during mix preparation by asphalt plant and makes it more eco-friendly [2]. World Bank estimates the sustainability of WMA and emphasized that each

* Corresponding author: saadtayyab@nit.nust.edu.pk

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10°C reduction in production temperature of asphalt mix decreases CO₂ emission by 1 kg and fuel consumption by 1 liter per ton [3]. Other WMA advantages include longer hauling distances, reduction in compaction effort, reduction in mix preparation temperature and aging, quicker turnover to traffic, reduction in greenhouse gases emission and improved working environment due to the absence of toxic gases. On the other hand, WMA has its own disadvantages such as bonding and coating problems, lack of its long-term performance data and greater vulnerability to moisture due to lower compaction temperature [4].

WMA technologies can be classified broadly as; foaming process (addition of water), organic additives (addition of organic additives or wax) and chemical additives (addition of chemical additives). These additives are used in asphalt mixes to improve the workability at low temperature [5]. In this study, Sasobit as an organic additive was used to produce WMA. The chemical formula of Sasobit is C_nH_{2n+2} and registered as number 8002-74-2 by Chemical Abstract Service. It is the product of Sasol Wax in South Africa. It is a long chain of about 40-115 carbon atoms of aliphatic hydrocarbons and produced by the process of coal gasification. It can be used directly on the mix of aggregate as a melted liquid with the help of dosing meter or solid prills (small pellets) [6].

Researchers are putting their efforts to have durable and sustainable pavement structure by maximizing the use of RAP. RAP is produced from asphaltic pavement structure which may deem unfit for further vehicular carrying load or has distressed beyond a certain level or has consumed its design lifetime. Nowadays where every construction industry desires for sustainable and durable approach, using RAP in asphalt mix is a step forward in this direction. Utilization of RAP in the preparation of fresh asphaltic mix as a partial replacement helps in different ways: (a) reduces overall materials (asphalt and aggregate) cost, (b) conserves fresh asphalt and aggregates, (c) environmental-friendly and energy saving, and (d) helps to resolve solid waste disposal problem [7]. Though, the utilization of high percentages of RAP in mix can raise the issue that belongs to cracking and fatigue of pavements in design life due to the presence of stiff and aged binder that produces stiffening effect in the pavement [8] and leads to compatibility problem. Due to the non-availability of proper documented information on the use of high percentages of high RAP content in mix for long term performance [9] which is mostly defined as 25% or higher percentage of RAP [10], while the maximum RAP contents permitted in HMA is commonly below 30% for wearing courses and may vary for base courses and binder [11]. Even though the practical utilization of high percentages of RAP content is limited and a lot of researches conducted by many practitioners and researchers to adopt ways to utilize high percentages of RAP content in the asphalt mix as possible for its economic and environmental benefits. A research study was conducted on HMA containing 30% RAP contents to determine the fatigue characteristics by using different testing methods and concluded that high percentages of RAP content may lead to shorter fatigue life of pavement based on beam fatigue and Superpave indirect tensile test [12]. According to a review conducted by Sharma et al. on the use of reclaimed material in WMA mixes. Based on the review it was concluded that 20% RAP content enhance the mechanical properties of WMA and considered as optimal percentage while higher percentages of RAP content up to 70% can be used for satisfactory performance in WMA [13]. Another research study on HMA with 40% of RAP contents determined that fracture resistance of asphalt mix was reduced when the RAP percentage was increased [14]. Thus, the outcomes of these research works highlighted that it remains to be seen if HMA mixes with high percentages of RAP would result in more severe fracture resistance and fatigue cracking as compared to virgin HMA.

The utilization of RAP contents can be increased with the addition of WMA. Some research studies determined that the combined effect of high percentages of RAP and WMA additives in a mix can improve moisture damage and rutting potential [15, 16]. Considering the aspect of sustainability that is associated with the utilization of high percentages of RAP contents and decrease in energy requirement that is associated with the addition of WMA additives, numerous researches have conducted in recent years to interpret the combined effect of WMA and high percentages of RAP contents. Fatigue resistance of HMA containing RAP and rejuvenating agent have been studied by Sharma et al. in their review article and determined that higher percentages of RAP make the pavement weaker in fatigue resistance. Further they investigated that higher percentages of RAP causes uncertainty in the mix. The uncertainty depends upon type and dosage of rejuvenating agent, method of intrusion of RAP material in plant production units and viscosity of aged binder [17]. Tao et al. and Mogawer et al. studied the combined effect of high RAP contents and different types of WMA additives on the workability of asphalt mix and concluded that WMA technologies lower the mixing and compaction temperature and improve workability of mix containing RAP [18, 19]. Albayati and Turkey determined the effect of using sustainability materials on the performance of asphalt mixture using Zeolite as WMA additive and different percentages (10, 30 and 50%) of RAP. The outcome of the results showed that WMA additive improved the fatigue resistance of asphalt by 29% as compare to HMA control specimen. However, the addition of RAP to WMA decreases the fatigue resistance of asphalt by 44, 74 and 89% for 10, 30 and 50% of RAP respectively [20]. A research study was conducted by Xiao et al. to determine the performance of RAP in HMA. They have concluded that increasing the percentage of RAP enhances the rutting potential, although the fatigue behavior of asphaltic pavement improves by adding RAP up to some limit but then decreases by further addition of RAP in HMA [21]. Another study by McDaniel et al. observed that in fact utilizing high RAP contents beyond certain limit increases the aged asphalt binder in mix that leads to a poor flexible pavement structure in terms of fracture and

fatigue cracking of asphaltic pavement during their design life [8]. In addition, D'Angelo et al. proposed that RAP contents in asphalt mix should be used under 25% of the total mix by weight [22] while Shu et al. proposed different percentages of RAP from 10 to 50% for moisture resistance based on WMA additives [2]. Zhao conducted a research to evaluate the high RAP contents in combination of WMA technologies and concluded that rutting resistance improve by increasing RAP from 15 to 40% for WMA mix regardless of the structure layer and WMA technologies [23]. However, the addition of RAP increases the fatigue resistance of WMA up to certain limit while decreases the fatigue resistance with the addition of RAP in HMA.

Cracking is very common at low temperature in asphaltic pavement due to their brittle nature at low temperature [24]. Fakhri et al. evaluated the combined effect of WMA and RAP on fracture resistance at 25°C and their results disclosed that the addition of high percentages of RAP decreases the fracture resistance of both HMA and WMA [25]. In the study of Saleh et al. it was determined that the addition of 25% of RAP to WMA showed higher or similar fracture resistance than the control HMA [26]. However, the addition of 50% of RAP to WMA showed less fracture resistance than the control HMA. Guo et al. and Yousefi et al. concluded that WMA helps to utilize high RAP contents in asphalt mix. However, the addition of very high percentages of RAP made asphalt mix brittle and reduced the potential of fracture resistance and fatigue resistance [27, 28]. Kavussi and Motevalizadeh conducted a research study on WMA prepared with water-based foam additive with the addition of RAP to determine the fracture resistance through cracking resistance index, fracture energy and flexibility index of asphalt using SCB test approach. They concluded that the addition of RAP up to 50% improves the fracture resistance while excessive RAP contents beyond 50% adversely affect the fracture resistance of foam-based WMA [29].

The fatigue behavior of asphalt pavement is determined by flexural beam fatigue test at intermediate asphalt pavement operating temperature and is known as four-point bending fatigue test. Four-point bending test simulates the fatigue cracking behavior of asphalt mix under repeated vehicular loading in the field [30]. A new concept to evaluate the fatigue life of asphaltic pavement by energy dissipation was proposed by Shen et al. and Carpenter et al. [31, 32]. This concept is based on the ratio of change in dissipated energy of two consecutive loading cycles divided by the dissipated energy of first cycle and is known as Ratio of Dissipated Energy Change (RDEC) while Plateau Value (PV) is the almost constant value of RDEC which defines a period of time where a constant percentage of input energy dissipated due to damage accumulation in the sample [33]. The damage in the sample can be determined by micro crack evaluation study due to applied loads. Ultimately the micro cracks accumulate and form a macro crack which leads to the failure of the sample and can be easily determined by RDEC plots.

Fracture cracking is the integral part of cracking mechanism to asphaltic pavement in low and intermediate temperature. Hence, important properties like fracture behavior of asphalt pavement must be incorporated to ensure long term performance of pavement [34]. The single edge notch beam approach is one of the conventional methods for evaluating the fracture behavior of asphalt [35]. However, many complexities are related with this approach such as, (a) not applicable to field core due to its circular disk shape [36], (b) complexity in preparing samples for testing, (c) crack formation in deep notched beams due to self-weight [37], (d) calculation error due to sagging of beam under self-weight [38]. Due to the limitations of notch beam approach, recently developed SCB approach has got much attention of the researchers for determining the fracture behavior of asphalt [39, 40]. The advantages of recently developed SCB approach as compared to single edge notch beam approach are: (a) repeatability in testing results, (b) effectiveness and ease in sample preparation, and (c) suitability for field core samples [41]. In SCB test, strain energy release rate (J-integral) is determined, which is the indication of tougher material to resist the cracks and their propagation. A higher J-integral value represents greater fracture resistant asphalt mix [42]. Flowchart of research methodology is shown in Figure 1.

2. Materials and Methods

In the current situation, the world is filled with too many problems like global warming, economic recession, and the high urban growth rate, the last of which leads in the development of transportation infrastructure including asphalt pavement. To lessen the harmful effects the above-mentioned issues, this research work is a step forward in improving recycling technologies and energy efficiency. The main objective of this research work is to evaluate the behavior of WMA mixtures with variable percentages of WMA additive and high percentages of RAP to minimize the adverse impact on the environment. Fatigue cracking behavior and fracture resistance of asphalt pavement were the two key concerns covered in this research. Hence, sixteen different types of mixtures were prepared including one control mix and the remaining fifteen were modified with varying percentages of WMA additive and RAP as presented in Table 1.

