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RIGA TECHNICAL UNIVERSITY

Mukul Rathore

HIGH RECLAIMED ASPHALT CONTENT MIXTURES: DESIGN PARAMETERS AND PERFORMANCE EVALUATION

Summary of the Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY
Faculty of Civil Engineering
Department of Roads and Bridges

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on September 2, 2022 at 14:15 at the Faculty of Civil Engineering of Riga Technical University, Kipsalas Street 6B Room 300.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Mukul Rathore ……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in English. It consists of 8 Chapters including an introduction; conclusion; 66 figures; 31 tables; the total number of pages is 143. The Bibliography contains 169 titles.

TABLE OF CONTENTS

1. INTRODUCTION

Asphalt is used for road surfacing on more than 90 % of the European roads. Typically, the aggregates constitute about 94–96 % (w/w) of total mixture and bitumen constitute about 4–6 % (w/w) of total mixture in the asphalt mix. With the expansion of global economy and existing road infrastructures, the raw materials required for pavement construction are depleting from the planet at a faster rate. To improve the sustainability of road construction, the principle of 3R's (reduce, reuse, and recycle) must be applied. This means, first, the asphalt pavements must be designed to last long, which in turn will 'reduce' the consumption of raw materials. After service life completion, the reclaimed asphalt (RA) material can be 'reused' in the same asphalt layer. If the RA material cannot be used in the same layer, it must be 'recycled' into lower bound layers (base layers) or used as a replacement of aggregates in unbound layers, road shoulders, or embankments. In Europe, 68 % of available reclaimed asphalt material is presently being used in new road construction and maintenance and around 20 % is being recycled in unbound layers and other engineering applications.

It has already been demonstrated in the laboratory that asphalt mixtures prepared using only RA material along with additives and recycling agents can provide satisfactory performance. However, currently, the reclaimed asphalt content in surface layer asphalt mixtures is limited to 10–30 % in most countries. The reason for this limitation is due to technical constraints and due to lack of confidence in the quality of high content RA mixtures. The Doctoral Thesis aims to improve the sustainability of asphalt road construction by fixing the design parameters for high reclaimed asphalt content mixtures, by improving the performance using rejuvenators or additives, and by highlighting the environmental benefits of high reclaimed asphalt mixtures compared to conventional asphalt mixtures.

1.1. Objective of the study

The objective of the Thesis is to develop new procedures for design and evaluation of high content reclaimed asphalt mixtures containing rejuvenators and investigate their long-term mechanical performance and environmental impact.

1.2. Tasks of the Thesis

To achieve the above objective, the following research tasks must be fulfilled:

1. To develop a mixing procedure for producing high content reclaimed asphalt mixtures in the laboratory for reliably comparing mechanical, rheological, and chemical properties of mixtures.
2. To design warm mix asphalt using a chemical additive and high content of reclaimed asphalt for comparing performance with conventional hot mix asphalt.
3. To perform field aging paions for evaluating the rheological and chemical changes in reclaimed asphalt mixtures modified using rejuvenators of different origins.
4. To ascertain rutting and cracking performance of recycled asphalt mixtures and determine correlation between mechanical indicators and optically measured strains.

5. To perform a life cycle inventory analysis for evaluating environmental impacts associated with high rate of asphalt recycling.

1.3. Scientific significance and novelty

Currently, there is no standardized procedure for preparation of reclaimed asphalt mixtures in laboratory. To address this problem and enable comparing of asphalt performance between the tests performed in different laboratories, a systematic research study was conducted to develop a new procedure for preparation for high reclaimed asphalt content mixtures in laboratory. A stage extraction method was developed as part of this work to extract multiple layers of binder from reclaimed asphalt mixtures. The new extraction method is an improvement over conventional extraction methods that are able to extract only a single layer of binder blend. A major concern in the industry is the unknown long-term performance of reclaimed asphalt mixtures, which has been addressed by simulating field aging on mixtures recycled using a variety of rejuvenators. Moreover, a new performance indicator for high content reclaimed asphalt mixtures has been presented in this study by combining the conventional fracture testing with digital image correlation technique. Finally, the aspects of pavement design have been integrated with life cycle assessment technique to compute the environmental impact for high rate of asphalt recycling.

1.4. Practical significance

All the publications included in the Thesis are available through open access to maximize the impact of current study. The recommended method for mixing high content reclaimed asphalt mixtures can be used by researchers and mix designer to control the parameters for performance evaluation of high content RA mixtures. The outcomes of comparing mixtures with high RA content produced using different binder modification techniques will improve the current mix design methodology and provide future direction for researchers to tackle the issues with high rate of asphalt recycling. The long-term performance comparison of different rejuvenators will serve as a guide for asphalt producers to select the rejuvenator catering to the requirements for a particular mixture. The method for fatigue characterisation combined with non-contact measurement technique can be used by researchers to evaluate the mixtures. Further, the life cycle assessment results can be used to encourage the use of recycled material in asphalt mixtures under similar conditions.

1.5. Theses to defend

1. The developed asphalt mixing procedure standardises laboratory mixing conditions thereby allowing to reliably compare the properties of different high content reclaimed asphalt mixture compositions.
2. The novel stage extraction method allows to recover multiple layers of bitumen from reclaimed asphalt mixtures for assessing the degree of blending between the binder and rejuvenator.
3. The novel indicator based on optically measured strains allows determining crack propagation in high content reclaimed asphalt mixtures.

4. The developed integrated life cycle assessment methodology of pavements enhances the robustness of environmental impact calculations by considering the effect of recycled asphalt mixture properties on thickness of pavement layers.

1.6. List of publications

1. **Rathore, M.**, Haritonovs, V., Merijs-Meri, R., Zaumanis, M., 2022. Rheological and chemical evaluation of aging in 100 % reclaimed asphalt mixtures containing rejuvenators. Construction and Building Materials. 318, 126026. https://doi.org/10.1016/j.conbuildmat.2021.126026.
2. **Rathore, M.**, Haritonovs, V., Zaumanis, M., 2021. Performance Evaluation of Warm Asphalt Mixtures Containing Chemical Additive and Effect of Incorporating High Reclaimed Asphalt Content. Materials. 14, 3793. https://doi.org/10.3390/ma14143793.
3. **Rathore, M.**, Zaumanis, M., 2020. Impact of laboratory mixing procedure on the properties of reclaimed asphalt pavement mixtures. Construction and Building Materials. 264, 120709, https://doi:10.1016/j.conbuildmat.2020.120709.
4. **Rathore, M.**, Zaumanis, M., & Haritonovs, V., 2019. Asphalt Recycling Technologies: A Review on Limitations and Benefits. IOP Conference Series: Materials Science and Engineering, 660, 012046. https://doi:10.1088/1757-899x/660/1/012046 .

1.7. Participation in conferences and workshops

1. 4th International Conference “Innovative Materials, Structures and Technologies” (IMST 2019), Riga, Latvia, 25–27 September 2019.
2. 57th Peterson Asphalt Research conference, Wyoming, US, 13–14 July 2020.
3. 9th Conference of the European Asphalt Technology Association, Vienna, Austria, 3–5 June 2021.
4. 30th International Baltic Road Conference, Riga, Latvia, 22–25 August 2021.
5. 1st SaferUP! Training Week at the University of Bologna, Italy. 1–5 April 2019.
6. SaferUP! Mid Term Meeting at the University College London. 12 June 2019.
7. Fundamentals for Innovative Research in Sustainable Transportation. Workshop held in Moena, Italy. 15–18 December 2019:
8. 2nd SaferUP! Training Week at the University of Cantabria. 28 September – 2 October 2020.
9. 3rd SaferUP! Training Week in Bonn, Germany, 19–23 April 2021.
10. 4th SaferUP! Training Week at the Coventry University, United Kingdom, 13–17 December 2021.

2. BACKGROUND

2.1. Reclaimed asphalt

The term reclaimed asphalt (RA) is given to milled asphalt material that is removed from an unserviceable pavement and can be recycled in new pavement application. Most commonly, the old pavement material obtained from the job site is hauled to the central plant and crushed, screened, sized, and stockpiled. The characteristics of RA material depends on several factors, including type and thickness of the original pavement, age of the pavement, the environmental and traffic conditions, and the quality and characteristics of the aggregates and used original binder, and the technology used to reclaim the material. Some problems and limitations related to reclaimed asphalt mixtures and their possible solutions are given in Table 2.1.

Table 2.1

Limitation of RA Material and its Solutions

Problem	Limitations	Solutions
High fine content	It limits the maximum RA content in asphalt mixtures due to specifications.	Avoid over-processing and use suitable methods that reduce dust generation, e.g., crushing.
Variability	Highly variable RA require multiple screening or crushing and increase the processing costs.	Well-managed arc-shaped, uniformly layered RA stockpiles are preferred to prevent segregation.
Moisture content	High RA moisture content reduces the plant's production rate and maximum RA content in the mixture.	Large conical piles can be used for stockpiling to reduce moisture retention.
Contamination	Toxic substances in RA can leach into the groundwater and affect the human health.	Stockpile on a solid surface prevents contamination or compaction of the underlying surface.

2.2. Warm mix asphalt (WMA)

WMA is a type of asphalt mixture in which the production temperature is reduced by around 20–40 °C compared to conventional asphalt production temperature with the help of softer binder. The basic principle behind this technology is that by adding certain additives at the final stages of mix production or by using a binder foaming process in which the coating of aggregates can be greatly enhanced and achieved at a considerably lower temperature. The reduced production temperature used in WMA facilitates the incorporation of high content of reclaimed asphalt due to the lower aged binder obtained in this process. Lower production temperature will also lead to lesser energy consumption and reduced emissions. WMA technologies are classified into three broad categories that include foaming processes, organic additives, and chemical additives.

2.3. Production of reclaimed asphalt mixtures

For hot mix asphalt production, the aggregates are heated typically around 150–190 °C. The most used method is to superheat the virgin aggregates (at 190–250 °C), so that when they encounter the RA material, they would dry and heat the RA material by conduction. Concerning the RA material, it is either heated at 110–160 °C (warm/hot recycling) or added at ambient temperature in the plant (cold feed recycling). Rejuvenators, also known as ‘recycling agents’, alter the properties of aged RA binder to achieve the required mechanical performance. These are typically added directly into virgin binder, as no additional equipment is used in this case. However, in some cases it is also possible to add rejuvenator directly into the RA material or into the mixture. In laboratory, the most commonly used RA material heating temperature is 110 °C for a heating time of 2 hours. However, when the high content (up to 100 %) RA is considered, the heating temperature of RA material is increased even above 155°C.

