PERFORMANCE CHARACTERISTICS OF CRUMB RUBBER MODIFIED ASPHALT MIXED WITH RECLAIMED ASPHALT PAVEMENT AND WASTE ENGINE OIL

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DISSERTATION SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ENGINEERING SCIENCE

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PERFORMANCE CHARACTERISTICS OF CRUMB RUBBER MODIFIED ASPHALT MIXED WITH RECLAIMED ASPHALT PAVEMENT AND WASTE ENGINE OIL

ABSTRACT

This study aimed to characterize the reclaimed asphalt pavement (RAP) mixes for the preparation of asphaltic concrete wearing course with 14 mm nominal maximum aggregate size (ACW14) mix. The RAP was incorporated with two waste materials comprising a 6% crumb rubber (CR) (by weight of virgin binder) as a binder modifier to enhance the rheological properties of the asphalt binder and 15% of waste engine oil (WEO) (by weight of aged binder) as a rejuvenator to restore the properties of the aged binder. A total of five different asphalt mixes were prepared where a replacement of 0%, 30%, 50%, 70%, and 100% RAP aggregates are incorporated in the mix (R0, R30, R50, R70, and R100). The Marshall method was used to determine the optimum binder content (OBC). Finally, the mechanical performances, resilient modulus (M_R), indirect tensile fatigue, moisture susceptibility, and mass loss (ML) tests of the five ACW14 mixes were conducted and analysed. Based on the results, it was found that 15% WEO (by weight of aged binder) was able to soften the extracted aged binder. In addition, the OBC gradually decreased with the addition of RAP content. The R0 recorded the highest OBC value (5.9%), while the OBC values of R30, R50, R70, and R100 mixes were 5.8, 5.7, 5.5, and 5.5%, respectively. Furthermore, the results showed that the Marshall parameters, moisture susceptibility, and ML values of the RAP mixes complied with the criteria outlined by the Public Works Department Malaysia. According to the M_R performance, the M_R increased with the increment in RAP content, and R100 obtained the highest value. The moisture susceptibility test revealed that all RAP mixes were more resistant to moisture damage as the tensile strength ratio (TSR) values were higher than the standard value. In terms of fatigue resistance, the R30, R50, and R70 mixes showed better performance than the R0, while the R100 mix showed approximately 5% less resistance to fatigue than the R0. The ML test indicated that all RAP mixes exhibited highly ravelling resistance. Statistically, the amount of RAP and binder used significantly affected the ACW14 mix's design performance.

Keywords: Reclaimed Asphalt Pavement, ACW14 Mix, Optimum Binder Content, Waste Engine Oil, Crumb Rubber.

CIRI-CIRI PRESTASI ASFALT TERUBAH SUAI DENGAN SERBUK GETAH DICAMPUR DENGAN TURAPAN ASFALT KITAR SEMULA DAN MINYAK ENJIN SISA