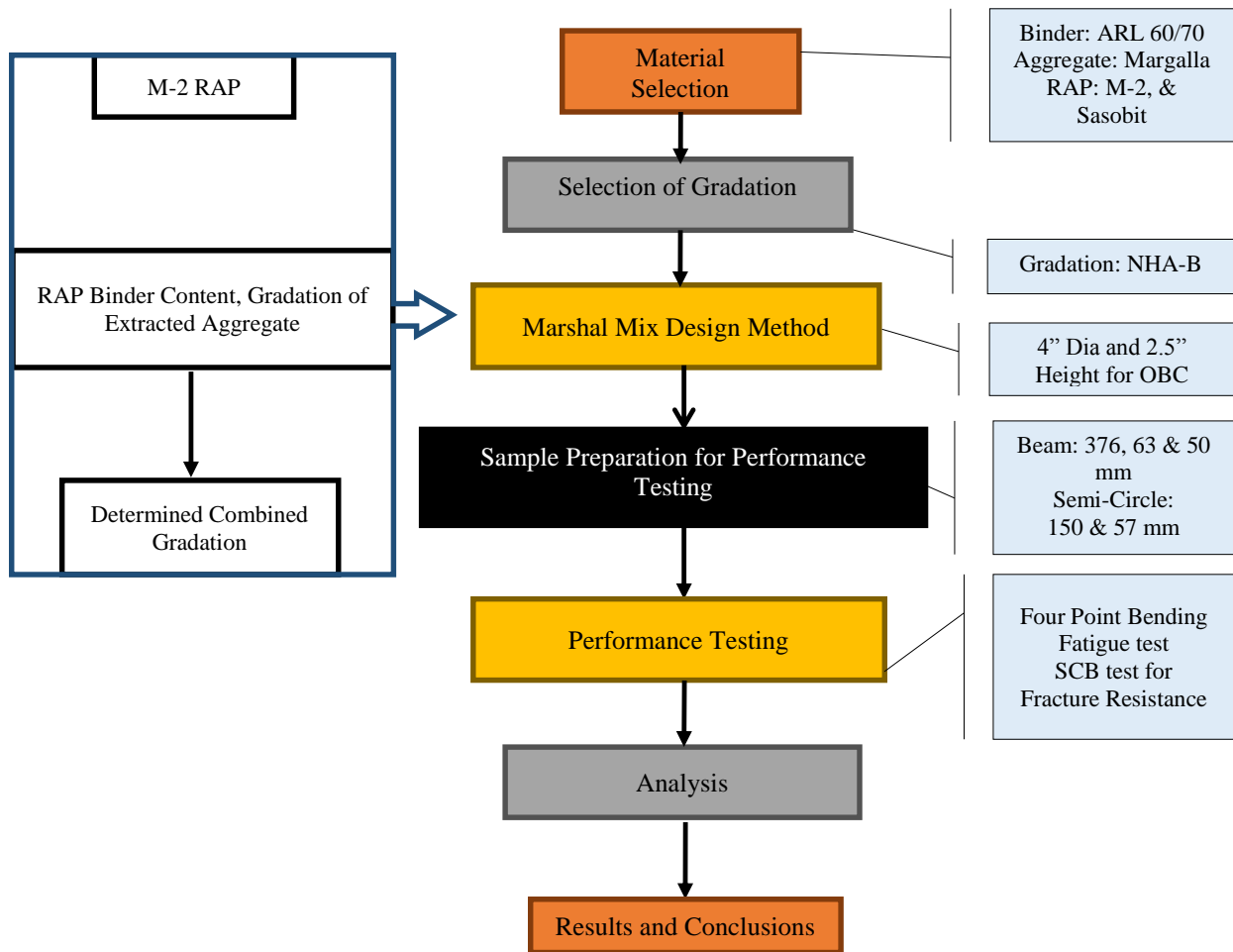


Figure 1. Research Methodology Flowchart

Table 1. Performance testing matrix

S.no.	Percentage of RAP replaced	Sasobit content (% of bitumen)	Number of Samples for Fatigue Testing	Number of Samples for Fracture Resistance
1	0	0	3	3
		2	3	3
		4	3	3
		6	3	3
2	20	0	3	3
		2	3	3
		4	3	3
3	40	0	3	3
		2	3	3
		4	3	3
4	60	0	3	3
		2	3	3
		4	3	3
		6	3	3
Total			48	48

2.1. Asphalt Binder

The current research work utilized 60/70 penetration grade virgin bitumen, which was supplied by Attock Refinery Limited (ARL) Rawalpindi, Pakistan. The reason for selecting 60/70 penetration grade bitumen is that it is appropriate for colder to moderate range of temperature and typically used in Pakistan. The basic properties of the above-mentioned asphalt binder are listed out in Table 2.

Table 2. Laboratory tests performed on virgin bitumen

S No.	Test Description	Specification	Results
1	Penetration Test @ 25 (°C)	AASHTO T 94-03	62
2	Flash Point (°C)	AASHTO T 48-89	261
3	Fire Point (°C)	AASHTO T 48-89	282
4	Specific gravity	AASHTO T 228	1.03
5	Softening Point (°C)	AASHTO T 53	48
6	Viscosity Test (Pa.sec)	AASHTO T 316	0.271
7	Ductility Test (cm)	AASHTO T 51	>100

2.2. WMA Additive

Sasobit an organic or wax based WMA additive was used in this study imported from Sasol chemicals, a division of Sasol South Africa (Pty) Ltd to lower the mixing and compaction temperature. Sasobit was selected as 2%, 4% and 6% by weight of binder, while the dosage recommended by the manufacturer varies from 0.8% to 3%. The technical specifications of Sasobit as per manufacturer data sheet are listed out in Table 3.

Table 3. Basic properties of Sasobit

Properties	Test Method	Units	Specification	Typical Values
Congealing Point	ASTM D 938	°C	100 - 110	101
Penetration at 25 °C	ASTM D 1321	0.1 mm	0 - 2	<1
Penetration at 65 °C	ASTM D 1321	0.1 mm	0 - 13	11
Brookfield Viscosity at 135 °C	Sasol 1010	cP	10 - 15	12
Visual Colour Compliance	Visual	-	Pass / Fail	Pass

2.3. RAP Material

RAP material was collected from Islamabad-Lahore Motorway (M-2) and brought to National Institute of Transportation (NIT), NUST laboratory for replacing natural aggregates and preparation of samples for Marshall Mix, fatigue and fracture resistance. RAP material was characterized by quality of aggregates, gradation of aggregate and asphalt content of RAP. Aged asphalt content of RAP was determined by Ignition method and was found to be 3% by weight of the total RAP. The physical properties of RAP are presented in Table-4 and gradation is presented in Figure 1.

2.4. Virgin Aggregates

Virgin aggregates of different sizes were collected from Margalla Hills Taxila Pakistan. These aggregates were characterized in the laboratory as per standards to check the suitability of aggregates in road construction. The basic properties of virgin aggregates are presented in Table 4. NHA Class B gradation was used in this research study, which was specified by National Highways Authority (NHA) Pakistan in 1998 and widely used for flexible pavement in the Pakistan. After blending the virgin aggregates with 20, 40, and 60% RAP, the gradation falls within the upper and lower limits of NHA Class B gradation, the gradation curves are presented in Figure 2.

Table 4. Physical properties of rap and virgin aggregates

Test	Standard	Result	Limits	
Flakiness Index	ASTM D 4791	10.20%	≤ 15 %	
Elongation Index		3.80%	≤ 15 %	
Aggregate Absorption	Fine	ASTM C 128	2.50%	≤ 3 %
	Coarse	ASTM C 127	0.69%	≤ 3 %
Impact Value	BS 812	15%	≤ 30 %	
Los Angles Abrasion	ASTM C131	20.60%	≤ 45 %	
Specific Gravity	Fine Agg	ASTM C 128	2.62	-
	Coarse Agg	ASTM C127	2.64	-

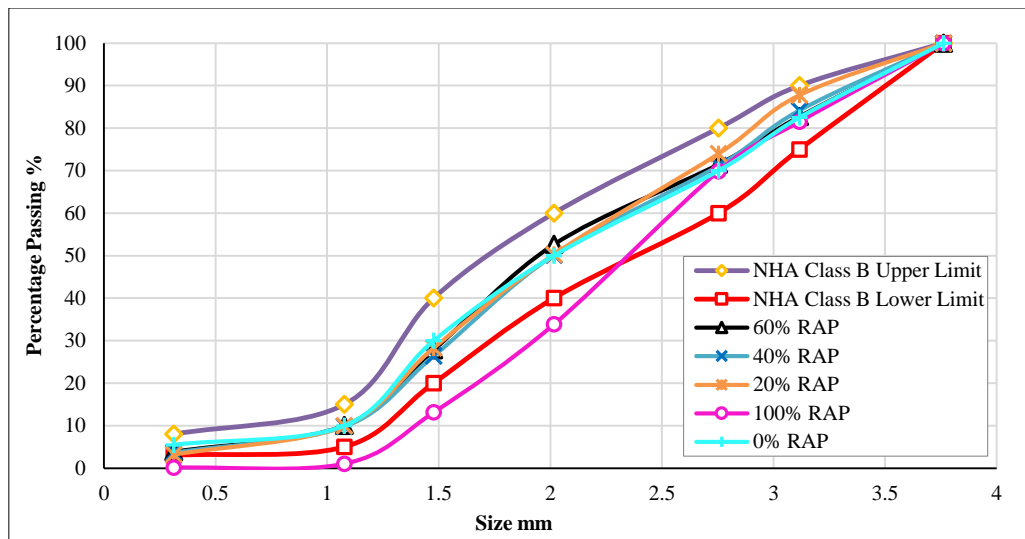


Figure 2. Gradation curves of different percentages of RAP

3. Laboratory Investigations

3.1. Marshall Mix Design

Marshall Mix Design was conducted for HMA mixtures with 0, 20, 40 and 60% RAP as per ASTM D6927 to determine Optimum Bitumen Content (OBC). 1200 g of Marshall samples having dimensions of 101.6 mm diameter and 63.5 mm height were mixed at 160°C and compacted at 135 °C temperature subjected to 75 number of blows. These specimens were prepared at varying binder contents ranging from 3.5 to 5.5% at the interval of 0.5%. OBC was determined to be 4.34 at 4% air voids. Meanwhile RAP contained about 3% of asphalt binder, therefore, quantity virgin asphalt content required for mixtures with different percentages of RAP content was adjusted accordingly.

