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HIGH RECLAIMED ASPHALT CONTENT MIXTURES: DESIGN PARAMETERS AND PERFORMANCE EVALUATION

Doctoral Thesis

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

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Doctoral thesis

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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)
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The Doctoral Thesis has been written in Latvian/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.

ANNOTATION

Asphalt mix is the most widely used material for pavement construction in the world. The conventional asphalt mix is produced using different sizes of aggregates that are sieved, dried, heated, and coated with hot bitumen to bind them together into a dense matrix. The production, construction, and maintenance of asphalt pavement involves high amount of energy consumption, exploits our natural resources, and emits various greenhouse gases in the atmosphere. Due to the above-mentioned environmental concerns, the asphalt industry is continuously looking to shift towards sustainable pavement technologies. The recycling of asphalt pavements has been considered as one of the most effective ways to reduce the carbon footprint associated with life cycle of pavement construction.

When a pavement reaches the end of its lifetime, it is no longer able to efficiently carry the traffic loads and should be replaced with a new hot mix asphalt layer with or without replacement of underlying layers. The old pavement is demolished, and the milled asphalt is generally either disposed to landfill or reclaimed in lower value applications such as unbound base layer of pavement, road shoulders, embankments, etc. However, the milled asphalt consists of valuable aggregates and binder that must be aimed to re-use in same application to support the idea of circular economy.

This doctoral thesis focused on developing a framework to improve the current recycling methodology and increase the use of reclaimed asphalt in the pavement mixtures. To achieve this goal, the primary task was to study the effect of laboratory mixing conditions on high content (60%) reclaimed asphalt mixtures properties to control the mixing parameters while performance comparison. The second task was to combine warm mix asphalt with high content reclaimed asphalt mixture and compare the performance to the conventional hot mixture to warm mixtures. The third task was to design and produce 100% of reclaimed asphalt mixtures using rejuvenators from various sources and compare the performance to conventional hot mix asphalt. The fourth task was to study the effect of aging on properties of 100% reclaimed asphalt mixtures and its leaching assessment. Finally, a life cycle assessment was carried out for different scenarios of recycling asphalt pavements in order to compare the environmental benefits during the pavement life cycle.

In first task, to evaluate the laboratory mixing process for high content reclaimed asphalt mixtures, three different rejuvenators incorporation methods, three mixing temperatures, three mixing times, and two types of mixers were used to produce asphalt mixtures containing 60% reclaimed asphalt content. The mixtures were characterised using stiffness test and moisture susceptibility test. Besides, the four layers of binders were recovered from the mixtures using a novel stage extraction method developed in this study. The results from this study showed that rejuvenator incorporation method and mixing time did not significantly change the properties of mixture. However, mixing temperature was found crucial as higher temperature resulted into excessive aging and stiffening of bitumen. From binder evaluation, it was also observed that the type of mixer will affect the degree of blending of binders.

In the second task, a chemical additive was used for production of warm mix asphalt at different temperatures. The temperature of warm mix asphalt was optimised and the effect of

incorporating 60% reclaimed asphalt without any further adjustment in binder was evaluated and compared to a conventional hot mix asphalt. The low-temperature performance, high-temperature performance, and moisture susceptibility evaluation were performed using tensile stress restrained specimen test, wheel tracking test, and indirect tensile strength test, respectively. The performance of unaged mixtures was also compared to the short-term oven aged mixtures to simulate the plant aging conditions. The results showed that incorporation of reclaimed asphalt in warm mix without modifying the binder using rejuvenator reduced both rutting and cracking performance. A significant effect of short-term aging was also observed on performance of the mixtures.

In the third task, three rejuvenators from different sources were used to produce 100% reclaimed asphalt mixtures and the performance of these mixtures was compared to the control hot mix asphalt. The rutting and cracking performance were evaluated from wheel tracking test and semi-circular bend test. Along with semi-circular bend test, a digital image correlation setup was used to examine the correlation between the optically measured strains and conventional energy parameters. The performance results showed that tall oil-based rejuvenator caused highest increase in fracture toughness but also led to highest rutting susceptibility of the mixture. A fair correlation was found between the optically measured strains and flexibility index calculated at 5 mm/min loading speed.

In the fourth task, the long-term effects of four rejuvenators on properties of 100% reclaimed asphalt mixtures was evaluated. On asphalt mixtures, the short-term and long-term aging was simulated by conditioning the loose mixtures for 135°C for 4 h and 85°C for 216 h, respectively. The rheological and chemical testing was performed on extracted bitumen samples using dynamic shear rheometer and Fourier transform infrared spectroscopy. The results showed that tall oil-based rejuvenator showed highest softening of bitumen in the long-term. The fatigue life for all four rejuvenators increased with aging of mixtures. Moreover, the rejuvenators did not show a negative effect on permanent deformation characteristics of binders. There was no significant difference between leaching properties of 100% reclaimed asphalt mixtures containing different rejuvenators.

In the final task, a life cycle assessment study was conducted for mixtures produced using warm mix technology and rejuvenators with high rate of reclaimed asphalt material. The original properties of reclaimed asphalt were varied to include a wide of reclaimed asphalt materials and take in account the variability of reclaimed asphalt for the environmental benefits. Additionally, two different traffic intensities were used, and pavement scenarios were designed using elastic layered program to increase the robustness of the evaluation. Based on cradle to gate analysis of asphalt mixtures, the highest emissions were observed during the asphalt production stage. It was also observed emissions were reduced with incorporation of reclaimed asphalt, but the benefits were offset by extra impacts coming from drying process of reclaimed asphalt with higher moisture contents.

ANOTĀCIJA

Asfalts ir pasaulē visplašāk izmantotais materiāls ceļa segumu būvniecībā. Tradicionālais asfalta maisījums tiek izgatavots, izmantojot dažāda izmēra pildvielas, kuras tiek sijātas, žāvētas, karsētas un pārklātas ar karstu bitumenu, lai tās apvienotu blīvā matricā. Asfalta seguma ražošana, ieklāšana un uzturēšana patērē lielu enerģijas daudzumu, izmanto neatjaunojamos dabas resursus un rada siltumnīcefekta gāzu emisijas atmosfērā. Iepriekš minēto vides problēmu dēļ asfalta ražošanas nozare virzās uz ilgtspējīgām seguma tehnoloģijām. Asfalta segumu otrreizēja pārstrāde tiek uzskatīta par vienu no efektīvākajiem veidiem, kā samazināt segumu būvniecības dzīves cikla siltumnīcefekta gāzu emisiejas.

Kad segums sasniedz sava kalpošanas laika beigas, tas vairs nespēj efektīvi uzņemt satiksmes slodzes un segums ir jāaizstāj ar jaunu karstā asfalta kārtu ar vai bez pamatu kārtu nomaiņas. Vecais segums tiek nojaukts, un frēzētais asfalts parasti tiek vai nu nokrauts atbērtnē, vai izmantots zemākas vērtības pielietojumos, piemēram, iebūvējot nesaistītā seguma pamatslānī, ceļa nomalēs, uzbērumos utt. Tomēr frēzētais asfalts sastāv no vērtīgām pildvielām un bitumen saistvielas, ko, atkārtoti izmantojot sākotnējam mērķim, tiktu atbalstīti aprites ekonomikas principi.

Šajā promocijas darbā galvenā uzmanība ir pievērsta ietvara izstrādei, lai uzlabotu pašreizējo otrreizējās asfalta pārstrādes metodiku un palielinātu reciklēta asfalta izmantošanu ceļa seguma maisījumos. Lai sasniegtu šo mērķi, darba primārais uzdevums bija izpētīt laboratorijas maisīšanas apstākļu ietekmi uz augsta satura (60%) reciklētu asfalta maisījumu īpašībām. Tas tika darīts veicot īpašību salīdzināšanu, variējot maisīšanas parametrus. Otrais uzdevums bija apvienot silto asfalta maisījumu tehnoloģiju ar augsta satura reciklēta asfalta izmantošanu un salīdzināt ekspluatācijas īpašības ar tradicionālo karsto maisījumu. Trešais uzdevums bija izstrādāt un izgatavot 100% reciklētu asfalta maisījumu, izmantojot dažādas atjaunojošās piedevas, un salīdzināt īpašības ar tradicionālo karsto asfalta maisījumu. Ceturtais uzdevums bija izpētīt novecošanās ietekmi uz 100% reciklēta asfalta maisījumu īpašībām un novērtēt šo piedevu izskaošanas potenciālu. Visbeidzot, tika veikts dzīves cikla novērtējums dažādiem asfalta segumu pārstrādes scenārijiem, lai salīdzinātu vides ieguvumus seguma dzīves cikla laikā.

Pirmajā uzdevumā, lai novērtētu augsta satura reciklēta asfalta maisījumu sagatavošanas procesu laboratorijā, tika izmantotas trīs dažādas atjaunojošo piedevu iestrādāšanas metodes, trīs maisīšanas temperatūras, trīs maisīšanas laiki un divu veidu laboratorijas maisītāji. Šādā veidā tika sagatavoti asfalta maisījumi ar 60% reciklētā asfalta saturu. Maisījumi tika raksturoti, izmantojot stinguma testu un mitruma jutības testu. Bez tam, no maisījuma tika atgūti un testēti četri saistvielas slāņi, izmantojot šajā pētījumā izstrādāto pakāpeniskās ekstrakcijas metodi. Šī pētījuma rezultāti parādīja, ka atjaunojošās piedevas iemaisīšanas metode un sajaukšanas laiks būtiski nemainīja maisījuma īpašības. Tomēr sajaukšanas temperatūra tika novērtēta kā svarīgs faktors, jo pārmērīgi augsta temperatūra noveda pie bitumena novecošanās. Saistvielu novērtēšanas laikā arī tika novērots, ka laboratorijas maisītāja veids ietekmē saistvielu sajaukšanās pakāpi.

Otrajā uzdevumā tika izmantota ķīmiska piedeva siltā asfalta maisījuma ražošanai pie dažādām temperatūrām. Vispirms tika optimizēta siltā asfalta maisījuma sagatavošanas temperatūra un tad tika izvērtēta 60% reciklēta asfalta pievienošanas ietekme uz siltā maisījuma īpašībām, tās salīdzinot ar karstā asfalta maisījumu īpašībām. Lai maisījumus izvērtētu, tika noteikas ekspluatācijas īpašības zemā un augstā temperatūrā, kas tika veikts izmantojot attiecīgi zemas temperatūras testēšanas metodi (TSRST) un riteņa sliedes testu. Ūdensjutība tika novērtēta izmantojot netiešās stiepes stiprības testu. Lai simulētu rūpnīcas novecošanas apstākļus, nenovecinātu maisījumu īpašības tika salīdzinātas ar krāsnī novecinātiem paraugiem. Rezultāti liecināja, ka reciklēta asfalta iestrādāšana samazina gan pretestību riteņa sliedes testā, gan pretestību zemes temperatūras plaisāšanai. Tika novērota arī būtiska īslaicīgas novecināšnaas ietekme uz maisījumu īpašībām.

Trešajā uzdevumā tika izmantotas trīs dažādu izcelsmju atjaunojošās piedevas, lai saražotu 100% reciklēta asfalta maisījumus un šo maisījumu īpašības tika salīdzinātas ar kontroles karstā asfalta maisījumu. Risu veidošanās un plaisāšanas pretestība tika novērtētas, izmantojot riteņu sliedes testu un puscilindra lieces testu. Puscilindra lieces testa lietošanas laikā tika izmantota arī digitālā attēla korelācijas iekārta, lai pārbaudītu korelāciju starp optiski izmērītajām deformācijām un mehāniskajiem enerģijas parametriem. Rezultāti apliecina, ka uz taleļļas bāzes ražotā atjaunojošā piedeva nodrošina vislielāko plaisāšanas pretestības palielināšanos, bet arī izraisīja vislielāko maisījuma jutību pret risu veidošanos. Tika konstatēta pozitīva korelācija starp optiski izmērītajām deformācijām un elastības indeksu, kas aprēķināts pie 5 mm/min slodzes ātruma.

Ceturtajā uzdevumā tika izvērtēta četru atjaunojošo piedevu ilgtermiņa ietekme uz 100% reciklētu asfalta maisījumu īpašībām. Maisījumu īstermiņa un ilgtermiņa novecošanās tika simulēta, nesablīvētus maisījumus kondicionējot 4 stundas pie 135°C temperatūras un 216 stundas pie 85°C temperatūras. Bitumena paraugi tika testēti, veicot reoloģisko un ķīmisko testēāsnu, izmantojot dinamisko bīdes reometru un Furjē transformācijas infrasarkano spektroskopiju. Rezultāti liecina, ka uz taleļļas bāzes veidotā atjaunojošā piedeva uzrādīja visaugstāko bitumena viskozitātes samazināšanu ilgtermiņā. Visu četru atjaunojošo piedevu noguruma kalpošanas laiks palielinājās līdz ar maisījumu novecošanos. Atjaunojošās piedevas neuzrādīja negatīvu ietekmi uz saistvielas plastisko deformāciju veidošanos. Netika novērotas būtiskas atšķirības starp ķīmisko elementu izskalošanos no 100% asfalta maisījumiem, nekatoties uz to kura atjaunojošā piedeva tika pielietota.

Noslēguma uzdevumā tika veikts dzīves cikla novērtējums maisījumiem, kas ražoti, izmantojot silto maisījumu tehnoloģiju un atjaunojošās piedevas, kā arī augstu reciklētā asfalta saturu. Vides ietekmes izvērtēšanas nolūkā reciklētā asfalta sākotnējās īpašības tika mainītas, iekļaujot plašu reciklēto asfalta materiālu klāstu un ņemot vērā reciklētā asfalta neviendabību. Tika simulētas divas dažādas satiksmes intensitātes, un, izmantojot elasīgo segumu modelēšanas programmu, tika izstrādāti dažādi scenāriji, kas nodrošināja izvērtējuma robustumu. Pamatojoties uz asfalta maisījumu analīzi ciklā no šūpuļa līdz vārtiem, lielākās emisijas tika novērotas asfalta ražošanas posmā. Tāpat tika secināts, ka, izmantojot reciklētu asfaltu emisijas samazinās, bet ieguvumus var neitralizēties dēļ ietekmes, ko rada reciklāta asfalta ar augstu mitruma saturu izmantošana ražošanā.

TABLE OF CONTENTS

1 INTRODUCTION

Asphalt is the most preferred material for road surfacing and is used in more than 90% of the European roads (EAPA & NAPA, 2011). The constituents of asphalt mixtures can vary significantly depending upon the mixture type and layer of its application (e.g., dense grade mixtures, open graded mixtures, stone mastic asphalt etc.). However, the typical asphalt mixtures contain about 90 to 95% of aggregates and 5 to 10% of bitumen by weight of the total mixture (Speight 2016). The extraction and transportation of raw materials used for asphalt mixture production require enormous amount of energy consumption. Additionally, these raw materials are available in limited quantity and therefore there is a need to optimise the use of these natural resources. The principle of 3R's (reduce, reuse, and recycle) is a key to eco-friendliness and applies to the field of pavement industry as well. Based on this principle, an asphalt pavement must be long-lasting and perform satisfactorily during its service life to minimize the consumption of additional materials during its lifetime from maintenance and rehabilitation operations. Further, after completion of service life of pavement, the end-of-life material known as reclaimed asphalt (RA) must be aimed to reuse in the new road construction in the same layer. If the existing asphalt material is undesirable to be used in same layer, it must be recycled in lower bound layers (base layers) or used as replacement of aggregates in unbound layers, shoulders, or embankments. In Europe, 68% of available reclaimed asphalt is already being used in new road construction and maintenance and around 20% is being recycled in unbound layers and other engineering applications (EAPA, 2019).

The most economical use of reclaimed asphalt (RA) is in the intermediate and surface layers of pavements where the less expensive binder from RA can replace a portion of the more expensive virgin binder (Copeland 2011). Even though it has been demonstrated in laboratory that asphalt mixtures prepared using only RA material along with some bitumen and recycling agent can provide satisfactory performance (Zaumanis et. al, 2020; Dinis-Almeida et. al, 2016; Elkashef & Williams 2017; Lizárraga et. al, 2018). The current reclaimed asphalt content in surface layer mixtures is limited to 10-30% in most of the countries (Abed et. al., 2018). Besides technical limitation of producing high content RA mixture in plant, there is a lack of confidence in quality of mixtures with high RA content and most importantly the long-term performance of these mixtures in pavement. Therefore, more studies are required in this direction to evaluate the performance of high content RA mixtures.

The design of high content RA mixtures is much more complicated as compared to conventional asphalt mixtures. Firstly, the processed RA material is in form of a cluster of coarse aggregates that are bonded with a mastic of fine aggregates and oxidised binder. The particle size distribution of RA material is usually finer than the original mixture due to crushing of aggregates from traffic loads during the service life as well as due to dust generation from milling process. Due to high quantity of fines, it becomes difficult to satisfy the gradation requirements of mixtures produced using RA material. Another important concerns of using reclaimed asphalt for many agencies is the variability of the material (McDaniel & Anderson, 2001). RA material consists of oxidised binder which needs to be modified using softer virgin binder, softening agents, or rejuvenators in order to produce asphalt mixtures with satisfactory performance. Among these, rejuvenators are most effective in treating aged bitumen as they not only soften the binder but also balance the properties of aged binder by adjusting the asphaltene/maltene ratio (Garcia et. al., 2011; You et. al., 2011). Rejuvenators diffuse into the aged binder, reduce its viscosity, and improve the workability of the asphalt mixture. However, there is a variety of rejuvenators based on different sources that can result into different degree of blending and their long-term effectiveness has not been widely explored in studies.

Overall, the mix design of high content RA mixtures is complicated due to several factors including variability of RA material, unknown amount of active binder in RA, unknown degree of blending in final mixtures, and rate of diffusion of rejuvenator, etc (Lo Presti et. al., 2020). Further the long-term performance of high content reclaimed asphalt mixtures containing rejuvenators is widely unknown. This thesis aims to improve the current recycling methodology by studying the effect of laboratory mixing process in performance evaluation, investigating the use of additives and rejuvenators for performance enhancement, predicting the long-term performance of high content RA mixtures, and performing life cycle assessment for computation of environmental benefits of high rate of recycling.

1.1 Objective of the study

The objective of this 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 simulations 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 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 asphalt performance between 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 impacts for high rate of asphalt recycling.

1.4 Practical significance

All the publications included in this thesis are available through open access to maximize the impact of current study. The recommended method for mixing of 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 Thesis 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 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 from present work

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 List of conferences and workshops

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

1.8 Structure and Volume of thesis

The Doctoral thesis consists of nine chapters, as follows:

Chapter 1: Introduction presents the background, identifies the gaps in research, defines the objective of thesis, develops the tasks of thesis, presents the novelty of thesis, and outlines the article published during the research progress.

Chapter 2: Literature review elaborates the theoretical background and describes the current state-of-the-art knowledge in the field.

Chapter 3: Experimental methods are described for preparation of test specimen and performance evaluation of mixtures and binders.

Chapter 4: Optimisation of mixing procedure was carried out for high content reclaimed asphalt mixtures.

Chapter 5: Performance comparison of conventional hot mix asphalt with warm asphalt mixtures containing high content of reclaimed asphalt.

Chapter 6: Rheological and chemical changes in long-term for rejuvenators in 100% reclaimed asphalt mixtures.

Chapter 7: Rutting and fatigue performance evaluation of 100% reclaimed asphalt mixtures containing various rejuvenators.

Chapter 8: Life cycle assessment for computation of environment benefits of high rate of asphalt recycling.

2 LITERATURE REVIEW

2.1 History

The terms “asphalt” and “bitumen” can be confusing, and their meaning tend to change with time and location. However, in Europe, “bitumen” is used to describe the liquid product obtained from crude oil distillation and should not be confused with “asphalt” which is natural occurring unrefined product usually containing high amount of mineral material (Speight 2016). In modern terminology "asphalt” is used to refers to “asphalt concrete” which is a mix of bitumen, coarse aggregates, sand, and filler. The reference to asphalt dates to antiquity, but the commercial use began in 1721, when a rock deposit was discovered at Val de Travers in the Jura Mountains of Switzerland and this material was also firstly used in 1839 for wearing surface of roads in Paris (Holley, 2003). The recycling of asphalt concrete pavements started in 1915 but became a common practice in mid-1970s due to astonish increase in asphalt binder prices (Kandhal and Mallick 1997). A field demonstration project by FHWA was carried in 1979 in New Jersey with incorporation of around 50% reclaimed asphalt in the mixture (Hellriegel 1980). The environmental and economic concerns of pavement construction have led to many innovations in the asphalt recycling technology in past few decades.

2.2 Reclaimed asphalt material

Reclaimed asphalt (RA) is the term given to end-of-life asphalt material that is removed from an unserviceable pavement which is further processed to return it back to pavement structure through hot or cold recycling. Most commonly the old pavement material obtained from the job site is hauled to the central plant and crushed, screened, sized, and stockpiled (Little & Epps, 1980). The properties of the RA material depend on several factors including, type and properties of the original asphalt mixture, the technology used to reclaim the material, the service life of the pavement, the environmental and traffic conditions, and the quality and characteristics of the aggregates and original binder used (Montanez et al. 2020). Some important characteristics of reclaimed asphalt are described in the next section.

2.2.1 Gradation

The particle size distribution of reclaimed asphalt material is generally finer than that of aggregate gradation used in the original mixture because of crushing of aggregates during traffic loading as well as due to dust generated during milling process. A high fine content in RA material limits its content in asphalt mixtures due to unfulfillment of mixture design specifications (Copeland 2011). Therefore, care must be taken to avoid operation that results into dust generation in reclaimed asphalt material. For example, the crushing method is known to cause lesser degradation of RA material and results into lower fines as compared to milling method (Kandhal & Mallick 1997). It is also recommended to avoid over-processing of RA material to limit the fine generation (West et al. 2013).

2.2.2 Variability

The variability of reclaimed asphalt material is another important concern for many agencies (McDaniel & Anderson, 2001). The RA material comes from different layers of asphalt pavements with different compositions, and the stockpiles are built with materials from different sources. An effective RAP stockpile management can be very important to reduce the variability of RA material properties. Mixing materials from multiple projects is undesirable because it can greatly increase the variability of the stockpile (McDaniel & Anderson, 2001). The millings from large jobs can be kept in separate stockpiles as they maintain the consistency and can be used in new mixes without further screening or crushing, saving processing costs (Newcomb et. al 2007, Copland 2011). It was found that well-managed RAP stockpiles can have a more consistent gradation than virgin aggregates (Nady, 1997). Arc-shaped, uniformly layered stockpiles are preferred for storing milled or unprocessed RAP material to prevent segregation (Copeland 2011).

2.2.3 Moisture retention

The problem of moisture retention is associated with stockpiling of reclaimed asphalt material (Kandhal and Mallick 1997). A high moisture contents in RA material can be a limiting factor in the plant's production rate and RA content limit in mixture (West et al. 2013). To prevent moisture retention, large conical piles can be used for stockpiling to shed the precipitation water, but this may also make the RA material more prone to segregation (West et al. 2013). It is recommended to limit the height of processed RA and millings stockpiles to 30 feet to reduce the potential for self-consolidation of the stockpile (West 2015). RA with siliceous aggregates should be examined to see if there is an excess of uncoated faces or particles (Newcomb et. al 2007).

2.2.4 Contamination

In the past, coal tar and other tar distillates were used in the asphalt mixture. In Europe, the RA material containing polycyclic aromatic hydrocarbons (PAHs) over 50 mg/kg, are rejected for hot recycled/ reuse process (EAPA 2017). The RA material can also accumulate toxic substance during service life such as, lead or chromium pigments from road marker paints, and PAHs from vehicle exhaust depositing onto the pavement (Murtagh and Vallette 2017). These toxic substances can release during the construction process or leach into the groundwater from RAP stockpiles, thus affecting the human health. The stockpile should be built on a solid surface to prevent contamination or compaction of the underlying surface (Kandhal and Mallick 1997). Furthermore, the efforts should be taken to screen and prevent toxic substances to be passed on along the supply chain.

2.3 Rejuvenators

The aged binder in RA material needs modification to restore its chemical and physical characteristics to a desired level for improving the performance of final mixtures. In the past, the materials used to alter the properties of RA binder have been called as softening agents, reclaiming agents, modifiers, recycling agents, fluxing oils, extender oils, and aromatic oils

(Epps 1980). Nowadays, most common recycling agents are known as “rejuvenators” which usually containing maltenes, and restore viscosity, plasticity, and flexibility of asphalt binder (Kandhal and Mallick 1997). The most important goal of rejuvenator is to restore asphaltenes/maltenes ratio in bitumen and compensates the hardening effect of aged binder (Garcia et. al., 2011; You et. al., 2011). Rejuvenators can be classified into following categories as shown in Table 2.1. as discussed in the next section. The effect of different types of rejuvenators on properties of reclaimed asphalt are summarized in Table 2.2.

Table 2.1. Classification of rejuvenators (NCAT 2014)

Category	Examples	Description
Paraffinic Oils	Waste Engine Oil (WEO)	Refined used lubricating oils
	Waste Engine Oil Bottoms (WEOB)	
	Valero VP165®	
	Storbit®	
Aromatic Extracts	Hydrolene®	Refined crude oil products with polar aromatic oil components
	Reclamite®	
	Cyclogen L®	
	ValAro 130A®	
Naphthenic Oils	SonneWarmix RJ™	Engineered hydrocarbons for asphalt modification
	Ergon HyPrene®	
Triglycerides & Fatty Acids	Waste Vegetable Oil	Derived from vegetable oils
	Waste Vegetable Grease	
	Brown Grease	
	Delta S*	
Tall Oils	Sylvaroad™ RP1000	Paper industry by-products
	Hydrogeen®	Same chemical family as liquid antistrip agents and emulsifiers

2.3.1 Paraffinic oils

The paraffin oils are obtained from the process of crude oil distillation and are known to possess low chemical affinity or reactiveness (Speight, 2014). These oils are used in vehicles as lubricants. The disposal of waste engine oils (WEO) is an environmental concern. Therefore, these oils are recycled for use in various applications. DeDene 2011 evaluated the feasibility of using these WEO to modify the aged binder. It was found that WEO can be used as recycling agents to chemically restore the properties of reclaimed asphalt and improve its low-temperature performance. Around 20–30% of waste engine oils cannot be effectively recycled due to the presence impurities and this residue is known as waste engine oil bottom (WEOB) (Li et. al., 2019). WEOB must be effectively utilized as the disposal may be detrimental to human health and environment. WEOB are black, adhesive, viscous materials similar in appearance to conventional petroleum bitumen though with high concentrations of lead (from petrol), engine wear metals and metals originally from oil additives (Herrington et. al., 1993). Apart from WEO and WEOB, there are several proprietary rejuvenators available in the industry that are based on paraffinic oils.

2.3.2 Aromatic oils

These are complex combination of hydrocarbon and are byproduct of solvent extraction during refining of crude oil. An epidemiological study has found that aromatic oil containing polycyclic aromatic compounds (PAC) are carcinogenic and the carcinogenic potential increased for extracts with higher PAC content (Doak et. al., 1985). Therefore, the industries worldwide are moving away from use of polar aromatics oils and looking for alternate options (Zaumanis et. al., 2013). However, there have been some improvement in refining operation to decrease the PAC level using physical and chemical methods (Carrillo et. al., 2019). Additionally, routine control tests have been established to confirm that the refining process delivers an acceptable PAC content, and the oil is non-carcinogenic (IP, 1996). As Therefore, several researchers have studied the effect of aromatic oils on properties of reclaimed asphalt (Zaumanis et. al., 2013; Ali et. al., 2016; Hong et al., 2020)

2.3.3 Napthenic oils

Similar to paraffinic oils, these oils are also obtained from the crude oil distillation process but are distinguished by a molecular structure composed of “rings” of hydrocarbons (Eastto, 2016). Naphthenic oils have intermediate viscosity index and very low pour points which makes them useful in the manufacture of specialty lubricants. Dewaxing is normally not required due to the low quantities of linear paraffins (n-paraffins). (Lynch 2007). These oils are commonly used to enhance the aging resistance of rubber and skidding resistance of tires (Liu et. al., 2009). Naphthenic oil can largely improve the low temperature of asphalt material by decreasing the rigidity of the material (Ye et. al., 2020). However higher dosage of naphthenic oil negatively affects the high temperature property and thermal stability (Li et. al., 2014; Lu et al., 2018).

2.3.4 Triglycerides & Fatty Acids

This category comprises of rejuvenators that are based on different resources of edible vegetable oils and animal oils that are generated after frying and cooking in the food industry. Out to the total consumption, only 20-30% of waste cooking oil is recycled (Chen et. al., 2014). The waste oil could be harmful to human health and the environment when disposed into kitchen sinks, waste bins, sewerage systems, or directly to land and water bodies (Kabir et al., 2014; Sanli et al., 2011). Therefore, these oils must be recycled properly to reduce the environmental impacts of improper handling. In past few years, waste cooking oils have been widely as rejuvenators either directly or with physical/chemical treatment to improve the properties of reclaimed asphalt (Zahoor et. al., 2020; Li et. al., 2021; Suo et. al., 2021).

2.3.5 Tall oils

Crude tall oil contains fatty acids, resin acids, and unsaponifiables (Behnood, 2019). These oils are viscous yellow-black odorous liquid obtained as a by-product of the kraft process of wood pulp manufacture when pulping mainly coniferous trees (Norlin, 2000). The availability of crude tall oil (CTO) is depended on output of the pulp production and the average yield of CTO is around 30 and 50 kg per tonne of produced pulp (Särkkä et. al., 2018). After production, CTO is separated by fractional distillation into five products including, heads, tall oil pitch (TOP), tall oil fatty acids (TOFA), tall oil rosin (TOR) and distilled tall oil (DTO) (Albuquerque et. al., 2021). Distilled tall oil (DTO) has been used by many researchers to rejuvenate the aged binder in reclaimed asphalt material (Zaumanis et. al., 2014; Mazzoni et. al., 2018).

Table 2.2. Effects of rejuvenators from various studies.

Source	Rejuvenator dosage % w/w binder	Observations	Reference
Soybean oil	3%	For 30% RA content, the chosen dosage met the performance criteria for PG 58-25 binder with PG 82-16 RA binder	Podolsky et al. 2020
Modified polyamines and vegetal oils	0.2%, 0.4%	For 40% RA content, the rejuvenator affected positively by reducing the low temperature (i.e., 0°C) stiffness of mixture, however, excessive reduction at intermediate and high temperature made susceptible to permanent deformation	Bonicelli et al. 2017
Unspecified	4%	Rejuvenator improved moisture resistance and low-temperature cracking, however, reduced the rutting and fatigue cracking properties.	Li et al. 2016
Waste cooking oil	13%, 20%, 27%	Increasing the rejuvenator content reduced the ITS value. The 13% rejuvenator content was found optimum for RA content upto 50%.	Mamun et al. 2018

Date seed oil	5%, 10%	The rejuvenator adversely affected the rutting performance and slightly improved moisture susceptibility, while improved fatigue life of the mixes.	Mirhosseini et al. 2019
Cotton seed oil	7%	The bio-oils render the binders softer, and therefore, make mixture more susceptible to permanent deformation and less susceptible to cracking.	Nogueira et al. 2019
Crude tall oil	6%	Restored the low temperature property while maintaining the high temperature performance.	Sotoodeh-Nia et al. 2019
Soybean oil	3%	Restored the low temperature property while decreased the high temperature performance.	Sotoodeh-Nia et al. 2019
Pine sourced liquid product	5%,6.8%,10%	50% RA mixture containing rejuvenator showed better rutting resistance and equivalent low temperature resistance to virgin mixture.	Tran et al. 2017
Waste vehicle tires	10%	The developed rejuvenator showed good colloidal stability and improved the fatigue life of 35% RA mixture	Zhang et al. 2019
Waste vehicle tires	10%	The developed rejuvenator softened the aged bitumen and improved low temperature properties but could not restore the visco-elastic property of unaged bitumen.	Jiang et al. 2018

2.4 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 a softer binder (Rubio et. al., 2012). 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, the coating of the aggregates by the binder can be greatly enhanced and achieved at a considerably lower temperature. The reduced production temperature in WMA facilitates the incorporation of a high content of reclaimed asphalt due to lower binder aging obtained in this process (Zaumanis et. al. 2015). The reduced production temperature in WMA will also lead to lesser energy consumption and reduced emissions.

The studies have shown that levels of polycyclic aromatic hydrocarbons PAHs (compounds that have been linked to carcinogenesis) (IARC 2010) along with other pollutants in asphalt production including, particulate matter (PM), and volatile organic compounds (VOCs), were greatly affected by the temperature (Kitto et. al., 1997; Xiu et. al., 2020). The efforts made to reduce the temperature of asphalt production will have a direct impact on occupational health. Though WMA is generally considered to offer benefits like longer hauling distances, reduced binder aging, improved workability, and better working environment for the paving crew (Hurley & Prowell, 2005; Hurley & Prowell, 2006), the type of WMA technology can greatly affect the environmental benefits and the performance of the mixtures (Cao et. al., 2019; Yousefi et. al., 2020). WMA technologies are classified into three broad categories that include foaming processes, organic additives, and chemical additives (Rubio et. al., 2012; Kumar & Suresha 2018). A summary of different warm mix asphalt technologies adopted with high content RA mixtures is described in Table 2.3.

2.4.1 Foaming process

In this process, small amount of cold pulverized water is added to preheated bitumen to obtain a bitumen foam (Van de Ven et. al., 2007). Foaming process can be subdivided into two groups namely, water based and water containing process (Zaumanis 2010) as seen in Figure 2.1. In the water-based process, the water is introduced into the process by means of a specific equipment to generate foam. In the water containing process, a synthetic zeolite (a crystalline hydrated aluminium silicate) which contains about 20% of water trapped in its structure is incorporated into the blend. In foaming process, the steam from vaporized water is encapsulated within the bitumen, resulting into a temporary expansion of volume along with reduction in viscosity. The reduced viscosity of binder enables lowering the production temperature of asphalt due to temporarily reduced viscosity of bitumen (Capitao et. al., 2012).

(a) Water based foaming (b) Water containing foaming using synthetic zeolite

Figure 2.1. Bitumen foaming process (Wirtgen 2019; Dubravský, & Mandula, 2015).