ABSTRAK

Kajian ini dijalankan untuk mencirikan sifat campuran asfalt konkrit dengan saiz aggregat nominal 14mm (ACW14) yang diubahsuai dengan kandungan asfalt kitar semula (RAP), 6% serbuk getah (CR) dan 15% minyak enjin terpakai (WEO). Campuran antara RAP dengan WEO adalah untuk menyegarkan kembali kandungan pengikat lama dalam RAP; manakala CR pula ditambah untuk meningkatkan lagi keupayaan reologi bahan pengikat lama tersebut. Sebanyak lima campuran asfal konkrit telah dibuat menggunakan peratusan RAP yang berbeza iaitu sebanyak 0%, 30%, 50%, 70% dan 100% (R0, R50, R70 dan R100). Kaedah Marshall telah digunakan untuk menentukan peratus kandungan pengikat optima (OBC) dan prestasi mekanikal seperti modulus ketahanan (M_R), kelesuan tidak langsung, kerentanan lembapan dan ujian kehilangan jisim (ML) bagi kelima-lima campuran asfal konkrit di atas telah diukur dan dianalisa. Hasil dari analisis, didapati sebanyak 15% WEO (dari berat bahan pengikat) telah Berjaya melembutkan bahan pengikat lama yang telah mengeras. Selain itu, didapati kandungan OBC perlahan-lahan menurun dengan peningkatan kandungan RAP. Sampel R0 mencatatkan nilai OBC tertinggi (5.9%) manakala nilai OBC bagi sampel R30, R50, R70 dan R100 masing-masing adalah sebanyak 5.8%, 5.7%, 5.5% dan 5.5%. Keputusan ujian bagi parameter Marshall pula menunjukkan kerentanan kelembapan dan nilai ML campuran RAP mematuhi kriteria yang digariskan oleh Jabatan Kerja Raya Malaysia. Nilai M_R pula meningkat dengan peningkatan kandungan RAP dengan sampel R100 memperoleh nilai tertinggi. Ujian kerentanan kelembapan pula menunjukkan yang kesemua sampel RAP mempunyai kerentanan kelembapan yang baik dengan nilai nisbah kekuatan tegangan (TSR) yang lebih tinggi dari nilai standard. Dari segi ketahanan kelesuan, sampel R30, R50 dan R70 menunjukkan prestasi yang baik manakala sampel R100 menunjukkan pengurangan ketahanan kelesuan sebanyak lebih kurang 5% dari sampel R0. Keputusan ujian ML pula menunjukkan kesemua sampel RAP mempunyai ketahanan lecetan yang baik. Secara statistik, didapati penambahan RAP dan bahan pengikat yang digunakan dapat meningkatkan prestasi turapan ACW14 dengan cemerlang.

Kata kunci: Turapan aspal yang kitar semula, campuran ACW14, Kandungan pengikat optimum, Minyak enjin sisa, Pengubah serbuk getah.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

AASHTO	:	American Association of State Highway and Transportation
ACW14	:	Asphaltic concrete wearing course with 14 mm nominal maximum aggregate size
AIV	:	Aggregate impact value
ANOVA	:	Analysis of variance
ASTM	:	American Society for Testing and Materials
BS	:	British Standard
BS EN	:	British Standard European Norm
cm	:	Centimetre
cP	:	Centipoise
CR	:	Crumb rubber
dmm	:	Deci millimetre
DSR	:	Dynamic shear rheometer
EI	:	Elongation index
FI	:	Flakiness index
g	:	Gram
h	:	Hour
HMA	:	Hot mix asphalt
Hz	:	Hertz
ITFT	:	Indirect tensile fatigue test
ITS	:	Indirect tensile strength
kg	:	Kilogram
kN	:	Kilonewton
kPa	:	Kilopascal
LVDT	:	Linear variable differential transformer
min	:	Minute
ML	:	Mass loss

mm	:	Millimetre
mPa	:	Megapascal
MQ	:	Marshall quotient
M_R	:	Resilient modulus
NA	:	Natural aggregates
OBC	:	Optimum binder content
Pa.s	:	Pascal-second
PWD	:	Public Works Department, Malaysia
R0	:	Asphalt with 0% RAP (control mix)
R30	:	Asphalt with 30% RAP
R50	:	Asphalt with 50% RAP
R70	:	Asphalt with 70% RAP
R100	:	Asphalt with 100% RAP
RAP	:	Reclaimed asphalt pavement
RPM	:	Rotation per minute
RAP mix	:	RAP mix indicated an asphalt mix incorporated with RAP.
s	:	Second
SSD	:	Saturated surface dry
SDG	:	Sustainable Development Goal
TSR	:	Tensile strength ratio
UMATTA	:	Universal material testing apparatus
VFB	:	Voids filled with binder
VIM	:	Air voids in mix
VMA	:	Voids in mineral aggregates
WEO	:	Waste engine oil
µm	:	Micrometre
°C	:	Degree celsius