2.4. Aging characteristics

Asphalt binder undergoes a series of physio-chemical changes during the service life of pavement, which deteriorates the pavement condition. The oxidation of bitumen is the main reason behind the deterioration of pavement during service life, and as a result, the pavement becomes more susceptible to thermal cracking and fatigue failure. The aging of asphalt mixtures is divided into two main stages: short-term aging, which is due to volatilization of the bitumen within the asphalt mixture during mixing and construction, and long-term aging, which is due to oxidation and steric hardening in the field. The binder aging approach is useful for ranking the aging susceptibility and understanding the aging mechanism, but it does not take in account the effects of mineral aggregate on the oxidation and asphalt mixture’s performance. The long-term aging of bitumen in field is a slow process and depends on several environmental factors.

2.5. Life cycle assessment

Life cycle assessment is a systematic method to quantitatively assess the environmental impacts of the products or services. LCA tools include all the processes associated with a product and quantify the related input and output flows in the system from cradle (raw material extraction) to grave (disposal). Several asphalt researchers have used LCA tools to compare the environmental benefits of various recycling alternatives. The life cycle assessment of pavements can be divided into the following stages: raw material extraction, material production, transportation, construction, use phase, maintenance, and end-of-life.

3. EXPERIMENTAL METHODS

For evaluation of mixtures and the binder, standard test methods have been adopted, as described in Table 3.1. A novel binder extraction method was developed to obtain four different layers of binder from the mixture. In addition, digital image correlation technique was used to develop a new indicator for evaluation of mixtures. A new index quantifying the modification effect of rejuvenator was also calculated from Fourier transform infrared spectroscopy analysis. All these test methods are briefly described in the next section.

Table 3.1

Standard Test Methods

Test	Standard	Measured property
Penetration & softening point	EN 1426, 1427	Hardness/softness of binder
Temperature and frequency sweep test	EN 14770	Stiffness of binder
Linear amplitude sweep test	AASHTO TP101	Fatigue performance of binder
Multiple stress creep recovery test	AASHTO TP70	Rutting performance of binder
Indirect tensile strength	EN 12697-23	Moisture susceptibility of mixture
Stiffness modulus test	EN 12697-26	Stiffness of mixture
Thermal stress restrained Specimen test	EN 12697-46	Low-temperature cracking performance of mixture
Wheel tracking test	EN 12679-22	High-temperature rutting performance of mixture
Semi-circular bend test	AASHTO TP 124-16	Fracture toughness of mixture
Horizontal dynamic surface leaching test	CEN/TS 16637-2	Leaching property

3.1. Stage extraction method

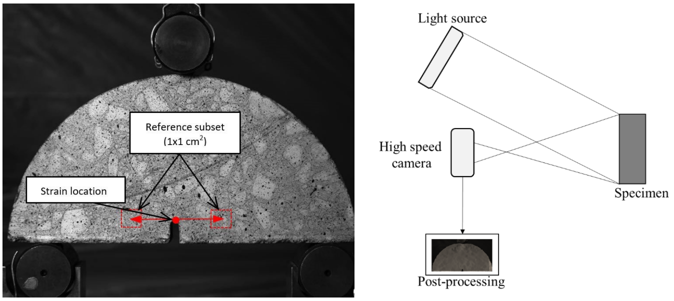
The method works on the principle that by immersing a loose asphalt sample into a solvent for a small period, a certain thickness of the bitumen layer can be dissolved. The stage extraction method developed for the current study can be described as follows:

- The asphalt mixture obtained after mixing was cooled down while loosening and separating to reduce the agglomeration of particles.
- 1400 g of the mixture was placed in a mesh bucket, and four cylindrical vessels large enough to accommodate the mesh buckets were filled with 1400 ml of toluene.
- For extraction, the mesh bucket was lowered down slowly into the first vessel and kept immersed for 1 minute. After 1 minute, the bucket was lifted to drain the toluene under gravity and immersed into the second vessel for another 2 minutes. This process was repeated for the third and fourth vessels with a soaking period of 3 minutes and 60 minutes, respectively.
- The solution obtained from all four vessels was then transferred to a centrifuge pump for the removal of fines.
- Finally, the bitumen was recovered from the filtered solution through a rotary evaporator according to EN 12697-3.

The rest period for each bucket was determined by preliminary trials to ensure that an approximately equal quantity of bitumen is recovered in each layer and the quantity of loose asphalt and toluene were selected to ensure complete immersion of asphalt, which is dependent on the soaking vessel and mesh bucket dimensions.

3.2. Digital image correlation

The basic principle of DIC is to track the same pixel points located in various deformed images. In this study, a high-resolution camera was used along with the semi-circular bend test setup as shown in Fig. 3.1 b to measure the full-field strain and analyse the crack propagation in the specimen. The exposure and focus were set manually at the beginning of each test to have the optimum brightness for measurement. During the test progress, the images were captured at a rate of 1000 frames/second. After the test completion, the post-processing of recorded data was done using Imetrum's Video Gauge™ program. The virtual strain gauges were placed at the tip of the notch to determine the horizontal strain (see Fig. 3.1 a).



(a) (b)

Fig. 3.1. (a) Virtual strain gauge placement; (b) schematic arrangement of components in digital image correlation setup

3.3. Analysis of Fourier transform infrared spectroscopy

The chemical functionalities in bitumen can be identified based on absorption intensities using FTIR spectroscopy. As shown in Fig. 3.2, a distinct peak for rejuvenator was observed around 1740 cm^{-1} on FTIR spectra. Thus, the tangential area around 1720 cm^{-1} to 1760 cm^{-1} was calculated for all the bitumen samples and divided by reference group area (1400 cm^{-1} to 1470 cm^{-1}) to define a new term known as the rejuvenation index (I_R).

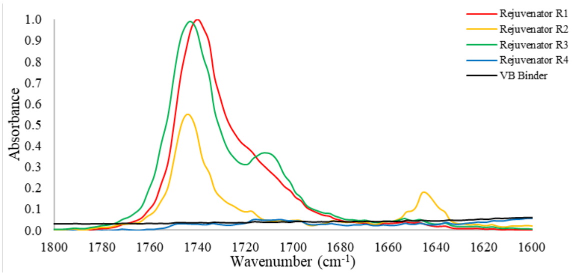


Fig. 3.2. Normalised FTIR spectra for all the rejuvenators used in this study

4. STUDY OF MIXING PARAMETERS

The chapter describes the results and analysis of study on the effect of mixing parameters on mechanical properties of high RA content mixtures produced in the laboratory. The laboratory experiments designed for this study can be divided into two stages which are illustrated in Fig. 4.1. The first stage is to evaluate the mechanical properties of asphalt mixtures, and the second stage comprises rheological and chemical characterization of the extracted binder.

Two fractions of reclaimed asphalt (RA 0/11 and RA 11/22), originating in Switzerland, virgin aggregates, and 70/100 penetration grade bitumen (5.5 % by weight of the mixture), and tall oil-based rejuvenator with a dosage of 4.8 % were used to prepare 60 % RA mixtures with AC-16 surface mixtures. For mixture evaluation, indirect tensile strength test and stiffness modulus tests were used, and dynamic shear rheometer and Fourier transform infrared spectroscopy analysis were used for binder characteristics.

The nomenclature of mixtures was based on mixing parameter, e.g., rejuvenation method (Spray- 2 hours/24 hours: Rejuvenator sprayed on rejuvenator followed by a rest period of 2 hours/24 hours; Blended: Rejuvenator blended into the virgin binder; Unrejuvenated: No rejuvenator); mixing time (2 min, 4 min, 7 min); mixing temperature (130°C, 155°C, 180°C); and type of mixer equipment (Small and Large mixer).

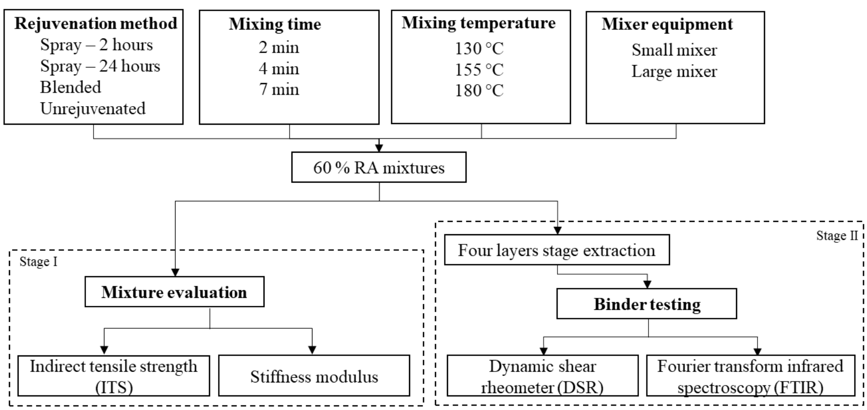


Fig. 4.1. Experimental plan

4.1. Volumetric results

The volumetric analysis test results are summarized in Table 4.1. The air void in *Spray – 2 hours* mixture was 33.1 % higher and in *Spray – 24 hours* mixture was 19.9 % higher than in the *Blended* mixture. Also, the air void was slightly reduced by increasing the mixing time from *2 min* to *4 min.* The increase in mixing time from 2 min to 4 min might have improved the homogeneity of mixture and resulted in enhanced compaction. Additionally, an increase in mixing temperature resulted in a reduction of air voids in the mixture.

The Tukey-Kramer groupings for the mixing temperature show that there is a substantial effect on compaction characteristics when the mixing temperature is increased above 155 °C. The air void for the mixture produced in the *Small mixer* was significantly lower than the mixture produced in the *Large mixer.* As all other parameters were the same for both mixtures, this difference in air voids indicates that the degree of blending between the RA binder and virgin binder can change with the type of mixing equipment used for mixing.