2.4.2 Organic additives

Organic additives usually based on wax and fatty amides are added directly to the mixture. When the temperature is risen above the melting point of the waxes, the viscosity of binder is reduced leading to an improvement in workability of mixture (Zaumanis 2010). After cooling of mixture, these additives solidify into a uniformly distribution and increase the stiffness of the binder similar to fiber-reinforced materials (Rubio et. al., 2012). Most commonly used organic additives include one of following three types of waxes: Fischer-Tropsch wax, fatty acid amide, and Montan wax. Sasobit® is one of the most commonly used WMA additives which is produced using Fischer-Tropsch process (Behnoond 2020). A systematic study showed that incorporation of Sasobit® improved the workability without negatively affecting the resilient modulus and rutting performance of asphalt mixture (Hurley & Prowell, 2005). Some organic additives have shown a slightly detrimental effect on moisture suspectibility of mixtures (Amelian et. al.,2018; Sobhi et. al., 2020; Julaganti et. al., 2017), therefore, care must be taken while selecting the type of organic additive.

2.4.3 Chemical additives

Chemical additives include a package of products including anti-stripping, aggregate coating promotors, emulsification agents, and surfactants (Behnood 2020). Unlike waxes or foaming technologies, these additives do not work on the principle of reducing viscosity, but they improve the coating, workability, compaction, and adhesion properties (Rubio et. al., 2012). There additives are usually blended with the bitumen before batching and adding into the mix. Depending on the type of additive used, the temperature reduction ranges from 15 to 30°C (REVIX) to 50-75°C (Evotherm ET) (Von Devivere et al., 2011). The chemical additives have been proven to improve the moisture susceptibility of asphalt mixtures (Julaganti et. al., 2017; Xu et. al., 2017; Guo et. al., 2020). The typical dosage of chemical additive ranges from 0.25-3% by weight of binder, depending upon the type of chemical additive (Behnood 2020).

Table 2.3. Summary of research studies on WMA containing RA materials

WMA type	Additive dosage (%w/b)	RA content upto (%)	Effect of WMA technology	References
Organic	2, 3	50	Reduced moisture resistance and increased fracture resistance	Yousefi et. al., 2020
Organic	3	75	Increased both stiffness and resistance to permanent deformation	Behbahani et. al., 2017
Organic	3	40	Increased both resilient modulus and moisture resistance	Goli et. al., 2020
Chemical	0.35	50	Increased both moisture and fracture resistance	Yousefi et. al., 2020
Chemical	0.3	50	Reduced moisture resistance and increase in fatigue life	Zhao et. al., 2012
Chemical	0.15	75	No significant change in stiffness and resistance to permanent deformation	Behbahani et. al., 2017
Foaming	5	50	Reduced moisture resistance and increased fracture resistance	Yousefi et. al., 2020
Foaming	-	60	Increased both low temperature crack resistance and fatigue life	Liu et. al., 2020
Foaming	0.3, 0.6	30	Increased stiffness and rutting resistance	Valdes-Vidal et. al., 2018

2.5 Plant production parameters

2.5.1 RA heating process

For hot mix asphalt production, the aggregates are heated typically around 150°-190°C (Rubio et al. 2012). These aggregates are mixed with hot binder at production facility and mixture is shipped to the job site for compaction. In asphalt plants when low RA contents are used, RA is either used as unheated aggregates or heated at very low temperature to remove the moisture. Though, using unheated RA has shown lower stiffness and poor blending of oxidized and virgin binder (Pérez Madrigal et al., 2016). On the contrary, it is also recommended not to heat RA to very high temperatures to avoid extra oxidation of binder as well as emissions from RA (Rathore et al. 2019). The most used method is to superheat the virgin aggregates (at 190–250°C) so that when they come in contact with RA material they would dry and heat the RA material by conduction (Zhang et. al., 2019; Zaumanis & Mallick, 2015). 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). The heating and drying mechanism will largely depend on the configuration of the plant.

2.5.2 RA incorporation method

RA material can be added to mixture in both batch plants (old technology) and drum mix plants. The batch plant and drum plant can incorporate up to 35% RA and 50% RA into asphalt mixtures, respectively depending on the superheating capacity and emission regulations (Brock & Richmond, 2006; Liu et. al. 2017). The delivery process for cold RA material into the mixture in a batch plant is shown in Figure 2.2. In this plant, an elevator is used to transfer the RA material from bin to weight hopper. Since, no heating mechanism for RA material is present here, steam is generated when cold RA material reaches to the hot aggregates. A high moisture content can lead to thermal explosion and emission of blue smoke from the plant. Several modifications can be made in batch plants to accommodate higher contents of RA material. This could be done by drying the RA material before feeding it into the mixer as shown in Figure 2.3. Here, a dryer drum is used to reduce the moisture content of RA material and feeding it directly to pugmill mixer or drum mixer. The steam from RA material is pulled from the pugmill mixer or drum mixer to the bag house.

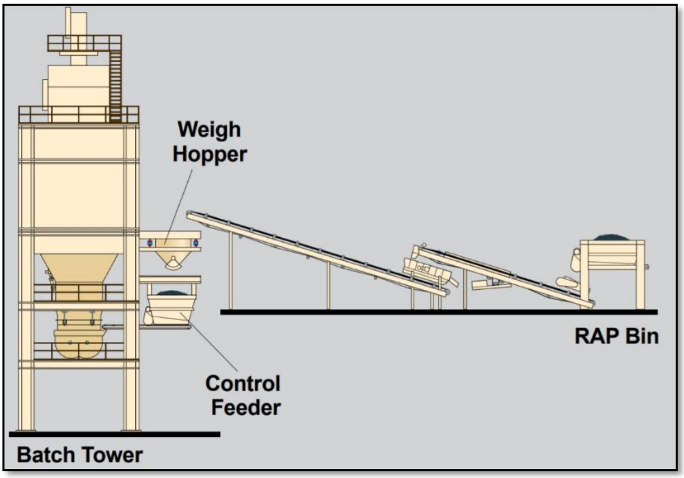
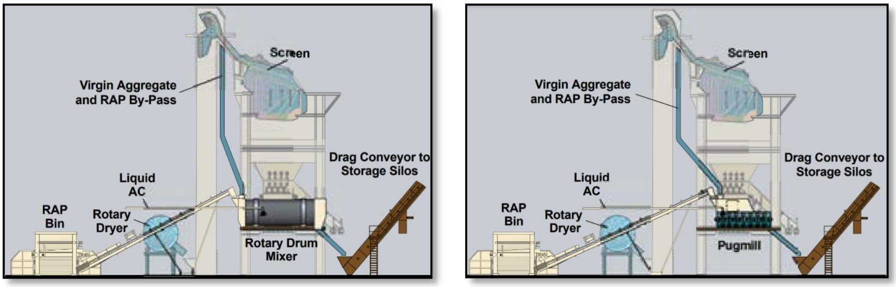


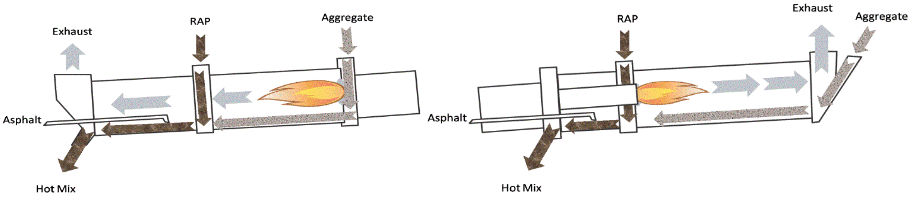
Figure 2.2. Batch plant configuration for cold RA material delivery (Brock & Richmond, 2006)



(a) (b)

Figure 2.3. Modified batch plant with hot RA material delivery to (a) pugmill; (b) drum mixer (Broch & Richmond, 2006)

The drum mix plant consists of either parallel flow or counter flow configuration as shown in Figure 2.4. In parallel flow mixer, the aggregates and the burner flame are in same direction. A center entry is used for introduction of RA material to superheated aggregates in the drum plant. In counter flow mixer, the aggregates move in direction opposite to that of burner flame and prevent the direct contact of RA material to the flame. Another drum mixer configuration consists of dual drum where the virgin material is heated in inner chamber and RA material, virgin aggregates, and binder are mixed in outer chamber. This configuration results into reduction in blue smoke emissions, higher production rate, and lower fuel consumption (Stroup-Gardiner & Wattenberg-Komas, 2013).



(a) (b)

Figure 2.4. Drum mixer configurations (a) parallel flow; (b) counter flow arrangement (Stroup-Gardiner & Wattenberg-Komas, 2013)

2.5.3 RA mixing process

In asphalt plants, the RA material mixing with the virgin aggregates and binder takes places in two stages that are known as “dry mixing” and “wet mixing” process. In the first stage, RA material at ambient/hot temperature is introduced with superheated virgin aggregates, and later the combination of RA and virgin aggregate is mixed with virgin binder (Brock and Richmond 2005). The dry mixing stage enhances the RA binder activation, and the wet mixing process distributes the binder uniformly and increases the diffusion between virgin binder and RA binder. The above two mixing process can take place either in a single drum of parallel/counterflow mixer or in a mixer accompanied with an outer coating chamber. The total mixing time in a pugmill is typically around 30–60 s and longer in the outer mixing chamber of the drum mixers approximately 40–90 s (Zhang et al. 2019). Depending on the plant type the total production cycle varies between 60 s, for both batch and drum plants, and 90 s for double barrel drum plants (Antunes et. al. 2019). As discussed earlier, parallel flow configuration heats the RA material through conductive mechanism by transferring heat from superheated aggregate to the RA material. During mixing, it is expected that the superheated aggregates will heat the RA material and melt its binder. However, due to short mixing time available, complete melting of binder may not be possible (Dedene et al., 2014). Counter-flow dryer mixer providing longer mixing time and can handle higher percentages of RA (West, 2015).

2.5.4 RA mixing temperature

Mixing of aggregates and asphalt has to be done at an appropriately selected temperature. The mixing temperature controls the dryness of the aggregates, the quality of the mixture, the time it takes for the mix to cool down during laying and the ease of compaction during paving (Shenoy, 2001). It will not be possible to have a uniform coating of bitumen over aggregates at lower mixing temperature. On the contrary, mixing temperature that is too high will make the bitumen to rapidly age and increase the cracking susceptibility of mix.

When high RA content is used, generally a higher virgin aggregates temperature is required to attain sufficient mix temperature in order to compensate the lower heating temperatures of RA. A laboratory study showed that for 50% RA mixtures, it was required to heat the virgin aggregates at 220°C to reach a mix temperature of 150°C where RA was heated at 120°C (Yu et al., 2017). The required superheating temperatures of virgin aggregates for 50% RA mixture production for different moisture contents of RA are given in Table 2.4. Based on this data, the superheating temperature of virgin aggregates needs an increment of around 156°C when RA material contains 5% moisture content compared to a dry RA material containing 0% moisture content.

Table 2.4. Virgin Aggregates temperature requirement at asphalt plant corresponding to discharge mix temperature for 50% RA: 50% aggregate mix* (NAPA, 1996).

Moisture Content (%)	Recycled mix discharges temperature, °C			
	104°C	116°C	127°C	137°C
	Virgin aggregates temperature requirement, °C			
0	210	235	257	282
1	241	268	288	310
2	271	293	318	343
3	302	327	349	374
4	338	360	377	404
5	366	391	413	438

*20˚F loss between dryer and pugmill assumed in these calculations

2.5.5 Rejuvenator incorporation

The most convenient method is to add rejuvenators into the virgin binder as no additional equipment is used in this case. In this case the rejuvenator is diluted by virgin binder and therefore may be less effective than the approach where the rejuvenator is added directly to the RA material. A method is widely used in Japan, where rejuvenators are mixed with heated RA in a small pugmill and then transferred to a surge bin to give additional conditioning time (2–3 hours). The finished mix with typical temperature of 160°C is very well coated and uniform even before it is transferred to the silo (West and Copeland, 2015). In a study by Zaumanis et al., 2018, a conventional approach of adding rejuvenator on hot RAP into mixer was compared to a rather innovative approach- spraying rejuvenator on cold RA at conveyer belt. No significant difference was observed from extracted binder properties in both the cases (Zaumanis et al., 2018). However, the mixture test results demonstrated potentially improved fatigue life in sprayed rejuvenator mix due to improved blending of the materials (Zaumanis et al., 2019).

Figure 2.5. Spraying system for rejuvenator application on conveyor belt 19 (Vansteenkiste & Duerinckx, 2017)

2.6 Laboratory mixing parameters

Table 2.5. summarizes the information mixing parameters adopted in the laboratory studies for high content RA mixtures. The RA content considered in these studies was from 40% and upto 100%. Based on these studies, the most commonly used RA material heating temperature was 110°C and heating time was 2 h. However, when high content upto 100% RA was considered, the heating temperature of RA material was increased even above 155°C (Moniri et. al. 2019; Daryaee et. al., 2020). The mixing temperature for HMA mixtures was around 155-165°C and for WMA mixtures was around 120-130°C. The information about the mixing time was not reported in most of the studies. Another important information that was not reported by most of the authors was the rejuvenator/ additive application method. In the next section, the effect of these parameters on properties of mixture are described.

Table 2.5. Laboratory mixing parameters adopted in recent high RA content studies

Reference	RA % upto	RA heating temperature	RA heating time	Mixing temperature	Mixing time	Rejuvenator/ additive
Colbert et. al., 2012	50%	135°C	2 h	155°C	NA	NA
Lopes etl al. 2014	50%	110°C	NA	HMA: 160°C WMA: 130°C	2.5 min	NA
Dinis-Almeida et. al. 2016	100%	130°C	NA	100-120°C	NA	Added to RA material
Lu et. al. 2016	70%	NA	NA	110°C	NA	Added to virgin binder
Fakhri et. al., 2017a	50%	125°C	2 h	125°C	NA	Added to mixture
Fakhri et. al., 2017b	40%	110°C	2 h	135°C	NA	Added to mixture
Kumari et. al. 2018	100%	110°C	1.5 h	156-159°C	NA	NA
Song et. al. 2018	50%	NA	NA	HMA: 150°C WMA: 125°C	NA	NA
Lizzarga et. al. 2018	100%	95-100°C	NA	NA	NA	NA
Kumari et. al. 2019	70%	110°C	NA	HMA: 163°C WMA: 130-140°C	NA	NA
Lu et. al. 2019	50%	NA	NA	115°C	NA	Two cases: Added to virgin binder; added to RA material
Moniri et. al. 2019	100%	163°C	2 h	163°C	5 min	Added to RA material
Daryaee et. al., 2020	100%	155°C	2 h	155°C	No information	Added to virgin binder

2.6.1 RA material heating in laboratory

In laboratory, heating temperature of 110°C (230°F) for a time of no more than 2 h is recommended for sample sizes of 1 to 2 kg as higher temperatures and longer heating times have been shown to change the properties of RA (Mcdaniel & Anderson, 2001). Mogawer et al. (2013) observed when RA material was heated for 2 hours prior to mixing, it resulted into lower air voids and heating time had to be increased to 4 hours to reach the desired air voids. The reason stated was that the heating time was not enough for commingling of binders. Results of another heating experiments showed that an appropriate method is to heat RA in oven at the mixing temperature for 1½ to 3 hours. Heating RA samples for more than 3 hours may cause excessive aging of the RA binder (Willis et. al. 2013).

In a study, four different RA heating process (cold, heated in a microwave, heated in an oven in covered pan, and heated in an oven in a non-covered pan) were adopted to prepare 25% RA mix in a laboratory and results shown no difference in stiffness and thermal cracking resistance (Basueny et al., 2014). A heating temperature of 110°C for 3 hours in an oven was recommended as the best option. It may be possible that the effect of conditioning process was not captured due to low content of RA. Microwave heating could also be used while heating RA at higher temperatures as microwave heat is more easily absorbed by the aggregates as compared to the binder, thus reducing its susceptibility to aging during production (Al-Qadi et al., 2007). In a study, to simulate the plant heating conditions, RA was not heated in an oven, but rather heated only by contact (conduction) from the superheated virgin aggregate. It was observed that the high conductive heat was sufficient to significantly age the binder (Willis et. al. 2013).

2.6.2 RA mixing time in laboratory

A sufficient mixing time is required for the aggregate-bitumen mix to form a uniform coating over the aggregates. AASHTO, (2008) has set down procedures to establish the accurate mixing time in laboratory which involves separating coarse aggregate particles from the mix on a selected sieve size and examining 200 to 300 particles are under a strong light. Usually, the minimum coating percentage required is around 90 and 95% for base and surface course respectively (Shenoy, 2001) The least time needed for the pugmill to achieve these minimums is taken as the most desirable mixing time.

When softer binder is used in high RA mix, diffusion between the two binders is better at higher mixing time, and that changes the properties of the mix (Abed et al., 2018). Results from the optical microscopy showed that by increasing the mixing time to double the normal time for 15% RA mixes, improves blending of RA and virgin binder (Hassan et al., 2015). Increased mixing time also has an impact on the physical and mechanical properties of laboratory mixtures. Longer mixing times tend to reduce the air voids in mixtures containing high RA material (Hassan et al., 2015; Madrigal et al., 2016). This is attributed to increase in blending between virgin and oxidized binder and thus having a better compactibility.

2.6.3 RA mixing temperature in laboratory

With the increase in mixing temperatures, the air voids in RA mixes were found to be reduced (Abed et al., 2018). This is due to the fact that at higher temperature, the particle clustering is lowered which in turn leads to increased compaction. Increasing mixing temperature improves the blending which leads to greater modulus. This change is more significant when RA percentage is increased (Madrigal et al., 2016). Navaro et al., (2012) observed if the mixing temperature is reduced by 30°C then, generally to obtain a recycled asphalt concrete with a binder of the same homogeneity, the mixing time has to be multiplied by factor of 2.5–3. Therefore, in some cases where high mixing temperatures are not possible, a longer mixing time will be required. Warm mix additives are also used to reduce the mixing temperature while maintaining the same workability of mix. The use of WMA technologies- foaming, organic or wax usually allows the incorporation of higher RA amounts than for HMA and appears to provide a synergetic effect on improving both the WMA and high RA mix performance (Zaumanis and Mallick, 2015). Xie et al. (2016) observed that WMA with 20% and 30% RA mixes showed similar compactibility as corresponding HMA mixes with the production temperature being approximately 30°F higher. Warm mixes are generally more susceptible to moisture damage due to lower mixing temperature.

Overheating the aggregates without preheating RA and extending mixing time has also proven to be good expedients to improve the cracking resistance of the mixtures Madrigal et al., (2016). But this is not always possible with higher RA contents and to heat the aggregates at very high superheated temperatures becomes practically difficult in plant. Where high mixing temperatures cannot be attained, mixing time can be increased upto a certain level to achieve desired air voids. For example, in a study on mix containing 50% RA, mixing at 135°C for 3 min was sufficient to achieve the target air voids of 5%, whereas at 115°C, a longer mixing time was required and the target air voids were barely obtained after 5 min of mixing. At 95°C, the target air voids were never achieved, even after 5 min of mixing (Abed et al., 2018).

2.6.4 Rejuvenator incorporation method in laboratory

Conventionally, for production of HMA in laboratory, all mineral aggregates are mixed together (dry mixing), followed by pouring the bitumen on this aggregate mixture (wet mixing) which is continued till the desired mixing time (Roberts et al., 1996). When high content of RA is being used in the mix, the incorporation of rejuvenators is also required in the process. Recycling agents offer many unique benefits as compared to the use of softer binders (Zaumanis and Mallick, 2013). In laboratory, the rejuvenators are generally incorporated by blending rejuvenator with virgin bitumen. This is the most convenient and widely used rejuvenator application method in laboratory. The rejuvenator is pre-blended into bitumen with the required dosage and then added directly to the mix. Though, this method simulates the plant operation of adding rejuvenator, it could be less efficient than other methods discussed below as some part of added rejuvenator may not be available to RA due to lower blending between virgin bitumen and RA bitumen.

Another method is to add rejuvenator directly to RA material. In this method, the rejuvenator is added directly to RA material (with or without preheating the RA material) in order to activate the stiff binder. This method facilitates the diffusion of the rejuvenator as rejuvenator is in direct contact with the RA binder maximizing the binder activation. However, in the previous method of blending with binder, the rejuvenator is diluted by virgin bitumen and therefore weakens the modifying effect (Yu et al., 2017). A sufficient rest period is likely to cause some diffusion of rejuvenator into RA binder and ultimately restore the original properties of binder.

2.7 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 deterioration of pavement during service life and as a result, 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 (Airey 2003). The researchers have been making effort in simulating the aging properties at both binder and mixture level which are described in the next section.

2.7.1 Short-term aging

As described earlier, short-term aging is referred to the hardening in binder that occur during the mixing, storing, transporting and placement of asphalt mixture. At binder level, rolling film thin oven (RTFO) is the most commonly used method to simulate the short-term aging and it was first adopted in 1970 (Airey & Brown, 1998). This test measures the combined effect of heat and air on a thin film of binder. In this test, a film of bituminous binder is heated in an oven to a specified temperature, for a given period of time, with a constant supply of air. Finally, the effect of aging is observed on recovered bitumen using chemical or physical characterization. The test conditions differ in different standards but are typically 163 °C (325 °F) for 75 min (EN 12607-1) or 85 min (ASTM D2872, AASHTO T240) (Southern 2015).

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. At mixture level, short-term aging is simulated by conditioning the loose mixtures at a temperature of 135°C for 4 h (CEN 12697-52: 2017). Several researchers have used short-term aging methods to understand the aging mechanism of asphalt mixtures containing RA material (Ziari et. al. 2019; Asib et. al. 2019).

2.7.2 Long-term aging

Long-term aging refers to the change in physical and chemical properties of asphalt binder during the service life of the pavement. The long-term aging is a slow process and varies significantly with climatic conditions of pavement location (Sirin et. al., 2018). Pressure aging vessel (PAV) test is used to simulated the long-term oxidative aging of bitumen. In this test, the short-term aged bitumen is kept in 140 mm diameter steel trays and heated for 20 h at temperatures between 90 and 110 °C with air pressure of 2.07 MPa (Southern 2015). The aging level in the PAV test simulated the aging of wearing course of 5–7 years old asphalt pavements (Migliori & Corte, 1999). A study found that 20h PAV aging period is not sufficient, and 62 h aging period could be used to simulate the aging level of wearing course binders in the hot climatic region (Sirin et. al., 2018). The long-term aging of bitumen in field is a slow process and depends on a number of environmental factors. Therefore, aging methods that consider the impact of reactive oxygen species have been developed to simulate the field aging (Hofko et. al., 2020, Mirwald et. al., 2020a). This method leads to different aging level which makes it more suitable to distinguish between aging susceptibility of different binders (Mirwald et. al., 2020b).

For long-term aging simulation on mixtures, the short-term aged loose mixtures are subjected to conditioning in oven either on perforated or non-perforated plate. A conditioning temperature of 85°C for 216 h is used for long-term aging on non-perforated plate according to RILEM recommendations (CEN 12697-52: 2017). Another method recommends conditioning on a perforated plate at 80 °C for 96 h (CEN 12697-52: 2017). After ageing on loose mixture, specimens are prepared at predetermined compaction temperature. However, compaction of loose mixtures specimen is problematic as the mixture becomes too stiff due to loss of volatility of binder (Reed, 2010). The stiff mixture will require higher compaction effort that may damage the structure of aggregates. The aging level also depends on spatial properties. It was shown that aging level of asphalt is much lower in base layer as compared to the wearing surface (Sirin et. al., 2018).

2.8 Life cycle assessment

Life cycle assessment is a systematic method to quantitatively assess the environmental impacts of the products or services. The use of LCA tools for determining the environmental impacts of pavements is becoming popular with the recent trend of shifting towards innovative pavement materials containing recycled products, as these applications have been known the reduce the consumption of natural resources and greenhouse gas emissions (Carpenter et. al., 2007). 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) (Giani et. al., 2015). 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 following stages: raw material extraction, material production, transportation, construction, use phase, maintenance, and end-of-life. Many of the studies use cradle to gate analysis which means all the process starting from raw material extraction to construction are considered. The use phase is often not taken in account due to complexities in calculation and unavailability of data which is one of the main limitations for LCA studies for pavements.

2.8.1 Steps in LCA

As per ISO standard, the LCA is divides into four main stages: goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO 14040:2006). The goal of the LCA study needs to be defined to justify the purpose of conducting the study. The scope of a LCA defines the system boundary, functional unit, and limitations of the study. The inventory analysis will quantify the inputs and outputs associated with each component of the product's life cycle within the system boundary. The impact assessment categorizes the inventory data into specific impact indicators including global warming potential, ozone depletion, human toxicity, particulate matter emission, acidification potential, smog creation potential, etc. The last step is to summarize all the previous steps including impact assessment results to develop conclusions.

2.8.2 State-of-the-art of LCA for reclaimed asphalt mixtures

A summary of recent studies on LCA for recycled asphalt technologies is shown in Table 2.6. Vidal et. al., (2013) conducted a life cycle study on asphalt pavements produced using warm mix asphalt and reclaimed asphalt materials. It was found that WMA had almost similar environmental impacts as that of HMA due to the presence of synthetic zeolites. However, all endpoint impacts as well as climate change, fossil depletion and total cumulative energy demand were decreased by 13–14% by adding 15% RA in the mixture. Hasan et. al., (2020) found that use of WMA instead of HMA reduced environmental impacts, e.g., global warming potential by 6.23% and fossil fuel depletion by 1.92%, the most notable reductions (around 15% in both) were due to 15% & 25% RA addition in wearing course and binder course layers. A similar study was conducted by Giani et. al., (2015) which found that reclaimed asphalt coupled with warm mix asphalt led to 12% and 15% reduction in CO_2 equivalent and energy consumption, respectively. There are several types of WMA technologies which can have different impacts on environment. Santos et. al., (2018) conducted LCA for two different WMA technologies (additive & foaming) with and without RA content. The most environment friendly alternative in this study was found to be foamed WMA with 50% RA employed in wearing course of pavement. It was also concluded that the alternate mixtures if do no provide satisfactory performance may results in overall higher environmental impacts due to maintenance & rehabilitation activities.

Apart from WMA, reclaimed asphalt mixtures have been coupled with various other materials. Farina et. al. (2017) evaluated the environmental impacts of different mixtures containing recycled products including crumb rubber and reclaimed asphalt. It was shown that mixtures produced using crumb rubber (18%) modified binder reduced the gross energy requirement and global warming potential by 36% and 45%, respectively. However, no significant change in environmental benefit was observed by inclusion of 10% reclaimed asphalt in the mixture. On the other hand, Bressi et. al., 2019 showed that small amount of crumb rubber used for bituminous mixtures application does not justify all the additional consumption of resources and emissions associated with its treatment.

Table 2.6. Summary of LCA studies using reclaimed asphalt material

Functional unit	Use stage	Inventory data	Impact assessment	RA % upto	Reference
1 km	No	Ecoinvent® and ETH-ESU 96®, literature	ReCiPe midpoint & endpoint	15%	Vidal et. al., (2013)
1 km	Yes	Material suppliers, Ecoinvent database and literature	Greenhouse Gas Protocol, ReCiPe 2008, Cumulative Energy Demand and Selected LCI results, and Additional: water consumption	20%	Giani et. al., (2015)
1 km	Yes	Real data collection, Eurobitumen report, Models	ReCiPe midpoint & endpoint	50%	Santos et. al., (2018)

1 m of pavement layer	No	Literature, interviews, Ecoinvent 2.2 database	Gross Energy Requirement (GER), Global Warming Potential (GWP), ReCiPe method	10%	Farina et. al. (2017)
1-mile	No	Online databases, peer-reviewed journal, conference papers, and reports	Greenhouse gases (GHG)	50%	Chen & Wang (2018)
1 mile	No	Data collection, literature	Energy consumption, Greenhouse gases (GHG)	50%	Aurangzeb et. al., (2014)
3.5 km	No	Field data, Literature Material supplier, Ecoinvent v3.3 database	ReCiPe midpoint method	25%	Hasan et. al., (2020)
1 m2 of layer	No	Survey, material supplier, Ecoinvent 3.6 database	ReCiPe 2016 hierarchist	70%	Moins et. al., (2022)
1-km	No	Data collection, system modelling, CM database Gabi	ReCiPe at midpoint level	40%	Bressi et. al., (2019)

Several researchers have compared the life cycle environmental impacts for recycling alternatives including hot-in-place recycling, hot-in-plant recycling, cold-in-place recycling etc to conventional asphalt construction. Thenoux et al. (2007) found that cold in-place recycling using foamed bitumen will have between 20-50% and up to 244% lower energy consumption compared to an HMA asphalt overlay and HMA asphalt reconstruction alternatives, respectively. Though cold-in-place process requires higher amount of bitumen than hot-in-plant recycling, the aggregate haulage can play significant effect on total energy consumption. Giani et. al., (2015) showed that cold-in-place recycling reduced 9% for whole lifecycle and 54% considering only the phase of recycling in terms of CO_2 equivalent emitted compared to recycling in plant. Gu et. al., (2019) showed that cold recycling technologies reduced the energy consumption by 56-64% and decreased the GHG emissions by 39-46%.

The researchers have been trying to improve the quality of LCA by considering as many factors as possible that affect the environmental impact of material during its lifetime. Chen & Wang (2018) conducted life cycle assessment for pavement recycling by considering the temporal aspect. A time dependent decay function for CO_2 was adopted to calculate GHG emissions. The results showed that environmental benefits of using reclaimed asphalt were overestimated when temporal aspect is not considered in the calculation. A hybrid LCA was conducted to evaluate the environmental impact of using a high RAP content in asphalt mixtures. The study showed a reduction of 26%, 33%, and 40% in feedstock energy for the mixtures with 30%, 40%, and 50% RAP, respectively Aurangzeb et. al., (2014). Moins et. al., (2022) modified the service life in LCA calculations and found that to have same environmental impacts, the service life of conventional surface layer without recycled material should be increased by 27% when compared with 40% RA inclusion in this layer, and the service life of conventional base layer without recycled material should be increased by 66% when compared with 70% RA inclusion in this layer.

3 EXPERIMENTAL METHODS

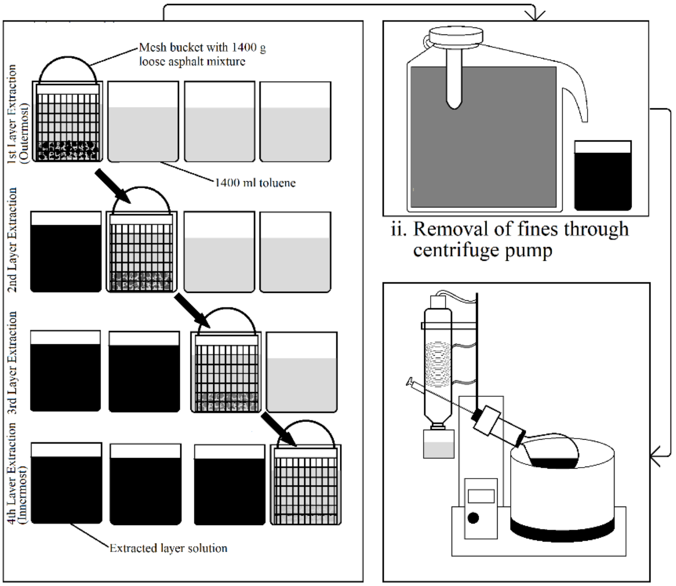
3.1 Binder tests

3.1.1 Penetration & Softening point test

There are various traditional tests that are used to describe the basic properties of given binder but can also be used for various other purposes including determination of rejuvenator content, state of aging in binder, and storage stability of modified binders, etc. In the present study, penetration test and softening test have been used for basic characterisation of binder. The penetration test has been according to EN 1426 (2015) which basically measure the hardness or softness of bitumen by recording the depth a 100 g needle penetrates the bitumen sample conditioned at 25°C in 5 s loading time. The penetration value is expressed at 1/10th of mm which means that for a 50/70 grade bitumen, the needle will sink between 5 to 7 mm in the sample. Softening point is another test which determines the temperature at which bitumen achieves a certain degree of softening when heated. This test was conducted according to EN 1427 (2015) and the softening point is reported as the mean of the temperatures at which the two discs soften enough to two standard balls, enveloped in bituminous binder, to fall a distance of 25 mm when heated underwater.

3.1.2 Stage bitumen extraction

Stage extraction method has been used to recover the bitumen present in different layers of asphalt mixtures and RA material. 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. This process can be applied sequentially for a sample to extract various layers of the bitumen into the solution. Noureldin and Wood (1987) used successive incremental of solvent quantity with a constant soaking time of 5 minutes for each layer to extract four layers of bitumen. Bower et al. (2014) used incrementally increasing soaking time to extract four layers of bitumen. Other studies have kept the solvent quantity and soaking time constant for each layer (Carpenter & Wolosick, 1980, Huang et. al., 2005). The determination of solvent quantity and soaking time for each extraction depends primarily on the quantity of bitumen required in each layer and the number of layers required. The stage extraction method developed for the current study is illustrated in Figure 3.1. and can be described as follows:



i. Four layer staged extraction

ii. Removal of fines through centrifuge pump

iii. Recovery of bitumen using rotary evaporator

Figure 3.1. Four layers stage extraction method adopted in the study

- The asphalt mixture obtained after mixing was cooled down while loosening and separating to reduce the agglomeration of particles.
- 1400 g of this mixture was taken 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 the four vessels was then transferred to a centrifuge pump for 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 approximately equal quantity of bitumen is recovered in each layer. The 60 minutes time for the fourth vessel was chosen to ensure removal of almost all of the traces of bitumen from the aggregates. The quantity of loose asphalt and toluene were selected to ensure complete immersion of asphalt, which is dependent on soaking vessel and mesh bucket dimensions.

3.1.3 Temperature and frequency sweep test

This test was performed using a dynamic shear rheometer according to EN 14770. The bitumen samples were conditioned at 20°C and were subjected to a set of 10 frequencies ranging from 0.1 Hz to 30 Hz. Following this, the temperature was raised with intervals of 10°C up to 80°C and a frequency sweep was performed at each test temperature. A 25 mm diameter spindle with 1 mm gap width was used under strain-controlled testing mode. The obtained data were shifted to the reference temperature of 20°C using temperature–time superposition principle to prepare mastercurves of complex shear modulus (G*). The shift factors were calculated using equation 3.1 given by Williams et. al. (1955). A sigmoidal function as defined by equation 3.2 was used for fitting the shifted data.

$$\log a_T = \frac{-C_1(T - T_{ref})}{C_2 + (T - T_{ref})} \tag{3.1}$$

$$\log G^* = \delta + \frac{\alpha}{1 + e^{\beta + \gamma(\log a_T + \log g)}} \tag{3.2}$$

Where a_T is shifting factor, C_1 and C_2 are material constants, and δ, α, β, γ are fitting parameters determined using the least squares method.