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

1.1 Research Background

One of the most critical challenges of using reclaimed asphalt pavement (RAP) in hot mix asphalt (HMA) is maintaining a sustainable quality over its high content usage (Han et al., 2019; Jahanbakhsh et al., 2020; Mirhosseini et al., 2019). Most road construction practices are primarily limited to low-content RAP for lower-value applications, such as a base layer, road shoulder, and rural roads (Zaumanis et al., 2016). In 2019, the United States incorporated 21% of RAP in the asphalt mix for road construction (Williams et al., 2020). Correspondingly, the road construction industry is constantly adopting new environmentally friendly, cost-effective, and affordable technologies. In recent decades, the fast-paced global development and urbanisation have led to the surge in demand for natural aggregates (NA) in road construction despite the harmful nature of NA production towards the environment, as it is known for exacerbating global environmental issues. For example, Malaysia produced 160 million tonnes of aggregates in 2015 for use in development work, which was about 36% more than the total production in 2011 (Bernhardt & Reilly, 2020).

In light of this, RAP is considered one of the key solutions to address the growing challenges of climate change and contribute to a sustainable environment, especially in the road construction industry. Furthermore, the usage of RAP has the potential to minimize mineral usage, energy consumption, landfill spaces, relevant pollution, and overall costs (Aurangzeb et al., 2014; Bressi et al., 2019; Izaks et al., 2015; Milad et al., 2020; Zaumanis, Mallick, & Frank, 2014). To date, several studies have revealed that the use of RAP could reduce harmful gas emissions and production costs by as much as 35% and 70%, respectively (Jahanbakhsh et al., 2020; Zaumanis, Mallick, & Frank, 2014; Zaumanis et al., 2016). Therefore, many countries like the USA, Japan are considering the use of RAP at an increased percentage in the construction industry as an alternative option to tackle the rising cost of materials and the continuous depletion of natural resources (Copeland, 2011; Randy C West & Copeland, 2015; Zaumanis, 2014).

1.2 Problem Statement

Currently, various approaches have been proposed to use RAP in the road construction industry. However, no uniform RAP recycling standard can be used as a guideline for a wider application of high content RAP in HMA design. Therefore, the lack of awareness and non-standard recycling requirements contributes to the limited application of high RAP in many countries (Baaj et al., 2013; R. S. McDaniel et al., 2012; Zaumanis et al., 2016). Realising the lack of RAP standards, researchers are currently developing the most appropriate approach for incorporating high content RAP into HMA design to conserve the use of natural resources, overall costs, energy consumption, and landfill space.

RAP is obtained by milling the surfacing layer of old asphalt pavements and primarily comprises two materials: aged binder and aggregates. The mechanical performance of the asphalt mix incorporated with RAP mainly depends on the property of the aged binder. Exposure to natural elements such as oxygen, light, heat, and water causes the base binder to age. As a result, the micro-surface roughness of the base binder rises, as do the functional groups of carbonyl and sulfoxide. The rheological behaviour of the asphalt binder is also greatly influenced by its micromechanics. Therefore, as the asphalt binder ages, its viscosity increases. This is how an aged binder exhibits morphological and rheological changes over time. Consequently, the aged binder greatly affects the properties of the new blend binder. Noferini et al. (2017) revealed how the internal interaction in aged binder affected the mechanical properties of the final blend binder. The use of aged binders also increased the risk of thermal and fatigue cracking in RAP mixes (Cao et al., 2018; Milad et al., 2020). Thus, the properties of the aged binder should be restored to incorporate high content RAP in an asphalt mix. Furthermore, high content RAP could influence the volumetric properties of the asphalt mix, which could affect its mechanical performance (Randy Clark West et al., 2013; K. Zhang et al., 2016).