Table 4.1

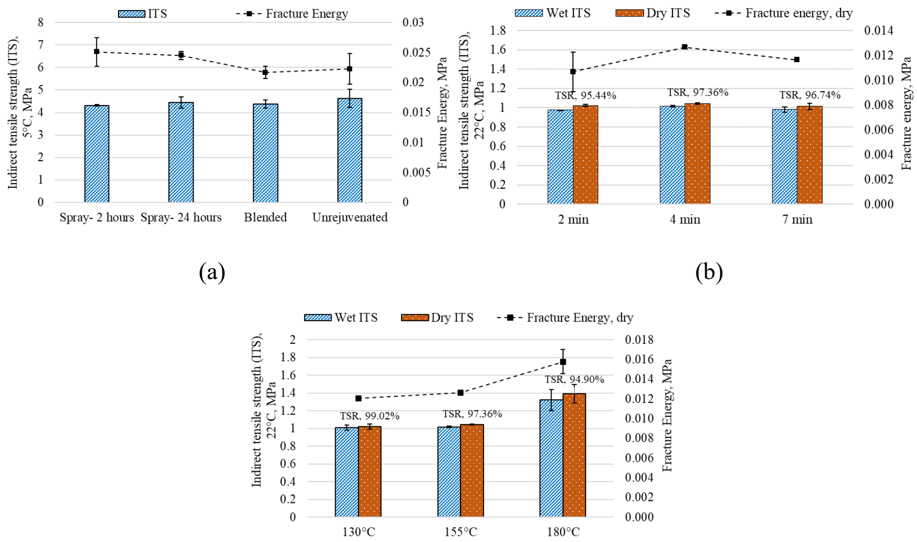
Volumetric Properties of Mixtures

Mixtures	Air voids, %	VMA, %	VFB, %	Tukey-Kramer group
Rejuvenation methods				
Spray – 2 hours	2.7	16.0	83.5	A
Spray – 24 hours	2.4	15.7	84.8	A
Blended	2.0	15.3	87.0	A
Unrejuvenated	1.8	15.1	88.0	A
Mixing time				
2 min	3.3	16.4	80.1	A
4 min	2.8	16.1	82.7	A
7 min	2.9	16.1	81.9	A
Mixing temperature				
130 °C	3.1	16.3	80.9	A
155 °C	2.8	16.1	82.7	A
180 °C	2.1	15.4	86.6	B
Mixer equipment				
Small mixer	2.0	15.3	87.0	A
Large mixer	2.8	16.1	82.7	B

4.2. Indirect tensile strength (ITS) test

The results of the indirect tensile strength test for different rejuvenation methods are shown in Fig. 4.2 (a). None of the rejuvenation methods was observed to be affecting the indirect tensile strength of the mixtures. *Spray – 2 hours* and *Spray –24 hours* showed slightly higher fracture energy compared to the remaining mixtures, which could be related to higher activation of aged RA binder for the case when the rejuvenator was sprayed directly over the RA material as opposed to blending the rejuvenator into the virgin binder.

The results of the indirect tensile strength test for different mixing times are shown in Fig. 4.2 (b). The mixing time also did not show any effect on the indirect tensile strength for dry as well as wet conditioned specimens. The high TSR ratios for all the mixtures indicate very low moisture damage in these mixtures. The results of the indirect tensile strength test at 22 °C for different mixing temperatures are shown in Fig. 4.3 (c). It can be observed that the mixture produced at 180 °C resulted in a higher ITS value compared to other mixtures, and the ITS values for 130 °C and 155 °C mixtures were not much different. This shows that the mixture stiffness increases substantially as a result of excessive oxidation when the temperature is raised above 155 °C.



(c)

Fig. 4.2. ITS results for different (a) rejuvenation methods; (b) mixing time; (c) mixing temperature. The error bars indicate one standard deviation.

4.3. Stiffness modulus of asphalt mixture

Stiffness modulus test was conducted to evaluate the change in stiffness of the mixture by varying the mixing parameters. A higher stiffness modulus value indicates higher stiffness of the mixture. It is clear from Fig. 4.3 (a) that all the three mixtures containing rejuvenator were less stiff as compared to the *Unrejuvenated* mixture. The rejuvenator had a softening effect on the binder and reduced the stiffness of the mixture. Figure 4.3 (b) shows that the increase in mixing time did not have any effect on the stiffness modulus of the mixtures. Concerning the effect of mixing temperature, Fig. 4.3 (c) shows that in the intermediate stiffness zone, all the mixtures were significantly different and the increase in temperature has resulted in a higher stiffness due to increased oxidative aging. Figure 4.3 (d) shows that the stiffness modulus values for the *Small mixer* were higher than for the *Large mixer*. However, the difference was not substantial for all the stiffness zones.

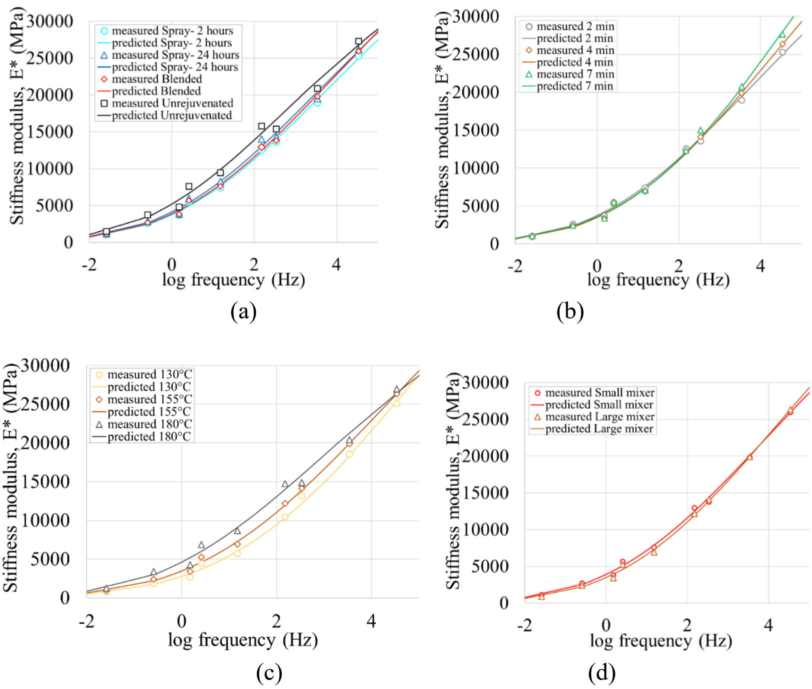


Fig. 4.3. Stiffness modulus mastercurves for different (a) rejuvenation methods; (b) mixing time; (c) mixing temperature; (d) mixing equipment

4.4. Complex modulus of binder

The average complex modulus of four layers was tested to see the overall effect of the rejuvenation method, as shown in Fig. 4.4 (a). The spraying of rejuvenator has resulted in lower overall bitumen stiffness (see *Spray -– 2 hours* and *Spray – 24 hours*) mixtures as compared to the *Blended* mixture. This may indicate that the softening effect of the rejuvenator was higher when the rejuvenator was sprayed. As shown in Fig. 4.4 (b), an increment in mixing temperature shifted the mastercurve upwards, indicating increased overall aging of the bitumen, which also agrees with the mixture test results. Mixers with internal heating are normally considered superior compared to small unheated mixers. It can be seen in Fig. 4.4 (c) that the *Small mixer* resulted in homogenous stiffness throughout the four binder layers, while as seen in Fig. 4.4 (d), the layers from the *Large mixer* have a much higher stiffness range. This may indicate an incomplete blending of virgin and RA bitumen.

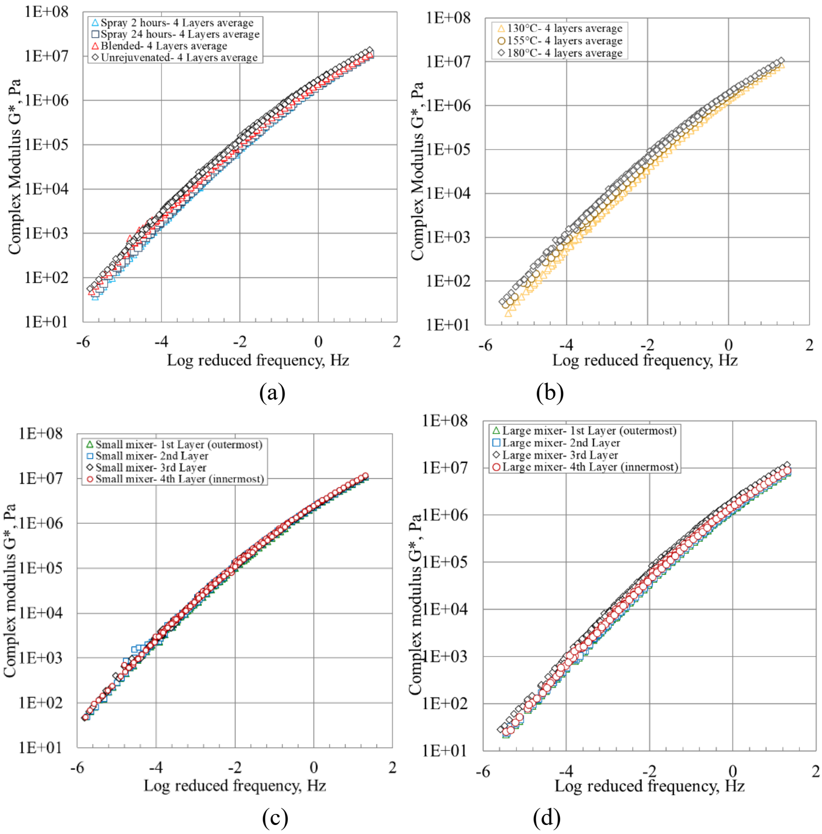


Fig. 4.4. Average complex modulus for different (a) rejuvenation methods and (b) mixing temperatures; and complex modulus for four binder layers in (c) Small mixer and (d) Large mixer

4.5. FTIR Characterisation

Carbonyl index is an indicator of the degree of aging in bitumen. It can be observed in Fig. 4.5 (a) that all the rejuvenated mixtures show lower carbonyl indices compared to the *Unrejuvenated* mixture except for the innermost layer. This could be due to chemical changes in the binder that occurred because of the rejuvenator addition. Figure 4.5 (b) shows that the presence of the rejuvenator was detected in all the layers (indicated by I_R values) of different mixtures except for the *Unrejuvenated* mixture (where $I_R \approx 0$).