In this study, to interpret the mastercurve results, two indices were defined, namely aging index (I_A) and softening index (I_S). The aging index indicates the increase in stiffness of bitumen as compared to the virgin bitumen. The softening index indicated the reduction of stiffness of bitumen as compared to the RA binder. Both of these indices are based on calculating the area under the mastercurve of given sample and a reference sample within a definite range of reduced frequencies as shown in Figure 3.2. The reference sample for aging index is the virgin bitumen, and the reference sample for softening index is the RA binder. Equation 3.3 and equation 3.4 were used to calculate the aging index (I_A) and softening index (I_S), respectively:

$$I_A = \frac{\int_{-5}^{-1} \log G^* \, df}{\int_{-5}^{-1} \log G^*_{VB} \, df} \tag{3.3}$$

$$I_S = \frac{\int_{-5}^{-1} \log G^*_{RA} \, df}{\int_{-5}^{-1} \log G^* \, df} \tag{3.4}$$

where, G* is complex modulus of binder for index calculation, f is logarithm of reduced frequency, G^*_{VB} and G^*_{RA}, are complex modulus of virgin bitumen and RA binder, respectively.

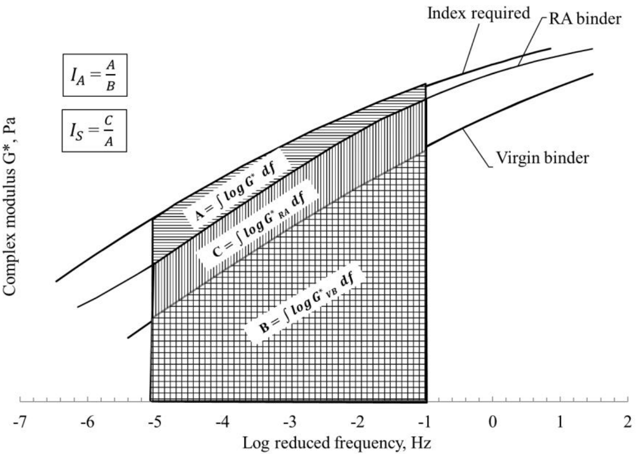


Figure 3.2. Principle of indices calculation from complex modulus mastercurves

3.1.4 Linear amplitude sweep test

Linear amplitude sweep test was performed on dynamic shear rheometer according to AASHTO TP101 (2012), to evaluate the fatigue characteristics of binder. The test is conducted in two stages using an 8 mm diameter spindle with a 2 mm gap width at a test temperature of 25°C. In the first stage, the bitumen is subjected to a frequency sweep to determine a damage analysis parameter (α). A load of 0.1 percent strain is applied over a range of frequencies from 0.2–30 Hz. The second stage consists of oscillatory shear, in strain-controlled mode, at a frequency of 10 Hz. Strain is increased linearly from 0.1% to 30% over the course of 3100 cycles of loading, for a total test time of 310 s. Peak shear strain and peak shear stress are recorded every 10 load cycles (1 s), along with phase angle and complex shear modulus. The fatigue life (N_f) is calculated using a viscoelastic continuum damage (VECD) model according to equation 3.5.

$$N_f = A\,(\gamma)^{-B} \tag{3.5}$$

where A and B are VECD model coefficients, and γ is the strain amplitude.

3.1.5 Multiple stress creep recovery test

Multiple stress creep recovery test was performed on dynamic shear rheometer according to AASHTO TP70 (2012), to evaluate the rutting characteristics of binder. The test was conducted in creep mode at 60°C using a 25 mm diameter spindle with 1 mm gap width. The test procedure includes applying a series of static loads, followed by a recovery period, and measure the non-recoverable creep compliance. The test starts at a stress of 0.1 kPa for 10 creep/recovery cycles, and then the stress is increased to 3.2 kPa and repeated for an additional 10 cycles. The typical results of this test as shown in Figure 3.3, can be used to calculate the percent recovery and non-recoverable creep compliance. The non-recoverable creep compliance at multiple stress levels is an indicator of the sensitivity to permanent deformation and stress dependence of bituminous binders.

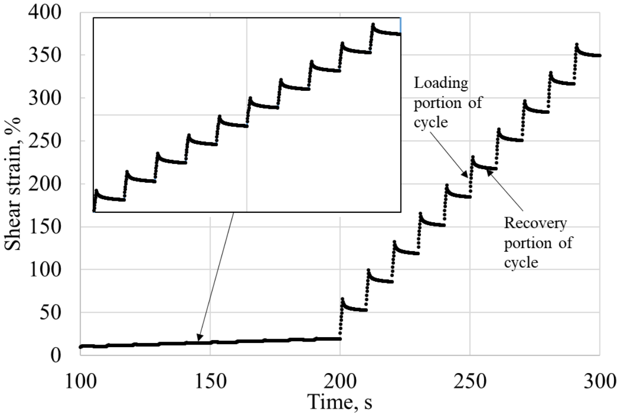


Figure 3.3. Typical results from multiple stress creep recovery test

3.1.6 Fourier transform infrared spectroscopy analysis

The reaction of asphalt with oxygen is accompanied by the production of functional groups including ketones, anhydrides, carboxylic acids, and sulfoxides (Rostler & White, 1959). These chemical functionalities can be identified based on absorption intensities using FTIR spectroscopy (Karlsson and Isacsson, 2003; Baqersad & Ali, 2019). FTIR analysis was used to evaluate the changes in functional groups of the binder. In this test, the spectra for all the bitumen samples were recorded in absorption mode from 4000 to 400 cm^{-1} at a resolution of 4 cm^{-1} and 32 scans for each measurement. For the RA binder as well as for extracted bitumen from mixtures, the carbonyl peak was observed from 1660 cm^{-1} to 1720 cm^{-1} as shown in Figure 3.4. From the normalised spectra, the tangential area around this region was calculated and divided by reference group area (1400 cm^{-1} to 1470 cm^{-1}) to calculate the carbonyl index ($I_{C=O}$). Research has shown that the sulfoxide index is not an appropriate indicator of aging in the bitumen (Zhang et. al., 2011; Yao et. al., 2013). Therefore, the sulfoxide index was not used in this study. A distinct peak for rejuvenator was observed around 1740 cm^{-1} on FTIR spectra which has been also seen for some oils/rejuvenators in past studies (Cavalli et. al. 2018; Li et. al., 2021). 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 calculate the rejuvenation index (I_R).

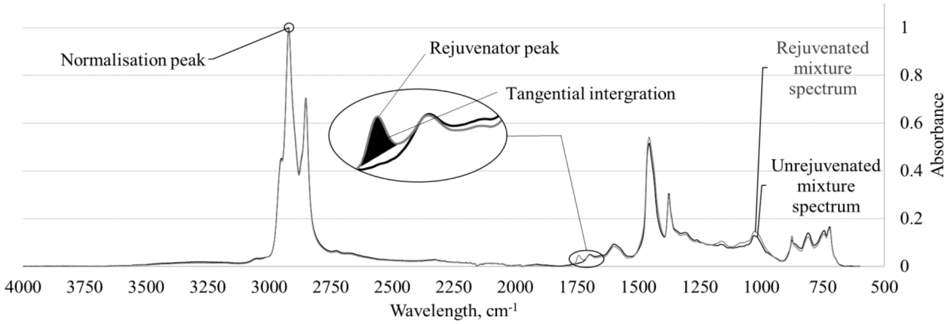


Figure 3.4. Typical FTIR spectrum results for unrejuvenated and rejuvenated mixture

3.2 Mixture tests

3.2.1 Indirect tensile strength

Indirect tensile strength (ITS) was conducted according to EN 12697-23 by applying a diametrical loading across the circular cross-section of the sample at a constant speed of 50 mm/min and recording the load to failure. The test samples were compacted using the Marshall compactor according to EN 12697-30 with 50 blows on each side for ITS evaluation and with 35 blows on each side for moisture susceptibility according to EN 12697-12. For moisture susceptibility evaluation, the ratio of the indirect tensile strength of wet specimens and dry specimens is calculated and expressed as a percentage to determine the moisture damage in the mixtures.

3.2.2 Stiffness modulus test

The stiffness modulus for all the mixtures was determined according to EN 12697-26. The load level was chosen by doing a pre-test inducing horizontal strain in the specimen in the range of 0.05% and 0.10% to ensure that stiffness is in the linear viscoelastic range. This test was carried out at three temperatures, −10°C, 10°C and 25°C and three frequencies, 0.1, 1, and 10Hz. This temperature range was chosen to obtain a wide range of stiffness values and draw the mastercurves. The data obtained from testing at multiple frequencies and temperatures was shifted to a reference temperature of 20°C by performing a temperature−time superposition principle. In this analysis, the shift factors were calculated using equation 3.1 given by Williams et. al. (1955) and a sigmoidal function as defined by equation 3.2 was used for fitting the shifted data.

3.2.3 Thermal Stress Restrained Specimen Test (TSRST)

Thermal stress restrained specimen test (TSRST) was performed according to EN 12697-46 [52] to determine the low-temperature cracking performance of the mixtures. The test is conducted by keeping the length of the specimen constant and reducing the chamber temperature until the sample generates cracks due to thermal stress. The initial test temperature is 20 °C and the temperature reduction rate is 10 °C/h until failure occurs. The specimens for the test were prepared by sawing the slabs to the required dimensions (160 mm × 50 mm × 50 mm). For each mixture, two specimens were tested, and the average value was reported.

3.2.4 Wheel Tracking Rest

The wheel tracking test was conducted in dry condition according to EN 12679-22 [53] to determine the rutting susceptibility of the mixtures. This test was conducted at 60 °C by applying a load of 700 N using a rubber tire and recording the rut depth using two linear variable deformation transducers (LVDT). The test was run up to 10,000 load cycles. The results of this test indicate rut depth for a single sample tested for each mixture. In addition, wheel tracking slope was also calculated from Equation 3.6 using rut depth obtained at 5000 and 10,000 load cycles.

$$WTS = \frac{(d_{10,000} - d_{5000})}{5} \tag{3.6}$$

where,

WTS is the wheel-tracking slope per 103 load cycles in mm, d5,000 and d10,000 are the rut depths in mm after 5000 and 10,000 load cycles, respectively.

3.2.5. Semi-circular bend test

Semi-circular bend test was used to determine the fracture toughness of the mixture. This test was conducted according to AASHTO TP 124-16. The load during the test is applied at the constant displacement rate (either 5 mm/min or 50 mm/min in this research) and the load (kN) and vertical displacements (mm) are recorded during the test at intermediate test temperature (25°C). Work of fracture was calculated by integrating the prior-peak and post-peak load portion of the load-displacement curve using the Eq. 3.7. as shown in Fig. 3.5.

$$W_f = \int_0^{u1} P_{max}(u)\, du + \int_{u1}^{u2} P_{final}(u)\, du \tag{3.7.}$$

Finally, the fracture energy (G_f) and flexibility index were calculated using the Eq. 3.8. and Eq. 3.9.

$$G_f = \frac{W_f}{\mathrm{Area}_{lig}} \times 10^6 \tag{3.8}$$

$$FI = \frac{G_f}{|m|} \times A \tag{3.9}$$

where, Area_{lig} is area of ligament of specimen (mm^2), |m| is the absolute value of post-peak slope (kN/mm), and A (0.01) is the factor for unit conversion and scaling. The average value of two specimens is reported in the results.

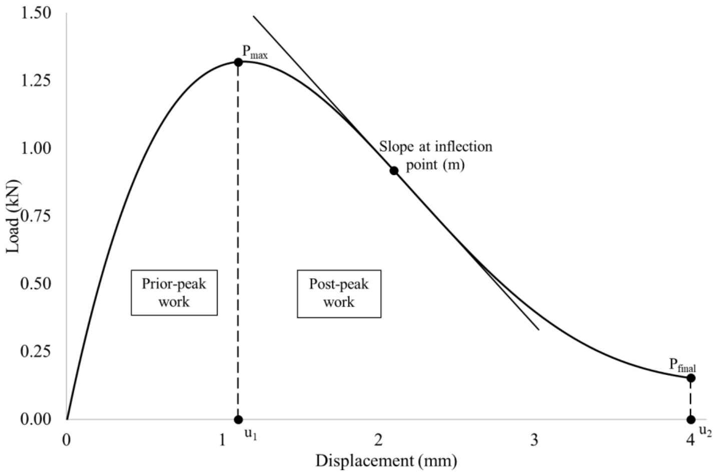


Fig. 3.5. Typical load vs displacement curve obtained from semi-circular bend test

3.2.5 *Digital image correlation*

A non-contact optical method known as digital image correlation was used with semi-circular bend test to obtain strain on surface of specimen. The basic principle of DIC is to track the same pixel points located in various deformed imaged. As shown in Figure 3.6, a square subset or so called sub-image centered at the considered point is tracked in the deformed images using selected correlation function such as zero-normalized cross-correlation (Pan et. al. 2009). By minimizing or maximizing the correlation coefficient, the location of a sub-image in the deformed image is found and the displacement components of this subset center can be determined. The corresponding point P’(x’, y’) after deformation relating to the coordinate O (x_0, y_0) in reference image can be calculated as per equations 3.10 and 3.11 (Gao et. al. 2014):

$$x' = x_0 + \Delta x + u + \frac{\partial u}{\partial x}\Delta x + \frac{\partial u}{\partial y}\Delta y \tag{3.10}$$

$$y' = x_0 + \Delta y + v + \frac{\partial v}{\partial x}\Delta x + \frac{\partial v}{\partial y}\Delta y \tag{3.11}$$

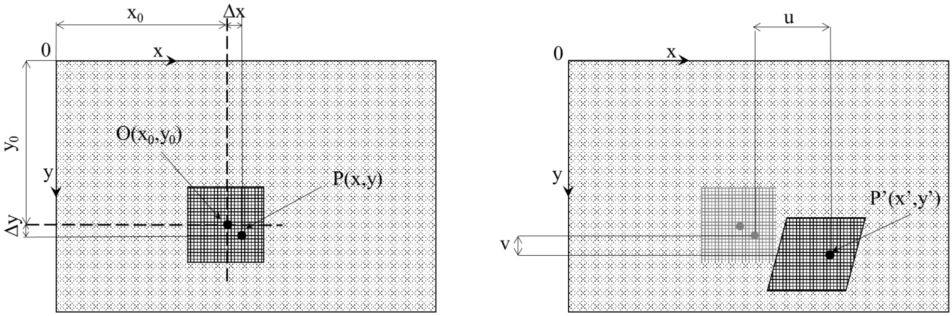
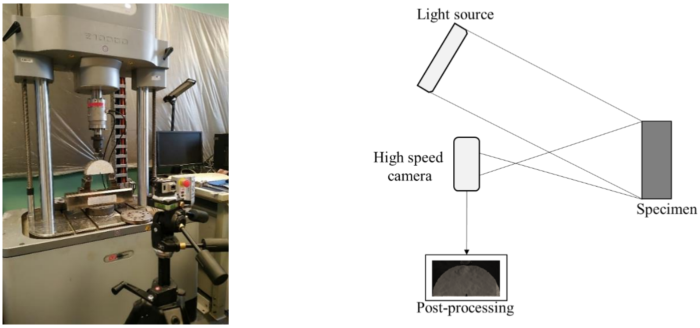


Figure 3.6. Schematic illustration of (a) reference square subset before deformation, and (b) target subset after deformation.

In this study, a high-resolution camera was used along with the semi-circular bend test setup as shown in Figure 3.7, 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^{TM} program. The virtual strain gauges were placed at the tip of the notch to determine the horizontal strain.



(a) (b)

Figure 3.7. (a) Digital image correlation (DIC) test setup; (b) Schematic of arrangement of different components of DIC system

3.2.6 *Leaching test*

For leaching assessment of asphalt mixture, the horizontal dynamic surface leaching test was performed according to the standard CEN/TS 16637-2. To perform the test, Marshall sample were prepared for the asphalt mixture with 75 blows on each side. The asphalt samples were placed in the glass tanks with sealed caps. As a leachant, deionized water was used, and the sample surface water volume was 50L/m. For each sample three replicates were used, and the mean values are reported. The room temperature as well as temperature of leachant was kept between 20-25°C. The leachant from the containers was sampled and renewed at time intervals of 0.25, 1, 2.25, 4, 9, 16, 36, and 64 days with the duration of each step being 0.25, 0.75, 1.25, 1.75, 5, 7, 20, and 28 days, respectively. The samples from leaching and control tests were collected to calculate the concentrations of Al, As, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, Pb, Sb, Se, Si, Tl, V, and Zn. The pH and electric conductivity of the samples were also measured for all the time intervals.

4 MIXING PARAMETERS STUDY

The current emphasis is on increasing the percentage of RA material in asphalt mixtures to maximize the benefits of RA usage. There have been several attempts to demonstrate that mixtures containing even up to 100% RA material can perform equal to or better than conventional hot mix pavements (Dinis-Almeida et. al. 2016; Zaumanis et. al., 2019; Lizzarga et. al., 2018). In most of the studies, however, the laboratory mixing parameters such as rejuvenator incorporation method, mixing temperature, mixing time, and mixer equipment are only vaguely described. If these parameters are not properly controlled, the results might not be reproducible. In addition, the mix design of high RA mixtures involves certain assumptions (Lo Presti et. al., 2016; NCHRP 927: 2020). Researchers generally agree that the RA binder does not behave as a "black rock" (a scenario when aged binder does not take part in mixing); rather, but the extent of active blending between RA binder and virgin binder depends on the mixing parameters. Imaging techniques have shown the existence of a partial black rock effect and a layered structure surrounding the RA aggregates, and the thickness of RA binder was found to be affected by mixing temperature (Cavalli et. al., 2017). This indicates that the chemical and physical properties of RA bitumen film may change as a result of the mixing process which needs to be taken into account for the mixture design.

Conventionally, for production of hot mix asphalt in the laboratory, at first, all mineral aggregates are mixed (dry mixing), followed by pouring the bitumen on aggregate mixture (wet mixing) which is continued for the desired mixing time (until a homogeneous mix is obtained) (Roberts 1996; Zhu et. al., 2020). In high RA mixtures, a rejuvenator is often added to restore the viscosity and elasticity of the aged binder (Zaumanis & Mallick 2015). These rejuvenators are generally pre-blended with virgin bitumen but can also be mixed with heated or unheated RA (Xie et. al., 2019). In a plant study, a conventional approach of adding rejuvenator on hot RAP into mixer was compared to a rather innovative approach where rejuvenator was sprayed on cold RA over a conveyor belt (Zaumanis et. al., 2018). No significant difference was observed from extracted binder properties between the rejuvenation methods. However, the mixture test results demonstrated potentially improved fatigue life when the rejuvenator was sprayed on RA, due to an improved blending of the materials (Zaumanis et. al., 2019). The mixing conditions in the asphalt plant are completely different from the laboratory. Therefore, the impact of the rejuvenator incorporation method on asphalt mixture properties may be explored in laboratory-scale studies. A study has shown that some variation in the traditional mixing method can also significantly improve the performance of high RA mixtures (Zhu et. al., 2020). Therefore, different sequences of mixing the aggregate components and bitumen may also be investigated to optimize the mixing method for high RA mixtures.

It is preferred to avoid high heating temperatures for RA material to limit the aging of the already oxidized RA binder and to prevent sticking of the RA binder to the heating facility (Mogawer et. al., 2013). In the laboratory, a heating temperature of 110°C for a time of no more than 2 hours was recommended since higher temperatures and longer heating times have shown to substantially change the properties of RA materials (Mcdaniel & Anderson 2001). However, to achieve a high RA content in the mixture, it becomes practically impossible to ensure the required mix discharge temperature without heating the RA to a high temperature. A laboratory study on 50% RA mixtures showed that virgin aggregates were required to be heated at 220°C to reach a resultant mix temperature of 150°C, when the RA material was heated at 120°C (Yu et. al., 2017). Additionally, lower preheating temperatures of RA may also result in higher air voids which may lead to consolidated rutting in the mixture and increase in moisture damage (Zhu et. al., 2020; Liu et. al., 2019).

Mixing time could be another important parameter to be controlled in the laboratory studies. The mixing time in an asphalt plant is much shorter compared to mixing time normally used in a laboratory setting. Therefore, the laboratory studies could be overestimating the degree of blending between the RA binder and virgin binder. It was shown in a study that during the short blending process, the complete diffusion of rejuvenator into the aged binder is not possible. As a result, outer layers of bitumen were less rut resistance as compared to the inner layer of bitumen (Ma et. al., 2015).

Very few studies have investigated the effect of mixing time on the properties of asphalt mixtures. A laboratory study using imaging techniques has shown that doubling the mixing time enhanced the homogeneity of the mixture and reduced the variation of air voids (Hassan et. al., 2015). In line with these findings, another study has reported improvement in homogeneity of the mixture observed as a result of increasing the mixing time (Nguyen 2013). Another study showed using X-ray CT system analysis that the optimum mixing time for regeneration of AC mixture with rubberized asphalt should not be less than 90 s to achieve good distribution of components (Zhu et. al., 2020). It should also be noted that longer mixing time in the laboratory may be accompanied by extra oxidation of binder and consequential stiffening of the mixture. Some studies have shown that mixing parameters could have an important impact on evaluating the performance of high RA mixtures in the laboratory. At the same time, the effect of different mixing parameters on the mixture properties is largely unknown because to best of our knowledge, no systematic study has been performed to evaluate it. Importantly, there is no common procedure for preparing mixtures containing RA in the laboratory, and thus the results from different research projects might be difficult to compare or replicate.

4.1 Objective

The objectives of this phase study are:

(a) To evaluate the effect of mixing parameters on mechanical properties of high RA content mixtures produced in the laboratory.

(b) To investigate physical and chemical changes in different layers of bitumen as a result of using different mixing processes.

4.2 Experimental procedure

This study evaluated the impact of laboratory mixing parameters on volumetric and mechanical properties of 60% RA content mixtures. In addition, binder evaluation was performed to examine the RA mixture bitumen layers and investigate the physical and chemical changes in binder characteristics as a result of the mixing process.

The laboratory experiments designed for this study can be divided into two stages which are illustrated in Figure 4.1. In the first stage, all the compacted RA mixtures produced with different mixing parameters were analyzed using indirect tensile strength (ITS) test and stiffness modulus test. Stage two consisted of extracting four layers of binders from mixtures and further evaluating binder using the dynamic shear rheometer (DSR) and the Fourier transform infrared (FTIR) spectroscopy. For binder evaluation, the mixing time parameter was not considered in this study.

In this study, nine different mixtures were prepared as summarized in Table 4.1. The experimental plan was developed in such a way that two of the nine mixtures were used for evaluating more than one mixing parameter. To simplify result expression, these mixtures are reported in the results with a name that corresponds to the variable that is evaluated at that time.

It should be noted that for each group only the parameter that is being analyzed was varied, while the other parameters were kept constant to represent a "typical" mixing procedure. In this study, a "typical" procedure was defined as mixing at 155°C for 4 minutes using the virgin binder blended with the rejuvenator.

Table 4.1. Mixture information

Mixture ID	Rejuvenation method	Mixing temperature	Mixing time	Mixer equipment
Spray- 2 hours	Sprayed on RA material with 2h rest period	155°C	4 minutes	Small mixer
Spray- 24 hours	Sprayed on RA material with 24 h rest period	155°C	4 minutes	Small mixer
Blended/Small mixer	Blended with the virgin binder	155°C	4 minutes	Small mixer
Unrejuvenated	No rejuvenator added	155°C	4 minutes	Small mixer
2 min	Blended with the virgin binder	155°C	2 minutes	Large mixer
4 min/155°C /Large mixer	Blended with the virgin binder	155°C	4 minutes	Large mixer
7 min	Blended with the virgin binder	155°C	7 minutes	Large mixer
130°C	Blended with the virgin binder	130°C	4 minutes	Large mixer
180°C	Blended with the virgin binder	180°C	4 minutes	Large mixer

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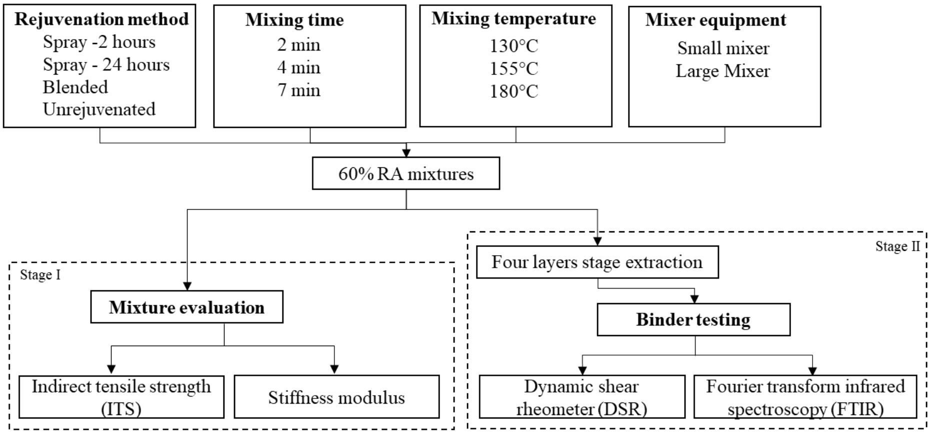


Figure 4.1. Experimental plan

4.3 Materials

Reclaimed asphalt pavement originating in Switzerland was screened on an 11 mm sieve at the RA processing facility resulting in RA 0/11 and RA 11/22 fractions. The two fractions of RA material were combined along with virgin aggregates to design final mixtures. RA content of 60% was used since this is typically the maximum RA content that can be added in a parallel drum plant setup. An AC-16 surface grading curve was selected as the target gradation (see Figure 4.2). The virgin binder used in this study is a 70/100 penetration grade bitumen and the total binder content for each mixture was 5.5 % by weight of the mixture. The recommended practice for the incorporation of recycling agents in RA mixtures is the reduction of the base binder by the full recycling-agent amount (NCHRP Report 927, 2020). Hence for mixture design, full binder replacement was considered which means the rejuvenator quantity and available RA binder were deduced from the total binder content of the mixtures. A commercial rejuvenator based on distilled tall oil was used in the study. The rejuvenator dosage of 4.8% by weight of RA binder was selected from binder tests by targeting the virgin binder penetration grade. The properties of the RA material, virgin aggregates, and RA binder are given in Table 4.2.

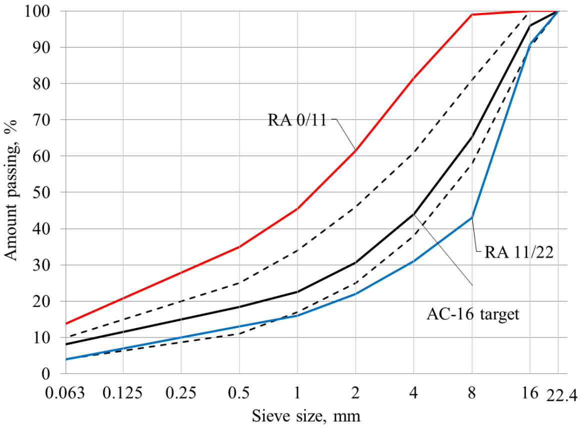


Figure 4.2. Aggregate grading curves

Table 4.2. Material properties

Sieve size (mm)	Passing, %					
	RA 0/11	RA 11/22	AG 11/16	AG 4/5.6	Stone dust	Filler
22.4	100	100	100	100	100	100
16	100	91	100	100	100	100
8	99	43	-	100	100	100
4	81.5	31	-	20.5	95.4	100
2	61.5	22	-	-	64.6	100
1	45.5	16	-	-	34.8	100
0.5	35	13	-	-	22.6	100
0.063	13.8	4	-	-	2.1	82
RA binder content, %	5.6	3.2				
RA binder penetration, 0.1 mm	23	34				
RA binder softening point, °C	60	65.4				

4.4 Laboratory mixing

The rejuvenator was either sprayed on the RA material or blended with the virgin binder, as shown in Figure 4.3. (a) For spraying, the RA material was distributed evenly on a sufficiently large tray to maximize the exposed surface area. A manual pressurizing oil spray bottle was used for spraying rejuvenator on RA material which was placed on a weighing balance. First, half the quantity of rejuvenator was sprayed followed by thorough mixing, and then the rest of the rejuvenator was applied. Three different rejuvenation incorporation cases were considered as follows:

- *Spray- 2 hours*: The rejuvenator was sprayed on cold RA material and then it was put in the oven for 2 hours heating, giving it a rest period of 2 hours with the rejuvenator before mixing.
- *Spray-24 hours*: The rejuvenator was sprayed on cold RA material and then given a rest period of 22 hours at room temperature (20±5°C). The mixture was finally heated for 2 hours in the oven before mixing, giving it a total rest period of 24 hours with the rejuvenator.
- *Blended*: The virgin binder was heated at a temperature of 155°C for 2 hours followed by addition of the rejuvenator and mixing them for 5 minutes using a high-rate mixer.

All the materials were heated at their respective mixing temperature for 2 hours before the mixing process. The mixtures to study the effect of different rejuvenation incorporation methods were produced in a small mixer while the mixtures considering different mixing temperature and mixing time were produced in a large mixer, as illustrated in Figure 4.3. (b) The small mixer is an open mixing system where the mixing bowl is kept in the oven for heated mixing. The large mixer is a closed mixing system with a controlled heating mechanism. After mixing, the loose mixtures were stored for 24 hours and then reheated for 2 hours in a covered pan for compaction.

(a) (b)

Figure 4.3. Laboratory mixing process (a) Spraying of rejuvenator on RA (left); Blending rejuvenator into the virgin binder (right), and (b) Small mixer (left) and Large mixer (right) used in the study

4.5 Results and Discussion

4.5.1 Volumetrics

Effect of Rejuvenation method on air voids

The volumetric analysis test results are summarized in Table 4.3. Due to the excessive fines in RA, lower air voids have been reported as a typical problem for high RA mixtures (Mogawer et. al., 2014). The air voids were found to be 33.1% higher in *Spray- 2 hours* and 19.9% higher in *Spray- 24 hours* mixture than the *Blended* mixture. One of the reasons for this could be that the spraying of rejuvenator may have resulted in more activation of RA material and consequently more fines are taking part in the mixing process and adhering to the coarse aggregates. Though, the Tukey-Kramer statistical groupings show no significant effect of the rejuvenation method on air voids.

Effect of Mixing time on air voids

As seen in Table 4.3., the air voids slightly reduced by increasing 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 into enhanced compaction. However, a further increase in the mixing time to 7 min did not affect the air voids in the mixture. This shows that increasing the mixing time after a certain level of homogeneity is achieved, will not have any effect of compaction properties. It may be noted that the Tukey-Kramer groupings did not show any effect of mixing time on air voids of the mixture.

Effect of Mixing temperature on air voids

Table 4.3. shows that an increase in mixing temperature resulted in a reduction of air voids in the mixture. At higher mixing temperature, the bitumen viscosity is reduced, and the compaction is enhanced. The Tukey-Kramer groupings for the mixing temperature showed that air voids for *180°C* mixture were significantly different from *130°C* and *155°C* mixture. This shows that there is a substantial effect on compaction characteristics when mixing temperature is increased above 155°C.

Effect of mixer equipment on air voids

As seen in Table 4.3., the air voids for the mixture produced in the *Small mixer* were significantly lower than that produced in the *Large mixer.* This was also confirmed from the Tukey-Kramer statistical groupings for the mixer equipment parameters. As all other parameters were same for these mixtures, this difference in air voids indicates that the degree of blending between RA binder and virgin binder could be significantly different for various mixing equipment. The material quantity mixed in the *Small mixer* is much less than the quantity in the *Large mixer.* Therefore, the *Small mixer* may have more homogeneously mixed the material and resulted in enhanced compactibility compared to the *Large mixer.*

Table 4.3. 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

4.5.2 Indirect tensile strength (ITS) test

Effect of Rejuvenation method on ITS

The results of the indirect tensile strength test for different rejuvenation methods are shown in Figure 4.4. From Table 4.4., it is confirmed that none of the rejuvenation methods had any significant effect on the indirect tensile strength of the mixtures. Although the *Unrejuvenated* mixture showed the highest ITS value, it was not statistically different from any of the mixtures containing rejuvenator. It may be noted from Figure 4.4., that *Spray- 2 hours* and *Spray- 24 hours* showed slightly higher fracture energy compared to the other two mixtures mixture. The higher fracture energy for *Spray- 2 hours* and *Spray- 24 hours* mixtures could be related to higher activation of aged RA binder when the rejuvenator was sprayed directly over RA material as opposed to blending the rejuvenator into the virgin binder. However, this effect was not statistically visible from Tukey-Kramer groupings as shown in Table 4.4.

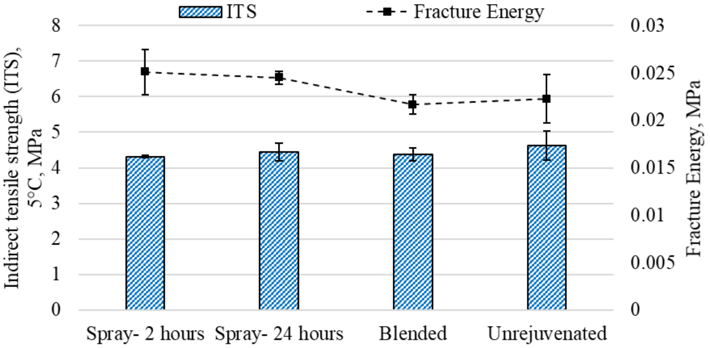


Figure 4.4. ITS results for different rejuvenation techniques. The error bars indicate one standard deviation.

Table 4.4. Tukey–Kramer Statistical Groupings (α = 0.05) for the effect of rejuvenation method on ITS value

Mixture	Indirect tensile strength, 5°C, MPa			Fracture energy, MPa			Post cracking energy, MPa			Toughness, MPa		
	N	Mean	Group	N	Mean	Group	N	Mean	Group	N	Mean	Group
Spray-2 hours	3	4.31	A	3	0.0251	A	3	0.029	A	3	0.051	A
Spray- 24 hours	3	4.45	A	3	0.0245	A	3	0.031	A	3	0.055	A
Blended	3	4.37	A	3	0.0217	A	3	0.034	A	3	0.055	A
Unrejuvenated	3	4.62	A	3	0.0223	A	3	0.037	A	3	0.062	A

Effect of Mixing time on ITS

The results of the indirect tensile strength test for different mixing time are shown in Figure 4.5. It can be observed from Figure 4.5., that the mixing time did not seem to have any effect on the indirect tensile strength for dry as well as wet conditioned specimens. For this reason, all the mixtures share the same group in statistical analysis for dry indirect tensile strength, as shown in Table 4.5. The high TSR ratios for all the mixtures indicate very low moisture damage in the mixtures. This is a common observation for high RA mixtures, and one reason is that lower air voids do not allow moisture to damage the aggregates (Zaumanis & Mallick 2015). Additionally, the double coating of bitumen on RA aggregates supports the moisture resistance.