1.3 Research Gap

Several researchers have suggested using 30% RAP in HMA with little or no complications (Miró et al., 2011; Singh & Sawant, 2016; Randy Clark West et al., 2013). Therefore, high RAP content in this study refers to an amount of RAP greater than 30%. Meanwhile, Idham and Hainin (2015) reported the addition of 60% RAP as the optimum amount into a virgin mix to increase the fatigue and rutting resistance. They recommended using 60% RAP in the virgin mix as an optimum content because it can improve fatigue and rutting resistance. Corroboratively, Su et al. (2009) stated that RAP quantities could be used 40% as a wearing course. They exhibited that 40% RAP could outperform the control mix to maintain Marshall stability. Furthermore, it obtained higher than the standard value (80%) in terms of moisture susceptibility. They recommended against utilizing 70% RAP due to fatigue concerns. While Widyatmoko (2008) proposed a 50% benchmark of RAP addition. It was observed that asphalt mix containing up to 50% RAP performed equal to or better than the control mix in terms of rutting, fatigue resistance, and moisture sensitivity. As the research on high content RAP is still progressing, some researchers have recorded successful incorporation of high content RAP (Hansen et al., 2011; J. Oliveira et al., 2011), but no clear framework for applying high content RAP has been developed yet. Additionally, the application of high RAP remains limited in many countries due to the lack of awareness and non-standard recycling requirements (Baaj et al., 2013; R. S. McDaniel et al., 2012; Zaumanis et al., 2016). The unproven performance of 100% RAP mix and the lack of a consistent and logical approach to materials selection and mix design are the main impediments to the widespread adoption of 100% recycling. Therefore, it is necessary to optimise and introduce a standard guideline on the RAP content in HMA design.

In addition, the use of RAP in the asphalt mix would influence the maltenes-to-asphaltenes ratio in an aged binder. As such, a higher RAP content indicates a higher maltenes-to-asphaltenes ratio. Therefore, the higher amount of RAP content in the asphalt mix results in a higher viscoelastic property, which could increase the stiffness and reduce the fatigue resistance (Al-Qadi et al., 2012; Han et al., 2019; R. McDaniel et al., 2000) as well as the workability of the mix (Hidalgo et al., 2020; Majidifard et al., 2019). Concurrently, rejuvenators have received increasing attention in asphalt technologies due to their ability to restore the properties of aged binders (Bilema et al., 2021; Elkashef et al., 2018a; Elkashef et al., 2018b). Waste engine oil (WEO) is one of the common rejuvenators that restores and softens the aged binder (Hill & Jennings, 2011; H. Li et al., 2019; Tarsi et al., 2020; Randy C West & Copeland, 2015) as well as enhances the workability of RAP mixes (H. Li et al., 2019; Majidifard et al., 2019; Mangiafico et al., 2016). Nonetheless, the potential reduction in the pavement's rutting resistance, as well as the inability to sustain the resistance of moisture damage, pose a major drawback over the use of rejuvenators (Jia et al., 2015; Majidifard et al., 2019; Mogawer et al., 2016). This is because rejuvenators could increase the flow value and softness of the mixes more than expected. The excessive incorporation of the rejuvenator affects the stripping, adhesion, rutting, and heat cracking, while inadequate dosages would lead to stiffed mix products (Cong et al., 2016; Im et al., 2016; Zaumanis, 2014). Therefore, the selection of the proper dosage of the rejuvenator is another critical issue (M. Chen, Leng, et al., 2014; Nayak & Sahoo, 2017; Reyes-Ortiz et al., 2012; Zaumanis, Mallick, & Frank, 2014) and its influence on the properties of the aged binder need to be addressed.

Furthermore, the crumb rubber (CR) modifier is a binder modifier that would serve as a suitable material alternative to support the rejuvenator's inadequacies (Crisman et al., 2020; Majidifard et al., 2019). This is due to the belief that incorporating CR could increase the viscosity of the binder. Hence, the binder modified by CR would increase the durability and stiffness of the asphalt mix (Fontes et al., 2010; Poovaneshvaran et al., 2020). Moreover, the use of CR in asphalt mix was reported to improve the stability, moisture resistance, cracking behaviour, fatigue resistance, and resilient modulus (Fakhri & Azami, 2017; J. Huang & Sun, 2020; Izaks et al., 2015; Kocak & Kutay, 2017; Majidifard et al., 2019; Wang, Liu, van de Ven, et al., 2020; Zaumanis & Mallick, 2015). However, research on the performance of high content RAP mixes through the combined use of WEO and CR has been very limited.