3.2. Four-Point-Bending Test

Mix was prepared in automatic mixture machine for preparing beams for four-point bending fatigue test. Slabs were prepared in wheel roller laboratory compactor having dimensions of 376 mm length, 205 mm width and 75 mm thickness. After compaction, the sample was allowed to remain in the compactor for about 24 hours. The slab was then further reduced to desired dimensions of 376 mm length, 63 mm width and 50 mm thickness with the help of water-cooled masonry sawing machine for further testing as shown in Figure 3.

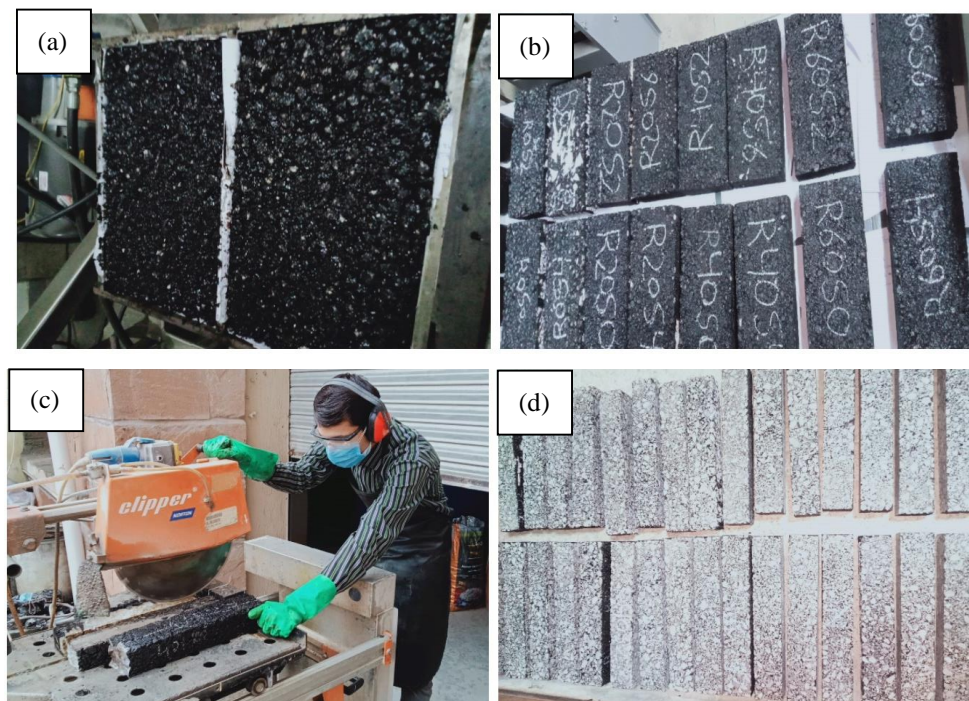


Figure 3. Preparation of beams from slabs for four-point bending test

The samples were then placed in the environmental chamber for two hours to achieve 20 ± 0.5 °C before beginning of the test. Strain-controlled approach was adopted at the level of 500 micro strains and loading frequency of 10 Hz. Failure criterion was set as 50% reduction in initial stiffness while initial stiffness was taken as stiffness corresponding to 50th load cycle. Dissipated energy for every 100 cycles of load was recorded and used for the determination of RDEC and PV.

To evaluate the fatigue performance of asphalt mixture with PV Power law model was incorporated to establish Dissipated Energy-Load Cycle (DE-LC) curves. Then average value of RDEC and PV at every 100 load cycles were determined by using Equations 1 and 2 respectively.

$$\text{RDEC} = \frac{1 - \left(1 + \frac{100}{a}\right)^s}{100} \quad (1)$$

$$\text{PV} = \frac{1 - \left(1 + \frac{100}{N_{f50}}\right)^s}{100} \quad (2)$$

where: a = Load Cycle; N_{f50} = Load Cycle corresponding to 50% stiffness reduction; and S = the exponential slope of power equation of regressed DE-LC curve.

3.3. Semi Circular Bending Test

Samples of 150 mm diameter for SCB test were prepared through Superpave Gyrotory Compactor by providing 125 gyrations to each sample. Three replicate samples were prepared for each percentage of change in RAP and Sasobit. Water-cooled masonry sawing machine was used for cutting the sample into our desired dimensions of 150 mm diameter and 57 mm thick circular discs. These circular discs were halved by the said machine. According to ASTM D 8044-16, an artificial crack called notch in the center of the specimen of lengths (25, 32, and 38 mm) with a thickness of 3 mm was generated to provide a predefined path for the crack as shown in Figure 4 and overall procedure from gyrotory sample to SCB test sample is shown in Figure 5.

The samples were kept inside the environmental chamber of UTM-25 KN and for a minimum of two hours to achieve a constant test temperature before testing. Afterward, the samples were placed one by one on three-point bending test fixture for testing. The fixture was composed of two roller supports and the span length between the support was 120 mm and lubricating oil was applied on the supports before the test to lessen the effect of friction during testing. A monotonic load was applied vertically on the top center of semicircular sample at the rate of 0.5 mm/min and the load continued to increase with deformation and declined gradually with the initiation of crack. The load vs. displacement was recorded from start until the load reached to 25-50% of peak load. The cracked specimen after testing is shown in Figure 6.



Figure 4. Specimen with 38 mm Notch Depth

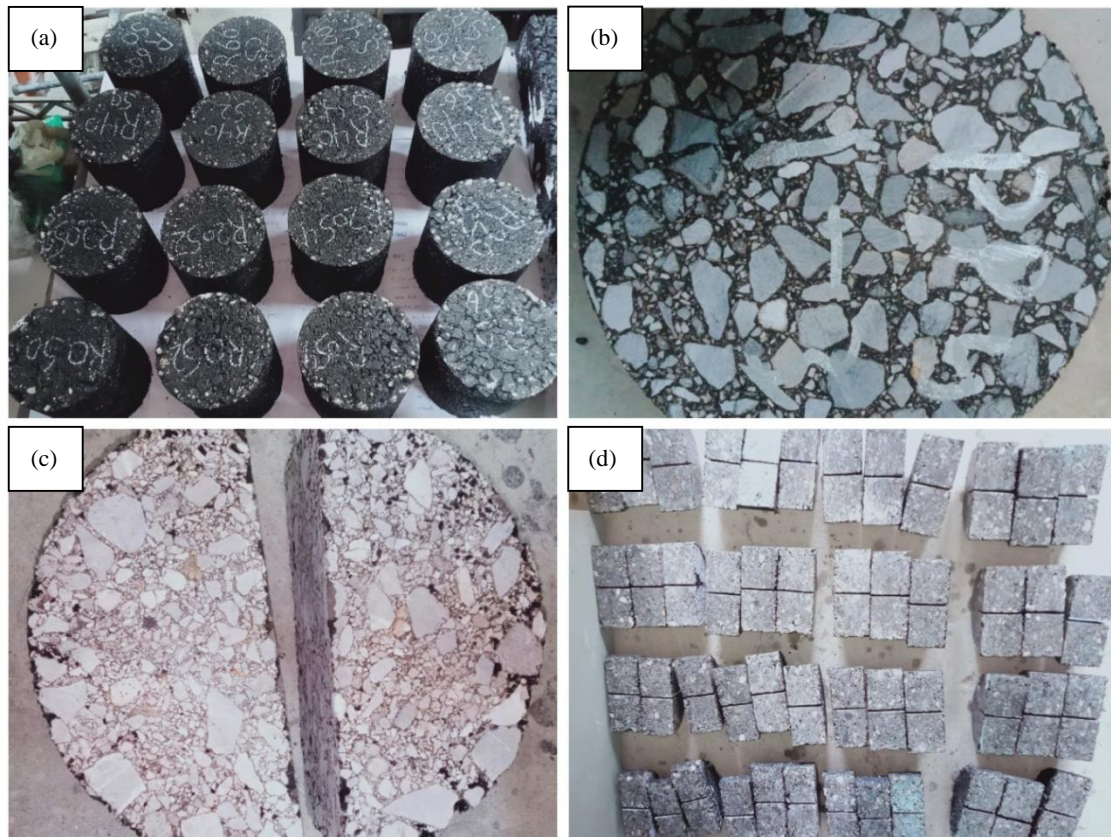


Figure 5. Preparation of semicircular shaped SCB test samples from gyratory samples

J-integral can be obtained by using the following equation:

$$J - \text{integral} = -\frac{1}{b} \left(\frac{dU}{da} \right) \tag{3}$$

where: *J*-integral = critical strain energy release rate (kJ/m²); *b* = thickness of sample (m); *U* = Strain energy to failure (KJ); *a* = notch depth (m); and *dU/da* = change of strain energy with notch depth (kJ/m).