The fracture energy for all the mixtures was found to be significantly different from each other as none of the mixtures share the same group (Table 4.5). This difference could be due to area calculation errors or test variability. The fracture energy shows large deviations for *2 min* mixture which could be related to the non-homogeneity of the mixture. This observation is supported by other studies that suggested to avoid very low mixing time in the laboratory as it could lead to increased non-homogeneity of mixture (Hassan et. al., 2015; Nguyen 2013).

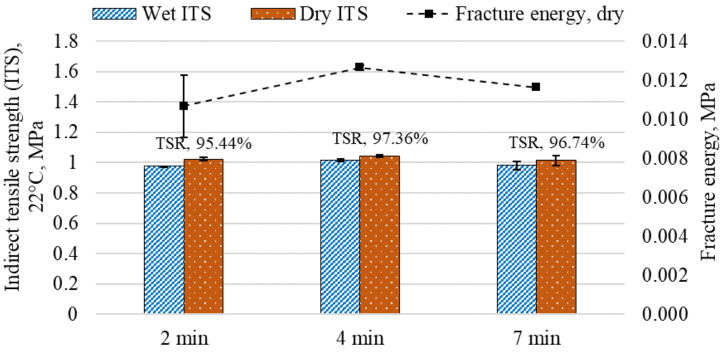


Figure 4.5. ITS results for different mixing times. The error bars indicate one standard deviation.

Table 4.5. Tukey–Kramer Statistical Groupings (α = 0.05) for the effect of mixing time on ITS value

Mixture	Indirect tensile strength, 22°C, dry, MPa			Fracture energy, dry, MPa			Post cracking energy, dry, MPa			Toughness, dry, MPa		
	N	Mean	Group	N	Mean	Group	N	Mean	Group	N	Mean	Group
2 min	3	1.02	A	3	0.011	A	3	0.014	A	3	0.025	A
4 min	3	1.04	A	3	0.013	B	3	0.016	A	3	0.029	B
7 min	3	1.02	A	3	0.012	C	3	0.015	A	3	0.026	A/B

Effect of Mixing temperature on ITS

The results of the indirect tensile strength test at 22°C for different mixing temperatures are shown in Figure 4.6. 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. The fracture energy and toughness for the mixture produced at 180°C were also significantly higher compared to other mixtures as observed from statistical grouping given in Table 4.6. This shows that the mixture stiffness increases substantially as a result of excessive oxidation when the temperature is raised above a certain threshold. This demonstrates that the mixing and heating temperature need to be carefully controlled when preparing mixtures in the laboratory. These results also show that the typical mixing temperature in the range of 155°C considered in asphalt plant is justified.

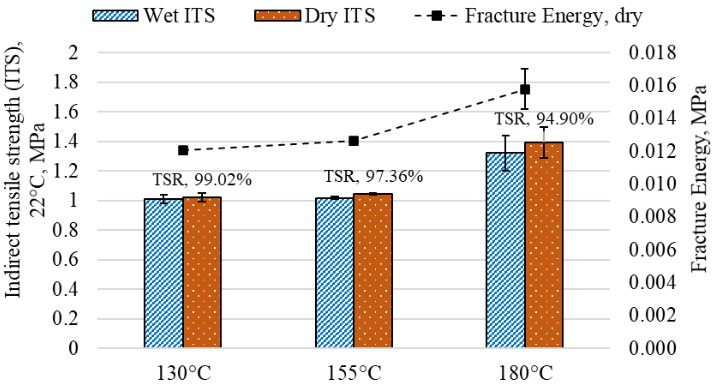


Figure 4.6. ITS results for different mixing temperature. The error bars indicate one standard deviation.

Table 4.6. Tukey–Kramer Statistical Groupings (α = 0.05) for the effect of mixing temperature on ITS value

Mixture	Indirect tensile strength, 22°C, dry, MPa			Fracture energy, dry, MPa			Post cracking energy, dry, MPa			Toughness, dry, MPa		
	N	Mean	Group	N	Mean	Group	N	Mean	Group	N	Mean	Group
130°C	3	1.020	A	3	0.0121	A	3	0.018	A	3	0.03	A
155°C	3	1.044	A	3	0.0127	A	3	0.016	A	3	0.03	A
180°C	3	1.392	B	3	0.0158	B	3	0.018	A	3	0.03	B

4.5.3 Stiffness modulus of asphalt mixture

This test was conducted to evaluate the change in stiffness of the mixture by varying the mixing parameters. The results of the stiffness modulus test were used to construct mastercurves for all the mixtures, which can be seen in Figure 4.7. For statistical evaluation of these results, the stiffness was divided into three zones, low stiffness zone (25°C+0.1Hz), intermediate stiffness zone (10°C+1Hz), and high stiffness zone (–10°C+10Hz) as shown in Table 4.7.

Effect of Rejuvenation method on stiffness modulus

It is clear from Figure 4.7. (a) that all the three mixtures containing rejuvenator were less stiff as compared to the *Unrejuvenated* mixture. This was also confirmed from statistical grouping for low and intermediate stiffness zones as given in Table 4.7. The rejuvenator had a softening effect on the binder and reduced the overall stiffness of the mixture. However, none of the rejuvenation methods was statistically different from each other.

Effect of Mixing time on stiffness modulus

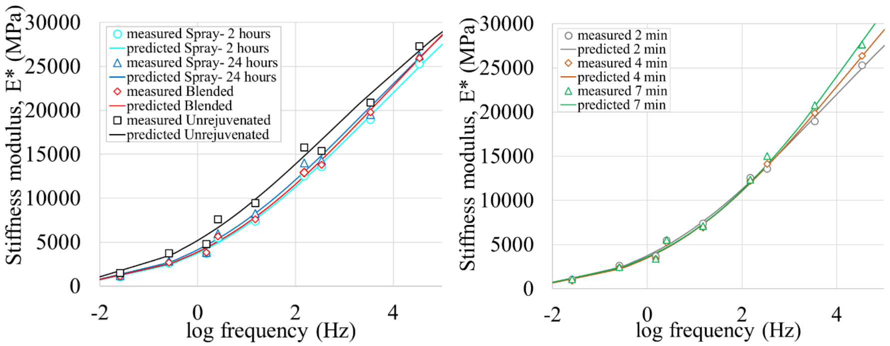
Figure 4.7. (b) shows that the increase in mixing time did not have any effect on the stiffness modulus of the mixtures. This was also confirmed from the Tukey-Kramer groupings shown in Table 4.7. These results are in agreement with the indirect tensile strength test where mixing time did not have any impact on mixture properties. Therefore, it is confirmed that additional oxidative aging that may occur by increasing mixing time up to 7 min is not enough to have a significant effect on the overall stiffness of the mixtures.

Effect of Mixing temperature on stiffness modulus

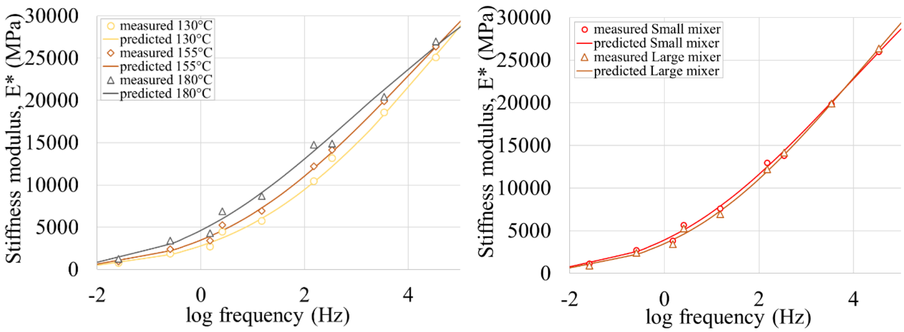
Figure 4.7. (c) shows the mastercurves for mixtures at different mixing temperatures. In the low stiffness zone, 130°C and 155°C mixtures were statistically similar, which is in agreement with ITS test results (see Table 4.7.). However, at the intermediate stiffness zone, all the mixtures were statistically different, and the increase in temperature has resulted in a higher stiffness indicating increased oxidative aging. The effect of mixing temperature was not statistically significant in the high stiffness zone.

Effect of Mixer equipment on stiffness modulus

The effect of mixer equipment on the stiffness modulus of mixtures is shown in Figure 4.7. (d). It shows that the stiffness modulus mastercurve for the small mixer was slightly above the large mixer. This could also be observed statistically from Table 4.7. at intermediate stiffness grouping. As the large mixer produces asphalt in a closed system while the small mixer is an open system with an abundant supply of oxygen and therefore this result could be explained by excessive oxidation of bitumen in the small mixer. Since the difference was not substantial for all the stiffness zones, it cannot be confirmed if this is the effect of the mixer equipment or inconsistency in test results.



(a) (b)



(c) (d)

Figure 4.7. Stiffness modulus mastercurves for effect of (a) rejuvenation method; (b) mixing time; (c) mixing temperature; (d) mixing equipment

Table 4.7. Tukey–Kramer statistical groupings (α = 0.05) for stiffness modulus test

	Low stiffness (25°C, 0.1Hz)			Intermediate stiffness (10°C, 1Hz)			High stiffness (-10°C, 10Hz)		
	N	Mean	Group	N	Mean	Group	N	Mean	Group
Rejuvenation method									
Spray-2 hours	3	1105	A	3	7336	A	3	25788	A
Spray- 24 hours	3	1186	A	3	8285	A	3	26191	A
Blended	3	1118	A	3	7604	A	3	25958	A
Unrejuvenated	3	1520	B	3	9460	B	3	27290	A
Mixing time									
2 min	4	918	A	4	7483	A	4	25077	A
4 min	4	1045	A	4	7003	A	4	26357	A
7 min	4	1074	A	4	7281	A	4	26988	A
Mixing temperature									
130°C	4	804	A	4	5937	A	4	25077	A
155°C	4	918	A	4	7003	B	4	26357	A
180°C	4	1283	B	4	8671	C	4	26988	A

Mixer type									
Small mixer	4	1118	A	4	7604	A	4	25958	A
Large mixer	4	932	A	4	7117	B	4	26294	A

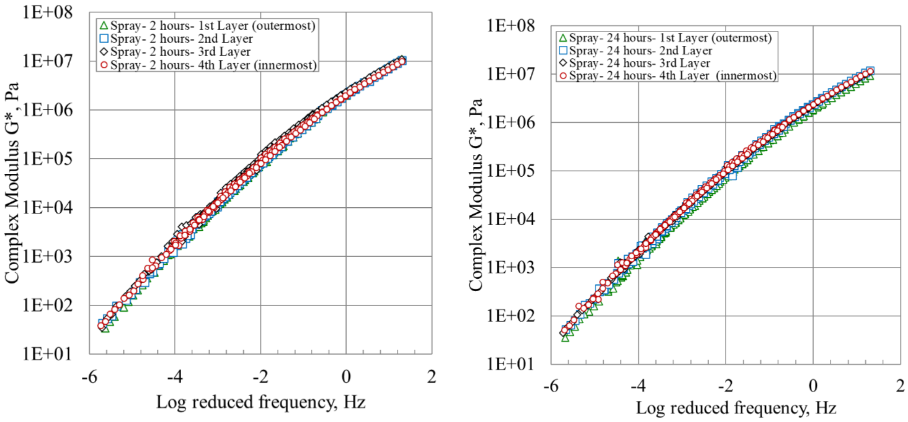
4.5.4 Complex modulus of binder

Effect of Rejuvenation method on complex modulus mastercurves

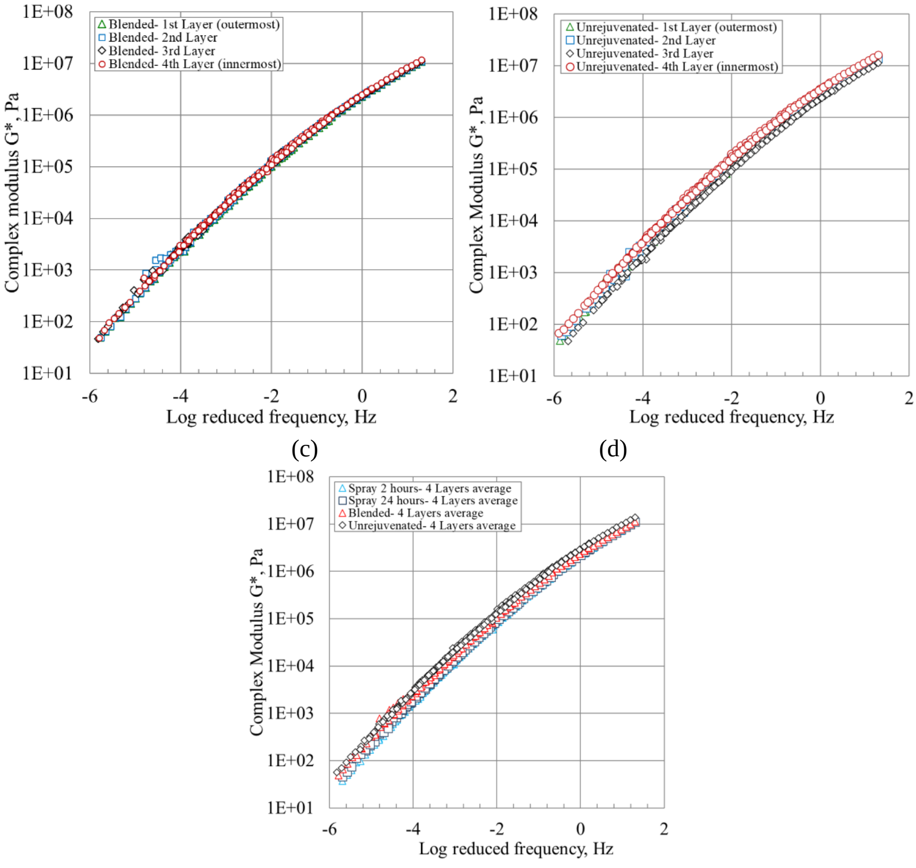
The rheological mastercurves obtained for four layers of bitumen for mixtures with different rejuvenation methods are shown in Figure 4.8. It can be observed from Figure 4.8. (a), (b), and (c) that complex modulus mastercurves for four layers of bitumen overlap for all the three rejuvenation methods. This indicates that there were no significant differences in stiffness among the four layers of bitumen for all the rejuvenation cases. A phenomenon defined by various researchers as the "black rock effect", where the RA material acts as a black rock and the RA bitumen either does not at all or partially blends with the virgin bitumen. Clearly, the effect of black rock aggregates was not observed in this case, as inner layers of bitumen showed equivalent stiffness to that of outer layers.

On the other hand, the *Unrejuvenated* mixture, as observed in Figure 4.8. (d), shows non-homogeneous stiffness between the four layers. The absence of rejuvenator resulted in inadequate blending between the RA binder and the virgin binder in this case.

The mean complex modulus of four layers was calculated to see the overall effect of the rejuvenation method, as shown in Figure 4.8. (e). The spraying of rejuvenator has resulted in lower overall stiffness of the *Spray- 2 hours* and *Spray- 24 hours* mixtures as compared to the *Blended* mixture. This may indicate that the softening effect of rejuvenator was higher when the rejuvenator was sprayed.



(a) (b)



(c) (d)

(e)

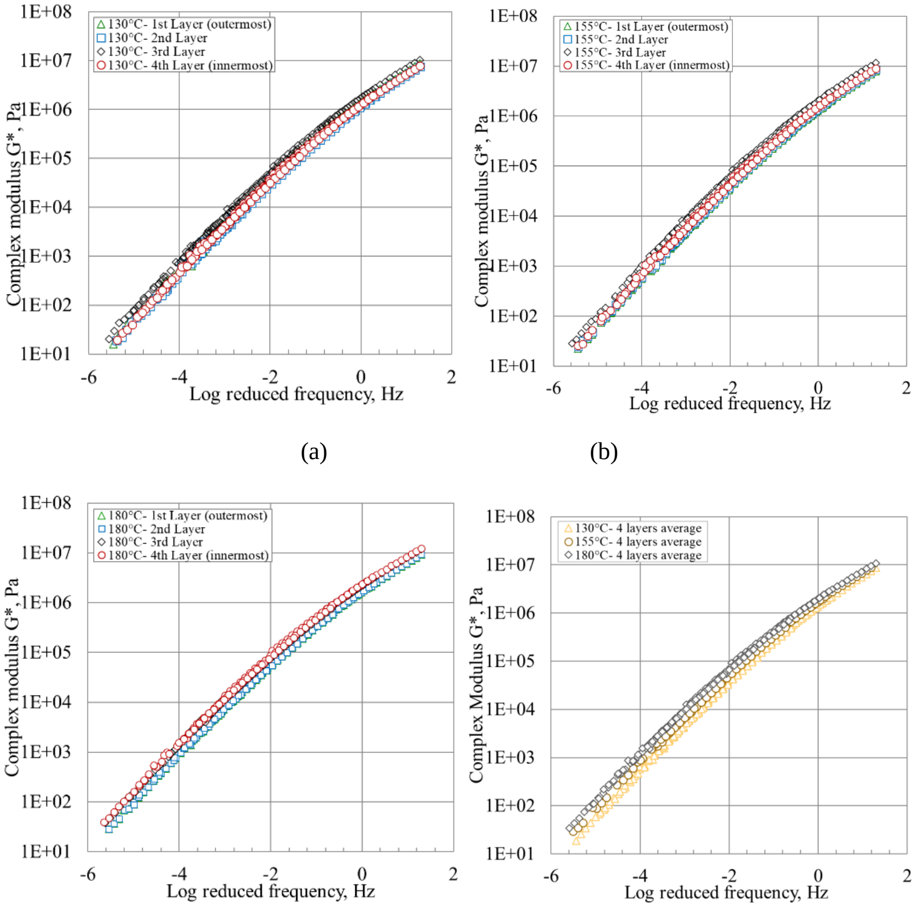
Figure 4.8. Complex modulus mastercurves of stage extracted bitumen for (a) Spray- 2 hours; (b) Spray- 24 hours; (c) Blended; (d) Unrejuvenated; (e) average complex modulus

Effect of Mixing temperature on complex modulus mastercurves

The rheological mastercurves obtained for four layers of bitumen with different mixing temperatures are illustrated in Figure 4.9. It can be observed from Figure 4.9. (a) and Figure 4.9. (b), that the third layer of bitumen showed higher stiffness compared to other layers of bitumen. The higher stiffness of the third layer in *130°C* and *155°C* mixtures may be an indication of the black rock effect where the stiff unactivated RA binder did not take part in the mixing process. The reason for the lower stiffness of the fourth layer could be explained by one of the drawbacks of the adopted stage extraction method. It is hypothesized that some virgin bitumen-fine aggregates clusters remain bonded during the short period of the first three extractions and were dispersed during the 60 minutes soaking period in the fourth extraction. As a result, a blend of RA binder and virgin bitumen was obtained in the fourth layer.

From Figure 4.9. (c), the complex modulus mastercurves for bitumen extracted from mixtures produced at 180°C show that the third and the fourth layers were stiffer than the first and the second layers. One of the possible reasons for this could be that higher heating temperatures of the RA aggregates stiffened the RA binder and resulted in a lower degree of blending between virgin and RA binder.

When the average value of the complex modulus of four layers of bitumen for all the three mixing temperatures was plotted as illustrated in Figure 4.9. (d), an increment in mixing temperature shifted the mastercurve upwards, indicating increased overall aging of the bitumen which also agrees with the mixture test results.



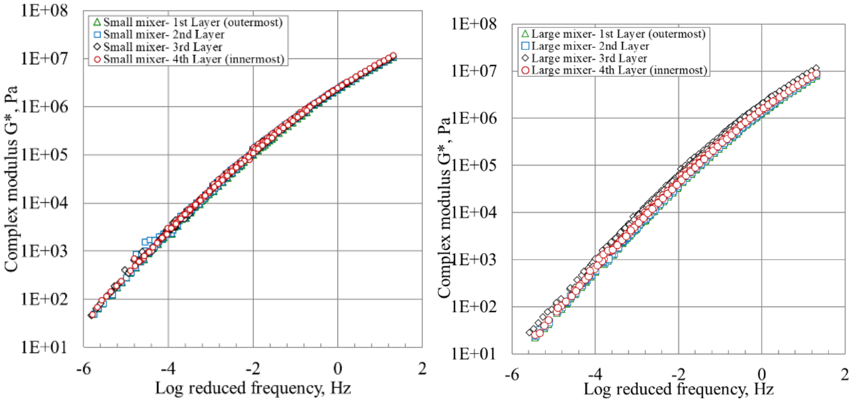
(a) (b)

(c) (d)

Figure 4.9. Complex modulus mastercurves of stage extracted bitumen for (a) 130°C; (b) 155°C; (c) 180°C; (d) average complex modulus

Effect of Mixer equipment on complex modulus mastercurves

Mixers with internal heating are normally considered superior compared to small unheated mixers. It can be seen from Figure 4.10. (a) that the *Small mixer* resulted in homogenous stiffness throughout the four binder layers, while as seen in Figure 4.10. (b) the layers from the *Large mixer* have a much higher stiffness range. This may indicate an incomplete blending of virgin and RAP bitumen (black rock effect). It is concluded that mixer equipment may affect the degree of blending between the RA binder and the virgin binder even when other parameters are kept the same.



(a) (b)

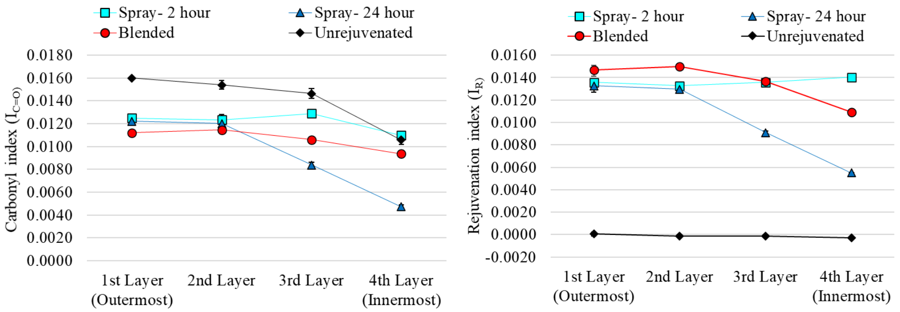
Figure 4.10. Complex modulus mastercurves of stage extracted bitumen for (a) Small mixer; (b) Large mixer

4.5.5 FTIR Characterisation

Effect of Rejuvenation method on FTIR indices

The FTIR characterisation results for different rejuvenation cases are shown in Figure 4.11. It can be observed from Figure 4.11 (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 as a result of rejuvenator addition. The inner layers are expected to contain more oxidised binder compared to outer layers. Contrary to this, the carbonyl index is reducing for all the mixtures moving from the first (outermost) layer to the fourth (innermost) layer except in the *Spray- 2 hours* mixture, where the differences were negligible amongst the four layers. These unexpected results may be due to the presence of two different sources of binder that may show different intensities around the carbonyl peak.

A rejuvenation index (I_R) was developed in this study to indicate the presence of the rejuvenator in binder layers. It is calculated by dividing the tangential area around the distinct rejuvenator peak with the reference area. Figure 4.11 (b) shows the rejuvenation index calculated for different rejuvenation methods. 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 $I_R \approx 0$). For the outermost layer, the rejuvenation index was the same for all the rejuvenated mixtures, but the difference was increasingly visible moving towards the inner layers. The higher difference in innermost layer I_R value among different rejuvenated mixtures may indicate that the diffusion of rejuvenator could be different for each rejuvenation method.



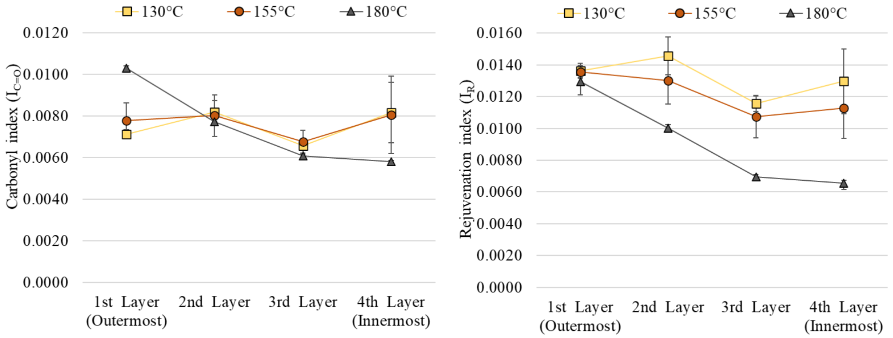
(a) (b)

Figure 4.11. Indices calculated from FTIR spectra analysis for different rejuvenation cases (a) carbonyl indices; (b) rejuvenation indices

Effect of Mixing temperature on FTIR indices

Figure 4.12. shows the indices for four layers of stage extracted bitumen for different mixing temperatures. Since the bitumen tends to age more at a higher temperature, the carbonyl index for mixtures produced at high temperatures were expected to be higher. Unexpectedly as seen in Figure 4.12. (a), except the outermost layer, the carbonyl index for *180°C* mixture, was found to be lower compared to *130°C* and *155°C* mixtures. Carbonyl peak is an indicator of relative oxidation and not the absolute oxidation of bitumen (Hofko et. al., 2018). The presence of two different binders may be one of the reasons that carbonyl index was not able to show increased oxidation as a result of increased mixing temperature. Another reason may be due to presence of rejuvenator. The functional groups including aldehydes, acid, anhydride, amides, and esters, overlap in the carbonyl band with binder oxidation products, which are common in bio-oils used as asphalt modifiers (Cucalon et. al., 2018). The rejuvenator presence may have complicated the chemical analysis and hence the changes in carbonyl area as a result of mixing process could not be observed in this analysis. In the future, it is recommended to analyze the FTIR spectra of binder without adding rejuvenator to have a more accurate assessment of the effects of mixing parameters.

There was no significant difference in carbonyl indices amongst the four layers of bitumen for *130°C* (p_{value}= 0.465) and *155°C* (p_{value}= 0.846) mixture. For the *180°C* mixture, the carbonyl index among four layers was found to be significantly different (p_{value}< 0.05). A similar trend was observed for the rejuvenation index as reported in Figure 4.12. (b), as rejuvenation index amongst four layers were statistically same for *130°C* (p_{value}= 0.462) and *155°C* (p_{value}= 0.497) and were different for *180°C* mixture (p_{value}< 0.05). It can only be inferred that as the mixing temperature was increased, the difference between indices of the four layers was increased. This may indicate that at higher mixing temperature, the binder may get excessively oxidized and reduce the degree of blending in the mixtures.

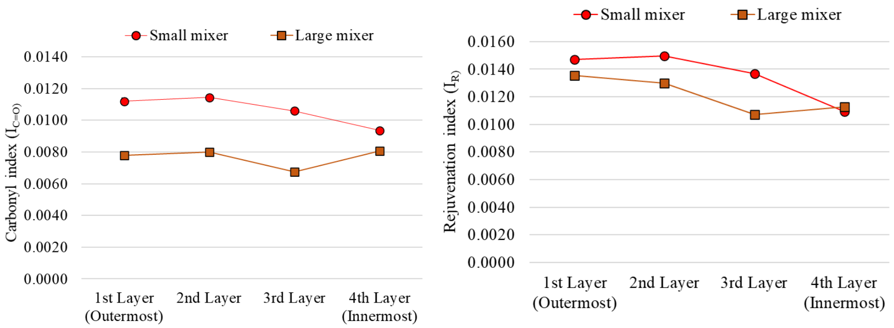


(a) (b)

Figure 4.12. Indices calculated from FTIR spectra analysis for different mixing temperatures (a) carbonyl indices; (b) rejuvenation indices

Effect of Mixer equipment on FTIR indices

A comparison between the carbonyl and rejuvenation indices for different mixer equipment can be seen in Figure 4.13. It can be observed from Figure 4.13. (a) that carbonyl indices for *Small mixer* were significantly higher compared to *Large mixer*. The higher index may be an indication of excess oxidative aging in *Small mixer* due to the open mixing system. This was in agreement with complex modulus bitumen results where *Small mixer* lead to higher stiffness of bitumen layers compared to *Large mixer*. As seen in Figure 4.13. (b), the rejuvenation indices for the *Small mixer* was 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.



(a) (b)

Figure 4.13. Indices calculated from FTIR spectra analysis for different mixer equipment (a) carbonyl indices; (b) rejuvenation indices

4.6 Section summary & conclusions

Laboratory mixing parameters can play an important role in evaluating the performance of high RA mixtures in the laboratory. This study considered 60% RA mixtures produced using a tall-oil based rejuvenator to evaluate the effect of laboratory mixing parameters, including rejuvenator application method, mixing temperature, mixing time, and mixer type. The mixtures properties were evaluated using the indirect tensile strength (ITS) test and the stiffness modulus test. A staged binder extraction method was used to study the properties of bitumen layers in RA mixtures and change in binder characteristics as a result of the mixing process. Binder evaluation was performed using Fourier transform infrared (FTIR) spectroscopy device and dynamic shear rheometer (DSR). Based on our analysis, the following conclusions can be made:

1. The addition of rejuvenator reduced the stiffness of the mixtures and resulted in more homogeneous properties in bitumen layers. At the same time, none of the rejuvenation methods showed a significant impact on the mixture or binder test results.
2. Mixing and heating temperature are critical parameters for high RA mixtures produced in the laboratory. Mixing at high temperature clearly increased the stiffness of the mixture and the binder layers. It is therefore important to carefully control the mixing and heating temperature of materials for evaluating high RA mixture performance in the laboratory. The simulation of the temperature used in the asphalt plant seems to be warranted.
3. The effect of the mixing time was not observed on indirect tensile strength and stiffness modulus of mixtures.
4. The rheological characterisation of different layers of bitumen shows that the black rock effect was partially observed in mixtures from the large mixer equipment, but not at all visible in the small mixer, which indicates that the degree of blending between the RA binder and the virgin binder may change with mixer equipment.
5. The carbonyl and rejuvenation index calculated from FTIR spectra were not consistent with the rheological properties obtained from the dynamic shear rheometer nor with the mixture results. Therefore, in this study, these indices were found unsuitable to predict the chemical changes in the binder as a result of changing different mixing parameters.

In summary, based on the results of this study, there was no difference found between any of the rejuvenation methods adopted in this study. However, other studies provide evidence that early addition of rejuvenator facilitates the activation of the RA binder (Zaumanis et. al., 2019; Lu et. al., 2019). Therefore, early addition on RA (instead of addition in binder) is recommended. The mixing and heating temperature of high RA mixtures should not exceed 155°C to avoid excessive aging of RA bitumen. A mixing time of 4 minutes is recommended in the laboratory. The laboratory studies should account for the type of mixer equipment used for preparing the mixtures since different mixers could lead to a different degree of blending for the same material.

The above recommendations for the laboratory mixing procedure are based on the indirect tensile strength test and the stiffness modulus test. Hence, in the future, the effect of mixing procedure on performance parameters such as rutting, fatigue, and low temperature cracking may be evaluated. Moreover, the parameters considered in this study were limited to laboratory mixing, and these results do not extend to mixtures produced in a plant. Ideally, the plant conditions should be simulated when mixing in the laboratory. For this reason, future studies may consider simulating the plant mixing process to investigate the effects of mixing parameters on high RA mixtures.

5 WARM MIX ASPHALT USING HIGH CONTENT RECLAIMED ASPHALT

The emissions from conventional hot mix asphalt (HMA) production are a complex mixture of fumes, vapors, and solid particulates (Lauby-Secretan 2011; Xu et. al., 2018). Although the bitumen used in HMA production contains a much lower concentration of polycyclic aromatic hydrocarbons (PAHs) (Mundt et. al., 2018), which are the compounds that have been linked to carcinogenesis [4], the epidemiological studies have found increased lung cancer incidence for occupational exposure to bitumen fumes (Randem et. al., 2003; Kauppinen et. al. 2003). The studies have shown that levels of PAHs along with other HMA pollutants including, particulate matter (PM), and volatile organic compounds (VOCs), were greatly affected by the temperature of production (Xiu et. al., 2020; Kitto et. al., 1997). The efforts made to reduce the temperature of asphalt production will have a direct impact on occupational health.

Warm mix asphalt (WMA) is one of the ways to lower the production temperature without compromising the workability and performance of the mixture (Rubio et. al., 2012; Kumar & Suresha 2018; Zaumanis 2014). The temperature reduction range in WMA is typically around 20–40 °C compared to conventional HMA temperature (140–190 °C) (Rubio et. al., 2012). Though WMA is generally considered to offer benefits like longer hauling distances, reduced binder aging, improved workability, and better working environment for the paving crew (Hurley & Prowell 2005; Hurley & Prowell 2006), the type of WMA technology can greatly affect the environmental benefits (Cao et. al., 2019) and the performance (Yousefi et. al., 2020) of the mixtures.

WMA technologies are classified into three broad categories that include foaming processes, organic additives, and chemical additives (Rubio et. al., 2012; Zaumanis 2014). Generally, the organic additives have shown a slightly detrimental effect (Amelian et. al., 2018; Sobhi et. al., 2020; Julaganti et. al., 2017), while chemical additives have improved the moisture resistance of mixtures (Julaganti et. al., 2017; Xu et. al., 2017; Guo et. al.,2020). A field performance study found that pavements with three WMA technologies (chemical, foaming, and organic) do not differ significantly in cracking and rutting performance (Zhang et. al., 2018). Multiple studies have confirmed that WMA significantly lowers the emissions and energy consumption compared to HMA production (Costa et. al., 2013; Wu et. al., 2021), but the life cycle studies have shown that the overall environmental impact for WMA can sometimes be equal to that of HMA due to the presence of additives (Vidal et. al., 2013; Vega-Araujo et. al., 2020) Thus, sustainability evaluation of WMA mixtures be-comes important when used alone.

Research shows that the incorporation of RA material greatly reduced the environmental impacts of WMA mixtures (Vidal et. al., 2013; Giani et. al., 2015; Hasan et. al., 2020). Additionally, WMA facilitates the in-corporation of a high content of reclaimed asphalt (RA) in mixtures and provides synergetic effects on mixture performance (Zaumanis & Mallick 2015). The high RA content mixtures are usually stiffer due to the presence of aged binder, and therefore need changes in the mix design using rejuvenators, additives, or softer binder

(Moghaddam et. al., 2016; Pradhan et. al., 2020; Al-Qadi et. al., 2007). The reduced mixing temperature of WMA limits the undesirable oxidation of bitumen and may compensate for stiff binder present in RA material. In addition, WMA is less affected by aging conditions compared to conventional HMA (Piccone et. al., 2020). Therefore, the use of WMA with RA material can be a viable alternative to conventional HMA, as long-term field performance of WMA mixtures has also been found to be equal to that of HMA mixtures, in terms of cracking and rutting (NCHRP 843, 2017).