1.4 Aim and Objectives

This study aimed to characterize the RAP mixes in asphaltic concrete wearing course with a 14 mm nominal maximum aggregate size (ACW14) mix design incorporated with two waste materials comprising WEO and CR. The following are the four objectives used to achieve the research aim:

(1) To examine the effect of WEO on the physical and rheological properties of the extracted aged binder.

(2) To analyse Marshall mix design parameters of five different ACW14 mixes incorporating different RAP contents (0, 30, 50, 70, and 100%).

(3) To investigate the mechanical performance of five different ACW14 mixes incorporating different RAP contents (0, 30, 50, 70, and 100%).

1.5 Scope of the Study

The scope of this study included the preparation of ACW14 mixes with and without RAP and evaluating their performances through various methods. The ACW14 mixes were prepared following the PWD standard specification (2008) for road works (JKR/SPJ/2008-S4) (Jabatan Kerja Raya, 2008). The RAP was incorporated in ACW14 mixes with two waste materials comprising WEO and CR. A total of five different mixes, R0, R30, R50, R70, R100, were evaluated in this study (for example, 0% RAP, denoted as R0). In general, different percentages such as 10, 20, 30, 40, …. 100% can be used to study the characterization of RAP mixes more accurately. However, due to time and cost constraints, the RAP proportions of 30, 50, 70, and 100% were chosen where R100 (100% RAP) was the maximum target because this study aimed to characterize the high content of the RAP mix.

Moreover, R30 was the lowest RAP mix because up to 30% of RAP mix in HMA mixes has little or no complication. Then, the other three middle mixes were chosen at regular intervals of 20%. The material's engineering properties of the prepared mixes were tested based on the related laboratory tests in conjunction with the American Society for Testing and Materials (ASTM) and the American Association of State Highway and Transportation Officials (AASHTO). The effect of the WEO on the properties of the extracted aged binder was also analysed. The performance and durability tests included: resilient modulus (M_R), moisture susceptibility, indirect tensile fatigue test (ITFT), and mass loss (ML) tests. Furthermore, statistical analysis was carried out to evaluate the significant effect of binder and RAP on the ACW14 mix. Finally, an arbitrary scale was developed as an alternative approach to compare and analyse the performance of RAP mixes. All experiments were conducted at the Highway Engineering Laboratory, Department of Civil Engineering, Faculty of Engineering, Malaysia, University of Malaya.

1.6 The Study Outlines

The dissertation is comprised of five chapters, as follows:

Chapter 1: This chapter introduces the research subject, including research background, statement of the research problem, research gap, key research objectives, study contribution, and scope of the study.

Chapter 2: This chapter presents a literature review on the use of RAP, CR, and WEO. It also includes an overview of the impact of RAP on the mechanical and durability performance of the ACW14 mix.

Chapter 3: The basic experimental and comprehensive test method used in this study to investigate the performance characteristics of materials and RAP mixes are discussed in this chapter.

Chapter 4: This chapter illustrates the results and engineering properties of the RAP mixes obtained in this study. The main part of this chapter is the discussion and analysis of the results and their relationship. Statistical analysis of test results is presented as well.

Chapter 5: This is the concluding chapter of the study, which summarises the critical elements. The study results were confirmed by the relevant literature provided to support the problem statement. Furthermore, some recommendations for further study are also presented in this chapter.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

A literature review was constructed to understand the recent developments and practices regarding the use of RAP in an ACW14 mix design and its properties and performance with rejuvenator and binder modifier.