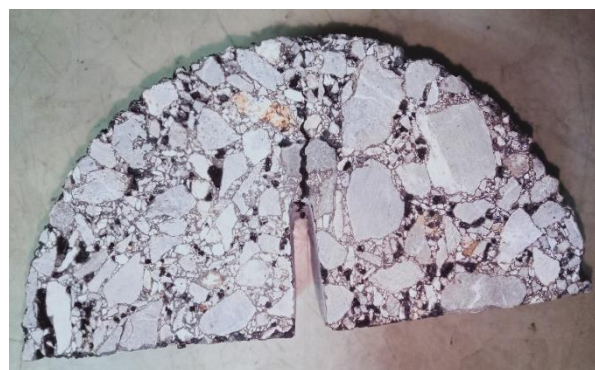


Figure 6. Cracked Specimen

4. Results and Discussion

4.1. Fatigue Cracking

Four-point fatigue beam test was performed according to AASHTO T-321 at frequency of 10 Hz and at fixed strain level of 500 micro strains. Dissipated energy for every 100th cycle was extracted and plotted against loading cycles and power law was used to fit the curve. Then plateau value (PV) was calculated by using Equation 2 at loading cycle corresponding to 50% of initial stiffness, which is regarded as fatigue life of asphalt pavement. PV for each mix is presented in Figure 7. Lowest value of PV was observed for mixture containing 40% RAP and 6% Sasobit while highest PV was observed for the mixture composed of 60% RAP and 0% Sasobit. PV increases by increasing the percentage of RAP in HMA and indicates lowering the fatigue life of asphalt mix. However, PV decreases by increasing percentage of RAP in WMA up to 40%. The PV of WMA tend to increase by adding the percentage of RAP greater than 40%.

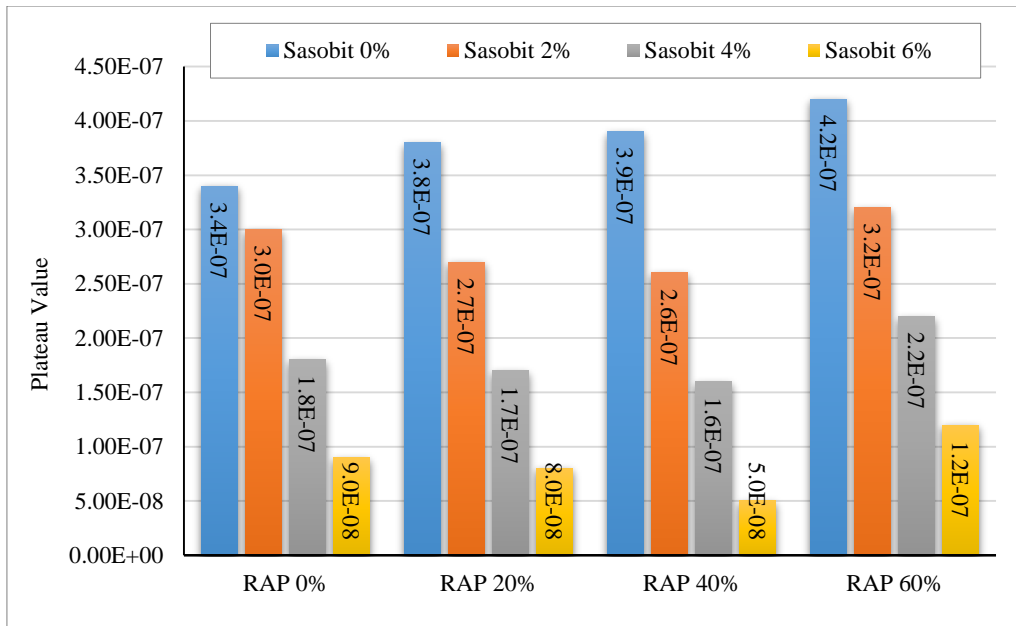


Figure 7. Plateau value from four-point bending test

According to Carpenter et al. PV is the sole indicator of fatigue life of asphalt. Graph between PV and loading cycles to failure (N_f) are plotted and presented in Figures 8 to 11 to validate the hypothesis. Decrease in PV was observed as load cycles increased which is similar to traditional fatigue curve plotted against strain level. In traditional fatigue approach number of load cycles are plotted against strain level and lower strain level indicates high fatigue life. Here, in energy-based approach lower PV indicates higher fatigue life, more load repetition, concept is validated from the plotted curves of our data. A higher coefficient of determination (R^2) between PV and loading cycles obtained from the energy curves indicate that there is strong relation between PV and cycles to failure.