While some studies show that incorporation of RA significantly improved the moisture damage (Yousefi et. al., 2020; Fakhri et. al., 2017; Izaks et. al., 2020), others have found that moisture resistance reduced with the incorporation of RA material (Goli et. al., 2020; Guo et. al., 2016; Nejad et. al., 2014; Farooq et. al., 2018). This confirms that RA material from various sources may be having a different impact on the moisture performance of the mixture. Generally, the incorporation of RA material has been shown to improve the high-temperature performance of mixture (Fakhri et. al., 2017; Guo et. al., 2016; Zhao et. al., 2013), which is a significant benefit for WMA mixtures, but the RA material incorporation has also been linked to a reduction in low-temperature resistance of the mixtures (Izaks et. al., 2020; Mogawer et. al., 2013).

The extensive research carried out across the globe on warm mix asphalt containing reclaimed asphalt pavement material shows that the performance of mixture can vary with WMA technology type; RA content; production temperature, and laboratory conditioning (Abduljabbar et. al., 2019; Almeida et. al., 2020). It becomes important to evaluate the performance of WMA mixtures on a case-to-case basis. The main aim of this paper is to compare the performance of conventional HMA mixture to WMA as well as with WMA containing 60% reclaimed asphalt (RA) content produced using a chemical WMA additive. The comparison of mixtures is based on the evaluation of low-temperature performance, high-temperature performance, and moisture susceptibility characteristics. In addition, the effect of mixture conditioning was also determined by comparing the performance of short-term aged mixtures to unaged mixtures.

5.1 Objective

The main aim of this study is to compare the performance of conventional HMA mixture to WMA as well as with WMA containing 60% reclaimed asphalt (RA) content produced using a chemical WMA additive. The comparison of mixtures is based on the evaluation of low-temperature performance, high-temperature performance, and moisture susceptibility characteristics. In addition, the effect of mixture conditioning was also determined by comparing the performance of short-term aged mixtures to unaged mixtures.

5.2 Experimental Plan

The experimental plan developed for this study is in Figure 5.1. The control mixture for this study was a conventional HMA prepared at a mixing temperature of 140 °C. For WMA, the optimum temperature was determined by preparing mixtures containing chemical additive at a range of mixing temperatures (110, 125 and 140 °C). The optimum temperature was determined based on volumetric requirements for AC-11 surface layer mixtures as given in Latvian road specifications [46]. Finally, the WMA mixtures were produced with 0 and 60% RA content at optimum temperature without any further binder modification. The low-temperature performance, high-temperature performance, and moisture susceptibility were evaluated using tensile stress restrained specimen test, wheel tracking test, and indirect tensile strength test, respectively. All the mixtures were produced using two conditioning methods to compare the unaged mixture to short-term aged mixtures.

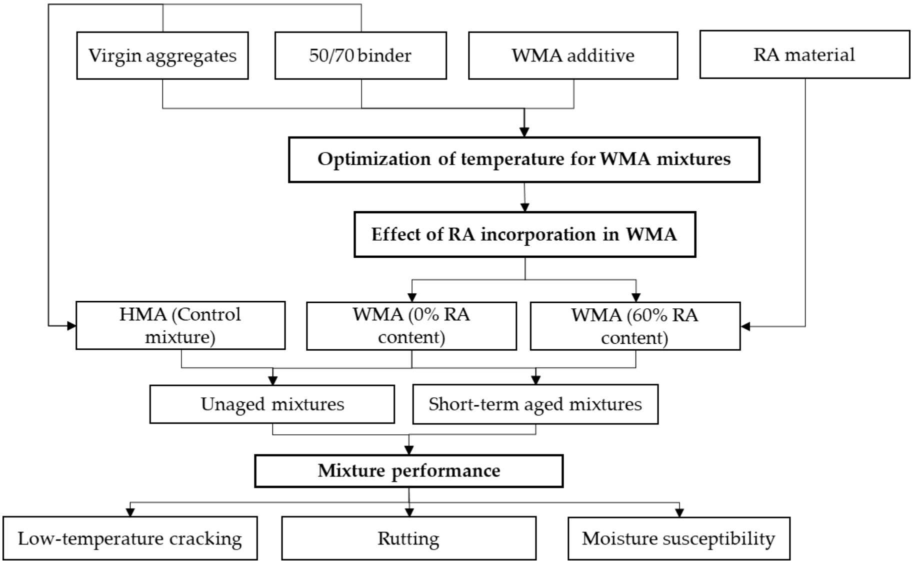


Figure 5.1. Experimental plan.

5.3 Materials and Methods

5.3.1 Virgin Aggregates and RA Material

The virgin aggregates used in the study consisted of Dolomite 8/11, Dolomite 5/8, Dolomite 2/5, Sand 0/4, and filler material. The RA material considered in this study was obtained from an asphalt plant in Vangazi, Latvia, where it was processed using standard operations. The extraction was performed on RA material according to EN 12697-1standard. The particle size distribution of extracted RA aggregates along with the gradation of mixtures produced in this study is shown in Figure 5.2. The shape index for coarse aggregates in RA material determined as per EN 933-4 was found to be 12. The flow coefficient for sand and fine RA aggregates determined according to EN 933-6 were 31.5 and 28, respectively.

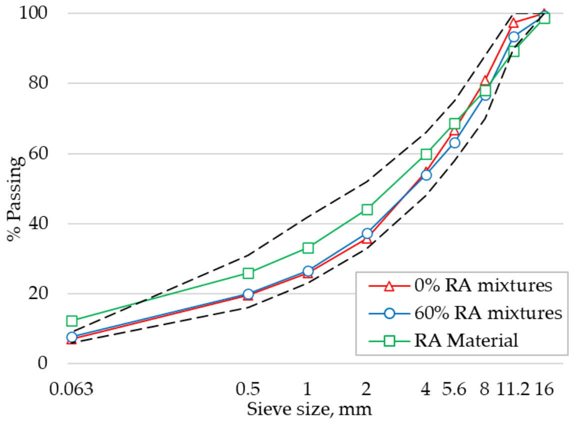


Figure 5.2. Mixture and extracted RA aggregates gradation.

5.3.2 *Virgin Binder and RA Binder*

The virgin binder used in this study was a 50/70 penetration grade bitumen obtained from ORLEN Asfalt, Mazeikiai, Lithuania. The RA binder was recovered from bitumen solution using a rotary evaporator according to EN 12697-3 standard. The RA material had a binder content of 4.35% and the penetration of RA bitumen was 39 × 0.1 mm. In this study, a chemical additive widely used in industry was utilized which is based on its surfactant properties. Typically, with this additive, the production temperature range is 85–115 °C for a dosage of 0.5% w/b [10]. In this study, the supplier recommended dosage of 0.4% w/b was used for all the WMA mixtures at different temperatures. The control HMA mixture used in this study was designed using the Marshall mix design method and the optimum binder content was determined as 5.5% by weight of aggregates. The binder content for virgin WMA and WMA containing 60% RA was 5.5% by weight of aggregates. For WMA mixtures containing 60% RA material, the aggregate gradation similar to virgin mixtures was achieved by proportioning the virgin aggregates. For these mixtures, the binder quantity was calculated by deducting the amount of reclaimed asphalt binder from the total binder requirement of WMA mixtures.

5.3.3 *Mixture Preparation*

The virgin aggregates and RA materials for all the mixtures were heated at their respective mixing temperature for 2.5 h in the oven. The WMA binder was prepared manually using a paddle mixer. For this, the 50/70 binder was heated at a temperature of 150 °C in the oven for one hour, and the required dosage of additive was added to the binder followed by mixing for 5 min. Prior to asphalt mixing, virgin binder and WMA binder were heated for 2.5 h in the oven at respective mixing temperatures of the mixture. Initially, all the constituent virgin aggregates, and RA material were mixed without bitumen in the mixer for 1 min to ensure a homogeneous blend of aggregates as well as to increase the activation of the RA binder. After 1 min, the bitumen was added, and mixing was continued for another 4 min. The unaged mixtures were compacted immediately after the mixing. The compaction temperature was 5 °C lower than the mixing temperature for all the mixtures. For simulating short-term aging, mixtures were conditioned in an oven with a covered pan for 4 h according to EN 12697-52 standard. HMA mixtures were conditioned at a temperature of 135 °C and WMA mixtures were conditioned at 120 °C. The conditioning temperature for short-term aging was kept 5 °C lower than the mixing temperature to consider the loss of temperature during the production stage. All the mixtures produced in this study are shown in Table 1. It should be noted that “WMA” only refers to the mixtures that are produced using the chemical additive, and the temperature for each mixture is indicated in Table 5.1.

Table 5.1. Mixture information.

Mixture	RA Content	Mixing Temperature	Conditioning Process
HMA0-140-UN	0%	140 °C	Unaged
WMA0-140-UN	0%	140 °C	Unaged
WMA0-125-UN	0%	125 °C	Unaged
WMA0-110-UN	0%	110 °C	Unaged
HMA0-140-STA	0%	140 °C	Short-term aged @ 135 °C for 4 h
WMA0-125-STA	0%	125 °C	Short-term aged @ 120 °C for 4 h
WMA60-125-UN	60%	125 °C	Short-term aged @ 120 °C for 4 h
WMA60-125-STA	60%	125 °C	Short-term aged @ 120 °C for 4 h

5.4 Results and Discussion

5.4.1 Volumetric Analysis

The volumetric analysis test results for all the mixtures are given in Table 2. 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 the mixtures (Rubio et. al., 2012, Kumar et. al., 2014; Zaumanis et. al., 2014). This shows that the chemical additives can be incorporated in the HMA mixtures without lowering the temperature when the main aim is to enhance the compactibility of the mixture

Table 5.2. Volumetric analysis results.

Mixture	Max Density, kg/m^3	Air Voids, %	VMA, %	VFB, %
HMA0-140-UN	2487	1.7	15	88.4
WMA0-140-UN	2493	1.2	14.7	91.2
WMA0-125-UN	2501	2.6	15.8	84.1
WMA0-110-UN	2523	4.1	17.2	76.4
HMA0-140-STA	2518	1.9	15.4	87.7
WMA0-125-STA	2496	2.7	15.2	87.5
WMA60-125-UN	2494	1.8	15.9	83
WMA60-125-STA	2507	2	15.5	86.5

As observed in Table 5.2, 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. This may be due to the fact that with the reduction in temperature, the viscosity of bitumen is increased. As a result of increased viscosity, the compactibility is reduced. The Latvian Road specifications require the air voids for AC-11 surface layer mixtures to be in the range of 1.5–4%. As seen in Table 5.2, only the WMA0-125-UN mixture meets the requirement for the air voids among all WMA mixtures without RA material. Based on these results, the optimum mixing temperature for WMA mixtures was selected as 125 °C. The subsequent WMA mixtures for performance evaluation were produced at a temperature of 125 °C in this study.

As seen in Figure 5.3, the air voids for the unaged mixtures were not significantly different from short-term aged mixtures. This indicates that even though the binder gets oxidized during 4 h short-term aging process and may become stiffer, the change is not enough to significantly affect the compaction characteristics of mixtures.

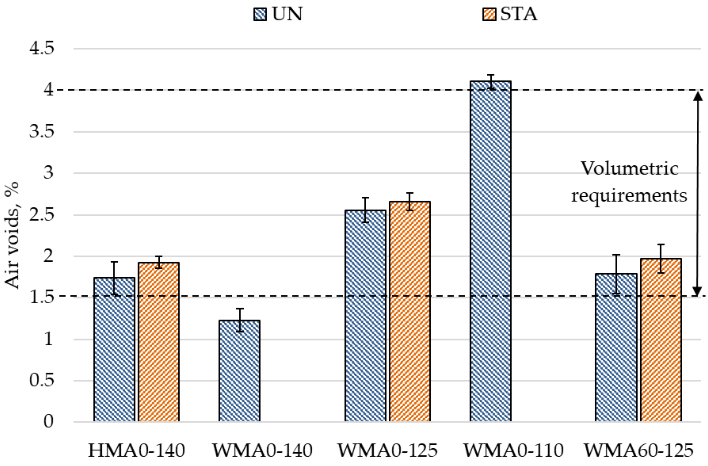


Figure 5.3. Volumetric analysis results.

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 60% RA material into WMA resulted in reduced air voids in the mixture. The lower air void content is a typical problem for high content RA mixtures (Zaumanis et. al., 2019). Considering, that the gradation of RA mixtures is the same as virgin mixtures in this study, it is likely that lower air voids in RA mixtures may be due to the presence of unbound fines from RA that did not mix well with the binder in the mixture. These unbound fines are generated during the milling process due to the crushing of aggregates.

5.4.2 Low-Temperature Performance

For mixtures produced in colder regions, low-temperature cracking is an important concern. Moreover, the inclusion of RA material increases the low temperature cracking susceptibility of mixtures due to presence of aged RA binder. The results of low temperature cracking test are shown in Figure 5.4. 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 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 modified binder in WMA mixtures is subjected to lower mixing temperature compared to the HMA binder which results in lower binder aging in WMA. The lower binder aging in WMA may be the reason for the better low-temperature performance of these mixtures.

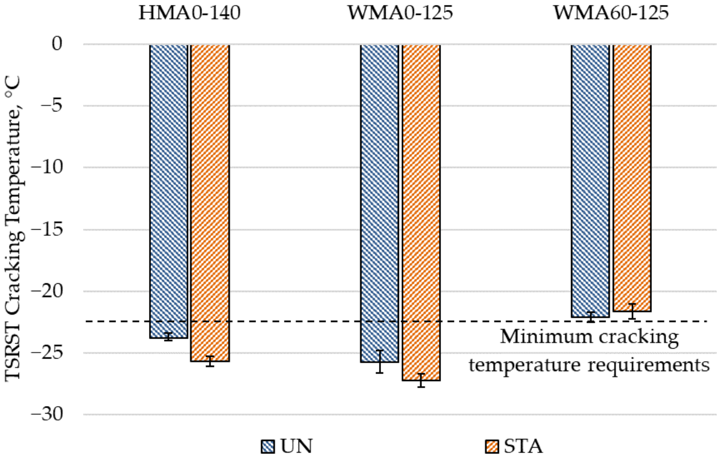


Figure 5.4. Low-temperature cracking test results.

It was expected that the short-term aging of the mixtures will degrade the low temperature cracking resistance of the mixtures as a result of oxidation of binder. However, the short-term aged mixtures (HMA0-140-STA and WMA0-125-STA) showed slightly lower cracking temperature (1.85 and 1.5 °C lower) compared to unaged mixtures (HMA0-140-UN and WMA0-120-UN). It is believed that this change might be due to the variability of materials, as the fracture temperature for TSRST is known to be highly sensitive to aggregate and asphalt type. This variability could also have come from glue due to stress concentration at the epoxy region in the specimen. Nevertheless, for these mixtures, WMA showed superior cracking resistance than HMA, which follows the same trend as unaged mixtures.

It can be seen that 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 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. The fine aggregates in RA are also more rounded than the virgin aggregates (flow coefficient value for RA mixtures was 28 compared to 31.5 for virgin mixtures), which could be another reason for the lower fracture resistance of these mixtures. As a result, the mixtures containing RA material could not fulfil the minimum requirement of −22.5 °C for low temperature cracking for AC-11 surface layer mixtures as per Latvian Roads specifications. Since the aim of this study was to isolate the effect of WMA technology, no further modifications in the binder were performed for the high RA mixture. However, it is clear that the additive alone is not sufficient, and the addition of a rejuvenator or softer binder may be required to improve the low-temperature cracking performance of high content RA mixtures.

The low temperature cracking resistance deteriorated on RA material incorporation which is in agreement with past studies (Izaks et. al., 2020; Mogawer et. al., 2014). Considering that 20–30% RA incorporation has not shown a reduction in low-temperature cracking (Guo et. al., 2020; Jung et. al., 1993; Yu et. al., 2016), lower RA content may be used with WMA to improve the low-temperature performance. However, the long-term performance of RA mixtures in low-temperature cracking needs to be evaluated.

4.3. Rutting Performance

Figure 5.5 shows the results of the wheel tracking test. It can be observed that proportional rutting depth for WMA0-125-UN mixture was 8.4% higher compared to rut depth in HMA0-140-UN mixture. The binder in WMA mixtures is softer than the virgin binder due to presence of the additive. The reduced stiffness of mixture due to binder modification increased the rutting susceptibility in WMA compared to HMA. It was also observed in past studies that WMA mixtures were more susceptible to rutting failure due to reduced aging of bitumen in the mixture (Hurley & Prowell 2015; Zhao et. al. 2012; Bairgi et. al., 2021).

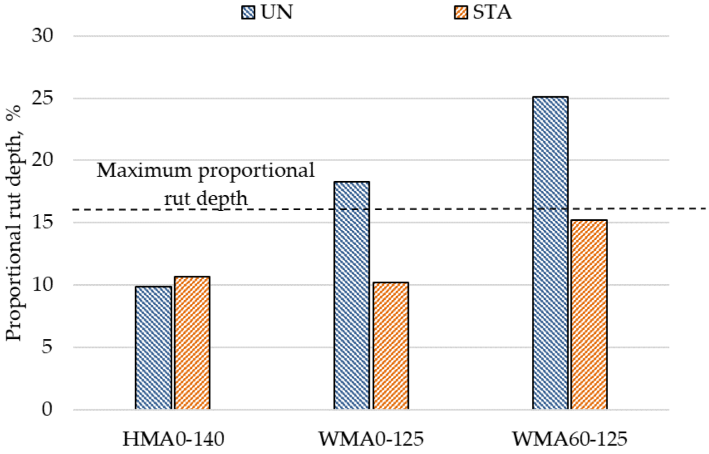


Figure 5.5. Proportional rut depth results.

The unaged WMA mixture containing 60% RA material showed the highest rutting potential among all the mixtures. The incorporation of 60% RA material increased the rutting depth by 6.8% in the WMA mixture. This is opposite to the general trend observed from past studies, where the rutting resistance was increased with the incorporation of RA material (Fakhri et. al., 2017; Guo et. al. 2016; Zhao et. al., 2013). One reason for the lower rutting resistance of RA mixture could be the low angularity of fine aggregates in RA material as the flow coefficient for fine RA aggregates was lower compared to the fine aggregates in the virgin mixture. Another reason may be lower degree of blending between RA binder and virgin binder ultimately resulting in an unstable mixture.

As shown in Figure 5.5, the short-term aging did not show any effect on the rutting performance of control HMA mixture. However, for the virgin WMA mixture, the rutting depth was considerably reduced on short-term aging to a level equal to that of control HMA mixture. For the 60% RA mixture, the rut depth was still 5% higher than the virgin WMA mixture in aged condition. The short-term aging of the WMA mixture may have resulted in oxidation of the binder which made the mixture stiffer than the unaged mixture. A past study has also shown that aged mixtures show higher stiffness and better rutting resistance than unaged mixtures (Almeida et. al., 2020). Both the unaged WMA mixtures (WMA0-125-UN and WMA60-125-UN) could not fulfill the proportional rut depth requirement. However, the short-term aged WMA mixtures fulfilled the proportional depth rutting criteria.

The Latvian Road specifications have set the requirement of a minimum of 0.1 mm/1000 for wheel tracking slope for the highest traffic level. None of the mixtures produced in the study fulfilled the wheel tracking slope criteria as shown in Figure 5.6. The short-term aging of the WMA mixture without the RA material has significantly reduced the wheel tracking slope which shows the importance of taking into account the effect of the conditioning process while evaluating the rutting performance of the mixtures.

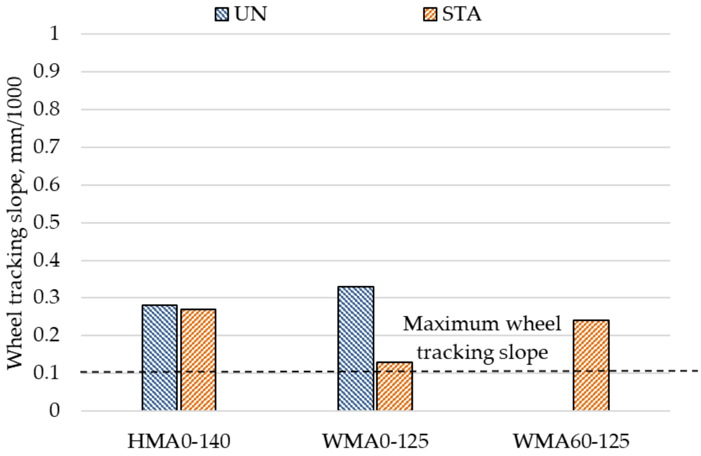


Figure 5.6. Wheel tracking slope results.

5.4.3 Moisture Susceptibility

The results of the indirect tensile strength test for all the mixtures are shown in Figure 5.7. It can be seen that indirect tensile strength for all the mixtures is not significantly changed after the moisture conditioning. This shows that reduction of temperature in WMA did not have any adverse effect on moisture performance. 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 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 from 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.

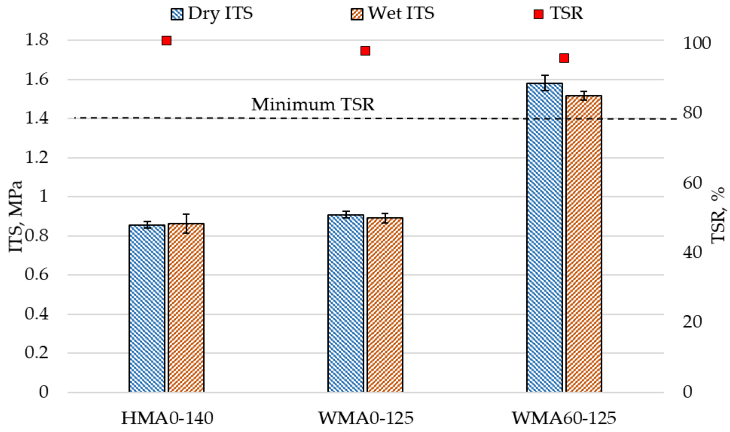


Figure 5.7. Moisture susceptibility results.

5.5 Section summary & conclusions

This study compared the laboratory performance of HMA mixture with virgin WMA mixture and WMA mixtures 60% RA material. The performance was evaluated using tensile stress restrained specimen test, wheel tracking test, and indirect tensile strength test. For all the mixtures, the performance was evaluated for unaged and short-term aged mixtures. Based on this study, the following conclusions are made:

1. The addition of chemical additive without changing the temperature enhanced the compactibility of the HMA mixture. A reduction of 15 °C in mixing temperature compared to HMA mixture was achieved for WMA mixtures using chemical additive. The incorporation of RA material reduced the air voids in the WMA mixture.

2. The low temperature cracking performance of virgin WMA mixtures was superior to control HMA mixture. However, the addition of RA material degraded the low-temperature cracking resistance of the WMA mixture.

3. The virgin WMA mixture showed higher rutting potential compared to the control mixture, due to binder modification and lower binder aging. The incorporation of RA material degraded the rutting resistance of the WMA mixture. The short-term aging of WMA mixtures also affected the rutting resistance compared to unaged mixtures.

4. The reduction in mixing temperature using chemical additive and incorporation of RA material did not show any negative effect on moisture characteristics of the mixtures. The indirect tensile strength for WMA mixture containing RA material was much higher than HMA and virgin WMA mixtures, due to the presence of oxidized RA binder.

5. More research is required to study the effect of the combination of rejuvenators and WMA additives on the activation of RA binder. However, careful selection of rejuvenator is required due to rutting concerns of mixtures, as observed in this study. Additionally, the conventional methods for designing mixtures may not be completely applicable to high RA mixtures due to high variability in properties of RA materials originating from different sources. Therefore, future studies should also look into developing performance-based specifications for the design of high RA content mixtures.

6 REJUVENATORS AGING STUDY

In laboratory, some of the studies have shown that asphalt mixtures containing 100% RA material provide satisfactory performance (Zaumanis et. al, 2020; Dinis-Almeida et. al, 2016; Elkashef & Williams 2017; Lizárraga et. al, 2018). However, the concept of 100% recycling, where the asphalt mixture is produced using only reclaimed asphalt, bitumen, and rejuvenators, needs validation through more studies. Most of the laboratory studies have used either a softer binder, an additive, or a rejuvenator to modify the reclaimed asphalt (RA) binder. Among these, rejuvenators are most effective in adjusting the properties of the RA binder and improving the performance of final mixtures. Rejuvenators can be petroleum based, bio-oil-based, waste cooking or industrial oil based, or specifically engineered additives (Bock et. al., 2020), and these rejuvenators can restore the asphaltenes/maltenes ratio in bitumen which compensates the hardening effect of aged binder (Garcia et. al., 2011; You et. al., 2011). However, rejuvenators from various sources may have different degree of effectiveness on improving the performance of the mixtures (Haghshenas et. al., 2016). For example, the organic based rejuvenators have outperformed the petroleum-based rejuvenators in improving the performance of reclaimed asphalt mixtures (Zaumanis & Mallick 2015). Another study found that rejuvenators based on paraffinic oil were less effective in improving fatigue life of mixtures compared to fatty acids-based rejuvenators (Guduru et. al., 2021). Though significant work has been conducted on understanding the effect of rejuvenators on RA binder properties (Cavalli et. al. 2018; Behnood 2019; Daryaee et. al., 2020, Yu et. al., 2020; Hossain et. al., 2020), relatively little is known about the long-term effectiveness of these rejuvenators and their interaction with asphalt binder during pavement aging.

The oxidation of bitumen is the main reason behind deterioration of pavement during service life and as a result, 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 (Airey 2003). The researchers have made efforts to simulate the field aging in the laboratory at both binder and mixture level. Rolling thin film oven test (RTFOT) and Pressure aging vessel (PAV) are the most frequently used methods on binder for short-term and long-term aging, respectively (Wang et. al., 2020; Colbert et. al. 2012; Mishra & Singh 2019; Tarsi et. al, 2018). However, the aging procedures on binder aging do not completely simulate the field conditions because aging depends on binder as well as on mix parameters (Brown et. al., 2009). The long-term aging of bitumen in field is a slow process and depends on a number of environmental factors. Therefore, aging methods that consider the impact of reactive oxygen species have been developed to simulate the field aging (Hofko et. al., 2020, Mirwald et. al., 2020a). This method leads to different aging level which makes it more suitable to distinguish between aging susceptibility of different binders (Mirwald et. al., 2020b). Even after considering the environmental factors, the aging in mixture differs from binder aging. For examples, it was shown that degree of aging was found to be spatially dependent which resulted in stiffness gradient within the asphalt layer (Jing et. al., 2019). Therefore, several studies have investigated the effect of short-term oven aging (Ziari et. al. 2019; Asib et. al. 2019) and long-term oven aging (Li et. al. 2020; Poulikakos et. al. 2014) on properties of asphalt mixtures containing RA material. It has to be noted, however, that the maximum RA content in asphalt mixture is limited to 50% or less in most of the studies. In the past, reclaimed asphalt has shown a slower aging rate compared to a virgin binder (Shen et. al., 2007; Singh et. al., 2012). Therefore, it becomes important to study the aging of binder in 100% RA mixtures, as these mixtures may contain high amount of inactive RA binder along with rejuvenated binder which may age at a different rate. Moreover, with a wide variety of rejuvenators available in the market, it is likely that the type of rejuvenator used in the mixture will also affect its binder aging phenomenon. All these factors will affect the rate of aging of mixtures which needs to be investigated.

6.1 Objective

The objective of this study is to evaluate the change in rheological and chemical properties of bitumen by simulating the aging on 100% reclaimed asphalt mixtures containing different sources of rejuvenators. The experimental plan is shown in Figure 1. The field aging simulation was conducted on loose mixtures in oven to consider the effect of varying aging rates of different stiffness of binder layers present in the RA material. The rheological characteristics were evaluated using temperature and frequency sweep test, fatigue performance was evaluated using linear amplitude sweep test, rutting performance was evaluated using multiple stress creep recovery test, and functional group characterization was performed using Fourier transform infrared spectroscopy.

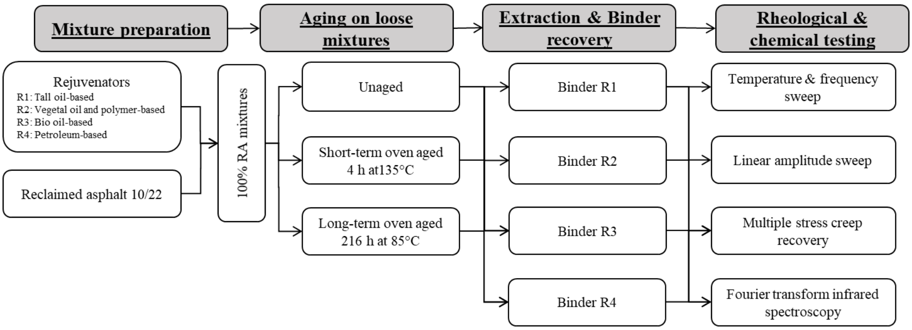


Figure 6.1. Research plan

6.2 Materials and Methods

6.2.1 Materials

The reclaimed asphalt material was collected from an asphalt plant in Latvia. The collected RA material was fractionated to 10/22 size to remove the fines in order to meet the gradation criteria of AC-16 mixtures from Latvian road specifications. The gradation of original RA material and 100% RA mixtures (10/22 RA material) are shown in Figure 6.2. The centrifuge extraction was performed on RA material according to EN 12697-1 (2005) and the binder was recovered from the solution using a rotary evaporator according to EN 12697-3 (2014). The properties of RA material are given in Table 1. 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 shown in Figure 6.3. The supplier recommended dosage for all the rejuvenators was approximately 5% w/b of RA binder and same was used for preparation of asphalt mixtures. The prominent functional group present in rejuvenators were identified from FTIR spectra using Bruker spectral interpretation library and are listed along with corresponding wavelength in Table 6.2. A distinct peak for rejuvenator has been observed in FTIR spectra of binders in the past studies (Cavalli et. al. 2018; Rathore & Zaumanis 2020; Li et. al., 2021). In this study around 1740 cm-1 as shown in Figure 6.4, the unique peaks were observed for three of the rejuvenators R1, R2, and R3, while it was absent for R4 (petroleum-based rejuvenator) as well as for virgin binder.

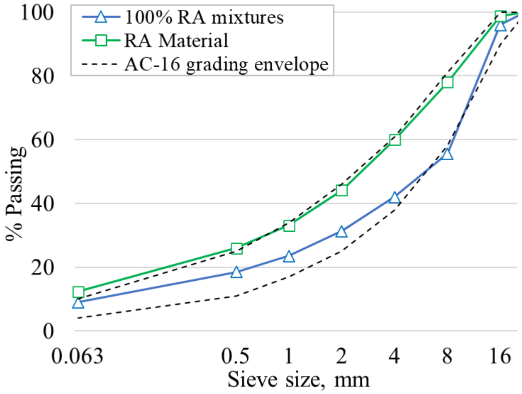


Figure 6.2. Aggregate gradation.

Table 6.1. RA material characteristics

Test method	Result	Standard
Binder content in RA material (%)	4.35	EN 12697-1 (2005)
Flow coefficient of fine aggregates	28	EN 933-6 (2014)
Shape Index of coarse aggregates	12	EN 933-4 (2008)
Penetration of RA binder (0.1 mm)	39	EN 1426 (2015)
Softening point of RA binder (°C)	58	EN 1427 (2015)

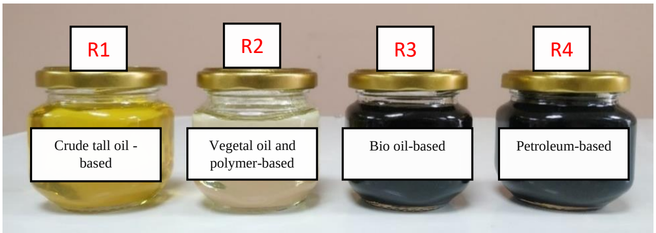
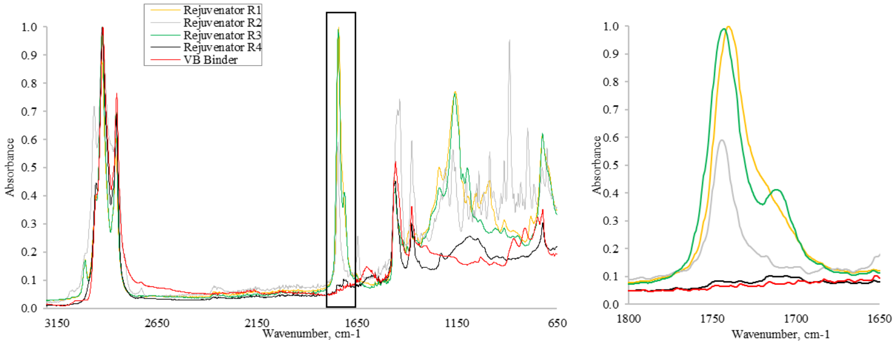


Figure 6.3. Rejuvenators used in this study

Table 6.2. Functional groups along with corresponding wavelength of absorption (in cm^{-1}) from FTIR spectrum analysis of rejuvenators.