As in Fig. 4.5 (c), except for the outermost layer, the carbonyl index for the 180 °C mixture, was found to be lower compared to the 130 °C and 155 °C mixtures. The presence of two different binders may be one of the reasons why the carbonyl index did not increase with increasing mixing temperature.

In Fig. 4.5 (e), the carbonyl indices for the *Small mixer* were significantly higher compared to the *Large mixer*. The higher index may be an indication of excess oxidative aging in *Small mixer* due to the open mixing system. As seen in Fig. 4.5 (f), the rejuvenation indices for the *Small mixer* were slightly higher compared to the Large mixers for all the layers except the innermost layer. Although the rejuvenation index was able to indicate the presence of rejuvenator in the bitumen, the earlier described complications of this analysis indicate that the rejuvenation index may not necessarily correspond to the quantity of rejuvenator present in the bitumen.

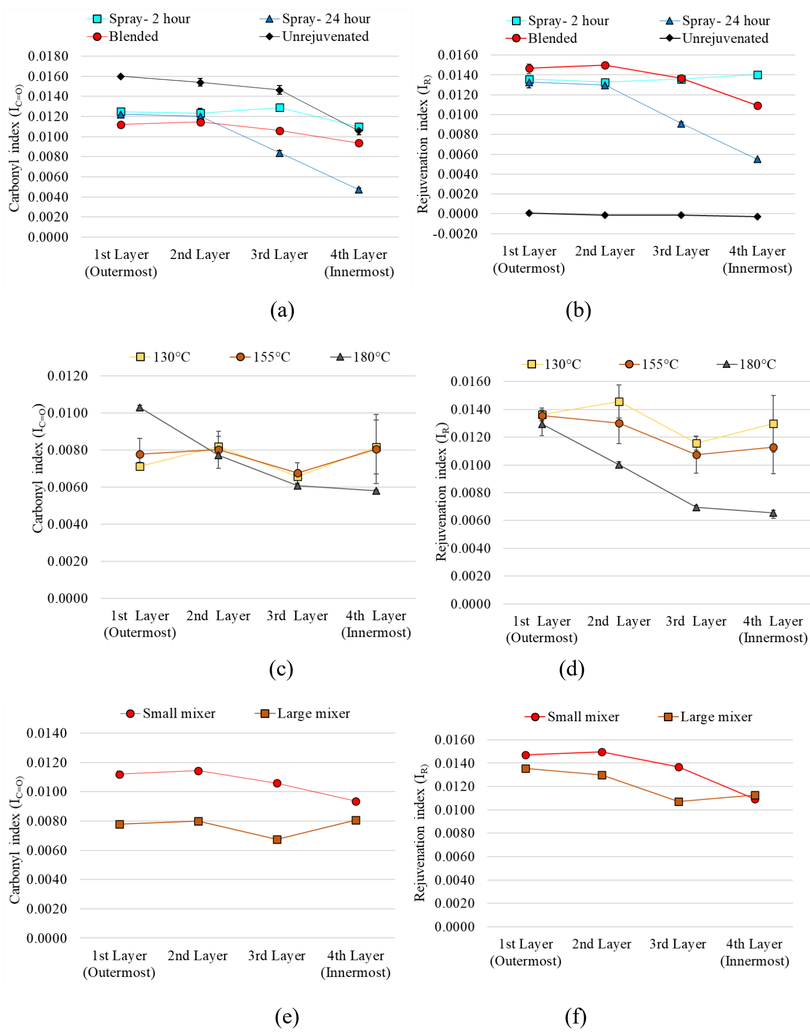


Fig. 4.5. Indices calculated from the FTIR spectra analysis for different rejuvenation methods, mixing temperatures, and mixer equipment

5. WARM MIX ASPHALT USING HIGH CONTENT RECLAIMED ASPHALT

This chapter describes the results of the study that compares the performance of conventional HMA mixture with WMA containing 60 % of reclaimed asphalt (RA). The experimental plan developed for this study is shown in Fig. 5.1. The RA material for this study was obtained from the asphalt plant in Vangaži, Latvia, and the virgin binder was a 50/70 penetration grade bitumen obtained from ORLEN Asfalt, Mazeikiai, Lithuania. A chemical additive with the supplier's recommended dosage of 0.4 % w/b was used for all the WMA mixtures.

The optimum binder content was determined as 5.5 % by weight of aggregates using the Marshall mix design method. All the mixtures were produced using two conditioning methods to compare the unaged mixture to short-term aged mixtures. For simulating short-term aging, the mixtures were conditioned in an oven with a covered pan for 4 hours according to the EN 12697-52 standard. HMA mixtures were conditioned at a temperature of 135 °C, and WMA mixtures were conditioned at 120 °C. It should be noted that 'WMA' refers only to the mixtures that are produced using the chemical additive, and the nomenclature of mixtures is explained in Fig. 5.2.

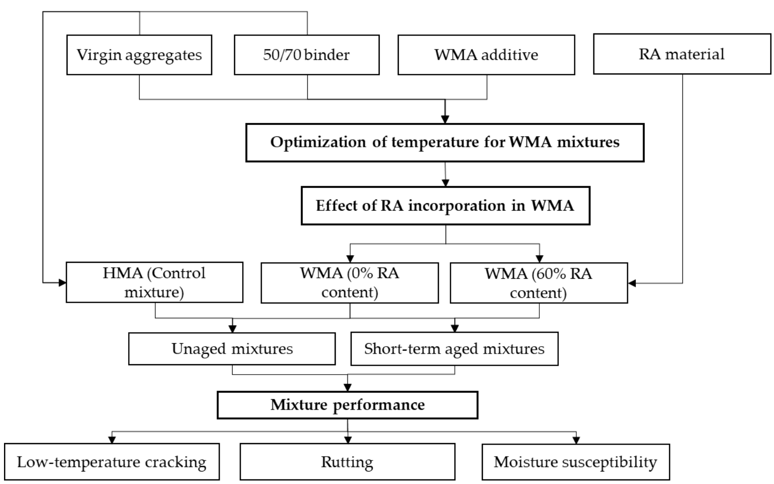


Fig. 5.1. Experimental plan

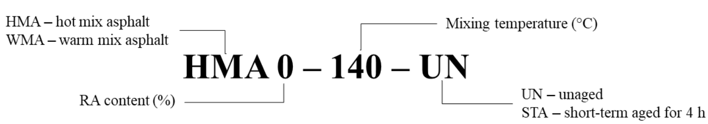


Fig. 5.2. Nomenclature of mixtures

5.1. Volumetric analysis

The volumetric analysis test results for all the mixtures are given in Fig. 5.3. The *WMA0-140-UN* mixture showed lower air voids as compared to the *HMA0-140-UN* mixture. In this case, the incorporation of additive without changing the temperature enhanced the compactibility of the mixture. This was an expected observation, as the chemical additives are well known to improve the coating, workability, and compactibility of mixtures.

WMA0-*125-UN* showed higher air voids than *WMA0-140-UN*, and the WMA0-110-UN mixture showed higher air voids than the *WMA0-125-UN* mixture. The reduction in mixing temperature of WMA mixtures showed an increase in air voids in the mixture due to the fact that with the reduction in temperature, the viscosity of bitumen is increased and compactibility is reduced. Only the *WMA0-125-UN* mixture meets the requirement for the air voids among all WMA mixtures for the Latvian Road specifications. Based on these results, the optimum mixing temperature for WMA mixtures was selected – 125 °C.

The *WMA60-125-UN* mixture showed 0.8 % lower air voids as compared to the *WMA0-125-UN* mixture, and the *WMA60-125-STA* mixture showed 0.6 % lower air voids as compared to the *WMA0-125-STA* mixture. This shows that the incorporation of the 60 % RA material into WMA resulted in reduced air voids in the mixture.

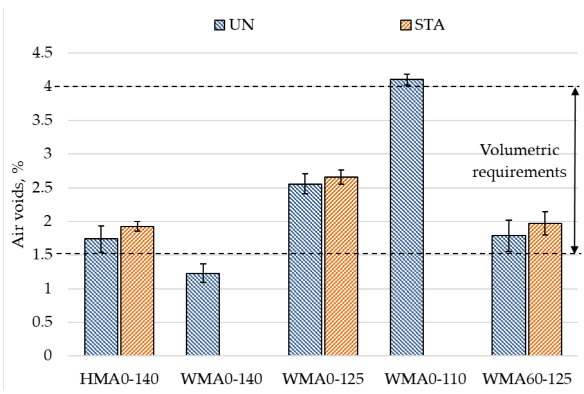


Fig. 5.3. Volumetric analysis results

5.2. Low-temperature performance

A lower fracture temperature indicates better performance in low-temperature cracking. It can be observed that WMA mixtures (*WMA0-125-UN* and *WMA0-125-STA*) showed lower cracking temperature (1.9 °C and 1.55 °C lower) than HMA mixtures (*HMA0-125-UN* and *HMA0-125-STA*) mixtures. This indicates that WMA mixtures are more resistant to low-temperature cracking compared to HMA mixtures.

The incorporation of 60 % RA material has substantially degraded the low-temperature cracking resistance of WMA mixtures. *WMA60-125-UN* and *WMA60-125-STA* mixtures showed significantly lower cracking temperatures (3.6 °C and 5.9 °C, respectively) compared to *WMA0-125-UN* and *WMA0-125-STA* mixtures. This is due to the presence of stiff oxidized binder from RA material that is ultimately making the mixture more brittle.

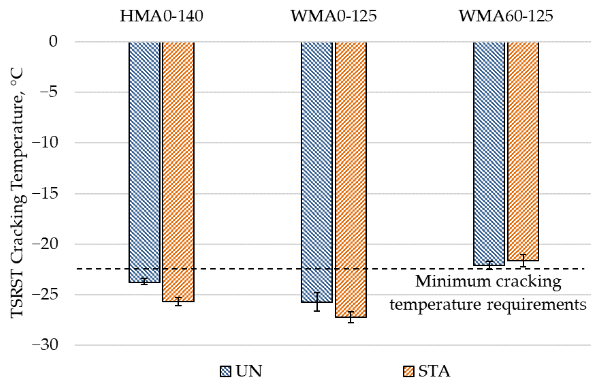


Fig. 5.4. Results of low-temperature cracking test

5.3. Rutting performance

It can be observed in Fig. 5.5 that the proportional rutting depth for the *WMA0-125-UN* mixture was 8.4 % higher compared to the rut depth in *HMA0-140-UN* mixture. The reduced stiffness of mixture due to binder modification increased the rutting susceptibility in WMA compared to HMA.