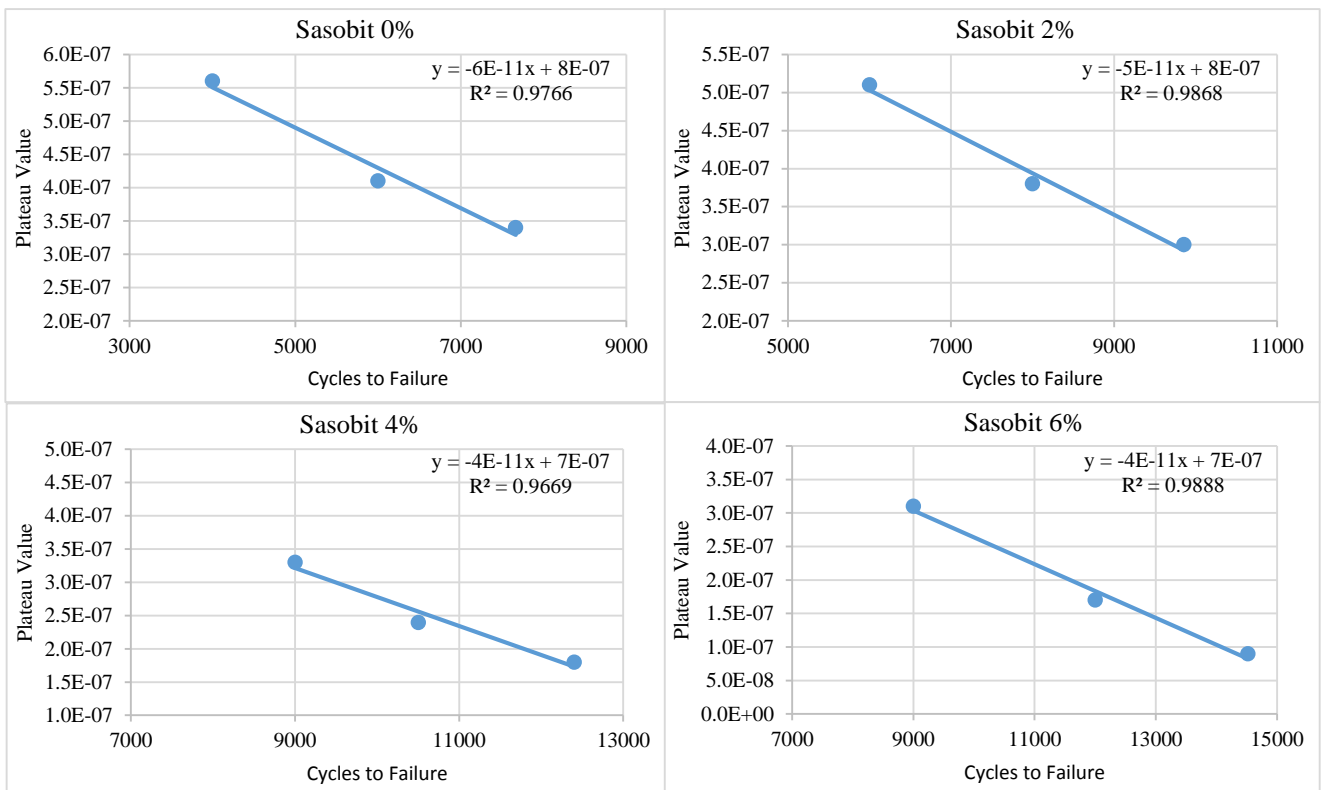


Figure 8. Energy-based approach for 0% RAP

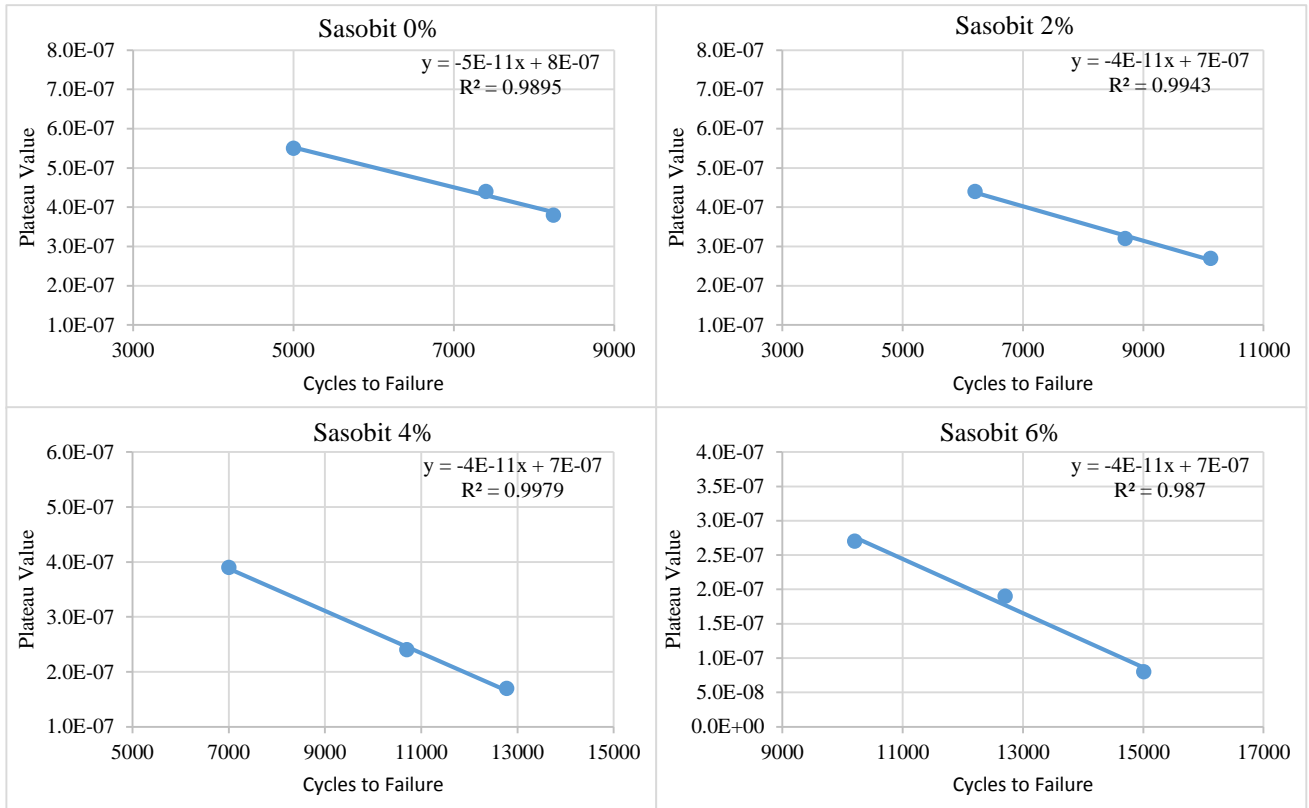


Figure 9. Energy-based approach for 20% RAP

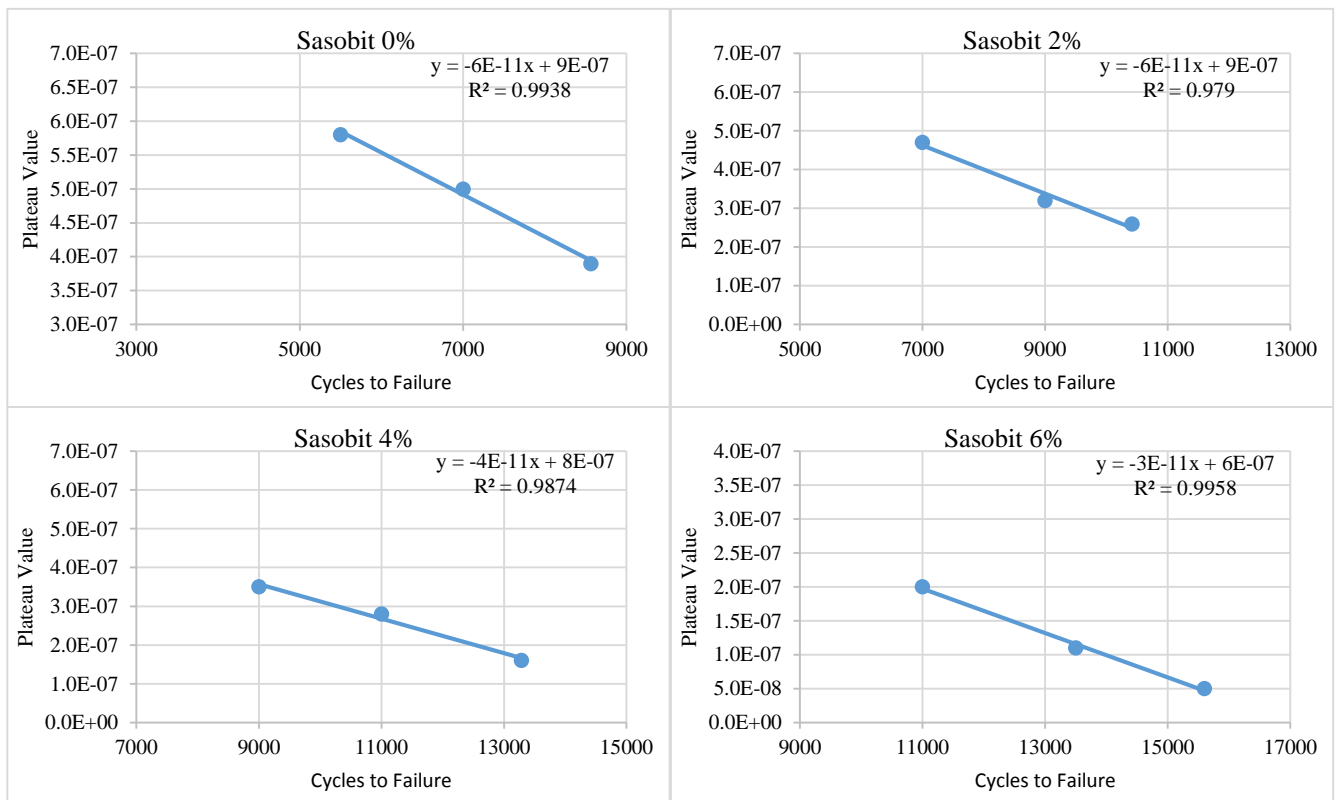


Figure 10. Energy-based approach for 40% RAP

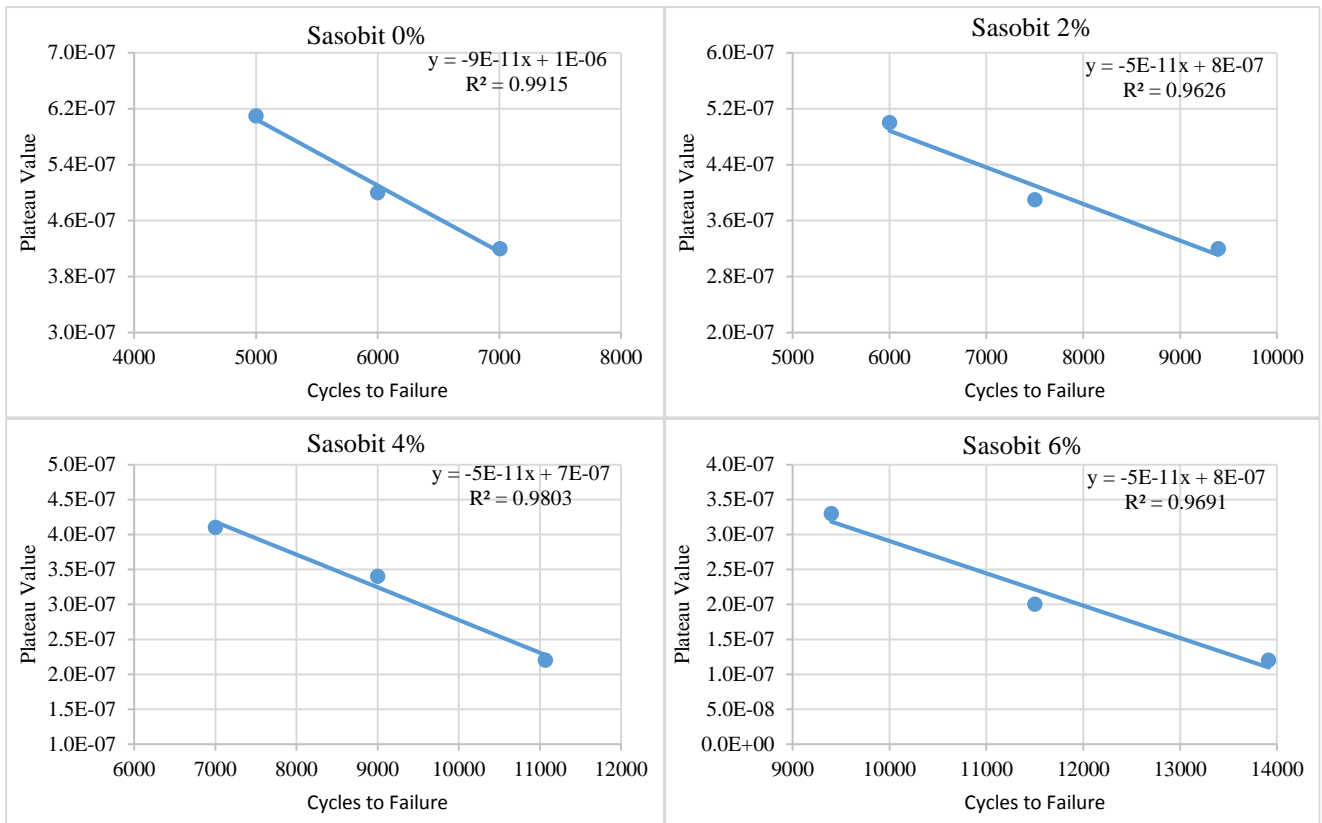


Figure 11. Energy-based approach for 60% RAP

From energy-based approach, it is observed that increase in loading cycles for each mix PV tends to decrease, which indicates a higher fatigue resisting more load repetitions.