	Aliphatic Propionate Esters	Olefins	Aliphatic hydrocarbon	Meta substituted aromatic hydrocarbons	Aliphatic Acetate Esters
R1	1750, 1200, 1100	3050, 1660	2890, 1450, 1375	×	×
R2	×	×	2915, 1450, 1375, 738	3050, 1900, 1600, 1500, 800	×
R3	×	3050, 1675	2925, 1463, 1375, 730	×	1750, 1250, 1065
R4	×	×	2915, 1463, 1375, 730	×	×



(a)

(b)

Figure 6.4. Normalised FTIR spectra for all the rejuvenators used in this study between 900-1800 cm^{-1} wavelength. (a) Full spectra; (b) magnified area

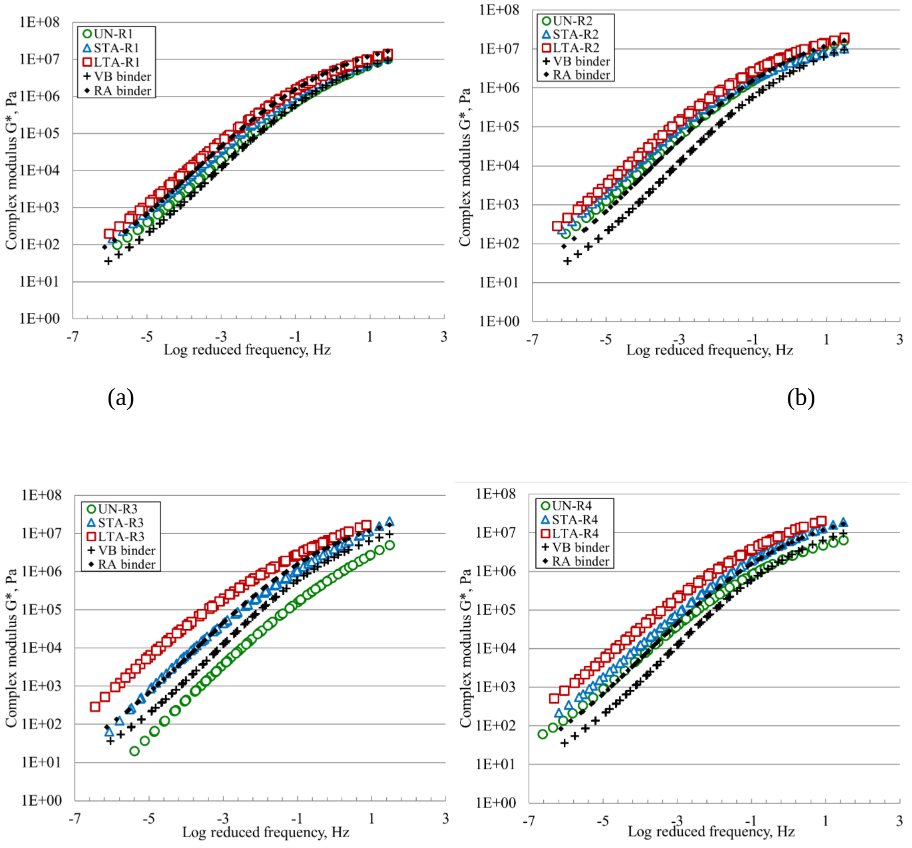
6.2.2 Sample preparation

For the preparation of asphalt mixtures, the RA material was heated at a temperature of 155°C for 2.5 h. The heated RA material was transferred to the mixing bowl and the rejuvenator was added on RA material in the mixer, followed by mixing for 5 min. The loose mixtures were subjected to one of the three aging conditions: unaged (UN), short-term aged (STA), and long-term aged (LTA). The unaged mixtures were stored at room temperature following the mixing process. For simulating the short-term aging, the loose mixtures were conditioned at a temperature of 135°C for 4 h according to SHRP-A-383 (CEN 12697-52: 2017). For simulating the long-term aging on mixtures, the loose mixtures were subjected to short-term aging, followed by conditioning at a temperature of 85°C for 216 h according to RILEM recommendations (CEN 12697-52: 2017). Finally, binder was extracted from all the mixtures using toluene as solvent in centrifuge method and recovered from the solution using rotary evaporator. A total of 12 bitumen samples with different rejuvenators and aging conditions were obtained from mixtures. For reporting the results, the bitumen samples are 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).

6.3 Results and discussion

6.3.1 Complex modulus mastercurves

Figure 6.5 shows the complex modulus (G*) mastercurves at reference temperature of 20°C for all the bitumen samples in this study. The effect of aging the mixtures can be seen from increase in complex shear modulus over wide range of frequencies. An increase in complex modulus indicates the stiffening of bitumen, which occurs due to increase in the asphaltenes/maltenes ratio in bitumen with aging. It is also seen from Figure 6.5, that in log scale, 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 long-term, most of rejuvenators (tall oil based, vegetal oil and polymer-based, and bio-oil-based) benefit more the low-temperature performance by causing less change in stiffness of bitumen at low temperatures compared to high 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.



(a) (b)

(c) (d)

Figure 6.5. Complex modulus mastercurves at 20°C for rejuvenator (a) R1; (b) R2; (c) R3; (d) R4

The aging of bitumen shows significant impact on the rheological properties of asphalt (Bi et. al. 2020; Rathore & Zaumanis 2020). To quantify the effect of rejuvenators on aging, an aging index (I_A) was developed based on area calculation over a wide range of frequencies. This index gives an indication about degree of aging in binder with reference to degree of aging in virgin bitumen. The numerical value $I_A>1$ indicates that stiffness of a bitumen sample over a selected range of frequencies is higher than the stiffness of virgin binder. Similarly, $I_A<1$ indicates that stiffness of a bitumen sample is lower than the stiffness of virgin binder. Therefore, the aging index for virgin binder will be unity in this case. It can be seen from Figure 6.6., that in unaged condition, except R3 all the bitumen show values $I_A>1$. This means that except R3, none of rejuvenators reduced stiffness of bitumen in unaged condition such that the resultant stiffness was lower than virgin bitumen stiffness. However, for R3, a dramatically high reduction in stiffness of bitumen ($I_A = 0.27$) was observed. This indicates that bio oil-based rejuvenator (R3) may provide very softening of binder and stiffness reduction in unaged condition. I_A for R1 was closest to unity, which indicates that this rejuvenator reduced stiffness of binder to a level reaching stiffness nearest to the virgin binder. The least reduction in stiffness of bitumen in unaged condition (indicated by highest $I_A = 3.05$), among all the four rejuvenators was observed for R2 suggesting the lowest softening achieved in this case with vegetal oil & polymer-based rejuvenator.

After short-term aging (see Figure 6.6.), the difference in aging index among all the four bitumen was reduced. The highest degree of aging was present in R2 ($I_A = 4.02$) followed by R4 ($I_A = 3.92$), which is similar to the aging index ranks of these binders in unaged state. However, the I_A values for these bitumen samples were very close, indicating less difference in stiffness of bitumen. Similarly, I_A for R3 was almost equal to that of R1. This indicates that stiffness of binder achieved after short-term aging was equivalent for R1 & R3, as well as for R2 & R4 pairs of binder.

All the long-term aged binders showed a very high difference in I_A values among each other, which suggests that rejuvenators play an important role in governing the long-term stiffness of the bitumen. R1 showed lowest I_A value among all binders indicating least stiffness of this binder achieved after long-term aging, which could be a positive sign for long term low-temperature performance of this binder. On other hand, R4 showed highest I_A value indicating highest stiffness of binder achieved in this case after long-term aging. It should be noted that the highest different between aging index of unaged and long-term aged binder was observed for R4 (6.51), while lowest difference was observed for R1 (1.86). This shows that in long-term, the tall-oil based rejuvenator (R1) was most effective and petroleum-based rejuvenator (R4) was least effective in reducing the stiffness of bitumen.

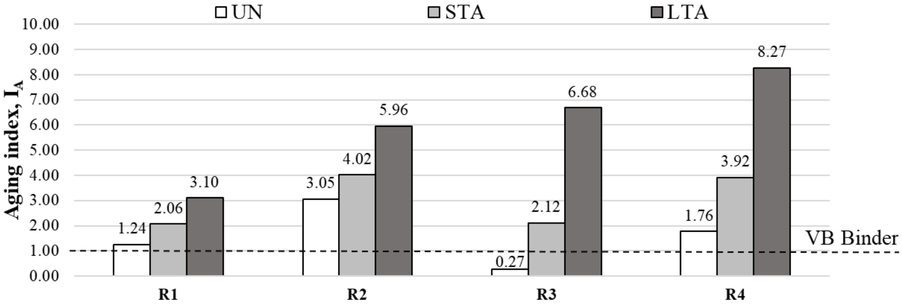


Figure 6.6. Aging index for bitumen samples at different aging stages

Another indicator known as softening index (IS) was calculated in this study, which is very similar to aging index, except the comparison is made with RA binder as a reference. Therefore, the IS values will indicate the change in stiffness of bitumen with respect of RA binder. $I_S>1$ indicates stiffness of a bitumen sample over a selected range of frequencies is lower than the stiffness of RA binder. Similarly, $I_S<1$ indicates that stiffness of a bitumen sample is higher than the stiffness of RA binder. Therefore, the softening index for RA binder will be unity in this case. It can be seen from Figure 6.7., that except R2, all the rejuvenators in unaged stage reduced the stiffness of bitumen to a level (I_S>1) that was lower than the stiffness of RA binder. For R2, the unaged binder stiffness was almost equivalent (I_S=0.95) to that of RA binder stiffness. This shows that vegetal oil and polymer-based rejuvenator (R2) did not provide any significant reduction in stiffness of the binder. After, short-term aging except R1 (I_S=1.41), all the bitumen aged to a level above the RA binder (I_S<1), which indicates that stiffness reduction was lost after short-term aging except in the binder with tall oil-based rejuvenator (R1). Further after long-term aging, the aging level in R1 was also reached above the aging level of RA binder, but the highest I_S value for R1 (I_S=0.94) indicates that retained effect of stiffness reduction was highest for this mixture containing tall oil-based rejuvenator compared to others in the long-term.

Overall, in long-term none of the rejuvenators used in this study could retain the reduced stiffness of bitumen obtained from rejuvenator addition to level below the RA binder stiffness. Additionally, the variation in aging and softening indices for all the bitumen samples at different aging stages shows that level of aging can vary significantly for different rejuvenators. Therefore, performance of mixtures produced using these rejuvenators can be extremely sensitive to mixture aging.

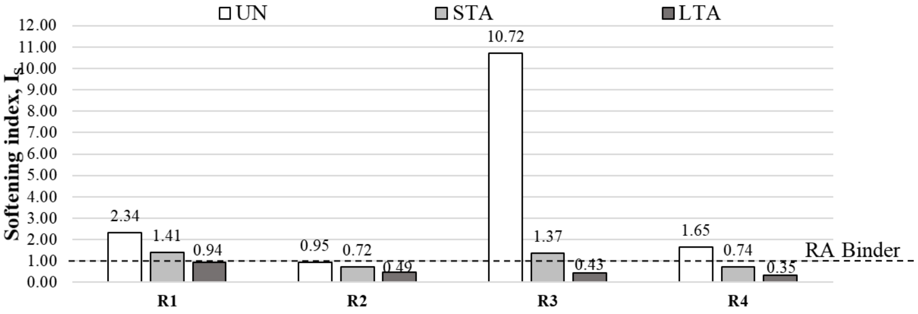
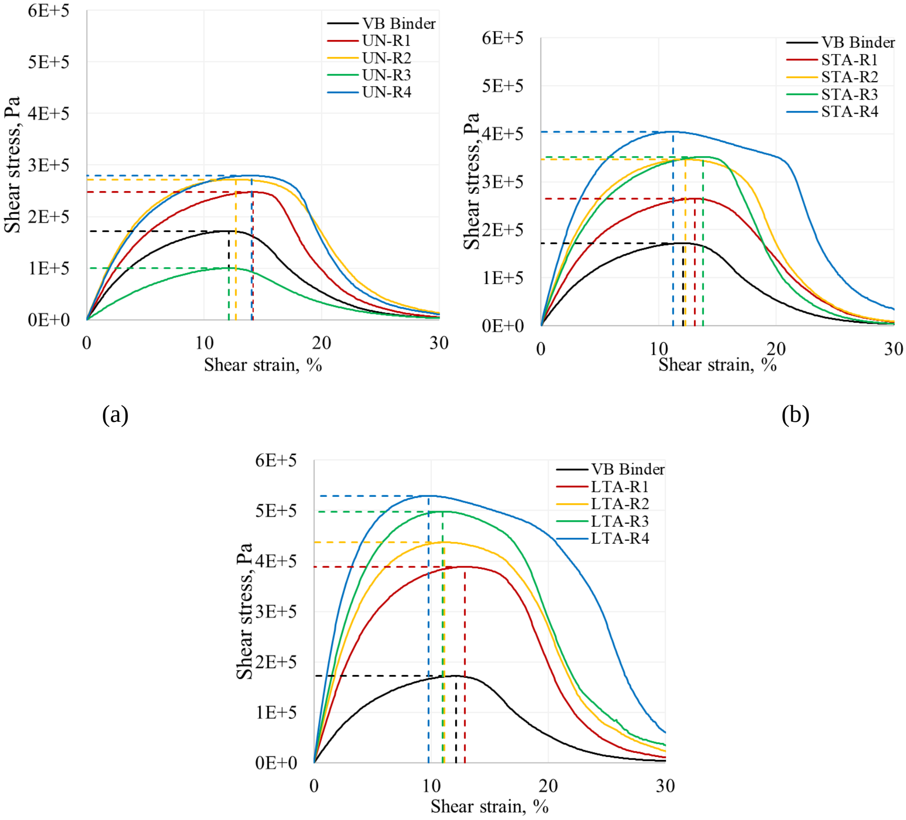


Figure 6.7. Softening index for bitumen samples at different aging stages

6.3.2 Fatigue resistance

Figure 6.8. shows the plots of shear stresses versus strain from linear amplitude sweep (LAS) test at a temperature of 25°C. It can be seen from Figure 6.8. (a)-(c) that the peak stress for all the unaged bitumen samples increased with short-term aging, and further after the long-term aging, as a result of stiffening of binder. Compared to virgin bitumen (VB) as shown in Figure 6.8. (a), all the unaged binders except R3, show higher peak stress due to presence of RA binder. For UN-R3, the peak stress was low due to high amount of softening from this rejuvenator as also observed from complex modulus mastercurves earlier. Further as seen in Figure 6.8. (a), the strains corresponding to peak stresses in all the unaged bitumen samples were equal or higher compared to strain in virgin binder. However, after long-term aging (see Figure 6.8. c), the strains in all the samples except R1, turn out to be lower compared to the strain in virgin binder. This implies the fact that the softer binders (unaged) exhibit lower peak stress, but

higher deformation compared to the stiff binders (aged). As seen in Figure 6.8. (c), both peak stress and corresponding strain were higher in LTA-R1 compared to VB, which could be a positive effect of R1 rejuvenator modification, as this binder may be able to undergo a greater number of cycles to fatigue failure at higher strains. However, the strain tolerance of binder indicates the fatigue performance only to a certain extent. Therefore, fatigue damage analysis was conducted for more information about the fatigue properties of binders.



(a)

(b)

(c)

Figure 6.8. Shear stress vs strain curve for 100% RA binders and virgin bitumen

Figure 6.9. shows the plot of predicted number of cycles to fatigue failure (N_f) for all the binders calculated using VECD model for a range of strain levels. The number of cycles for fatigue failure for 2.5% and 5% strain levels is shown in Table 6.3. It can be seen that from Table 6.3 that fatigue lives for all the unaged bitumen samples (except UN-R3) were higher than 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 binder modified using rejuvenator R3 was higher compared to virgin binder, as a result 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 unaged state, at both 2.5% & 5% the strain levels (see Table 6.3). The short-term aging significantly increased the stiffness of the binder facilitating the bitumen to undergo higher number of cycles until fatigue failure. The lowest increment in fatigue life after short-term aging was observed for R1 bitumen (27% & 8% at 2.5% & 5% strain level, respectively). However, this is not a disadvantage for R1 as it already shows much higher fatigue life than the virgin binder.

After long-term aging, the fatigue life for R2 and R4 were reduced, while fatigue life for R1 and R3 were increased. Though, the stiffnesses of both R2 and R4 bitumen were increased after the long-term aging as seen in Figure 6.4. earlier, there may be a loss in elastic compounds in these bitumen samples that resulted in higher damage and reduction in number of cycles to fatigue failure. 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. In long term, R1 showed the lowest fatigue life at 2.5% strain level but highest fatigue life at 5% strain, which indicates that when used in thin pavements, tall oil-based (R1) rejuvenator can provide better fatigue resistance compared to other rejuvenators. Similarly for thick pavements, the bio-oil based rejuvenator (R3) may provide highest fatigue life in the long-term as the fatigue life for this binder was highest at 2.5% strain level.

As observed in this study, long-term aging increased the fatigue life in all the cases, which may not be completely accurate in field conditions. This outcome could be affected due to limitation of the test adopted, as fatigue damage does not occur solely due to cohesive damage, but also due to loss of adhesion between bitumen and aggregates (Jing et. al, 2019). Aging may improve fatigue life due to increased stiffness but may also reduce it by weaking the bond between bitumen and aggregates. Additionally, stress-controlled testing could be more important than strain-controlled testing for fatigue characterisation of stiff mixtures, as in this case the high stiffness is the fundamental parameter associated with fatigue life instead of elastic recovery properties (Artamendi & Khalid, 2005). Therefore, further investigations are required to understand the effect of aging on fatigue behaviour of binder.

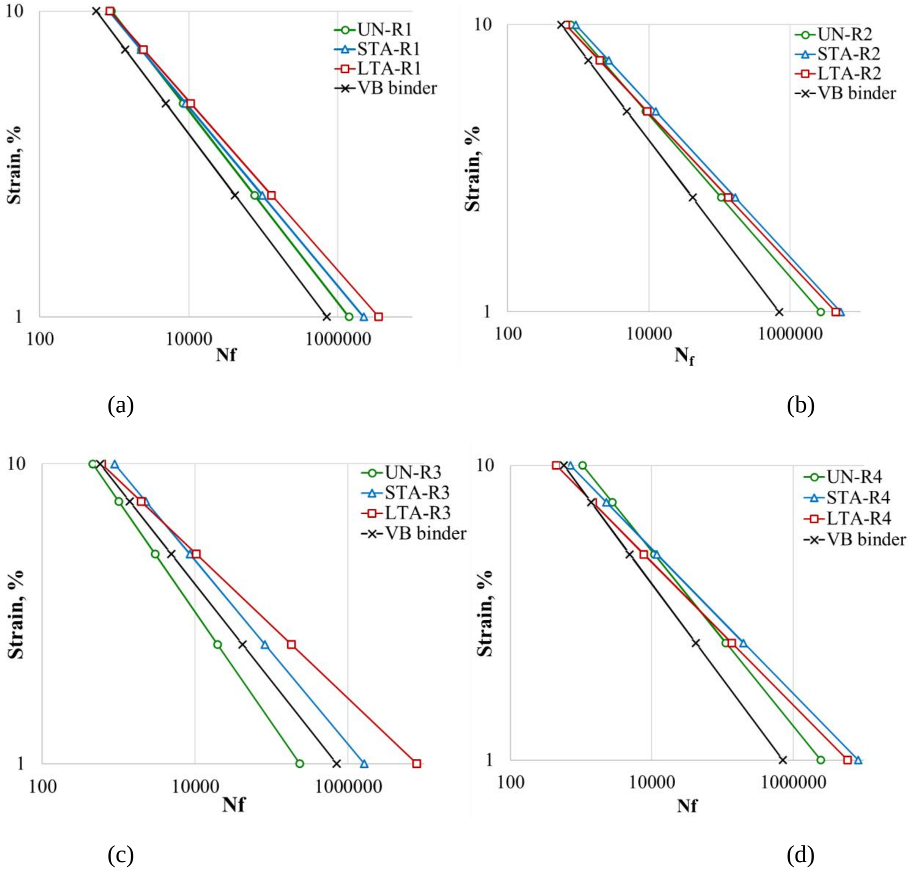


Figure 6.9. Fatigue life vs strain relationship.

Table 6.3. Predicted fatigue life from 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

6.3.3 *Rutting resistance*

Multiple stress creep recovery test (MSCRT) was conducted at 0.1 kPa and 3.2 kPa stress levels. These stress levels do not necessarily represent the nonlinear stress levels in binder, but a higher stress level may predict the rutting resistance more clearly (Jafari & Babazadeh, 2016). Therefore, the results of non-recoverable creep compliance and percent recovery from multiple stress creep recovery test at 3.2 kPa stress level have been reported. Lower values of non-recoverable creep compliance (J_{nr}) in bitumen have been correlated to better rutting performance of the mixtures (D'Angelo, 2009). The percent recovery is a measure of recoverable viscoelastic strain in creep portion after removal of shear stress. As shown in Figure 6.10., in unaged (UN) conditions, R1 and R3 showed considerably higher J_{nr} values compared to other bitumen. Additionally, R1 and R3 did not show any percent recovery in unaged conditions as shown in Figure 6.11. Therefore, the bitumen samples modified using tall oil based (R1) and bio-oil based (R3) rejuvenator may be more susceptible to rutting compared to other binders in unaged condition. However, this does not mean that R1 and R3 binders will show poor rutting performance. In fact, the J_{nr} for R1 and R3 was almost equal to that of Jnr of virgin bitumen, which also did not show any percent recovery, which indicates these bitumen samples in unaged condition may show same rutting performance as that of virgin binder. The short-term aging (STA) of mixtures has considerably reduced the J_{nr} value and increased the percent recovery for all the bitumen, 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 and increase in percent recovery shows that these binders have undergone excessive stiffening that led to increased rutting resistance of bitumen. The long-term aged binders show different J_{nr} values indicating that even after aging, the binder containing different rejuvenators will have distinct rutting performance. Overall, all the bitumen samples show J_{nr} values within the permissible limits (4 kPa^{-1}) given by AASHTO MP 19-10 (2010). This confirms that rejuvenators do not inhibit the binder to fulfil the acceptable rutting performance in 100% RA mixtures.

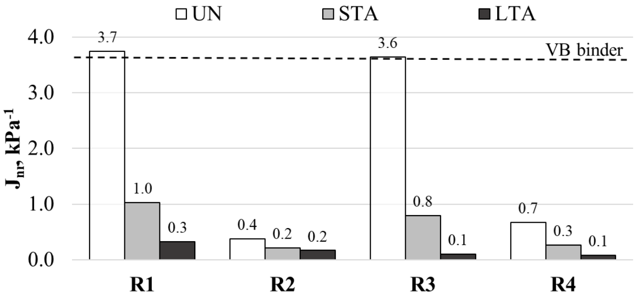


Figure 6.10. Non-recoverable creep compliance (J_{nr}) from multiple stress creep recovery test at 60°C

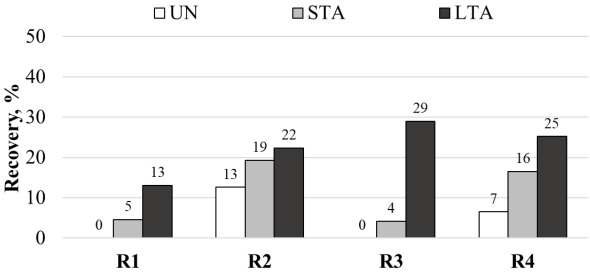


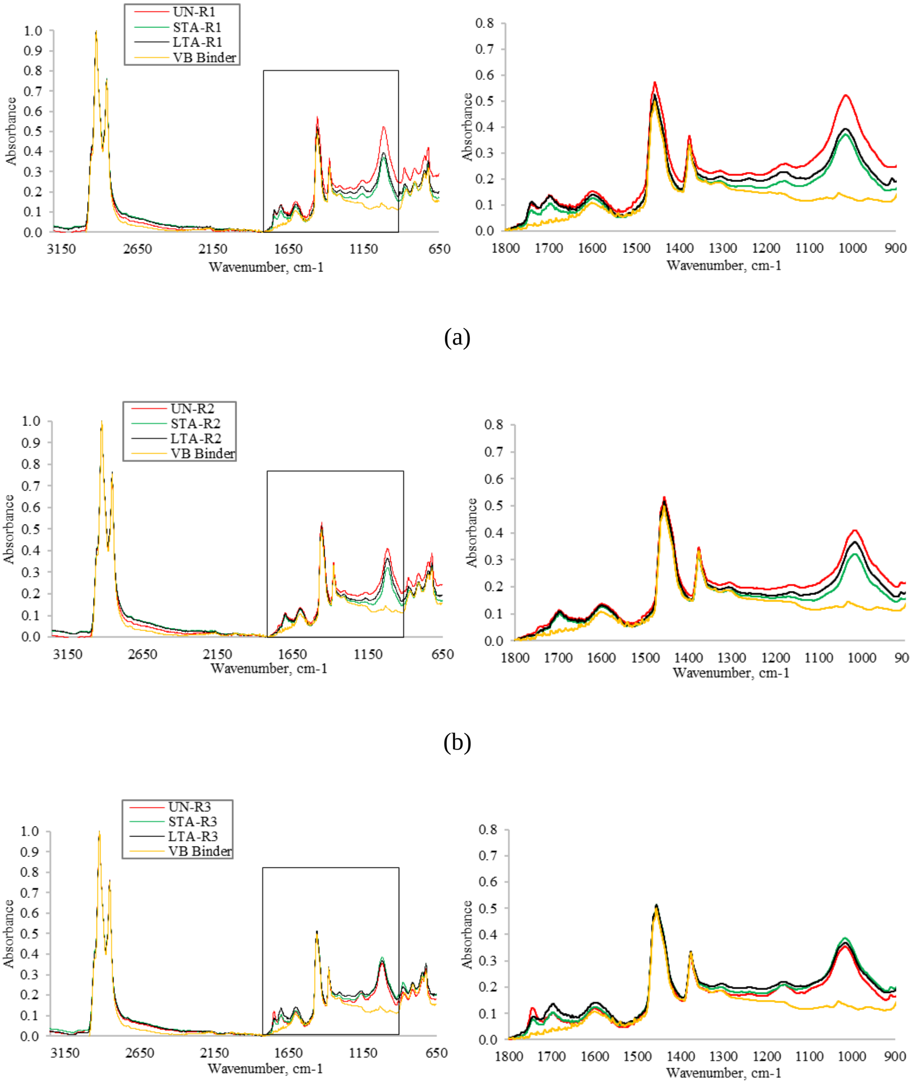
Figure 6.11. Percent recovery from multiple stress creep recovery test at 60°C

6.3.4 Chemical characterisation

In this study, absolute baseline integration was performed on normalised spectra to calculate the carbonyl and sulfonyl indices, as best repeatability of FTIR results has been shown using this method (Hofko et. al, 2017). An increase in carbonyl index has shown positive correlation with oxidation of bitumen in past studies (Rostler & White, 1959, Karlsson and Isacsson, 2003; Baqersad & Ali, 2019). It can be seen from Table 6.4. that carbonyl index values that all the unaged rejuvenated binders were higher than the carbonyl index of virgin binder (0.1). The higher index for these samples indicates higher binder aging level in these samples due to presence of reclaimed asphalt binder. The carbonyl peaks for rejuvenated samples can also be seen in region 1660 cm^{-1} to 1720 cm^{-1} in Figure 6.12, while these peaks were not present in virgin binder. The peaks shown by three out of four rejuvenators around 1740 cm^{-1} wavelength in Figure 6.4. earlier were also seen for rejuvenated binders R1 and R3 in all the three aging stages as shown in Figure 6.12 (a) & (c). For R2, this peak was observed only in unaged condition (UN-R2), and the diminishing peak for aged samples could be due to oxidation of rejuvenator. However, the peaks around this region could also be affected by oxidation of bitumen. After short-term aging, the binder is more oxidised 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 be due to material variability or it is possible that short-term aging of binder was not enough to show a considerable increase in carbonyl peak intensity. A study also found that the binder short-term aging simulation did not show any visible increase in carbonyl index, and a distinct band of carbonyl structures was detected only after long-term aging simulation of binder (Poulikakos et. al, 2019). All the short-term aged bitumen samples showed equal carbonyl index with exception of STA-R4. This sample also showed unusually large sulfoxide peak in region 1100 cm^{-1} to 920 cm^{-1} which could be due to presence of filler residue in the recovered bitumen. As a result, the index calculation for this sample was confounded due to change in intensity of aliphatic band (reference group). 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 with 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 presence of rejuvenator in the binder. For this reason, the assessment of carbonyl index in blends with rejuvenators is considered problematic (Margaritis et. al., 2021). Further as shown in Table 6.4, no clear trend can be observed for sulfoxide index of bitumen samples at different aging states. It was also observed in some of the previous research that the sulfoxide index is not an appropriate indicator of aging in the bitumen (Zhang et. al., 2011; Yao et. al., 2013). Overall, the known FTIR indices that reflect the aging state of bitumen need more investigation when characterising for reclaimed asphalt binder containing rejuvenators.

Table 6.4. Calculation results of carbonyl indices from normalised spectrum

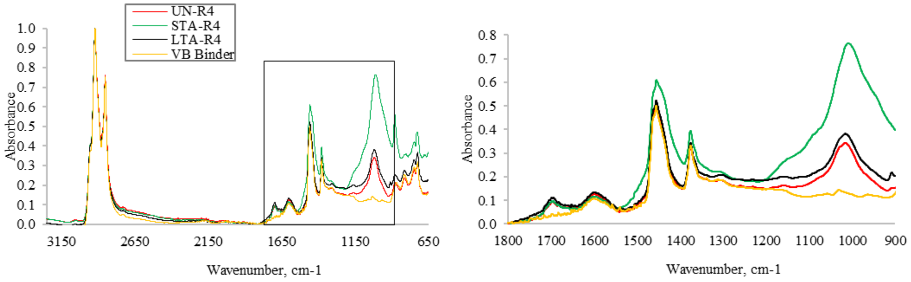
Material	Aging state	Average carbonyl index ($I_{C=O}$)	SD	Average sulphonyl index ($I_{S=O}$)	SD
VB	UN	0.10	0.005	1.20	0.108
R1	UN	0.20	0.009	1.93	0.364
	STA	0.17	0.018	1.56	0.045
	LTA	0.22	0.004	1.69	0.010
R2	UN	0.18	0.017	1.71	0.164
	STA	0.17	0.003	1.40	0.020
	LTA	0.18	0.004	1.57	0.031
R3	UN	0.18	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


UN-R1
STA-R1
LTA-R1
VB Binder
UN-R2
STA-R2
LTA-R2
VB Binder
UN-R3
STA-R3
LTA-R3
VB Binder
Absorbance
Wavenumber, cm-1
3150
2650
2150
1650
1150
650
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

(a)

(b)

(c)



(d)

Figure 6.12. FTIR spectra for all the rejuvenated binders used in this study along with magnified area in 900-1800 cm^{-1}.

6.3.5 *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 Figure 6.13. The results show that there was no significant difference in pH values for different mixtures. The pH values at Day 64 were in between 8.28-8.35 for all the asphalt mixtures. The evolution of electrical conductivity of all the asphalt mixtures at different time intervals can be seen in Figure 6.14. According to this the electrical conductivity for UN-R1, UN-R2, UN-R3, UN-R4 samples were in the range of 304-561, 389-721, 336-597, 380-755 respectively at different time intervals.

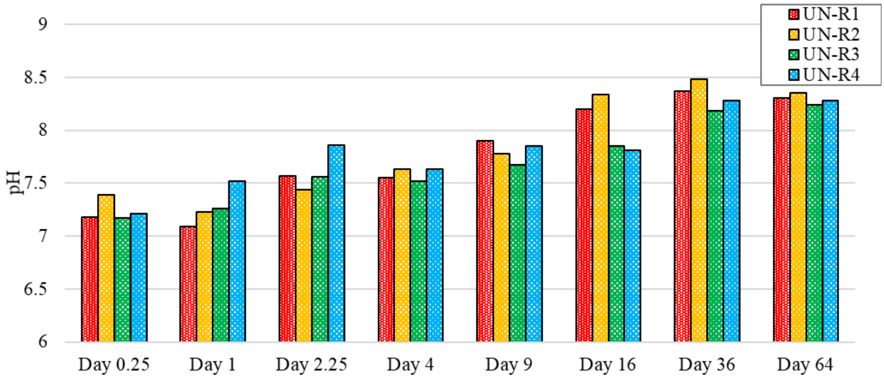


Figure 6.13. pH value of leachant samples during the horizontal dynamic surface leaching test

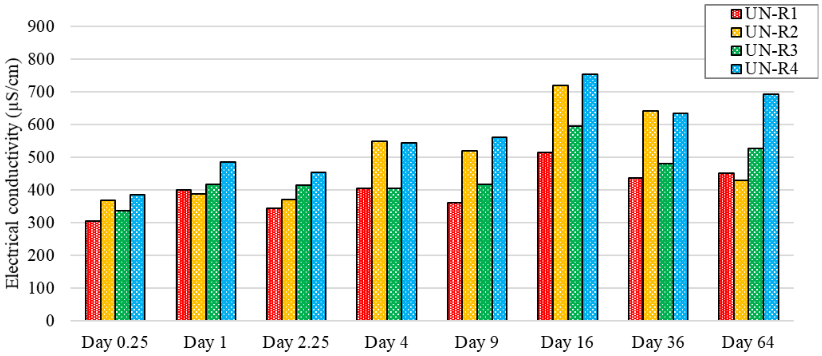


Figure 6.14. Electrical conductivity value of leachant samples during the horizontal dynamic surface leaching test

The cumulative concentration of released heavy metals and trace elements per unit of asphalt mixture sample is shown in Table 6.5. According to these results, no concentration of B, Cd, Sb, Tl, & V were found in all four of the asphalt mixtures. Looking at the concentration of other elements, it appears that all the four mixtures show very similar leaching property. Overall, it can be concluded, there was no significant effect for any of four rejuvenators on leaching properties of asphalt mixture.

Table 6.5. Cumulative concentration of released heavy metals and trace elements (in mg/m^2)

Element	UN-R1	UN-R2	UN-R3	UN-R4
Al	97.22	90.4146	78.7482	111.803
As	1.17	1.1817	1.287	1.287
B	-	-	-	-
Ba	22.61	22.1578	18.088	26.0015
Ca	73.29	74.0229	59.3649	60.0978
Cd	-	-	-	-
Co	12.23	13.5753	14.3091	12.4746
Cr	3.66	4.3554	3.5136	3.6966
Cu	247.15	254.5645	224.9065	205.1345
Fe	78.63	66.0492	71.5533	68.4081
Hg	4.16	3.6608	4.6592	3.952

K	3716.81	3047.7842	3939.8186	3122.1204
Mg	7.81	8.0443	8.6691	6.8728
Mn	0.12	0.0984	0.1236	0.1344
Mo	2.64	2.904	2.9304	3.1152
Na	2529.75	2555.0475	2049.0975	2276.775
Ni	8.48	9.4976	7.7168	9.2432
Pb	5.17	4.653	4.9632	4.3428
Sb	-	-	-	-
Se	2.78	2.363	2.9746	2.2796
Si	25.72	27.7776	21.3476	26.7488
Tl	-	-	-	-
V	-	-	-	-
Zn	123.21	136.7631	147.852	117.0495

6.4 Section summary & conclusions

Using rheological and chemical analysis, the effect of rejuvenators on aging of 100% reclaimed asphalt mixtures was investigated. The aging was simulated on the mixtures which was followed by extraction of binder for analysis. The tests conducted in this study include temperature and frequency sweep, linear amplitude sweep, multiple stress creep recovery, and Fourier transform infrared spectroscopy. Based on the test results, the following conclusions are made:

1. From temperature-frequency sweep test, the effect of aging was seen as shift in complex modulus mastercurves for all the bitumen. The results showed that rejuvenators play important role in governing the long-term properties of rejuvenated bitumen. In long-term, the highest reduction in stiffness of bitumen was achieved by tall oil-based rejuvenator, while lowest reduction in stiffness was achieved by petroleum-based rejuvenator.
2. From linear amplitude sweep test, the long-term aged bitumen showed much higher fatigue life than the unaged sample due to the increase in stiffness of the bitumen with aging. Considering the general view that fatigue damage may increase after long-term aging due to weakening of the bond between aggregates and the bitumen, the contradictory observation in this study indicates towards limitation of LAS test for fatigue performance evaluation of aged bitumen.