The incorporation of 60 % RA material increased the rutting depth by 6.8 % in the WMA mixture. This is opposite to the general trend, as the RA material is known to improve the rutting resistance. The reason for the lower rutting resistance of RA mixture could be the lower flow coefficient for fine RA aggregates compared to the fine aggregates in the virgin mixture. For the virgin WMA mixture, the rutting depth was considerably reduced on short-term aging to a level equal to that of the control HMA mixture. Further, only short-term aged WMA mixtures fulfilled the proportional depth rutting criteria set in the SJSC "Latvian State Roads" specifications.

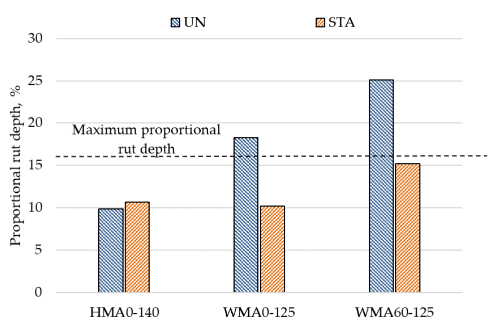


Fig. 5.5. Proportional rut depth results

5.4. Moisture susceptibility

It can be seen in Fig. 5.6 that indirect tensile strength for all the mixtures has not significantly changed after the moisture conditioning. This shows that reduction of temperature in WMA did not have any adverse effect on moisture performance of mixtures. As a result, all the mixtures fulfilled the minimum tensile strength ratio (TSR) criteria of 80 %.

The WMA mixture containing 60 % RA material (*WMA60-125*) showed a 74 % higher dry ITS and 70 % higher wet ITS compared to the virgin WMA mixtures. This is due to the presence of the oxidized binder of the RA material that made the mixture stiffer and increased the indirect tensile strength of the mixture. The incorporation of RA material did not show a significant change in moisture susceptibility of WMA mixtures.

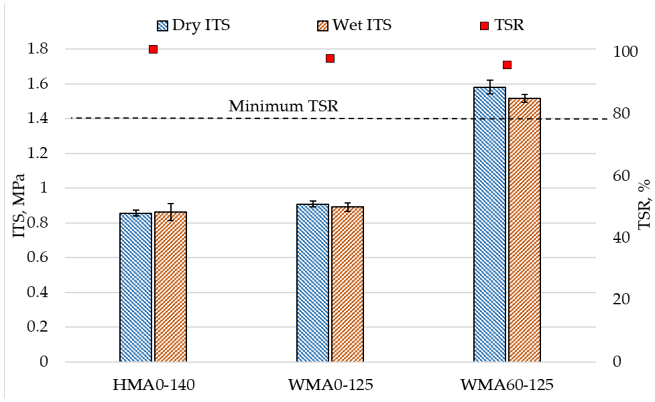


Fig. 5.6. Moisture susceptibility results

6. REJUVENATOR AGING STUDY

This chapter describes the study on evaluation of changes in rheological and chemical properties of bitumen after aging simulation in 100 % reclaimed asphalt mixtures containing different rejuvenators. The experimental plan is shown in Fig. 6.1. The RA material was obtained from an asphalt plant in Vangaži, Latvia, and the virgin binder was a 50/70 penetration grade bitumen obtained from ORLEN Asfalt, Mazeikiai, Lithuania. The 100 % RA mixtures were designed to target the AC-16 gradation from the SJSC "Latvian State Roads" specifications.

Four commonly used commercial recycling agents, including one tall oil-based rejuvenator (R1), one vegetal oil and polymer-based rejuvenator (R2), one bio-oil-based rejuvenator (R3), and one petroleum-based rejuvenator (R4) were used in this study. The supplier's recommended dosage for all the rejuvenators was approximately 5 % w/b of the RA binder.

The field aging simulation was conducted on loose mixtures. Finally, the binder was extracted from all the mixtures and total of 12 bitumen samples with different rejuvenators, and aging conditions were obtained from mixtures. For reporting the results, the bitumen samples were identified based on their respective aging condition (VB – virgin bitumen, UN – unaged, STA – short-term aged, or LTA – long-term aged) and type of rejuvenator (R1, R2, R3, or R4).

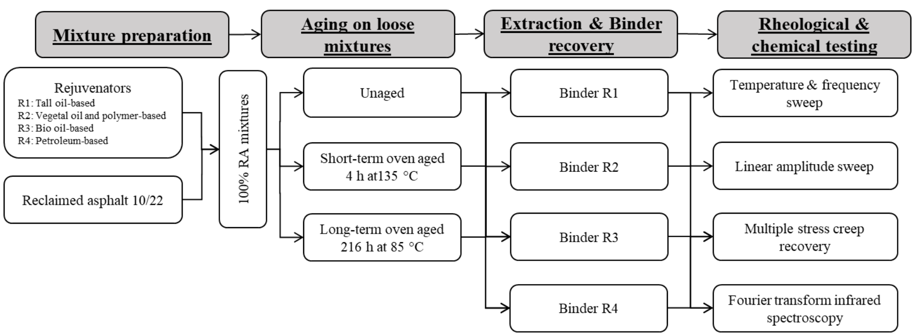


Fig. 6.1. Research plan

6.1. Complex modulus of binder

An increase in complex modulus indicates the stiffening of bitumen, which occurs due to increase in the asphaltenes/maltenes ratio in bitumen with aging. The effect of simulating the aging on mixtures can be seen from the increase in complex shear modulus over a wide range of frequencies (see Fig. 6.2). It is also seen that the increase in complex modulus with aging is more prominent at low frequencies (or high temperatures) as compared to high frequencies (or low temperatures) for all the bitumen, except for the R4. This may indicate that in the long term, most rejuvenators (tall oil-based, vegetal oil and polymer-based, and bio-oil-based) benefit more the low-temperature performance by causing less change in the stiffness of bitumen at low temperatures. The rejuvenator used in R4 was petroleum-based and was less effective in improving the long-term low-temperature performance compared to other rejuvenators used in this study.

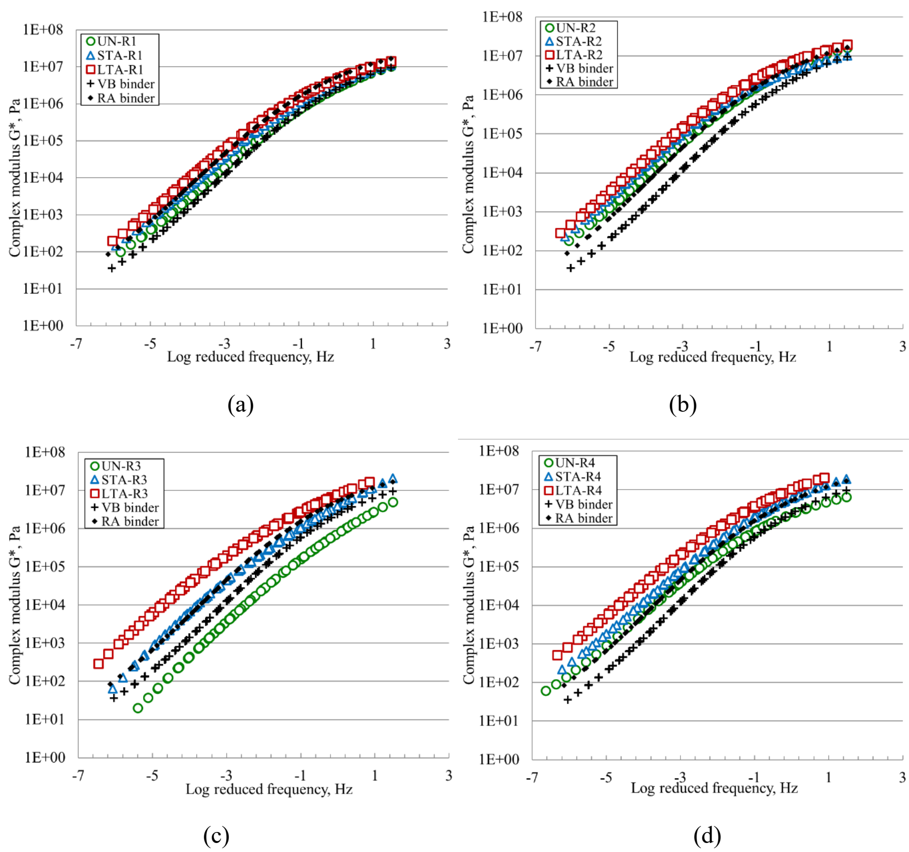


Fig. 6.2. Complex modulus mastercurves at 20 °C for binder (a) R1; (b) R2; (c) R3; (d) R4

6.2. Fatigue resistance of binder

It can be seen in Table 6.1 that fatigue lives for all the unaged bitumen samples (except UN-R3) were higher than for the virgin binder at both the strain levels. This was due to higher stiffness achieved in unaged bitumen samples compared to virgin bitumen that benefitted their fatigue life. The softening achieved in the binder modified using rejuvenator R3 was higher compared to the virgin binder, as a result the fatigue life of UN-R3 turned out to be lower at various strain levels.

After short-term aging, all four bitumen samples showed higher fatigue life compared to the unaged state, at both 2.5 % & 5 % strain levels. After long-term aging, the fatigue life for R2 and R4 was reduced, while the fatigue life for R1 and R3 was increased. This could indicate that tall oil-based (R1) and bio oil-based (R3) rejuvenators are more beneficial for long-term fatigue performance of bitumen compared to vegetal oil & polymer-based (R2) and petroleum-based (R4) rejuvenators.