4.2. Fracture Resistance

Fracture resistance of asphalt mix was evaluated by the comparison between control specimens and specimens modified with different percentages of RAP and Sasobit according to ASTM D8044-16. A total of 48 samples were prepared at OBC. The samples were tested at 25°C ((HT+LT)/2+4°C) by adjusting the temperature of environmental chamber. Snapshot of loading vs. displacement chart from the software is shown in Figure 12. The load (KN) and displacement (m) data after each test was plotted on a graph as shown in Figure 13. The information that can be extracted from the graph is: (i) peak Load, (ii) displacement against peak load and (iii) strain energy to failure (U). The strain energy to failure was determined by finding the area under the curve. The strain energy to failure was plotted against each notch depth and a best fit line joining these three points was drawn as shown in Figure 14. The slope of which is known as change of strain energy with notch depth (dU/da). The change of strain energy with notch depth was divided by the average thickness of the specimen to determine critical strain energy release rate (J -integration) as explained in Equation 3. The Coefficient of Variance (COV) values were calculated for each mix and presented in Figure 16.

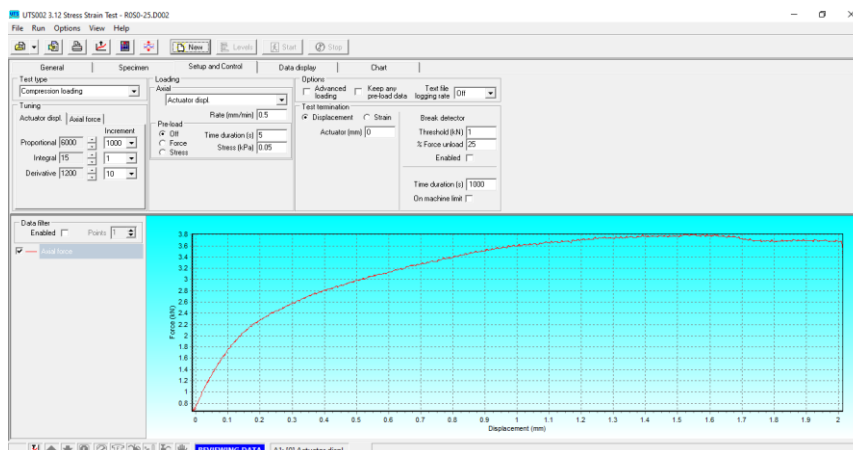


Figure 12. Software Output Display

4.2.1. Effect of Mix Properties on Fracture Resistance

Fracture resistance of asphalt mix vary greatly by increasing or decreasing the percentages of RAP and Sasobit. *J*-integral vs. each percentage change of RAP and Sasobit is presented in Figure 13.

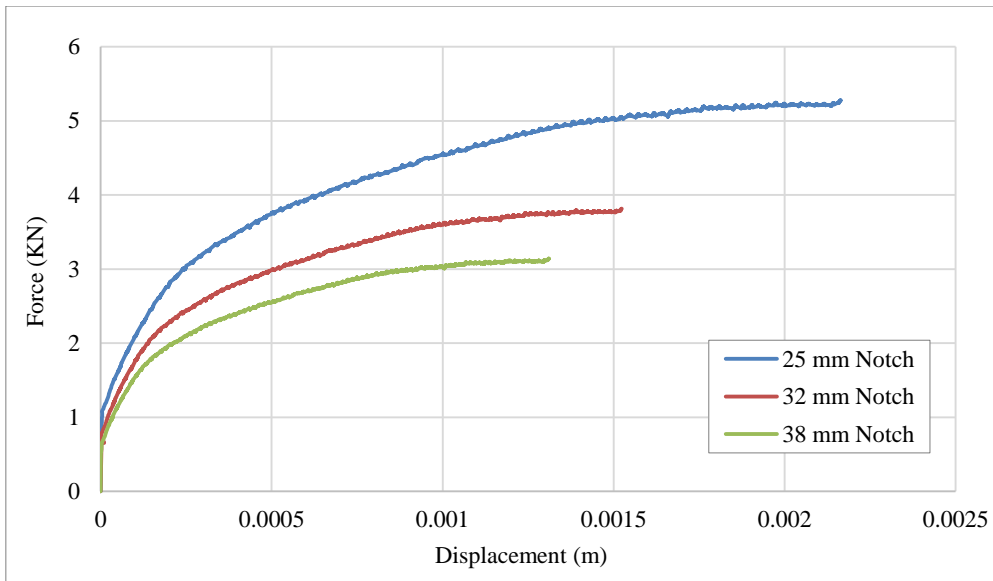


Figure 13. Force vs. displacement curve

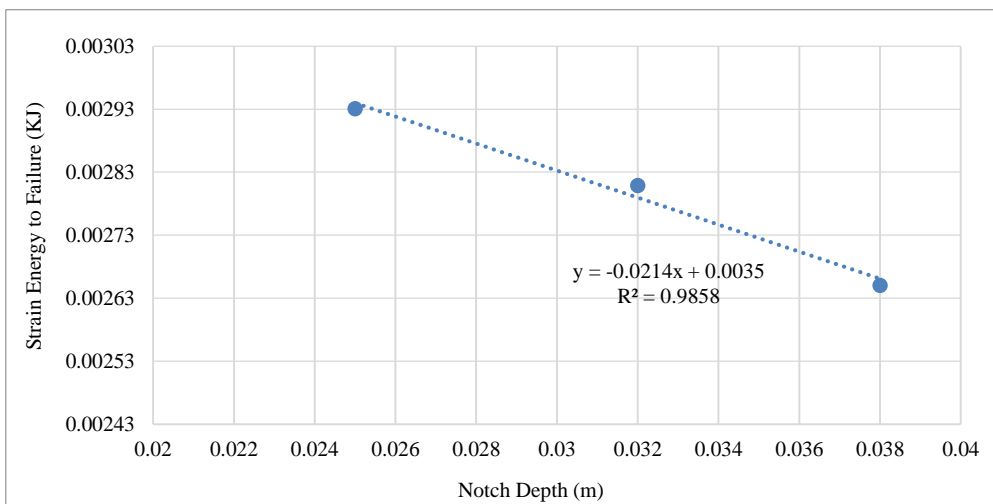


Figure 14. Strain energy vs. notch depth

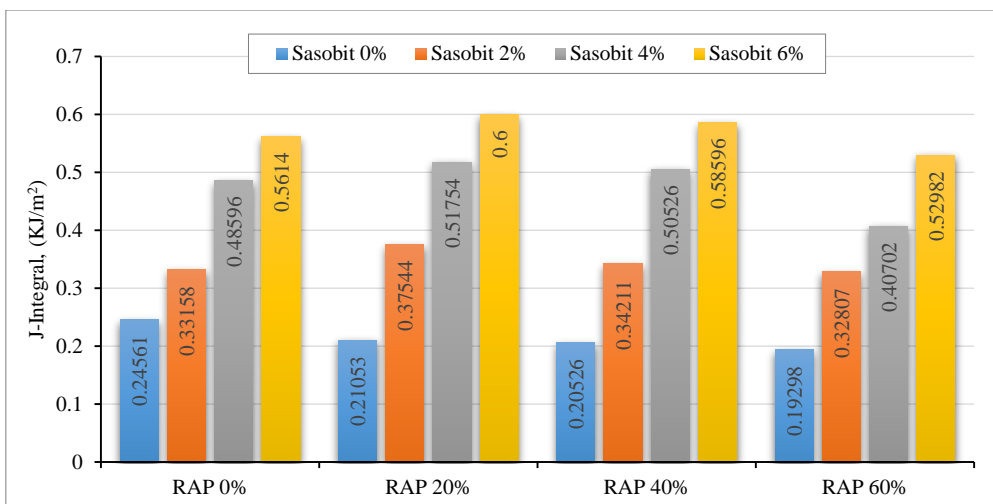


Figure 15. Critical strain energy release rate

It can be extracted from the graph shown in Figure 15 that fracture resistance of asphalt mix increases as the percentage of Sasobit increases. However, the fracture resistance of WMA increases by adding RAP in the mix up to 20 percent but fracture resistance tends to decrease by increasing the percentage of RAP beyond 20 percent of the mix. However, fracture resistance decreases with the addition of RAP to HMA. Furthermore, fracture resistance is negatively affected as compared to control samples when the percentage of RAP increases beyond 40 percent. COV for each percentage of RAP, Sasobit and notch depth are presented in Figure 16. The COV value of every mix falls within the range of acceptable limit which is 20%.

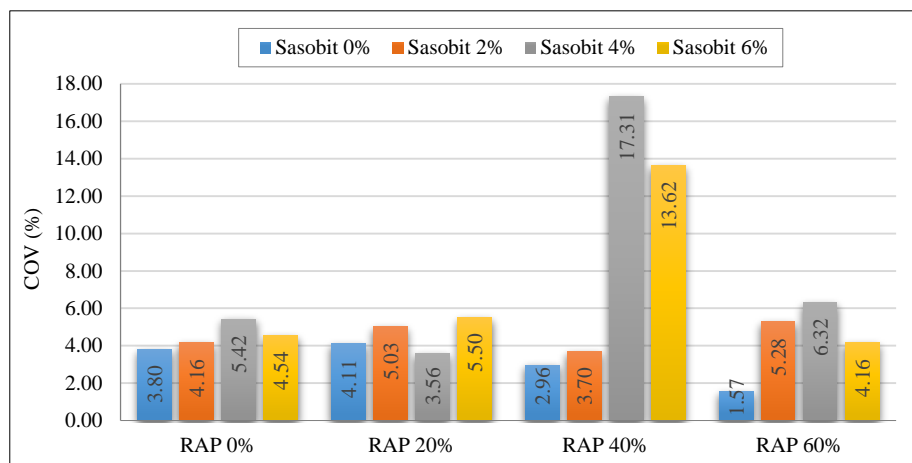


Figure 16. Coefficient of variance

5. Environmental and Economic Impacts

The high cost and adverse impacts on the environment involved with the production of virgin HMA are attributed to the high material cost and high energy requirement for mix production [43]. The release of harmful gases and high energy consumption are the consequences of heating bitumen and natural aggregates at temperature above 140 °C [44, 4]. Due to high temperature during mix production, fumes generated from bitumen consists of carcinogenic Polycyclic Aromatic Hydrocarbon (PAH) compounds [45]. WMA technologies reduce the PAH compounds up to 50% and thus reducing the exposure of workers to PAHs and fumes [46]. D’Angelo et al. revealed in their research study that the use of WMA reduces CO₂, NO_x, SO_x, and other volatile organic compounds up to 15-70% [22]. Utilizing RAP is the most emerging sustainability practice and results in energy saving up to 23% [43]. Using WMA technologies to utilize high percentages of RAP contents along with the reduction up to 35% of fuel consumption [47]. Vaitkus et al. concluded that Sasobit reduces fuel costs by 40% as compared to HMA and this reduction is associated with lower mixing and compaction temperature of WMA technologies [48]. Aurillo et al. conducted a research study on two projects in Canada by using 1.5% of Sasobit [49]. They revealed that neither pushing nor shoving was verified during compaction and the fuel consumption cost was reduced by 30%.