3. The bitumen containing rejuvenators showed acceptable rutting performance and with aging the rutting performance of binders was enhanced due to stiffening of bitumen. The tall oil-based rejuvenator and bio oil-based rejuvenator showed higher rutting susceptibility of binder compared to other rejuvenators, however these binders showed comparable rutting performance to virgin binder. The long-term rutting susceptibility of the binders was found to be affected by type of rejuvenator used in the mixture.

4. The FTIR spectra for all the rejuvenated binders except the one containing petroleum-based rejuvenator, showed unique peaks in the same range where the peaks were observed for respective rejuvenators. The short-term aging of mixtures did not show a considerable increase in carbonyl peak intensity. However, after long-term aging an increase in carbonyl index was observed for all the four binders. Besides, the leaching properties of mixtures produced using four rejuvenators were not significantly different.

To sum up, this study showed that different rejuvenators age in a distinct way, which implies the importance of considering the long-term performance of bitumen for selection of a rejuvenator. Dynamic shear rheometer can be used to quantify the degree of aging from change in stiffness of bitumen. However, the conventional binder performance tests using dynamic shear rheometer have some limitations and may not truly represent the aging characteristics of stiff materials like high reclaimed asphalt content mixtures. Therefore, further studies should develop new methods for binder performance evaluation that show good correlation with field performance of high reclaimed asphalt content mixtures. It is also important to compare the progressive aging in conventional mixtures with reclaimed asphalt mixtures containing rejuvenator to calculate the benefits of using rejuvenators during the entire life cycle of the pavement. The future studies may also explore the long-term effect of rejuvenators on low-temperature performance of reclaimed asphalt mixtures.

7 100% RECYCLED MIXTURE PERFORMANCE

Recent studies have proven asphalt mixtures containing 100% of reclaimed asphalt provide satisfactory performance compared to conventional mixtures (Zaumanis et. al, 2020; Dinis-Almeida et. al., 2016; Elkashef & Williams 2017; Lizárraga et. al., 2018). These studies have shown that it is feasible to produce mixture entirely from reclaimed asphalt by following good mix design practices and using rejuvenators. However, 100% reclaimed asphalt mixtures still have many concerns and require more investigation before they are widely adopted by the industry (Zaumanis et. al., 2016). The main reason for reluctance in using high content of RA in hot mix asphalt is the presence of oxidized binder in RA that make the asphalt mixture highly susceptible to cracking (Zaumanis et. al., 2014a; Rathore et. al., 2021). Other problems in implementation of such mixtures include a more complicated mix design as compared to conventional mixtures, variability of RA material, the amount of active binder in RA, unknown degree of blending in mixtures, and rate of diffusion of rejuvenator, etc (Lo Presti et. al., 2020).

For using RA at high contents in mixtures, the binder needs to be modified using softer virgin binder, softening agents, or rejuvenators in order to produce asphalt mixtures with satisfactory performance. Among these, rejuvenators are most effective in treating aged bitumen as they not only soften the binder but also balance the properties of aged binder by adjusting the asphaltene/maltene ratio (Garcia et. al., 2011; You et. al., 2011). Rejuvenators diffuse into the aged binder, reduce its viscosity, and improve the workability of the asphalt mixture. The diffusion of rejuvenator is considered to be a function of time and temperature (Cong et. al., 2018). This means that a longer contact period of rejuvenator with RA binder is expected to increase the diffusion and thus the degree of blending in the mixture. A laboratory study showed that adding rejuvenator directly to RA material was more effective than adding it to virgin bitumen, as rejuvenator had longer contact period with oxidized binder in the former case (Lu et. al., 2019). It was also confirmed in a full-scale production that adding rejuvenator on cold RA aggregates led to improved fatigue resistance as compared to adding rejuvenator in the mixer (Zaumanis et. al., 2019). Contrary to this, a past study found no effect of rejuvenator incorporation method on properties of reclaimed asphalt mixtures (Rathore & Zaumanis, 2019). In any case, the estimation of diffusion efficiency can be helpful in selection of rejuvenator for producing a durable asphalt mixture. However, it was suggested that diffusion is only one of the several processes taking place apart from mechanical mixing and homogeneous dispersion of rejuvenator (Zaumanis & Mallick, 2013). These processes can vary significantly with the type of rejuvenator used in production of asphalt mixture.

There is a variety of rejuvenators available in the industry based on different sources and most rejuvenators contain high concentration of maltenes (Behnood, 2019). The rejuvenators typically used are petroleum-based, bio-based oils, waste cooking or industrial oils, etc (Bock et. al., 2020). Multiple studies have shown that the rejuvenators reduce the stiffness and improve the fatigue life, low-temperature performance, and moisture damage resistance of asphalt mixtures (Mirhossein et. al., 2019; Rathore & Zaumanis, 2019; Tran et. al., 2017; Zaumanis et. al., 2014b; Kuang et. al., 2018; Hajj et. al., 2013). However, the incorporation of rejuvenators has also been associated with reduction in rutting resistance of the mixtures (Haghshenas et. al., 2016; Lu et. al., 2016). Therefore, the selection of rejuvenator for high RA content mixtures must be done carefully based on overall performance so that the rejuvenators are able to increase the cracking resistance without compromising the rutting resistance of the mixture.

7.1 Objective

The main objective of this study is to evaluate the rutting and fracture performance of 100% reclaimed asphalt mixtures containing produced using three different rejuvenators and compare it with a conventional hot mix asphalt. Another goal was to measure the strain on 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.

7.2 Materials and Methods

This study used reclaimed asphalt (RA) material that was collected from an asphalt plant in Vangazi, Latvia. The RA material was fractionated to 10/22 size to reduce the proportion of fines and increase the proportion of coarse aggregates. For evaluating the RA material properties, the extraction was performed on RA material according to EN 12697-1 and the binder was recovered from the solution using a rotary evaporator according to EN 12697-3. The extracted RA aggregates showed a gradation similar to AC-16 mixtures from Latvian roads specifications as shown in Figure 7.1. Therefore, the control mixture was designed using Dolomite 8/11, Dolomite 5/8, Dolomite 0/5, and filler material to obtain AC-16 gradation. The shape index for coarse aggregates in RA material determined as per EN 933-4 was found to be 12. The flow coefficient for sand and fine RA aggregates determined according to EN 933-6 were 31.5 and 28, respectively. The RA material had a binder content of 4.35% and the penetration of RA bitumen was 39 × 0.1 mm. 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.

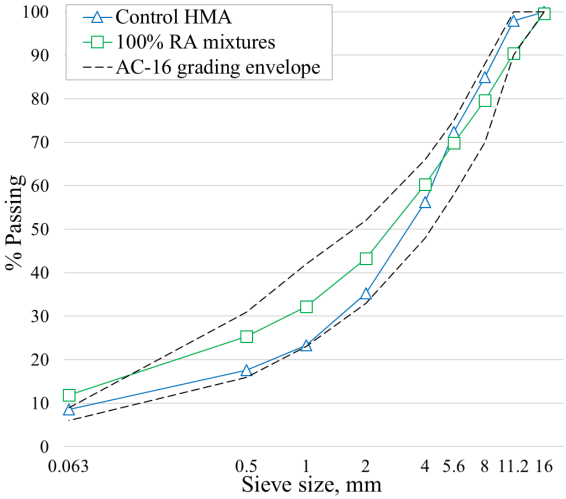
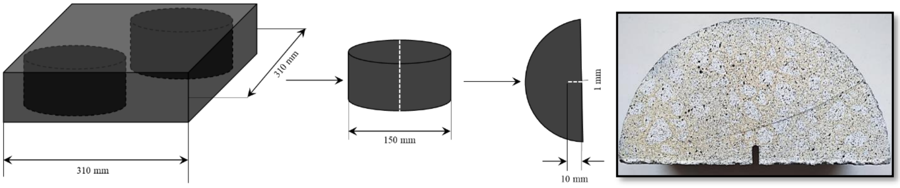


Figure 7.1. Mixture gradation.

7.3 Mixture preparation

For the preparation of mixtures, the RA material, virgin aggregates, and virgin bitumen were heated at a temperature of 155°C for 2.5 h. The heated aggregates were transferred to the mixing bowl and the rejuvenator was added to RA material directly in the mixer. Finally, the required amount of virgin bitumen was added into the mixer and the mixing was done for 5 min. The asphalt slabs from mixture were compacted using a roller compactor according to EN 12697-33. Additionally, from the compacted slabs, the 150 mm diameter semi-circular bend (SCB) specimens were obtained using coring machine, and a notch of 1 mm width and depth of 10 mm was cut, as shown in Fig. 7.2. The surface of the SCB specimen was prepared by forming a speckle pattern using matt finish black and white spray paints. This was done to allow the digital camera to measure the strain field on the surface of SCB specimen during fracture toughness test.



(a) (b)

Figure 7.2. (a) Coring and notching of slab for semi-circular specimen fabrication. (b) Speckle paint pattern.

7.4 Results and Discussion

7.4.1 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). It can be seen that both R1 and R2 mixtures showed poor rutting resistance and reached the maximum rut depth prior after 2650 and 4750 cycles, respectively. On the other hand, R3 mixture showed somewhat better rutting resistance than 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.

Rutting is affected by number of factors including aggregate gradation, aggregate shape and texture, binder properties, and compaction effort. All three 100% RA mixtures showed significantly different number of rutting cycles to failure. Since these mixtures consist of same grading of aggregates, it is most certain that this effect is coming from resultant binder properties due to different rejuvenators in the mixtures. With the given dosage, the tall oil-based rejuvenator in R1 may have provided higher softening followed by and vegetal oil and polymer-based rejuvenator in R2, which led to increased rutting resistance. The lowest softening effect was observed in bio-oil based rejuvenator in R3 as this mixture showed the rutting resistance nearest to the control HMA mixture C.

Table 7.1. Wheel tracking test results.

Mixture	Average number of rutting cycles	Average rut depth to at 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

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

As shown in Table 7.1, R1 & R2 mixtures also very lower air voids compared to control HMA mixture (C) which indicates higher softening effect of these rejuvenators. For mixture R3, the air voids were slightly higher than the above two mixtures which may be due to lower softening effect compared to other rejuvenators. The use of RA material in various studies has been shown to improve the rutting performance of the mixtures (Fakhri et. al, 2017; Guo et al, 2016; Zhao et. al, 2013). On the contrary, research showed that most of 60% RA mixtures considered in the study experienced accelerated rutting and reached the maximum rut depth of 12.5 mm in less than 5,000 load cycles. (Arámbula-Mercado et. al., 2020). Another past study showed that addition of 60% RA material reduced the rutting resistance of the mixture (Rathore et. al., 2021). 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 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.

7.4.2 Cracking performance

Figure 7.3. shows the mean values of load vs displacement results for all the mixtures obtained from fracture toughness test. The curves for all the mixtures show higher peak load achieved at loading rate of 50 mm/min compared to 5 mm/min, which is due to the fact that mixture behaves stiffer at higher loading rates. The peak load was highest for R2 at both the loading speeds. In addition to fracture energy, a parameter known as flexibility index (FI) which takes in account the slope of shape of the curve was calculated. This index is important to characterize the fracture characteristic as FI values at loading rate of 50 mm/min have been shown to have good correlation with cracking in the field (Al-Qadi & Ozer, 2015).

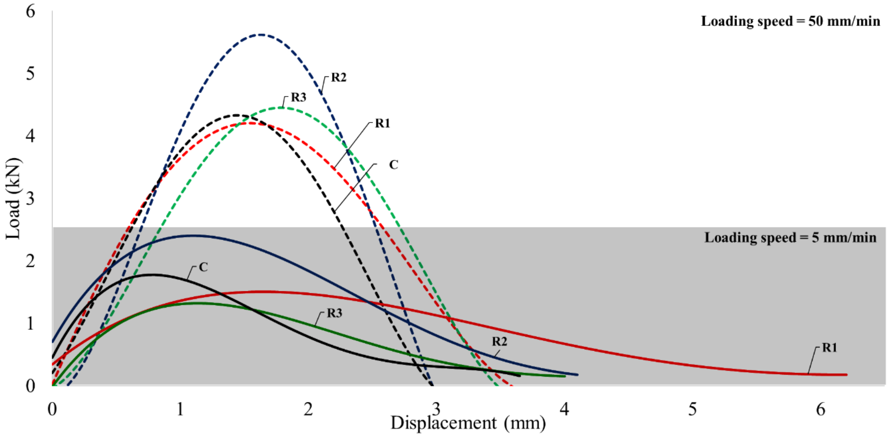


Figure 7.3. Load vs displacement curve for semi-circular bend test at 5mm/min

At 5 mm/min loading rate, as shown in Figure 7.4., 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, 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 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 50 mm/min loading speed test, as shown in Figure 7.5., 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. The flexibility index at this loading speed has shown high correlation with field cracking, as described in literature (Al-Qadi & Ozer, 2015). It can be seen from Figure 7.5., that flexibility index for mixtures ranks in following order, R1 > R3 > R2 ≈ C. From this observation, it can be attributed that R1 mixture containing tall oil-based rejuvenator may possess highest resistance to cracking. Surprisingly, R2 shows lowest flexibility index among 100% RA mixtures, which indicates that the binder replacement using this vegetal & polymer-based rejuvenator improved the toughness value as observed in Figure 7.3., but may reduce the overall cracking resistance in the mixtures.

The average calculated fracture energy for the mixtures in 5 mm/min test as shown in Figure 7.6. was ranked in the following order, R2 > R1 > R3 ≈ C. The mean fracture energy for control mixture was 1128 (J/m^2) and was higher for 100% RA mixtures varying from 1272 to 2154 J/m^2. The highest fracture energy for R2 among all the 100% mixtures, is attributed to presence vegetal oil & polymer-based rejuvenator as described earlier. Following this, R1 showed second highest fracture energy which was on average 40% higher than the next ranked mixture R3. This high difference is also believed to be the coming from effect of different source of rejuvenators used in these mixtures. Overall, all the 100% RA mixtures showed higher or comparable fracture energy than the control HMA mixture in 5 mm/min loading rate test, which shows their higher fracture toughness.

Based on fracture energy, the highest toughness was observed for mixture R2 at 5 mm/min loading rate, but this mixture also turned out to be worst performing mixture in cracking on basis of FI value at 50 mm/min loading rate. This shows that the presence of aged binder to some extent is beneficial for fracture toughness of mixtures due to higher stiffness, but the embrittlement from RA binder can have a negative effect on crack propagation. Therefore, these combined effects may have the potential to counteract each other In this study, flexibility index results were more consistent as, R1 showed a better cracking resistance compared to any other mixture at both 5 mm/min and 50 mm/min loading rates. This mixture also showed high fracture energy at both 5 mm/min and 50 mm/min loading rates.

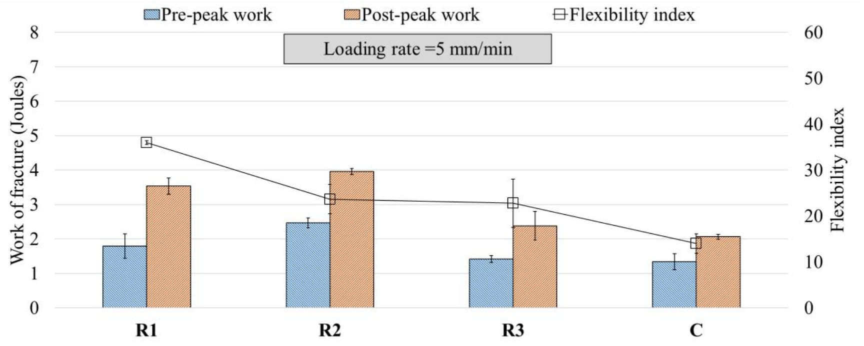


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Figure 7.4. Work of fracture and flexibility index for all the mixtures at 5 mm/min loading speed. The error bars represent the range.

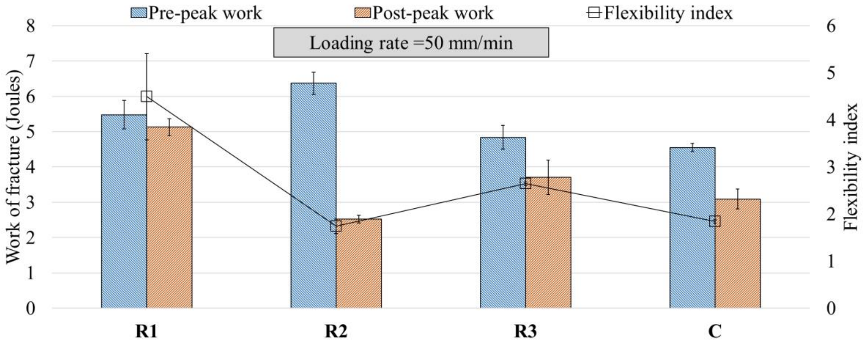


Figure 7.5. Work of fracture and flexibility index for all the mixtures at 50 mm/min loading speed. The error bars represent the range.

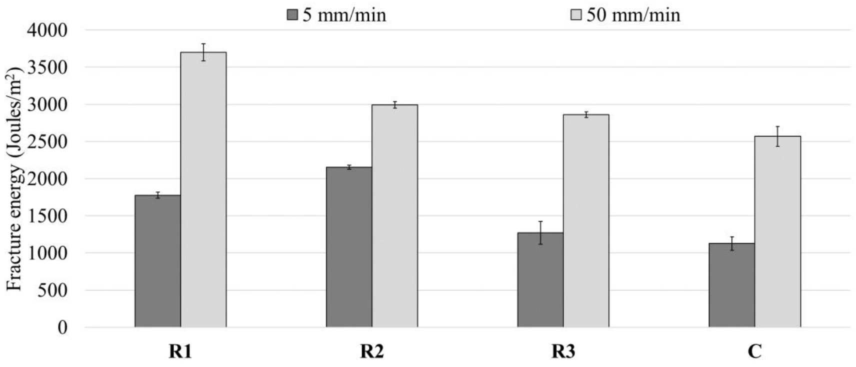


Figure 7.6. Fracture energy for all the mixtures at 5 mm/min & 50 mm/min loading speed. The error bars represent the range of data.

7.4.3 Digital image correlation (DIC) results

DIC was used in order to determine the distribution of stresses within the asphalt-binder system and investigate the correlation between optical measured strains and conventional energy parameters. The images captured during the fracture toughness test were processed to visualize the full field horizontal strain map during the low-speed loading rate. It was not possible to obtain the full field strain map for the high-speed loading rate test due to lower resolution of DIC system. The full field horizontal strain maps for all the mixtures in 5 mm/min loading rate test are shown in Figure 7.7. These maps show the horizontal tensile strain distribution at peak loading. The different behavior between the 100% RA mixtures and the control mixture can be observed. All the mixtures containing rejuvenators show highly concentrated strain developed at the notch position during peak loading as observed in Figure 7.7 a, Figure 7.7 b, & Figure 7.7 c. This could be due to presence of aged binder in these mixtures, which led the stress to be homogeneously distributed making the mixtures acting like a toughened matrix. On the other hand, the control mixture shows highly localized damage with strain increasing at multiple locations during peak loading as seen in Fig. Figure 7.7 d. The tensile strains developing at aggregate-binder interface can be observed in the control mixture (see Fig. Figure 7.7 d). This may be due to difference between the stiffness of aggregates and bitumen in this mixture, and as a result of which strain may have been accumulated within the binder.

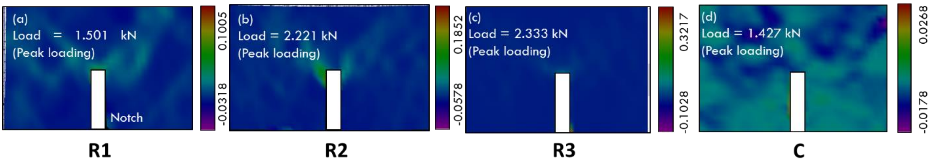
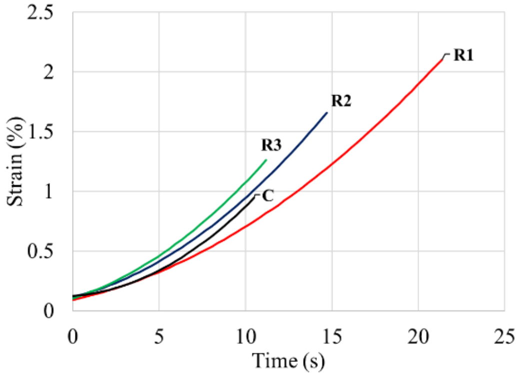
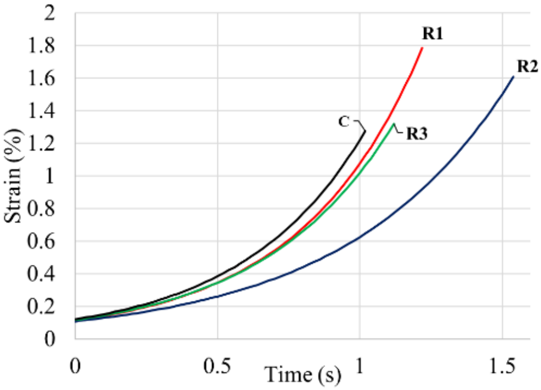


Figure 7.7. Full field horizontal strain (ε_{xx}) field for all the mixtures.

The mean values of horizontal strains (ε_{xx}) at notch tip until peak loading for 5 mm/min and 50 mm/min loading rate test calculated from 1x1 cm^2 scanned areas are shown in Figure 7.8. (a) and Figure 7.8. (b), respectively. Peak load is an important benchmark as the macrocracks start developing in asphalt mixture after the peak loading (Ling et. al, 2020). A higher notch strain at peak loading indicates the ability of material to undergo higher ultimate deformation before macrocracks formation, which in other terms represents higher flexibility of the mixture. As shown in Figure 7.8. (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 much 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 horizontal notch strain and flexibility index at 5 mm/min loading rate, as shown in Figure 7.9. (a). For 50 mm/min loading rate, the ranking of mixtures based on mean horizontal strain values followed the same order as in 5 mm/min loading rate, R1 > R2 > R3 > C, as shown in Figure 7.8. (b). However, in this case, the horizontal strain showed poor correlation with both flexibility index and fracture energy as shown in Figure 7.9. (a) & 9(b). One reason for this could be due to low precision in strain measurement in high speed loading due to instant brittle fracture of specimen. Due to scope of this work, this paper shows preliminary results of DIC measurement. Future studies may focus on obtaining more information about microstructural properties and investigate the correlation with macroscopic characteristics of the mixture.

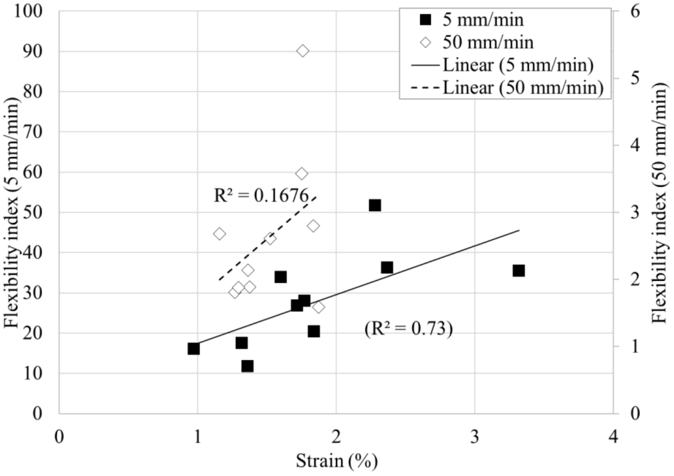


(a)

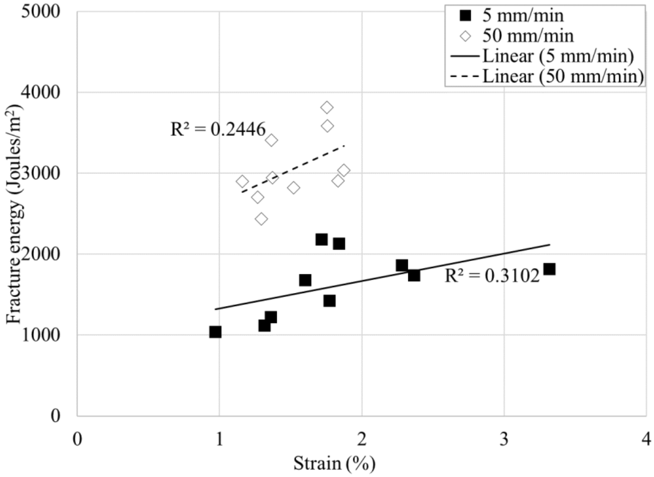


(b)

Figure 7.8. Horizontal strain at tip of notch in semi-circular bend test. (a) Loading speed = 5 mm/min. (b) Loading speed = 50 mm/min.



(a)



(b)

Figure 7.9. Correlation coefficient between notch strain and fracture parameters.

7.5 Section summary & conclusions

This study evaluated the performance of 100% RA mixtures containing three rejuvenators based on different sources and compared it to conventional hot mix asphalt. Wheel tracking test was conducted to evaluate the rutting susceptibility, and semi-circular bend test was conducted to evaluate the fracture toughness. Besides, a digital image correlation setup was used with semi-circular bend test to analyze the full field horizontal strain maps and measure the horizontal strain at a fixed location on surface of the specimen. Based on test results following conclusions can be made:

1. Rutting susceptibility of 100% RA mixtures was significantly affected by type of rejuvenator used in the mixtures. All the three 100% RA mixtures showed inferior rutting resistance compared to the control HMA mixture which is thought to be linked either to presence of highly round aggregates in RA material or due to not optimizing the rejuvenator content for mix design.
2. In fracture toughness test, all the 100% RA mixtures with rejuvenators performed superior to control HMA. Among various parameters calculated, flexibility index values gave more consistent observations, and it was observed that tall oil-based rejuvenator possessed highest fracture toughness among all the mixtures at both loading speeds used in this study.
3. Using digital image correlation setup along with fracture toughness test, a fair correlation was found between the flexibility index (FI) and optically measured notch strains at 5 mm/min loading rate. However, more investigation on use of digital image correlation setup with conventional asphalt tests is required to gain information on microstructural characteristics of mixture.

8 LIFE CYCLE ASSESSMENT FOR ASPHALT RECYCLING

8.1 Introduction

Asphalt pavements are a major contributor of environmental impact in the road construction industry. In Europe, the greenhouse gas (GHG) emissions from raw materials extraction, manufacturing, construction, and rehabilitation of buildings and infrastructures is estimated around 5-12% of total national GHG emissions (IRP, 2020). European commission has set a target of 55% CO_2 savings by 2030 and aims for Europe to become the first climate-neutral continent (EAPA, 2019). Since more than 90% of 5.5 million kilometers of European roads are surfaced with asphalt (EAPA, 2020), the paving industry is encouraged to improve the sustainability of road construction by using cost effective and environment friendly materials in the mixtures.

The use of reclaimed asphalt (RA) material in pavement mixtures is considered a viable alternative to conventional hot mix asphalt and it will mitigate the GHG emissions associated with extraction and transportation of materials. However, it is important to ensure that pavements containing RA are performing satisfactorily during their design life in order to avoid extra cost of maintaining pavement that could outweigh the benefits of using RAP. Another technology known as warm mix asphalt, where asphalt mixtures are manufactured at lower temperature, has also gained particular attention in past years as an environment friendly alternative to conventional mixtures. Warm mix asphalt can be beneficial to high content RA mixtures as the lower production temperature will prevent the aging of already oxidized RA binder. Though warm mix asphalt will require less fuel for heating of aggregates and bitumen compared to conventional mixtures, it will include an additional production technology or additive which will further add to the environmental impacts. Therefore, it is important to evaluate the environmental impacts of such technologies in order to compare the benefits in their entire life cycle.

Life cycle assessment (LCA) is one of the tools that has been used to evaluate the environmental impact of any material or technology during its entire life cycle. For performing the life cycle assessment, the information about the properties of material and long-term performance is also required. Most of the studies have not considered the use phase while carrying out the life cycle assessment of pavement alternatives. However, the main impact over the life of a road is the emissions from vehicles riding on it. The emissions from vehicles increase drastically with the worsening of roughness level of the pavement (Ranawaka & Pasindu, 2020)

8.2 Objective

This objective of this study is to quantify the environmental impacts of alternatives for the reconstruction of an asphalt pavement on a heavy traffic urban road section. A comparison is made for different alternatives consisting of various contents of reclaimed asphalt in different layers produced using warm mix additives & rejuvenators. The diversity aspect of reclaimed asphalt material coming from various sources has been taken in account by considering a wide range of properties for reclaimed asphalt material along with its handling process.

8.3 LCA methodology

8.3.1 Goal & scope

This study aims to perform the life cycle assessment of pavement structure for conventional hot mix asphalt and warm mix asphalt produced using virgin materials and compare with warm mixtures containing 100% reclaimed asphalt materials produced using rejuvenator. A wide range of original properties of RA material were considered including different moisture contents, and different degree of activations (DoA), to consider the diversity of RA materials available in the industry. This study is intended to provide information about the environmental benefits that can be obtained and to what factor using the recycled asphalt mixtures as compared to conventional mixtures. 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.

8.3.2 Functional unit

The functional unit is a measure of the function of the analysed product system, and it provides a reference to which the inputs and outputs can be related. Functional unit needs to be fixed to enable the comparison of two different systems. Pavement researchers have used different functional units for example, unit length (1 km or 1 m of pavement section) or unit area (1 m^2 of built pavement layer) with case specific thickness (Giani et. al., 2015; Farina et. al. 2017; Moins et. al., 2022). This is one of the main disadvantages which makes it difficult to compare various LCA studies. While a single FU cannot be established for all projects due to their inherit differences, the efforts should be made to consider the traffic level in the functional unit along with the physical dimensions. For a fixed design life, the pavement thickness is mainly affected by the traffic loading during that period. To increase the robustness of current LCA study and to be able to compare with similar design, two different traffic intensities were considered and pavement thicknesses for each traffic category was calculated using elastic layered pavement design method. 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.

8.3.3 System boundary

The system boundary of this study is illustrated in Figure 8.1. The life cycle of road pavements is divided into five major stages including: material production, construction, use, maintenance, and end-of-life (Santero et al., 2010). However, in this study the process associated with raw material extraction, transportation, asphalt production, and construction have been considered. There are various studies that have proven that asphalt mixtures containing up to 100% provide performance equal to that of conventional mixtures (Zaumanis et. al, 2020; Dinis-Almeida et. al., 2016; Elkashef & Williams 2017; Lizárraga et. al., 2018). Therefore, it has been assumed that all the pavement scenarios considered will provide the similar durability during the service life. This also indicates that maintenance (dismantling, disposal, & resurfacing) frequency will occur at same period for all the scenarios. Therefore, these operations have not been included in the system boundary. This type of assessment is also known as cradle-to-gate analysis and is considered more appropriate when material do not differ in durability (European Commission – Joint Research Centre – Institute for Environment and Sustainability 2010).

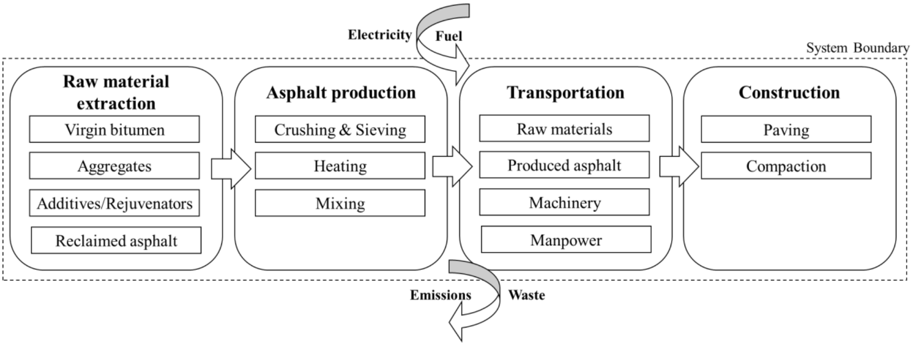


Figure 8.1. System boundaries for pavement systems.

8.3.4 Pavement scenarios

The plan for LCA study is described in Figure 8.2. For the current scenario, the asphalt pavement construction site is located in Central administrative district of Riga city council in Latvia. The asphalt pavement sections considered in this study have been designed using KENPAVE elastic layered software. The design traffic loading was considered in terms of cumulative number of equivalent standard axle load of 80 kN expressed in the unit of million standard axle (msa) repetitions. For mixtures without reclaimed asphalt (HMA & WMA), two traffic intensities (medium = 15 msa & high = 20 msa) are considered which gives a total of 2×2 = 4 cases. For 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.

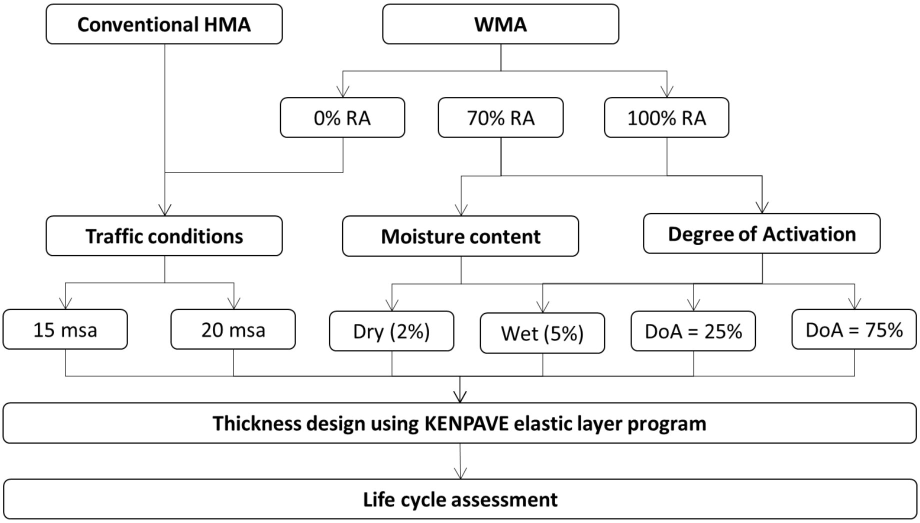
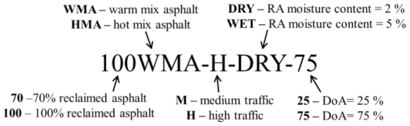


Figure 8.2. LCA study plan

Therefore, in total 20 cases will be evaluated for the LCA study. The pavement scenario is identified as follows:



The reference hot mix asphalt (HMA) used in this study is a dense-graded mixture with nominal maximum aggregate size (NMAS) of 16 mm. This mixture is designed with a conventional asphalt binder of penetration 50/70. The production temperature hot mix asphalt in this study is 160°C. The temperature of mixture production is reduced by 30°C for warm mix asphalt (WMA) using a chemical additive at a dosage of 0.5% of weight of total binder. For reclaimed asphalt mixtures produced at 70% and 100% RA content, a tall oil-based rejuvenator is used at a rate of 5% of weight of active RA binder along with chemical additive at a dosage of 0.5% of weight of total binder. The binder content, volumetric properties, elastic modulus for mixture have been obtained from various mixture databases and literature which are described in Table 8.1. (Lizárraga et. al., 2017). Even though the pavement section has been designed with all the layers, only binder layer properties are varying in different scenarios. As a result, the environmental impacts for layers other than binder layer will cancel out in the life cycle assessment. Therefore, in the inventory analysis, the calculations for binder layer will only be considered.