Table 6.1

Predicted Fatigue Life in VEDC Model for 2.5 % and 5% Strain Levels

Binder	UN		STA		LTA	
	2.5 % N_f	5 % N_f	2.5 % N_f	5 % N_f	2.5 % N_f	5 % N_f
VB Binder	41,812	4898	×	×	×	×
R1	76,546	8414	97,508	9125	129,223	10,652
R2	106,019	9073	168,539	12,494	135,006	9502
R3	19,535	2993	82,058	8523	181,708	10,433
R4	112,143	10,835	199,611	11,875	134,771	7767

6.3. Permanent deformation of binder

The results of non-recoverable creep compliance from multiple stress creep recovery test at 3.2 kPa stress level are shown in Fig. 6.3. Lower values of non-recoverable creep compliance (J_{nr}) in bitumen indicate better rutting performance of the mixtures. In unaged (UN) conditions, R1 and R3 showed considerably higher J_{nr} values compared to the remaining two bitumen samples. Therefore, the bitumen samples modified using tall oil-based (R1) and bio-oil-based (R3) rejuvenators may be more susceptible to rutting compared to other binders in unaged conditions.

However, J_{nr} for R1 and R3 was almost equal to that of J_{nr} of virgin bitumen, which indicates that these bitumen samples in unaged condition may show the same rutting performance as that of the virgin binder. The short-term aging (STA) of mixtures has considerably reduced the J_{nr} value, which indicates that the oxidation of bitumen during short-term aging can considerably improve the high-temperature deformation resistance. After long-term aging, a further reduction in J_{nr} values shows that these binders have undergone excessive stiffening that led to increased rutting resistance of bitumen.

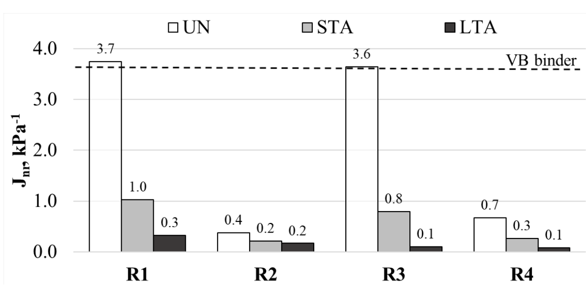


Fig. 6.3. Non-recoverable creep compliance (J_{nr}) from the multiple stress creep recovery test at 60 °C

6.4. Chemical characterisation of bitumen

It can be seen in Table 6.2 that carbonyl index values for all the unaged rejuvenated binders were higher than the carbonyl index of virgin binder (0.1). The higher index for these samples indicates a higher binder aging level in these samples due to the presence of reclaimed asphalt binder. After short-term aging, the binder is more oxidized and is expected to show an increase in carbonyl index. Surprisingly, after short-term aging, the carbonyl index for all the bitumen samples decreased. The difference may be either due to material variability or it is possible that the short-term aging of binder was not enough to show a considerable increase in carbonyl peak intensity.

After the long-term aging, the carbonyl indices of all the bitumen samples were increased as compared to short-term aged samples. This indicates that after long-term aging, a considerable increase in carbonyl peak intensity occurs. However, when comparing to unaged bitumen samples, R1, R3, and R4 showed slightly higher, but R2 showed equal, carbonyl index in long-term aged bitumen. These inconsistencies may indicate that carbonyl peaks could also be affected due to the presence of rejuvenator in the binder.

Table 6.2

Calculation Results of Carbonyl Indices from Normalized Spectrum

Material	Aging state	Average carbonyl index ($I_{C=O}$)	SD	Average sulphonyl index ($I_{S=O}$)	SD
VB	UN	0.10	0.005	1.20	0.108
R1	UN	0.20	0.009	1.93	0.364
	STA	0.17	0.018	1.56	0.045
	LTA	0.22	0.004	1.69	0.010
R2	UN	0.18	0.017	1.71	0.164
	STA	0.17	0.003	1.40	0.020
	LTA	0.18	0.004	1.57	0.031
R3	UN	0.18	0.007	1.57	0.075
	STA	0.17	0.004	1.69	0.063
	LTA	0.23	0.063	1.64	0.301
R4	UN	0.16	0.003	1.47	0.025
	STA	0.11	0.005	2.46	0.035
	LTA	0.18	0.017	1.65	0.049

6.5. Horizontal dynamic surface leaching test

The change in pH values during the horizontal dynamic surface leaching test for all the 100 % RA mixture containing various rejuvenators are shown in Fig. 6.4. The results show that there was no significant difference in pH values for different mixtures. The pH values at Day 64 were between 8.28–8.35 for all the asphalt mixtures. The electrical conductivity for UN-R1, UN-R2, UN-R3, and UN-R4 samples was in the range of 304–561, 389–721, 336–597, and 380–755 µS/cm, respectively, at different time intervals.

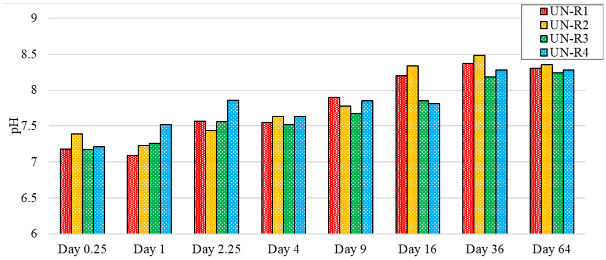


Fig. 6.4. pH value of leachant samples during the horizontal dynamic surface leaching test

7. PERFORMANCE OF 100 % RECYCLED MIXTURE

This chapter describes the study on the evaluation of rutting and fracture performance of 100 % reclaimed asphalt mixtures produced using three different rejuvenators and comparing it with a conventional hot mix asphalt. Another goal of this study was to measure the strain on the surface of the asphalt specimens using a non-contact digital image correlation setup and examine the correlation between optical horizontal strain and conventional energy parameters in fracture tests.

100 % RA mixtures were designed to fulfil AC-16 mixtures requirements of SJSC "Latvian State Roads" specifications. The virgin bitumen used in this study was a 70/100 bitumen obtained from ORLEN Asfalt, Mazeikiai, Lithuania. Three commonly used commercial rejuvenators, including one tall oil-based (referred to as R1 in the rest of the paper), one vegetal oil & polymer-based (R2), and one bio-oil-based (R3) were used for 100 % reclaimed asphalt mixtures in this study. The same dosage of 5 % was used for all three rejuvenators to produce the mixtures, as this was also the approximate dosage recommended from all the three rejuvenator suppliers.

7.1. Rutting performance

Table 7.1 shows the wheel tracking test results for 100 % RA mixtures with three different rejuvenators (R1, R2, & R3) along with the control HMA mixture (C). Both R1 and R2 mixtures showed poor rutting resistance and reached the maximum rut depth after 2650 and 4750 cycles, respectively. On the other hand, the R3 mixture showed somewhat better rutting resistance than the above mixtures and failed after undergoing 7350 cycles. Notably, the control mixture C completed the 10,000 loading cycles and showed significantly higher rutting resistance than all the 100 % RA mixtures.

For mixtures where the test was terminated before reaching 10,000 cycles, the wheel tracking slope was calculated from the linear part of the rut depth curve according to EN 12697-22. Since wheel tracking slope is calculated for the development of rut depth between 5,000 and 10,000 cycles, it excludes the initial consolidation and takes into account the deformation during the secondary stage of the test. The ranking of mixtures from the wheel tracking slope remains the same as obtained from the number of cycles.

Table 7.1

Wheel Tracking Test Results

Mixture	Average number of rutting cycles	Average rut depth at the end of rutting cycles, mm	Wheel tracking slope, mm/1000 cycles	Average air voids, %
R1	2650	19.42	4.28	2.6
R2	4750	19.74	2.39	1.7
R3	7350	16.28	1.46	3.5
C	10000	7.97	0.36	5.2

In this study, the flow coefficient of fine aggregates in RA material was lower as compared to the virgin aggregates mixtures. The presence of round aggregates in the RA material could be the reason for poor rutting resistance of 100 % RA mixtures. Another reason could be that the rejuvenator content was not optimized for the mix design, and hence a lower rejuvenator content could possibly reduce the rutting susceptibility.

7.2. Fracture toughness

Figure 7.1 shows the mean values of load vs displacement results for all the mixtures obtained from the fracture toughness test as per AASHTO TP 124-16 standard. The curves for all the mixtures show a higher peak load achieved at a loading rate of 50 mm/min compared to 5 mm/min, which is because the mixtures behave stiffer at higher loading rates. The peak load was highest for R2 at both loading speeds. In addition to fracture energy, a parameter known as flexibility index (FI), which takes into account the slope of the shape of the curve, was calculated.

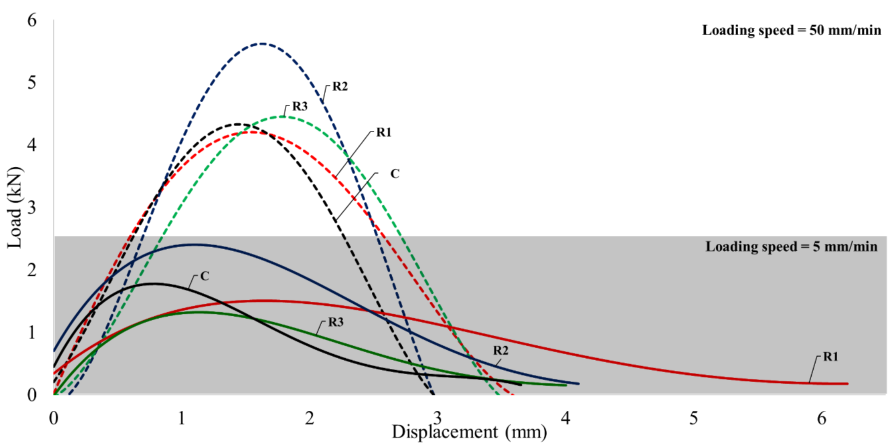


Fig. 7.1. Load vs displacement curve for semi-circular bend test at 5mm/min

At 5 mm/min loading rate, as shown in Fig. 7.2, the pre-peak work and post-peak work for R2 was highest among all the mixtures. Compared to R2, the average pre-peak work was 27 % lower in R1 and 43 % & 46 % lower in R3 and C, respectively. Similarly, compared to R2, the average post-peak work was 11 % lower in R1 and 40 % & 48% lower in R3 and C, respectively. The highest fracture toughness for R2 among all the 100 % mixtures is attributed to the softening effect of vegetal oil & polymer-based rejuvenator, and it is also a widely known fact that polymers improve the fracture toughness properties of asphalt mixtures.