One kilometer of road section is assumed for the cost comparison of virgin mix and modified mix containing RAP. Standard road width of 3.6 meter was assumed with thickness of 50 mm. Cost for the lower layers base and subbase and preparation cost of the subgrade was completely ignored as they were assumed of similar properties for both the mixtures, only cost of HMA surface course is considered in this comparison. Density of asphalt was found in Marshall Mix Design as 2374 kg/m³ and 2372 kg/m³ for virgin HMA and WMA with RAP respectively. For estimation of cost, Composite Schedule Rates (CSR) is used. The difference between the construction cost of virgin HMA and WMA with RAP per kilometer per lane of a road section is presented in Figure 17.

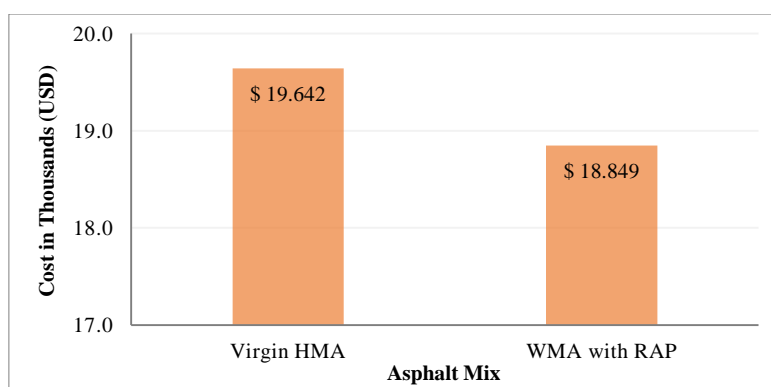


Figure 17. Cost Comparison

6. Conclusions

The current research work evaluates the fatigue and fracture behavior of HMA and WMA with further addition of different percentages of RAP to alleviate the emissions of greenhouse gases and growing demand of natural aggregate. Therefore, the main aim was to develop environment friendly pavement by utilizing high percentage of RAP with the help of Sasobit. Based on the laboratory test results, the following conclusions can be summarized.

- HMA mixtures showed lower fatigue and fracture resistance as compared to corresponding WMA mixtures.
- Due to the addition of RAP to HMA, fatigue and fracture resistance decrease regardless of the percentages of RAP.
- The decrease in the fatigue and fracture resistance of HMA is due to the increase in stiffness characteristics with the addition of RAP.
- The increase in the percentages of Sasobit, fatigue and fracture resistance increase as compared to the corresponding control specimen.
- The addition of RAP increases the fracture resistance of WMA mixtures than corresponding HMA mixtures. Meanwhile, the effect of RAP might be compromised in fracture resistance by introducing RAP more than 30%.
- The addition of RAP improves the fatigue resistance of WMA as compare to corresponding HMA. However, the addition of RAP more than 40% might compromise the effect of RAP.
- WMA results in cost saving of approximately 5%, which is only the monitory benefit during construction besides other benefits like improved properties and environmental benefits.

7. Declarations

7.1. Author Contributions

Conceptualization, S.T. and A.H.; methodology, S.T., A.H. and F.H.; validation, S.T., A.H., A.K. and F.H.; writing—original draft preparation, S.T. and F.H.; writing—review and editing, A.H. and A.K.; supervision, A.H.; project administration, A.H. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available in article.

7.3. Funding

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7.5. Conflicts of Interest

The authors declare no conflict of interest.

8. References

- [1] Zhu, Juncai, Kun Zhang, Kefei Liu, and Xianming Shi. "Performance of Hot and Warm Mix Asphalt Mixtures Enhanced by Nano-Sized Graphene Oxide." *Construction and Building Materials* 217 (August 2019): 273–282. doi:10.1016/j.conbuildmat.2019.05.054.
- [2] Shu, Xiang, Baoshan Huang, Emily D. Shrum, and Xiaoyang Jia. "Laboratory Evaluation of Moisture Susceptibility of Foamed Warm Mix Asphalt Containing High Percentages of RAP." *Construction and Building Materials* 35 (October 2012): 125–130. doi:10.1016/j.conbuildmat.2012.02.095.
- [3] Mohamad Taher, Mohammad Nasir. "Performance of advera® warm mix asphalt with reclaimed asphalt pavement materials." PhD diss., Universiti Tun Hussein Onn Malaysia, (2019).
- [4] Rubio, M. Carmen, Germán Martínez, Luis Baena, and Fernando Moreno. "Warm Mix Asphalt: An Overview." *Journal of Cleaner Production* 24 (March 2012): 76–84. doi:10.1016/j.jclepro.2011.11.053.

- [5] Syroezhko, A. M., M. A. Baranov, S. N. Ivanov, and N. V. Maidanova. "Influence of Natural Additives and Those Synthesized by the Fischer-Tropsch Method on the Properties of Petroleum Bitumen and Quality of Floated Asphalt." *Coke and Chemistry* 54, no. 1 (January 2011): 26–31. doi:10.3103/s1068364x11010066.
- [6] Damm, K. L. "Asphalt Flow Improvers - a New Technology for Reducing Mixing Temperature of Asphalt Concrete Mixes with High Resistance Against Permanent Deformation." *Sixth International RILEM Symposium on Performance Testing and Evaluation of Bituminous Materials* (2003). doi:10.1617/2912143772.065.
- [7] Singh, Dharamveer, Prabin Kumar Ashish, and Srinivas F. Chitragar. "Laboratory Performance of Recycled Asphalt Mixes Containing Wax and Chemical Based Warm Mix Additives Using Semi Circular Bending and Tensile Strength Ratio Tests." *Construction and Building Materials* 158 (January 2018): 1003–1014. doi:10.1016/j.conbuildmat.2017.10.080.
- [8] McDaniel, Rebecca S., and R. Michael Anderson. Recommended use of reclaimed asphalt pavement in the Superpave mix design method: technician's manual. No. Project D9-12 FY'97. National Research Council (US). Transportation Research Board, (2001).
- [9] Vargas-Nordbeck, Adriana, and David H. Timm. "Rutting Characterization of Warm Mix Asphalt and High RAP Mixtures." *Road Materials and Pavement Design* 13, no. sup1 (June 2012): 1–20. doi:10.1080/14680629.2012.657042.
- [10] Stroup-Gardiner, Mary. "Use of Reclaimed Asphalt Pavement and Recycled Asphalt Shingles in Asphalt Mixtures" (September 12, 2016). doi:10.17226/23641.
- [11] FHWA, User Guidelines for Waste and Byproduct Materials in Pavement Construction. (2016).
- [12] Shu, Xiang, Baoshan Huang, and Dragon Vukosavljevic. "Laboratory Evaluation of Fatigue Characteristics of Recycled Asphalt Mixture." *Construction and Building Materials* 22, no. 7 (July 2008): 1323–1330. doi:10.1016/j.conbuildmat.2007.04.019.
- [13] Sharma, Ankit, Praveen Kumar, and Ashish Walia. "Use of Recycled Material in WMA- Future of Greener Road Construction." *Transportation Research Procedia* 48 (2020): 3770–3778. doi:10.1016/j.trpro.2020.08.042.
- [14] Mogawer, Walaa, Thomas Bennert, Jo Sias Daniel, Ramon Bonaquist, Alexander Austerman, and Abbas Booshehrian. "Performance Characteristics of Plant Produced High RAP Mixtures." *Road Materials and Pavement Design* 13, no. sup1 (June 2012): 183–208. doi:10.1080/14680629.2012.657070.
- [15] Hill, Brian, Behzad Behnia, William G. Buttlar, and Henrique Reis. "Evaluation of Warm Mix Asphalt Mixtures Containing Reclaimed Asphalt Pavement through Mechanical Performance Tests and an Acoustic Emission Approach." *Journal of Materials in Civil Engineering* 25, no. 12 (December 2013): 1887–1897. doi:10.1061/(asce)mt.1943-5533.0000757.
- [16] Dinis-Almeida, Marisa, João Castro-Gomes, and Maria de Lurdes Antunes. "Mix Design Considerations for Warm Mix Recycled Asphalt with Bitumen Emulsion." *Construction and Building Materials* 28, no. 1 (March 2012): 687–693. doi:10.1016/j.conbuildmat.2011.10.053.
- [17] Sharma, A, G D Ransinchung, P Kumar, and D S N V A Kumar. "Design Mixture of RAP-HMA Pavements: A Review." *IOP Conference Series: Materials Science and Engineering* 1075, no. 1 (February 1, 2021): 012025. doi:10.1088/1757-899x/1075/1/012025.
- [18] Tao, Mingjiang, and Rajib B. Mallick. "Effects of Warm-Mix Asphalt Additives on Workability and Mechanical Properties of Reclaimed Asphalt Pavement Material." *Transportation Research Record: Journal of the Transportation Research Board* 2126, no. 1 (January 2009): 151–160. doi:10.3141/2126-18.
- [19] Mogawer, Walaa S., Alexander J. Austerman, and Ramon Bonaquist. Evaluating effects of warm-mix asphalt technology additive dosages on workability and durability of asphalt mixtures containing recycled asphalt pavement. No. 09-1279. 2009.
- [20] Albayati, Amjad H., and Waleed Arrak Turkey. "The Effect of Using Sustainable Materials on the Performance-Related Properties of Asphalt Concrete Mixture." *Civil Engineering Journal* 5, no. 12 (December 1, 2019): 2727–2737. doi:10.28991/cej-2019-03091444.
- [21] Xiao, Feipeng, and Serji N. Amirghanian. "Laboratory Investigation of Moisture Damage in Rubberised Asphalt Mixtures Containing Reclaimed Asphalt Pavement." *International Journal of Pavement Engineering* 10, no. 5 (October 2009): 319–328. doi:10.1080/10298430802169432.
- [22] d'Angelo, John, Eric Harm, John Bartoszek, Gaylon Baumgardner, Matthew Corrigan, Jack Cowser, Thomas Harman et al. Warm-mix asphalt: European practice. No. FHWA-PL-08-007. United States. Federal Highway Administration. Office of International Programs, (2008).
- [23] Zhao, Sheng, Baoshan Huang, Xiang Shu, and Mark Woods. "Comparative Evaluation of Warm Mix Asphalt Containing High Percentages of Reclaimed Asphalt Pavement." *Construction and Building Materials* 44 (July 2013): 92–100. doi:10.1016/j.conbuildmat.2013.03.010.