Table 8.1. Description of four types of binder course mixtures considered in this study.

	HMA	WMA	70WMA	100WMA
Description	Conventional hot mix asphalt using virgin materials	Warm mix asphalt containing using virgin materials	Warm mix asphalt containing 70% reclaimed asphalt	Warm mix asphalt containing 100% reclaimed asphalt
Elastic modulus	2124	2350	2276	3900
Poisson ratio	0.35	0.35	0.35	0.35
Bulk density	2.450	2.455	2.434	2.424
Air voids	4.9	4.2	3.7	3.9
RA %	0	0	70	100
Rejuvenator, %w/r	0	0	5	5
Binder content, %w/a	5	5.2	5.9	5.8
Additive, %w/b	0	0.5	0.5	0.5

%w/r – precent weight of RA binder, %w/a – precent weight of aggregates, %w/b – precent weight of total binder

The pavements scenarios were designed using a mechanistic-empirical design approach, where the pavement section is analyzed for critical response using linear elastic layered theory and the thicknesses are selected based on allowable number of load repetitions. In this study, KENPAVE was used to analyze the multilayered system. The inputs for KENPAVE are elastic modulus, Poisson ratio, and thickness of layers and the output are critical strains and deformation in the layers. As shown in Figure 8.3., the critical responses were horizontal strain at bottom of asphalt layer and compressive strain at top of subgrade. The rutting (N_R) and fatigue (N_f) life of the pavement was calculated using equation 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 8.3.

The pavement design was conducted considering a 5-layer pavement system resting above the subgrade comprising of surface layer, binder layer, aggregates interface layer, cement treated base, and granular subbase layer. The thicknesses of non-asphalt layers were assumed as shown in Table 8.3 based on indicative value for the respective traffic according to IRC 37-2018. The surface layer is considered as a non-structural layer and a constant thickness 40 mm was considered for all the cases. For design, a trial thickness for the binder layer is assumed and the strain for entire pavement system at critical locations are evaluated and compared with allowable repetitions based on rutting and fatigue criteria as given in Eq. 8.1. & 8.2. If the strains are within the allowable limits, the design is considered to be correct. Otherwise, the thickness of binder layer is increased to limit the strain values at critical locations.

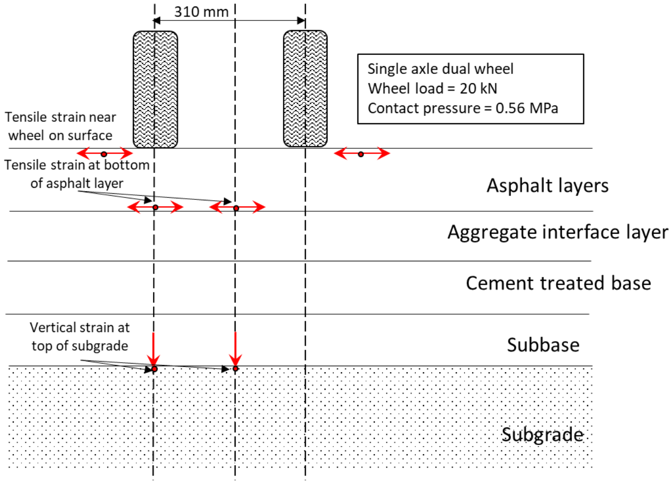


Figure 8.3. Critical response for design of pavement thickness in KENPAVE

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

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

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

Where, ε_v = vertical tensile strain at bottom of asphalt layer, ε_t = horizontal compressive strain at top of subgrade, M_{Rm} = Resilient modulus of bottom asphalt layer, V_{be} = percent volume of effective bitumen in the mix, V_a = percent volume of air voids in the mix.

Table 8.2. Elastic modulus of materials in various other layers (Indicative values from IRC 37:2018)

Layer	Elastic modulus	Poisson ratio
Surface course	3550	0.35
Aggregate interface layer	450	0.35
Cement treated base	5000	0.25
Granular subbase	200	0.35
Subgrade	100	0.45

Table 8.3. Pavement thickness design based on computed strains from KENPAVE for two different traffic intensities. 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

8.4 Life cycle inventory

8.4.1 Raw material stage

The raw materials in asphalt production consist of aggregates, binder, reclaimed asphalt, additives, and rejuvenators etc. The LCI data for raw materials were taken from literature, material suppliers, and technical databases. Asphalt binder is a refined product obtained from crude oil distillation. It plays a major role in contributing to greenhouse gases in the environment. A new document has been published in 2020 by the European Bitumen Association life-cycle inventory for bitumen, which will be used in this study (European Bitumen Association, 2020). It shows that for production of 1 tonne of bitumen – with infrastructure 27 kg of natural gas, 22 kg of crude oil, and 1115 L of water is required. In this process, the emissions to air are shown in Table 8.4.

Table 8.4. GHG's emission for production of 1 tonne of bitumen – with infrastructure (European Bitumen Association, 2020)

Emissions to air	Quantity (kg)
CO_2	189.343
SO_2	0.94
NO_x	1.224
CO	0.494
CH_4	0.535
NMVOC	0.455
Particulates	0.271

The virgin aggregates used for production of conventional mixtures without RA material consist of limestone 8/11 (15% of aggregates), 5/8 (12% of aggregates), 2/5 (12% of aggregates), 0/5 (64% of aggregates), & filler (9% of aggregates) based on mix design for AC-16 base layer as per Latvian specifications. For mixtures containing RA material, the virgin aggregate gradation was proportioned to achieve the same gradation as that of conventional mixtures. All the process associated with aggregate production from quarry will be considered and the final product will be dried virgin aggregates at the factory. Therefore, the transport of aggregates from the factory to the asphalt production site will be considered separately in the transportation section. The data required for aggregate production was taken from Ecoinvent 3 database.

For RA material extraction, the process associated with milling will be considered. The productivity of milling machine is taken from literature as 150 t/h with fuel consumption of 90 l/h of diesel oil (Oreto et. al., 2021; Autostrade per l'Italia, 2011). The treatment of the RA material at asphalt plant will require a certain amount of energy for sieving and crushing the recycled material. This amount of energy will be taken to be equal to 0.0212 MJ per kg of RA material (Zaumanis et al. 2012). The environmental impacts for the rejuvenator and additives will be selected from the Ecoinvent database. The quantities of material for different mixtures are shown in Table 8.5.

Table 8.6. Quantities of raw material for required for 1 km of pavement section.

Scenario	Material quantity (tonne)				
	Virgin aggregates	Reclaimed asphalt	Bitumen	Rejuvenator	Additive
HMA-M	2100	0	105	0	0
WMA-M	1924.8	0	100.1	0	0.50
HMA-H	3150	0	157.5	0	0
WMA-H	2974.7	0	154.7	0	0.77
70WMA-M-DRY-25	517	1217	91.2	0.53	0.56
70WMA-M-DRY-75	517	1238	70.1	1.58	0.67
70WMA-M-WET-25	517	1217	91.2	0.53	0.56
70WMA-M-WET-75	517	1238	70.1	1.58	0.67
70WMA-H-DRY-25	776	1825	136.8	0.79	0.68
70WMA-H-DRY-75	776	1856	105	2.38	0.53
70WMA-H-WET-25	776	1825	136.8	0.79	0.68
70WMA-H-WET-75	776	1856	105	2.38	0.53
100WMA-M-DRY-25	0	1733	84.6	0.75	0.57
100WMA-M-DRY-75	0	1763	54.5	2.20	0.72
100WMA-M-WET-25	0	1733	84.6	0.75	0.57
100WMA-M-WET-75	0	1763	54.5	2.20	0.72
100WMA-H-DRY-25	0	2254	110	0.98	0.55
100WMA-H-DRY-75	0	2292	71.0	2.93	0.36
100WMA-H-WET-25	0	2254	110	0.98	0.55
100WMA-H-WET-75	0	2292	71.0	2.93	0.36

8.4.2 Transportation

This phase mainly consists of the following processes: transportation of extracted raw materials from the quarry/refinery to the asphalt plant; transportation of reclaimed asphalt from milling site to the asphalt plant; and delivery of produced asphalt mixes to the construction site. The asphalt plant is located at 23 km from construction site in Kekava Parish in Latvia and the RA material will be milled from the site of construction. The virgin aggregates will be coming from a quarry site located at 70 km distance from the asphalt plant in near Lancenieki in Latvia,. The bitumen, additive, and rejuvenators are transported from the manufacturing company located 100 km from the asphalt plant in Pūre parish in Latvia. For the transport of material, two types of vehicles were used in the study. For RA material, bitumen, aggregates and produced asphalt, a truck of gross axle weight capacity of 32 tonnes and for the additives and rejuvenator, a vehicle with of gross axle weight capacity of 7.5 tonnes were considered.

8.4.3 Asphalt production

This stage will consider all the process after the acquisition of raw materials by the asphalt plant. The asphalt production stage consists of handling the aggregates, drying for production, sieving, and fractionating according to mix design, mixing, and storing for transportation. The energy consumption involved during production of asphalt mixtures mainly consist of fuel and electricity. Electricity was required to run the whole plant and natural gas was utilised to heat the aggregates. For asphalt production with low content of RA materials, the virgin aggregates are generally superheated and heat transfer in RA is through conduction mechanism. However, in this study with very high contents of RA material, the RA material is required to be heated at 130°C. Using WMA technology, a total reduction in heating temperature of aggregate obtained was 30°C. For calculation of heating energy, the values given in Table 8.7. will be used for HMA & WMA mixtures. The electricity consumption in asphalt plant for production of asphalt mixtures will be taken as 8.7 kWh/tonne and water requirement will be 0.0067 m3/tonne of asphalt mixture produced (Giani et. al., 2015). The energy required for heating are calculated using equations 8.1- 8.5 (Almeida-Costa et. al., 2016):

$$E_{ha} = Q_a \times m_a \times (t_a - t_{amb}) \tag{8.1}$$

$$E_{hw} = Q_w \times (h/100) \times m_a \times (373.15 - t_{amb}) \tag{8.2}$$

$$E_{vw} = L \times (h/100) \times m_a \tag{8.3}$$

$$E_{hs} = Q_s \times (h/100) \times m_a \times (t_a - 373.15) \tag{8.4}$$

$$E_{hb} = Q_b \times m_b \times (t_b - t_{amb}) \tag{8.5}$$

where,

E_{ha}, E_{hw}, E_{vw}, E_{hs}, E_{hb} = energy required for heating aggregates, heating water, vaporising water, heating steam, heating bitumen (J),

Qa, Q_w, Q_s, Q_b = specific heat of aggregates, water, steam, bitumen (J/kg^{-1}. K^{-1}),

m_a = mass of aggregates (kg),

t_a & t_b = heating temperature of aggregates & bitumen (in K)

t_{amb} is the ambient temperature (K).

h = moisture content of aggregates (%).

L = latent heat of water vaporising(J/kg).

The heating energy required for producing 1 tonne of asphalt mixture calculated using above equations is shown in Table 8.8. The quantity of natural gas is computed by considering lower heating value which was taken as 47,141,000 J/kg (Almeida-Costa et. al., 2016). The emissions released into the atmosphere during production of asphalt in plant are taken from literature and were measured at the chimney of the asphalt plant as shown in Table 8.9.

Table 8.7. Value used for calculation of heating energy.

Parameter	HMA	WMA
Aggregates heating temperature, °C	160	130
Bitumen heating temperature, °C	170	
Ambient temperature, °C	15	
Moisture content of virgin aggregates, %	3	
Specific heat (aggregates), J/kg^{-1}. K^{-1} (Almeida-Costa et. al., 2016)	920.5	
Specific heat (water), J/kg^{-1}. K^{-1} (Almeida-Costa et. al., 2016)	4192.3	
Specific heat (steam), J/kg^{-1}. K^{-1} (Almeida-Costa et. al., 2016)	507.2	
Specific heat (bitumen), J/kg^{-1}. K^{-1} (Almeida-Costa et. al., 2016)	2093.5	
Latent heat of water vaporization, J/kg	2250000	

Table 8.8. Energy consumption for heating of 1 tonne of asphalt mixture.

Parameter	HMA	WMA	70WMA				100WMA			
			DRY		WET		DRY		WET	
			25	75	25	75	25	75	25	75
	Heating energy (J)									
Aggregate	1.3E+8	1.0E+8	1.0E+8	1.0E+8	1.0E+8	1.0E+8	1.0E+8	1.0E+8	1.01E+8	1.03E+8
Water	1.0E+7	1.0E+7	7.8E+6	7.9E+6	1.5E+7	1.5E+7	6.8E+6	6.9E+6	1.70E+7	1.73E+7
Vapor	6.4E+7	6.4E+7	4.9E+7	5.0E+7	9.4E+7	9.5E+7	4.3E+7	4.4E+7	1.07E+8	1.09E+8
Steam	8.7E+5	4.3E+5	3.3E+5	3.4E+5	6.4E+5	6.4E+5	2.9E+5	2.9E+5	7.25E+5	7.37E+5
Bitumen	1.5E+7	1.6E+7	1.6E+7	1.2E+7	1.6E+7	1.2E+7	1.5E+7	9.7E+6	1.51E+7	9.72E+6
Total	2.2E+8	1.9E+8	1.7E+8	1.7E+8	2.3E+8	2.3E+8	1.7E+8	1.6E+8	2.4E+8	2.4E+8
Natural gas (kg)	4.67	4.03	3.61	3.61	4.88	4.88	3.61	3.39	5.09	5.09

Table 8.9. Emissions to air in kg per ton of asphalt produced (Giani et. al., 2015)

	Emissions in HMA (kg/t)	% Reduction in WMA
CO_2	9.58	-35%
N_2	278.87	-
O_2	52.42	-
Dust	1.08E-3	-40%
NO_x	7.26E-3	-65%
TOC	4.4E-3	-50%
PAHs	0.0024E-3	-

8.4.4 Construction

This stage includes the milling of clearing of construction site, paving process, and compaction. The environmental burden from this stage includes fuel consumption for machinery and greenhouse gas emissions. Although the compaction effort required to reach the target density may differ for each mixture, due to unavailability of information, it was assumed that all the mixtures will require same compaction energy. Therefore, the environmental impacts due to this phase will only depend on the quantity of mixture compacted for each scenario. The fuel consumption for various machineries for pavement construction are shown in Table 8.10.

Table 8.10**.** Energy consumption in construction

Equipment	Brand/Model	Engine Capacity (hp)	Productivity (t/hr)	Fuel Consumption (l/hr)	Fuel Type
Paver	Dynapac F30C	196	2400	49	diesel
Pneumatic roller	Dynapac CP132	100	668	26	diesel
Tandem roller	Ingersol rand DD110	125	285	33	diesel

8.5 Life cycle impact assessment

As described earlier, 20 scenarios for binder layer of pavement section were considered for life cycles assessment using SimaPro 9.2.0.2 tool. The environmental impacts for all the scenarios were evaluated using ReCiPe 2016 Midpoint (H) method. Among all the parameters evaluated from above method, four parameters have been discussed in this study: Global warming potential, Freshwater ecotoxicity, Human carcinogenic toxicity, and Fossil resource scarcity.

8.5.1 Global warming potential

The impact on global warming is expressed in terms of kg of CO_2 equivalent. These results are shown in Figure 8.4. It can be seen that among all the phases considered in this study the highest CO_2 emissions were caused by the asphalt production. These impacts from asphalt production process are in the range between 45-53% of total kg of CO_2 equivalent for various scenarios. The lowest impact on global warming was observed during the construction stage which was around 1% of overall kg eq of CO_2. For comparison, Giani et. al., 2015 also found that the highest impact was caused from the material extraction and processing stage, which was around 40% of total impact during the life cycle. However, in the above study, feedstock energy of bitumen was considered which is approximately 7 times the process energy of the refinery, therefore it significantly affects the results of the assessment. In the present study, the overall CO_2 equivalent for various scenarios were found in the range of 0.048-0.063 kg of CO_2 equivalent which is comparable to 0.052–0.0602 kg CO_2 eq per kg of mixture value found in the previous study (Giani et. al., 2015).

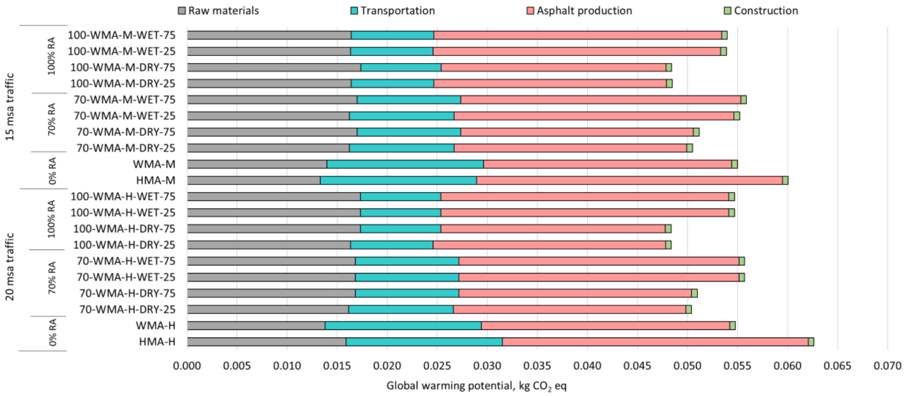


Figure 8.4. Impact on global warming in kg of CO_2 equivalent.

During asphalt production process, high amount of energy is required to run the asphalt plant which along with high emissions contributed to the highest overall CO_2 equivalent during this stage. As a result, this stage could be considered to have the highest impact on global warming. Following the asphalt production stage, the second highest impact on global warming potential was either raw material stage or transportation stage depending upon the type of the mixture. For virgin mixtures without RA material (HMA & WMA mixtures), the transportation stage showed higher impact on global warming than the raw material, while it was vice-versa for mixtures containing RA material (70-WMA & 100-WMA mixtures). The reason for this observation is that for production of virgin mixtures, high quantity of aggregates is required which are transported on trucks over a long distance, which contributes to higher emissions. On the other hand, the mixtures with RA material require lesser quantity of aggregates which further reduces the emissions associated with the transportation of material. However, these results are affected by the assumptions made with the input data for life cycle inventory. The impacts will change significantly when parameters such as transportation distance, mix design, or RA content are varied.

Figure 8.5. shows the percent reduction in emission in terms of kg CO_2 eq for various mixtures when compared to HMA mixture. It can be seen that highest reduction (23% & 19%) was observed for 100-WMA-DRY-25 and 100-WMA-DRY-25 mixture for medium traffic and high traffic intensities respectively. This is obvious because these mixtures do not require any virgin aggregates and therefore high amount of emissions associated with production, processing, and transportation of virgin aggregates are saved in this process. It should be noted that degree of activation (DoA = 25% or DoA = 75%) considered for the RA material did not show any significant effect on overall emissions from the life cycle of pavement. 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. In fact when 70% RA content with high moisture content was used, this mixture showed higher overall emissions compared to WMA mixture in 20 msa traffic condition. This is due to high amount of energy required in drying the RA aggregates which offsets the benefit gained in transportation and raw material extraction stage. This signifies the importance of following proper RA material management practices in order to achieve the highest benefit of asphalt recycling.

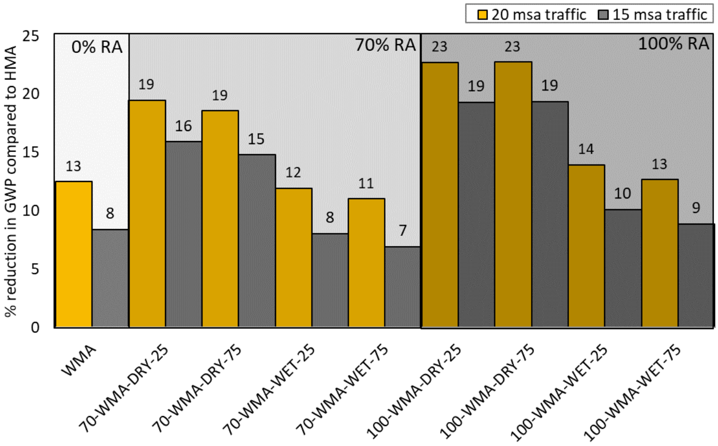


Figure 8.5. Percent reduction in GWP (kg CO_2 eq) compared to HMA mixture.

8.5.2 Freshwater ecotoxicity

Water in freshwater form is considered as one of most important natural resources on Earth. The freshwater lakes are used for drinking water, agriculture, industrial use, hydroelectricity generation and recreational activities etc. (Rousso et. al., 2020). Asphalt mixtures used for building highway may contain heavy metals and hydrocarbons that potentially contribute to polluting the water (Zhou et. al. 2021). The results of freshwater ecotoxicity (FE) calculated from LCA analysis is expressed in terms of kg 1,4-dichlorobenzene equivalent (1,4-DB) as shown in Figure 8.6. It can be seen that highest contribution on freshwater toxicity is observed for the asphalt production stage (around 78-90 % of overall freshwater toxicity) for different mixtures. The reason for this could be that during the asphalt production, huge amount of hydrocarbon-based products are involved which have high potential to pollute the freshwater. The impact on freshwater ecotoxicity was lowest for construction stage followed by the raw material stage.

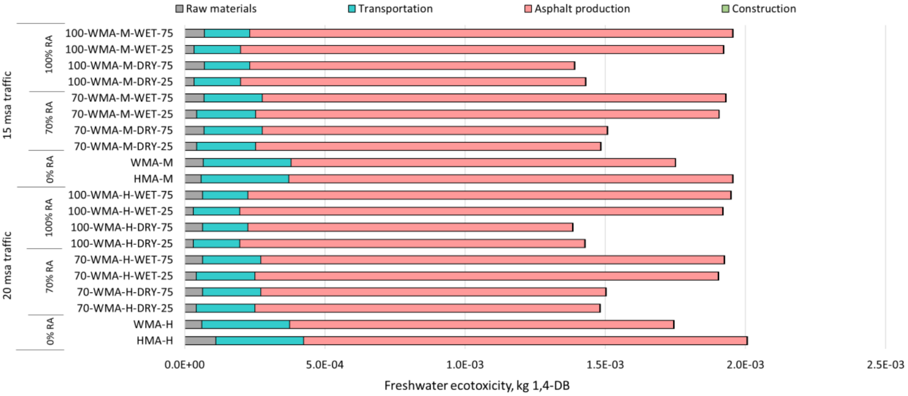


Figure 8.6. Impact on freshwater ecotoxicity in kg of 1,4-DB equivalent.

Figure 8.7. shows the percent reduction in emission in terms of kg 1,4-dichlorobenzene equivalent (1,4-DB) for various mixtures when compared to HMA mixture from LCA calculations. It can be seen that WMA mixtures due to their reduced production temperature showed 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 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.

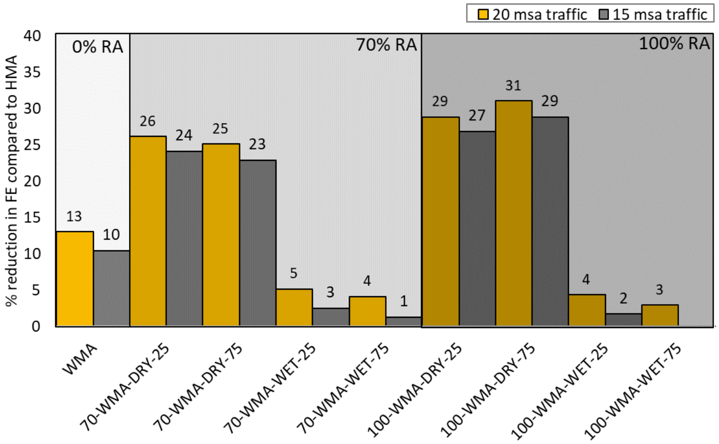


Figure 8.7. Percent reduction in freshwater ecotoxicity (kg 1,4-DB eq) compared to HMA mixture.

8.5.3 *Human carcinogenic toxicity*

In this study, the human carcinogenic toxicity was evaluated in kg equivalent of 1,4-dichlorobenzene (1,4-DB). As seen in Figure 8.8., all the pavement scenarios have significantly different human toxicity potential, which are again highest for the asphalt production stage, similar to previous observation with freshwater ecotoxicity. It can also be seen that in the raw material stage, the human toxicity potential for virgin mixtures (HMA & WMA) were significantly higher (8-11%) compared to human toxicity potential for mixtures containing RA material (2-6%). This is due to the fact that virgin mixtures are produced with materials that require heavy processing during the extraction process which increase the potential of human carcinogenic toxicity.

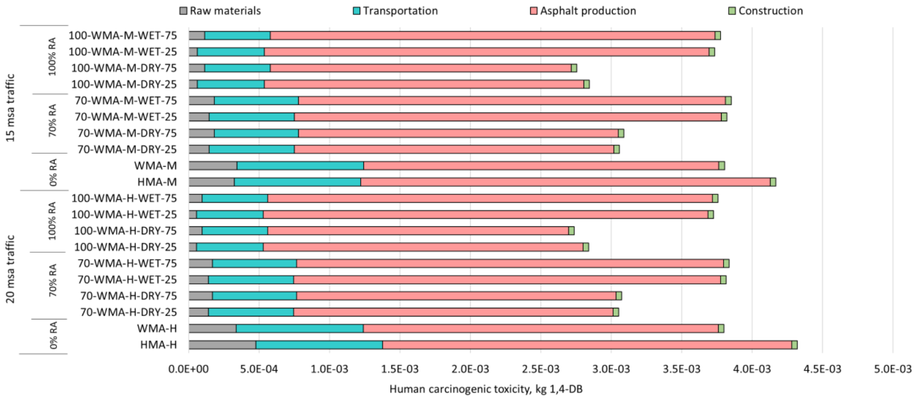


Figure 8.8. Impact on human carcinogenic toxicity in kg of 1,4-DB equivalent.

As seen in Figure 8.9., WMA mixtures showed significant reduction (9-12%) in human carcinogenic toxicity compared to HMA mixture due to reduction in production temperature. However, the highest reduction (26-32%) was observed with incorporation of 70% and 100% RA material with low moisture content. As seen, the benefit observed in reduction of human carcinogenic toxicity with inclusion of RA material was offset when the RA material was incorporated with a high moisture content. In this case, the energy required for drying the RA aggregates increased the human carcinogenic toxicity to same level as that of virgin WMA mixture. The effect of degree of binder activation was highest for 100-WMA mixture when the RA material was considered at lower moisture content. At lower DoA (25%), the virgin binder requirement is higher to fulfil the binder content, but due to presence of lesser active binder, less quantity of rejuvenator is required, when compared to higher DoA (75%). As a result, the resultant impacts for degree of binder activation will depend on the several properties of mixture such as binder content, RA content, etc. Overall, the results indicate that incorporation of high amount of well managed RA material can reduce the damage to human health as compared to conventional mixtures.

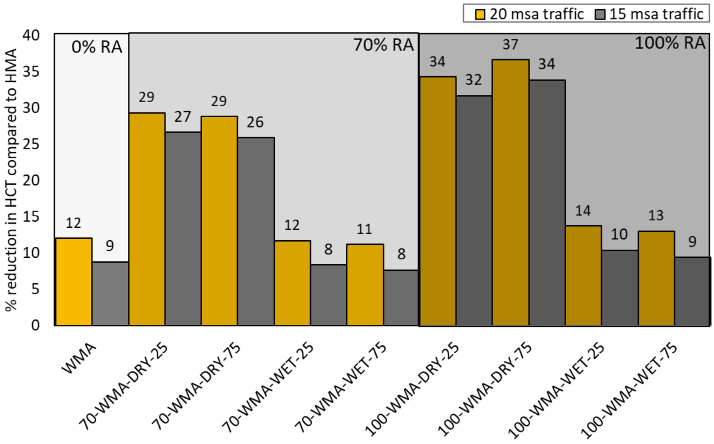


Figure 8.9. Percent reduction in human carcinogenic toxicity (kg 1,4-DB eq) compared to HMA mixture.

8.5.4 Fossil resource scarcity

Fossil resource scarcity was measured in terms of kg of oil equivalent. As seen in Figure 8.10, the highest contribution to FRS was from asphalt production phase (around 45-57%) which was followed by transportation stage (around 21-39%). This is an expected observation since high quantity of fuel (diesel) is required for vehicle operation for transportation of materials as well as natural gas for heating & drying of aggregates. Both the above energy sources are based on fossil origins. As a result, these phases have the highest impact on life cycle of payment mixtures. Similar to all the previous indicators, the construction phase showed the lowest impact on fossil resource scarcity.

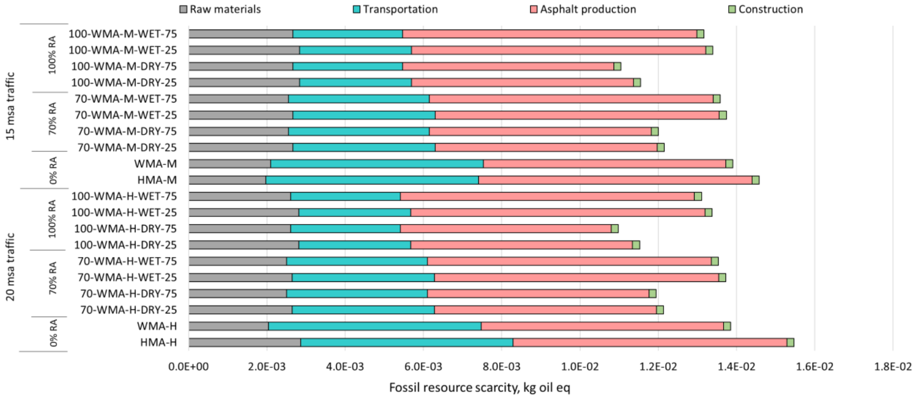


Figure 8.10. Impact on fossil resource scarcity in kg of oil equivalent.

As seen in Figure 8.11., the FRS was reduced by 5% & 10% with 30°C reduction in production temperature for medium traffic & high traffic scenario, but this difference is not very high when comparing to benefits observed in previous categories like global warming potential, freshwater ecotoxicity, & human carcinogenic toxicity. The reason for this could be due to added burden associated with additive production and transportation. As observed here, for medium traffic design, the negligible (5%) change in FRS. However, it can be seen in Figure 8.10., that for 15 msa design, the raw material impacts were significantly higher for WMA compared to HMA, which could be offsetting the benefits from reduced production temperature.

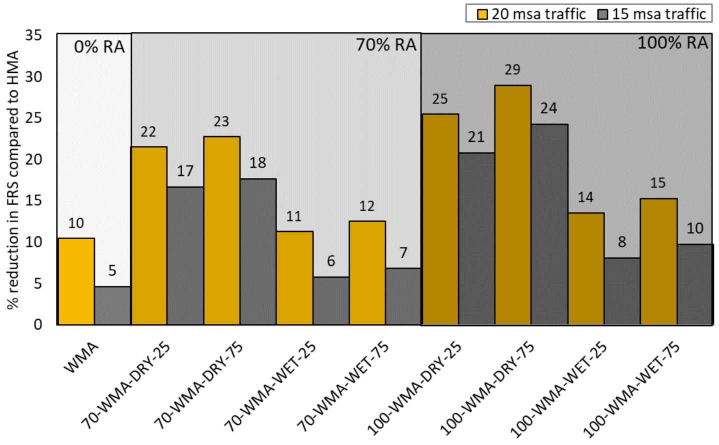


Figure 8.11. Percent reduction in fossil resource scarcity (in kg of oil eq) compared to HMA mixture.

8.6 Section summary & conclusions

This study aimed to quantify the environmental benefits of using high content reclaimed asphalt in the mixtures using the warm mix technology and rejuvenators. To consider the variability of RA material obtained from various sources, two moisture contents, and two degrees of binder activation were considered in the analysis. To ensure the robustness of the study, two different traffic intensities were considered, and the thickness of pavement was designed using an elastic layered program. The results obtained from life cycle assessment highlighted the benefits of using reclaimed asphalt and the need to ensure adequate management practices for RA material to prevent it from moisture infiltration. Based on the study, following conclusions can be made:

1. Based on this cradle to gate analysis, the highest CO_2 emissions were observed during the asphalt production phase, which was due to high quantity of emissions released during the asphalt production process. The total emissions were lowest for 100% reclaimed asphalt mixture when the reclaimed asphalt material was considered with a low moisture content. It was also observed that reduced emissions associated with incorporation of 70% reclaimed asphalt into the warm mix asphalt can be offset by the extra emissions generated if reclaimed asphalt with higher moisture contents is used.

2. The asphalt production process accounted for 78-90% contribution to the total overall freshwater toxicity for different mixtures due to large quantities of hydrocarbon-based materials consumed in the asphalt plant operation. There were almost negligible benefits (<5%) for reducing the production temperature and using reclaimed asphalt with higher moisture content when compared to impacts from conventional hot mix asphalt.

3. The virgin mixtures showed much higher human carcinogenic toxicity potential compared to mixtures containing reclaimed asphalt material in raw material phase due to high amount of processing required for virgin materials. The benefit observed in reduction of human carcinogenic toxicity with inclusion of RA material was offset when the RA material was incorporated with a high moisture content. The degree of binder activation determines the virgin bitumen and rejuvenator quantities, therefore, the resultant impact for degree of binder activation will depend largely on mixture properties.

4. Apart from asphalt production stage, which relies on natural gas for heating & drying of aggregates, the transportation stage showed very high impact on fossil resource scarcity as both the above energy sources are based on fossil origins. The benefits observed from reducing temperature on fossil resource scarcity were offset by the raw material impacts particularly coming from the additive used in warm mix asphalt.

CONCLUSIONS

This 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 impacts 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 this thesis, the following conclusions can be drawn:

1. A laboratory mixing procedure for high content reclaimed asphalt mixtures was developed in this study that 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 mixtures in the laboratory. Further, the type of mixer should be taken into account when comparing mixtures.

2. A 15°C reduction in 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% 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 the four rejuvenators. The tall oil-based rejuvenator showed up to 37% higher number of fatigue cycles at 5% strain level and 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 compare with conventional mixtures. Based on results of global warming impact category, the asphalt production stage showed the highest impact which was between 45-53% of total global warming impact, due to the high quantity of emissions released from this stage. The calculated emissions were reduced by up to 26% with the incorporation of 70% 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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