In the 50 mm/min loading speed test, as shown in Fig. 7.3, the average pre-peak work for R2 was highest among all the mixtures, which is similar to observation at the 5 mm/min loading rate test. However, the average post-peak work for R2 was lowest among all the mixtures, which might be indicating a higher speed of crack propagation after failure in this mixture. It can be seen in Fig. 7.3, that the flexibility index for mixtures ranks in the following order: R1 > R3 >

> R2 ≈ C. From this observation, it can be attributed that the R1 mixture containing tall oil-based rejuvenator may possess the highest cracking resistance. Surprisingly, R2 shows the lowest flexibility index among 100 % RA mixtures, which indicates that the binder replacement using this vegetal & polymer-based rejuvenator improves the toughness value but may reduce the overall cracking resistance in the mixtures.

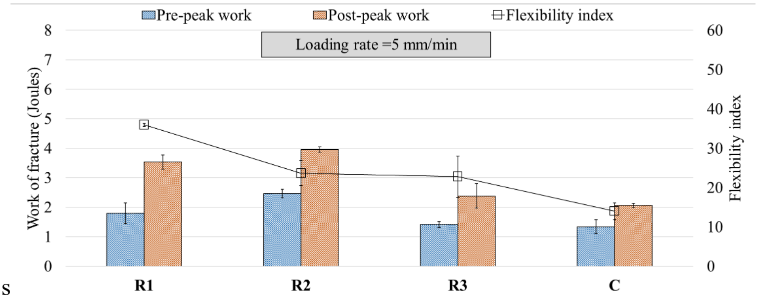


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Fig. 7.2. Work of fracture and flexibility index for all the mixtures at 5 mm/min loading speed. The error bars represent the range.

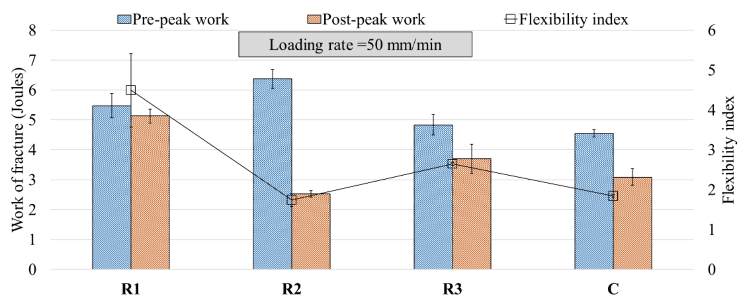


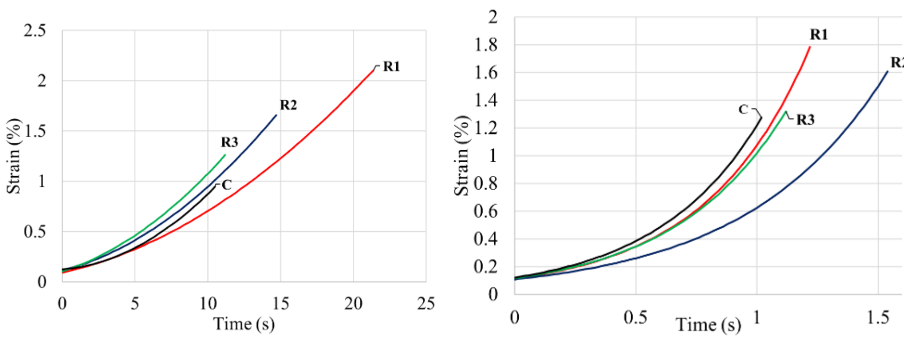
Fig. 7.3. Work of fracture and flexibility index for all the mixtures at 50 mm/min loading speed. The error bars represent the range.

7.3. Digital image correlation (DIC) results

DIC was used to determine the distribution of stresses within the asphalt-binder system and investigate the correlation between optical measured strains and conventional indicators. A higher notch strain at peak loading indicates the ability of the material to undergo higher ultimate deformation before macrocracks formation, which in other terms represents higher flexibility of the mixture.

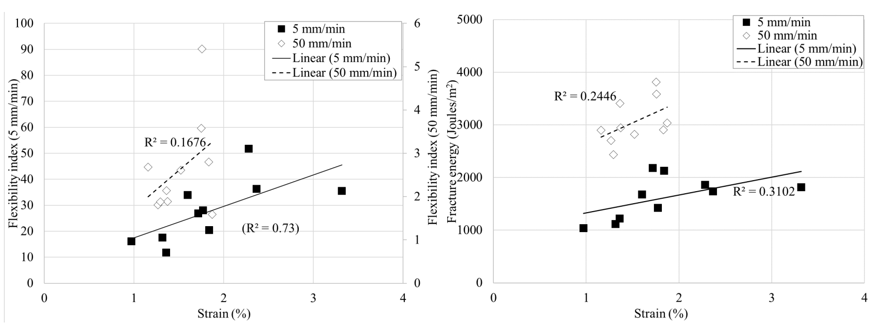
As shown in Fig. 7.4 (a), the ranking of mixtures based on mean horizontal strain values follows the order, R1 > R2 > R3 > C, for 5 mm/min loading rate. The average strain at peak loading for R1 was 2.1 %, which was higher compared to average strains in R2 (1.6 %), R3 (1.2 %), and C (0.9 %) mixtures. These results indicate higher flexibility of R1 mixture, which is consistent with the ranking of mixtures in flexibility index at 5 mm/min loading rate. As a result, a fair correlation (R^2 = 0.73) was observed between the horizontal notch strain and flexibility index at 5 mm/min loading rate, as shown in Fig. 7.5 (a).

For 50 mm/min loading rate, the ranking of mixtures based on mean horizontal strain values followed the same order as in the 5 mm/min loading rate, R1 > R2 > R3 > C, as shown in Fig. 7.4 (b). However, in this case, the horizontal strain showed poor correlation with both flexibility index and fracture energy, as shown in Fig. 7.5 (a), (b). One reason for this could be low precision in strain measurement in high-speed loading due to instant brittle fracture of the specimen.



(a) (b)

Fig. 7.4. Horizontal strain at the tip of notch in semi-circular bend test: (a) loading speed = 5 mm/min; (b) loading speed = 50 mm/min.



(a) (b)

Fig. 7.5. Correlation coefficient between the notch strain and fracture parameters

8. LIFE CYCLE ASSESSMENT FOR ASPHALT RECYCLING

This chapter describes the life cycle assessment study on the comparison of different alternatives of reclaimed asphalt pavements produced using warm mix additives & rejuvenators. The test plan for LCA study is described in Fig. 8.1. For WMA mixtures containing 70 % & 100 % reclaimed asphalt content (*70WMA* & *100WMA*), two traffic intensities (medium = 15 msa & high = 20 msa), two RA moisture contents (dry = 2 % & wet = 5 %), and two degrees of RA binder activations (DoA = 25 % & DoA = 75 %) have been considered, which gives a total of 2 × 2 × 2 × 2 = 16 cases. The virgin mixtures consist of conventional HMA and WMA with two traffic conditions giving a total of 2 × 2 = 4 cases. Therefore, in total, 20 cases will be evaluated for the LCA study. The nomenclature can be seen in Fig. 8.2. A process-based LCA will be conducted using SimaPro 9.2.0 to quantify the environmental impacts from following processes: material extraction, transportation, asphalt production, and construction. SimaPro is an analytical software used to measure the environmental footprint of products and services.

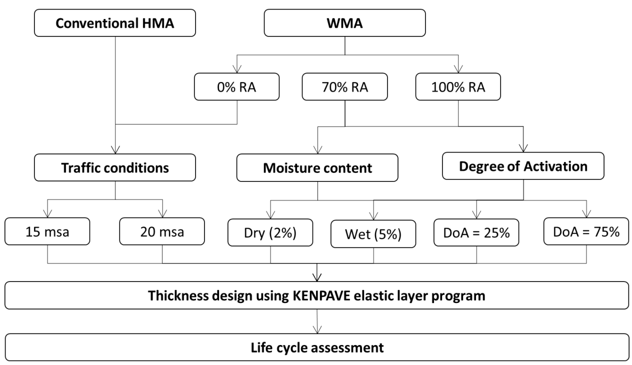


Fig. 8.1. LCA study plan

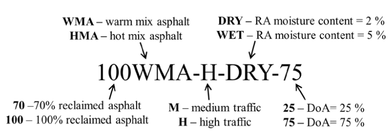


Fig. 8.2. Nomenclature of pavement scenarios

8.1. Functional unit & System boundary

In the current study, the functional unit is considered as 1 km of built pavement section with a width of 15 m and the thickness corresponding to respective traffic loading. The system boundary of this study is illustrated in Fig. 8.3. In this study, the processes associated with raw material extraction, transportation, asphalt production, and construction have been considered.

The pavement scenarios were designed using a mechanistic-empirical design approach, where the pavement section is analyzed for the critical response using linear elastic layered theory, and the thicknesses are selected based on the allowable number of load repetitions. In this study, KENPAVE was used to analyze the multilayered pavement system. The design traffic loading was considered in terms of the cumulative number of equivalent standard axle load of 80 kN, expressed in the unit of million standard axles (msa) repetitions. The rutting (N_R) and fatigue (N_f) life of the pavement was calculated using Equations (8.1) and (8.2), respectively, as given in given by IRC 37-2018 for 90 % reliability. The results of structural design for different design traffic are shown in Table 8.2.