RAP was first used in 1915 (Taylor, 1997), but it began to gain recognition in the 1970s (Kandhal & Mallick, 1997; Pires et al., 2017; Silva et al., 2012; Randy C West, 2015). When the Kyoto Protocol was revealed in 2005, pavement recycling received significant attention and a comprehensive implementation was introduced, including the construction of pavement (Barbieri et al., 2019; Reyes-Ortiz et al., 2012). To date, RAP recycling is one of the most recyclable materials and cost-effective solutions to mitigate the increasing demand of NA and the skyrocketing prices of these materials. Given that all roads are periodically replaced or repaired, this makes recyclable materials such as RAP highly valuable and suitable to be used. In the United States, the total amount of RAP used was 82.2 million tonnes in 2018, which saw a massive increase of 46.8% from the total amount of RAP used in 2009 (Williams et al., 2019). A similar trend was observed in Japan where almost 47% of RAP was used in asphalt paving in 2013 (Randy C West & Copeland, 2015). Moreover, RAP is classified as a suitable replacement for NA and binder that mitigates environmental consequences by minimising energy usage, mineral resources, and related pollution as well as reducing the costs while satisfying all performance expectations (Aurangzeb et al., 2014; Izaks et al., 2015; Shingles, 2014; Zaumanis, Mallick, & Frank, 2014). Ultimately, the use of RAP would reduce gas emissions and production costs by as much as 35% (Zaumanis et al., 2016) and 70%, respectively (Jahanbakhsh et al., 2020; Zaumanis, Mallick, & Frank, 2014). Besides, one of the major problems affecting the environment is the accumulation of waste products. To alleviate the severity of this problem, motor vehicle-derived wastes, such as CRM and WEO, have gained interest in improving road asphalt pavements.

Owing to insufficient awareness and non-standard recycling requirements, the application of RAP remains limited in many countries (Baaj et al., 2013; R. S. McDaniel et al., 2012; Zaumanis et al., 2016). Therefore, there is a need to establish a RAP assessment framework, especially when various RAP proportions are used in an HMA design. As such, the use of 30% RAP in HMA was reported to cause little or no complications at all (Al-Qadi et al., 2007; Miró et al., 2011; Singh & Sawant, 2016; Randy Clark West et al., 2013).

Nonetheless, the incorporation of high RAP content into HMA faces many challenges because the mechanical performance of RAP mixes mainly depends on the aged pavement's ingredients. In particular, the aged binder components in the RAP mix increase stiffness, viscosity, and the critical mix temperature, and thus, lower fatigue and thermal cracking properties are assumed to have occurred (Abdo, 2016; Chesner et al., 2002; Hussain & Yanjun, 2013; Izaks et al., 2015; Vargas-Nordcbeck, 2007). In particular, the laboratory study indicated that the aged binder in RAP affects the mechanical properties of the mixes due to its internal interaction (Noferini et al., 2017). Therefore, the properties of the RAP mix rely primarily on the consistency of the aged binder. Even though the progression in binder grade at low RAP mix is small, the impact of RAP is significant at high RAP mix. Some studies showed that the rejuvenator is a high-performance additive that could help restore the properties of aged binders (Hill & Jennings, 2011; Randy C West & Copeland, 2015).

2.2 Reclaimed Asphalt Pavement (RAP)

When an item is said to be "reclaimed", it means that it will be reused in its existing state, either for its original purpose or for another. on the other hand, "Recycled" refers to an item manufactured from old materials that have been disassembled and repurposed into something new. Therefore, the term 'reclaimed' in RAP refers to the reprocessing of aged asphalt by milling the surfacing layer of old asphalt pavements to obtain the RAP. All roads are periodically replaced or repaired regularly, resulting in highly valuable and reusable reclaimed materials. Generally, RAP can be re-used partially or entirely as a replacement material in virgin asphaltic mixes. It can conveniently be added because it contains both the aggregates and binder. It has been a highly valued part of the asphalt mix for decades. Moreover, the use of RAP as an alternative material offers a range of advantages, such as cost reduction (El-Maaty & Elmohr, 2015; Izaks et al., 2015; Jahanbakhsh et al., 2020; Pouranian & Shishehbor, 2019; Rath et al., 2019; Shingles, 2014; Shirodkar et al., 2013; Randy Clark West et al., 2013; Zaumanis, Mallick, & Frank, 2014), energy conservation, reduced CO_2 emission, preservation of valuable natural resources, and minimise the capacity of waste materials disposal in landfill (Aurangzeb et al., 2014; El-Maaty & Elmohr, 2015; Jahanbakhsh et al., 2020; N. Lee et al., 2012; Randy C West & Copeland, 2015; Zaumanis, Mallick, & Frank, 2014; Zaumanis et al., 2016). In addition, RAP is classified as a suitable replacement for NA and binder that mitigates environmental consequences by minimising energy usage, mineral resources, and related pollution as well as reducing the costs while satisfying all performance expectations (Aurangzeb et al., 2014; Izaks et al., 2015; Shingles, 2014; Zaumanis, Mallick, & Frank, 2014). Ultimately, the use of RAP would reduce gas emissions and production costs by as much as 35% (Zaumanis et al., 2016) and 70%, respectively (Jahanbakhsh et al., 2020; Zaumanis, Mallick, & Frank, 2014). Thus, RAP is one of the most valuable recyclable materials globally (Reyes-Ortiz et al., 2012;