- [24] Aliha, M.R.M., M. Fakhri, E. Haghighat Kharrazi, and F. Berto. "The Effect of Loading Rate on Fracture Energy of Asphalt Mixture at Intermediate Temperatures and Under Different Loading Modes." *Frattura Ed Integrità Strutturale* 12, no. 43 (December 29, 2017): 113–132. doi:10.3221/igf-esis.43.09.
- [25] Fakhri, Mansour, and Amin Ahmadi. "Evaluation of Fracture Resistance of Asphalt Mixes Involving Steel Slag and RAP: Susceptibility to Aging Level and Freeze and Thaw Cycles." *Construction and Building Materials* 157 (December 2017): 748–756. doi:10.1016/j.conbuildmat.2017.09.116.
- [26] Lu, Dai Xuan, Mofreh Saleh, and Nhu H. T. Nguyen. "Evaluation of Fracture and Fatigue Cracking Characterization Ability of Nonstandardized Semicircular-Bending Test for Asphalt Concrete." *Journal of Materials in Civil Engineering* 32, no. 8 (August 2020): 04020215. doi:10.1061/(asce)mt.1943-5533.0003292.
- [27] Guo, Meng, Haiqing Liu, Yubo Jiao, Liantong Mo, Yiqiu Tan, Dawei Wang, and Meichen Liang. "Effect of WMA-RAP Technology on Pavement Performance of Asphalt Mixture: A State-of-the-Art Review." *Journal of Cleaner Production* 266 (September 2020): 121704. doi:10.1016/j.jclepro.2020.121704.
- [28] Yousefi, A., S. Pirmohammad, and S. Sobhi. "Fracture Toughness of Warm Mix Asphalts Containing Reclaimed Asphalt Pavement." *Journal of Stress Analysis* 5, no. 1 (2020): 85–98.
- [29] Kavussi, Amir, and Seyed Mohsen Motevalizadeh. "Fracture and Mechanical Properties of Water-Based Foam Warm Mix Asphalt Containing Reclaimed Asphalt Pavement." *Construction and Building Materials* 269 (February 2021): 121332. doi:10.1016/j.conbuildmat.2020.121332.
- [30] American Association of State Highway and Transportation, AASHTO T321-07. "Determining the Fatigue Life of Compacted Hot-Mix Asphalt (HMA) Subjected to Repeated Flexural Bending." (2007).
- [31] Shen, Shihui, and Samuel H. Carpenter. "Application of the Dissipated Energy Concept in Fatigue Endurance Limit Testing." *Transportation Research Record: Journal of the Transportation Research Board* 1929, no. 1 (January 2005): 165–173. doi:10.1177/0361198105192900120.
- [32] Carpenter, Samuel H., Khalid A. Ghuzlan, and Shihui Shen. "Fatigue Endurance Limit for Highway and Airport Pavements." *Transportation Research Record: Journal of the Transportation Research Board* 1832, no. 1 (January 2003): 131–138. doi:10.3141/1832-16.
- [33] Shen, Shihui, and Samuel H. Carpenter. "Dissipated energy concepts for HMA performance: fatigue and healing." Vol. 67, no. 11. (2006).
- [34] Saha, Gourab, and Krishna Prapoorna Biligiri. "Fracture Properties of Asphalt Mixtures Using Semi-Circular Bending Test: A State-of-the-Art Review and Future Research." *Construction and Building Materials* 105 (February 2016): 103–112. doi:10.1016/j.conbuildmat.2015.12.046.
- [35] Petersen, DR, RE Link, MP Wagoner, WG Buttlar, and GH Paulino. "Development of a Single-Edge Notched Beam Test for Asphalt Concrete Mixtures." *Journal of Testing and Evaluation* 33, no. 6 (2005): 12579. doi:10.1520/jte12579.
- [36] Nsengiyumva, Gabriel. "Development of semi-circular bending (SCB) fracture test for bituminous mixtures." (2015).
- [37] Wagoner, Michael P., William G. Buttlar, Glaucio H. Paulino, and Philip Blankenship. "Investigation of the Fracture Resistance of Hot-Mix Asphalt Concrete Using a Disk-Shaped Compact Tension Test." *Transportation Research Record: Journal of the Transportation Research Board* 1929, no. 1 (January 2005): 183–192. doi:10.1177/0361198105192900122.
- [38] Mull, M. A., K. Stuart, and A. Yehia. "Fracture resistance characterization of chemically modified crumb rubber asphalt pavement." *Journal of materials science* 37, no. 3 (2002): 557–566. doi:10.1023/A:1013721708572.
- [39] Saeidi, Hadi, and Iman Aghayan. "Investigating the Effects of Aging and Loading Rate on Low-Temperature Cracking Resistance of Core-Based Asphalt Samples Using Semi-Circular Bending Test." *Construction and Building Materials* 126 (November 2016): 682–690. doi:10.1016/j.conbuildmat.2016.09.054.
- [40] Saha, Gourab, and Krishna Prapoorna Biligiri. "Stato-Dynamic Response Analyses through Semi-Circular Bending Test: Fatigue Life Prediction of Asphalt Mixtures." *Construction and Building Materials* 150 (September 2017): 664–672. doi:10.1016/j.conbuildmat.2017.06.035.
- [41] Li, X.-J., and M. O. Marasteanu. "Using Semi Circular Bending Test to Evaluate Low Temperature Fracture Resistance for Asphalt Concrete." *Experimental Mechanics* 50, no. 7 (October 14, 2009): 867–876. doi:10.1007/s11340-009-9303-0.
- [42] Ameri, M., Sh. Nowbakht, M. Molayem, and M. R. M. Aliha. "Investigation of Fatigue and Fracture Properties of Asphalt Mixtures Modified with Carbon Nanotubes." *Fatigue & Fracture of Engineering Materials & Structures* 39, no. 7 (February 19, 2016): 896–906. doi:10.1111/ffe.12408.

- [43] Chiu, Chui-Te, Tseng-Hsing Hsu, and Wan-Fa Yang. "Life Cycle Assessment on Using Recycled Materials for Rehabilitating Asphalt Pavements." *Resources, Conservation and Recycling* 52, no. 3 (January 2008): 545–556. doi:10.1016/j.resconrec.2007.07.001.
- [44] Capitão, S.D., L.G. Picado-Santos, and F. Martinho. "Pavement Engineering Materials: Review on the Use of Warm-Mix Asphalt." *Construction and Building Materials* 36 (November 2012): 1016–1024. doi:10.1016/j.conbuildmat.2012.06.038.
- [45] Ventura, Anne, Agnès Jullien, and Pierre Monéron. "Polycyclic Aromatic Hydrocarbons Emitted from a Hot-Mix Drum, Asphalt Plant: Study of the Influence from Use of Recycled Bitumen." *Journal of Environmental Engineering and Science* 6, no. 6 (November 2007): 727–734. doi:10.1139/s07-022.
- [46] Anderson, E.J.O., Norway: Norwegian Public Roads Administration, WAM-Foam-An Environmentally Friendly Alternative to Hot-Mix Asphalt. (2007).
- [47] Prowell, Brian D., Graham C. Hurley, and Bob Frank. *Warm-mix asphalt: Best practices*. Lanham, MD: National Asphalt Pavement Association, (2011).
- [48] Vaitkus, A., D. Čygas, A. Laurinavičius, and Z. Perveneckas. "Analysis and Evaluation of Possibilities for the Use of Warm Mix Asphalt in Lithuania." *The Baltic Journal of Road and Bridge Engineering* 4, no. 2 (June 22, 2009): 80–86. doi:10.3846/1822-427x.2009.4.80-86.
- [49] Aurillo, V., and L. L. Michael. "Sasobit Warm Mix Asphalt Technology: Victoria Street Trial in the City of Ottawa." In *Proceedings of the Fifty-third Annual Conference of the Canadian Technical Asphalt Association (CTAA) Canadian Technical Asphalt Association*. (2008).