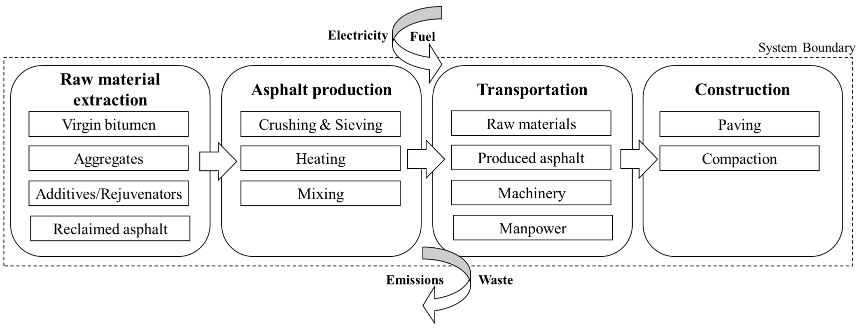


Fig. 8.3. System boundaries for pavement systems

$$N_R = 1.41 \times 10^{-8}[\frac{1}{\varepsilon_v}]^{4.5337} \quad , \tag{8.1}$$

$$N_f = 0.5161 \times C \times 10^{-4}\left[\frac{1}{\varepsilon_t}\right]^{3.89} \times \left[\frac{1}{M_{Rm}}\right]^{0.854} \quad , \tag{8.2}$$

$$C = 10^M \text{ , and } \quad M = 4.84\,(\frac{V_{be}}{V_a + V_{be}} - 0.69) \quad , \tag{8.3}$$

where ε_v is vertical tensile strain at the bottom of asphalt layer; ε_t is horizontal compressive strain at the top of subgrade; M_{Rm} is the resilient modulus of the bottom asphalt layer; V_{be} is the percentage of volume of effective bitumen in the mix; and V_a is the percentage of the volume of air voids in the mix.

Table 8.2

Pavement Thickness Design: M – 15 msa, H – 20 msa.

	HMA		WMA		70WMA		100WMA	
	Design thickness (mm)							
Traffic intensity	M	H	M	H	M	H	M	H
Surface course	40	40	40	40	40	40	40	40
Binder course	60	90	55	85	50	75	50	65
Aggregate interface layer	100	100	100	100	100	100	100	100
Cement treated base	100	100	100	100	100	100	100	100
Granular subbase	200	200	200	200	200	200	200	200
	Critical pavement response from KENPAVE and allowable traffic *(IRC:37-2018)*							
Tensile strain at bottom of BC (μ)	210.4	198.1	206.4	196.0	177.5	171.1	163.1	160.3
Maximum fatigue cycles (msa)	16	21	16	20	17	20	19	20
Compressive strain at top of subgrade (μ)	406.7	356.3	414.2	361.7	415.4	365.7	411.1	379.2
Maximum rutting cycle (msa)	33	61	31	57	30	54	32	46

8.2. Life cycle impact assessment

It can be seen in Fig. 8.4 that the highest reduction in global warming potential (23 % & 19 %) was observed for *100-WMA-DRY-25* and *100-WMA-DRY-25* mixture for medium traffic and high traffic intensities, respectively, due to zero use of virgin aggregates in these mixtures. An interesting observation from this analysis is that when the moisture content in RA material was high (5 %), the life cycle emissions from recycled mixtures (*70-WMA-WET* & *100-WMA-WET*) were almost similar to the WMA mixture without any RA material. Therefore, the high amount of energy required in drying the RA aggregates offsets the benefit gained in the transportation and raw material extraction stage.

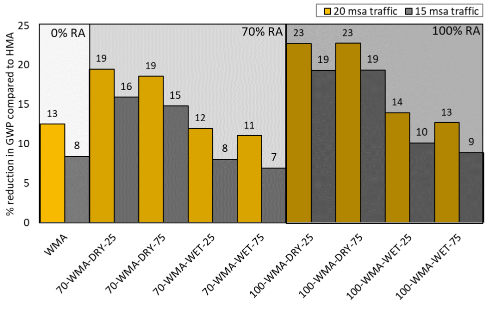


Fig. 8.4. Percentage reduction in GWP (kg CO_2 eq) compared to HMA mixture

Figure 8.5 shows that WMA mixtures due to their reduced production temperature showed a 10–13 % reduction in freshwater ecotoxicity potential compared to HMA mixtures. However, the maximum reduction was observed with RA incorporation content, which was in the range of 23–31 % for different mixtures (*70-WMA-DRY* & *100-WMA-DRY*). Interestingly, when high moisture content RA material was used, the 70 % & 100 % RA mixtures did not show a greater benefit (less than 5 %) in freshwater ecotoxicity reduction. This again highlights the importance of using a low moisture content RA material for life cycle benefits.

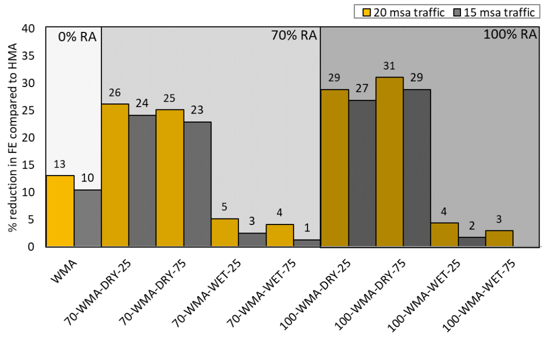


Fig. 8.5. Percentage reduction in freshwater ecotoxicity (kg 1,4-DB eq) compared to the HMA mixture

As seen in Fig. 8.6, WMA mixtures showed significant reduction (9–12 %) in human carcinogenic toxicity compared to the HMA mixture. However, the highest reduction (26–32 %) was observed with the incorporation of 70 % and 100 % RA material with low moisture content. The effect of degree of binder activation was highest for the 100-WMA mixture when the RA material was considered at lower moisture content. At lower DoA (25 %), the virgin binder requirement is higher to fulfill the binder content, but due to the presence of less active binder, less quantity of rejuvenator is required, when compared to higher DoA (75 %).

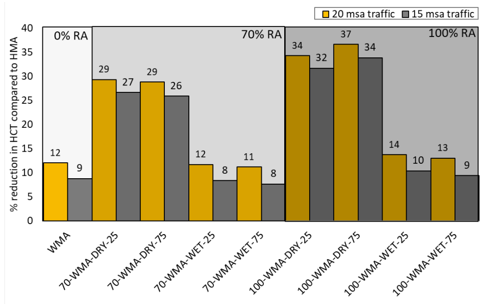


Fig. 8.6. Percentage reduction in human carcinogenic toxicity (kg 1,4-DB eq) compared to the HMA mixture

As seen in Fig. 8.7, the fossil resource scarcity was reduced by 5 % & 10 % with a 30 °C reduction in production temperature for medium traffic & high traffic scenario, but this difference is not very high when compared to benefits observed in previous categories like global warming potential, freshwater ecotoxicity, and human carcinogenic toxicity. The reason for this could be the added burden associated with additive production and transportation.

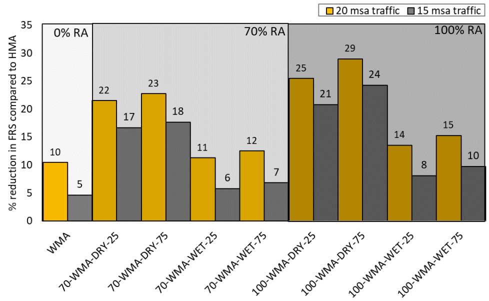


Fig. 8.7. Percentage reduction in fossil resource scarcity (in kg of oil eq) compared to the HMA mixture

CONCLUSIONS

The Thesis addresses major issues related to the design and evaluation of high content reclaimed asphalt mixtures containing rejuvenators. To optimize the laboratory mixing procedure of high content reclaimed asphalt mixtures, the most important mixing parameters were varied and their effect on mechanical and rheological properties of mixtures was evaluated. Further, the performance of recycled asphalt mixtures prepared using warm mix technology was compared to conventional asphalt mixtures. To evaluate the long-term impact of rejuvenators on reclaimed asphalt properties, the field aging simulations were conducted on recycled asphalt mixtures. The correlation between mechanical indicators and optically measured strains were also investigated. Lastly, the effect of reclaimed asphalt characteristics on the life cycle environmental impacts of pavement was evaluated. Based on the Thesis, the following conclusions can be drawn:

1. A laboratory mixing procedure for high content reclaimed asphalt mixtures was developed in this study, which ensures that the effect of mixing parameters on the performance is minimized and enables the reliable comparison of properties of high content reclaimed asphalt mixture composition. According to the developed mixing procedure, it is recommended to add the rejuvenator directly to the reclaimed asphalt. The heating and mixing of reclaimed asphalt must not be done above 155 °C, and a mixing time of 4 minutes is satisfactory for preparing the mixtures in the laboratory. Further, the type of mixer should be taken into consideration when comparing mixtures.
2. A 15 °C reduction in the heating and mixing temperature of asphalt was achieved using the given warm mix technology by optimizing the air voids in the range of 1.5–4 % specified in the Latvian standard. By incorporating 60 % of the reclaimed asphalt material into the warm mix asphalt, the air voids were reduced by 0.8 % and 0.6 % for unaged and short-term aged mixtures, respectively. The need for using a rejuvenator along with a warm mix additive was observed from the findings of this study to increase the blending and compensate for the aged binder.
3. An aging index based on complex modulus was developed in this study to compare the degree of aging of different bitumen samples. Based on long-term performance, the tall oil-based rejuvenator resulted in the lowest aging index value (3.10), and the petroleum-based rejuvenator resulted in the highest aging index value (8.27) among all four rejuvenators. The tall oil-based rejuvenator showed up to 37 % higher number of fatigue cycles at 5 % strain level, and the bio-oil based rejuvenator showed up to 41 % higher number of fatigue cycles at 2.5 % strain level compared to other rejuvenators.
4. Based on selected test completion criteria, the maximum rutting cycles for conventional HMA mixtures were higher by the range of 2630–7330 cycles compared to the 100 % reclaimed asphalt mixtures, depending on the type of rejuvenator. Compared to conventional HMA, all the 100 % reclaimed asphalt mixtures with rejuvenators showed 11–44 % higher fracture energy at 50 mm/min loading speed and 13–91 % higher fracture energy at 5 mm/min loading speed. Based on flexibility index values at 50

mm/min loading speed, the tall oil-based rejuvenator showed the highest fracture toughness among all the rejuvenators.

5. A life cycle assessment was conducted to evaluate the environmental benefits of recycled asphalt mixtures and to compare with conventional mixtures. Based on the results of global warming impact category, the asphalt production stage showed the highest impact, which was between 45–53 % of the total global warming impact, due to the high quantity of emissions released during this stage. The calculated emissions were reduced by up to 26 % with the incorporation of 70 % of the reclaimed asphalt, but it was shown that these benefits can be offset by extra emissions generated during the drying process of high moisture content reclaimed asphalt.

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