Zaumanis et al., 2016). These RAP materials are most commonly used in low-value applications such as base layers, road shoulders, and rural roads (Zaumanis et al., 2016). However, the most economical application of RAP materials would be at the surface and intermediate levels of HMA pavements. The RAP binder can be used to replace the more expensive virgin binder. Therefore, many countries consider using high content RAP in mix design (Copeland, 2011; Randy C West & Copeland, 2015; Zaumanis, 2014). Meanwhile, some researchers have recorded successful incorporation of high content RAP (Hansen et al., 2011; J. Oliveira et al., 2011), but no clear framework for applying high content RAP has been developed yet.

RAP recycling is one of the most recyclable materials and cost-effective solutions to mitigate the increasing demand for NA and the skyrocketing prices of these materials. RAP was first used in 1915 (Taylor, 1997), but it began to gain recognition in the 1970s (Kandhal & Mallick, 1997; Pires et al., 2017; Silva et al., 2012; Randy C West, 2015). When the Kyoto Protocol was revealed in 2005, pavement recycling received significant attention, and a comprehensive implementation was introduced, including the construction of pavement (Barbieri et al., 2019; Reyes-Ortiz et al., 2012). In the United States, the total amount of RAP used was 82.2 million tonnes in 2018, which saw a massive increase of 46.8% from the total amount used in 2009 (Williams et al., 2019). In Japan, a similar trend was observed where almost 47% of RAP was used in asphalt paving in 2013 (Randy C West & Copeland, 2015).

Nonetheless, incorporating high RAP content into HMA faces many challenges because the mechanical performance of RAP mixes mainly depends on the aged pavement's components. In particular, the aged binder components in the RAP mix increase stiffness, viscosity, and the critical mix temperature, and thus, lower fatigue and thermal cracking properties are assumed to have occurred (Abdo, 2016; Chesner et al., 2002; Hussain & Yanjun, 2013; Izaks et al., 2015; Vargas-Nordcbeck, 2007). In particular, the laboratory study indicated that the aged binder in RAP affects the mechanical properties of the mixes due to its internal interaction (Noferini et al., 2017). Therefore, the properties of the RAP mix rely primarily on the consistency of the aged binder. Even though the progression in binder grade at low RAP mix is small, the impact of RAP is significant at high RAP mix. In this regard, Antunes et al. (2019) depicted some challenges besides some benefits of using RAP shown in Figure 2.1.

Figure 2.1: Some benefits and challenges of using RAP (Antunes et al., 2019)

Owing to insufficient awareness and non-standard recycling requirements, the application of RAP remains limited in many countries (Baaj et al., 2013; R. S. McDaniel et al., 2012; Zaumanis et al., 2016). Therefore, there is a need to establish a RAP assessment framework, especially when various RAP proportions are used in an HMA design. As such, the use of 30% RAP in HMA was reported to cause little or no complications at all (Al-Qadi et al., 2007; Miró et al., 2011; Singh & Sawant, 2016; Randy Clark West et al., 2013).

2.3 The Influence of Binder in Asphalt Mix with RAP Incorporation

Binder is a thermoplastic viscoelastic adhesive material for the construction of the pavement. Binder has a deep black semi-solid appearance resulting from the distillation of crude oil in petroleum during atmospheric and vacuum processing (Croney &

Croney, 1991; Mashaan, Ali, et al., 2014). It is critical for pavement engineering because of its strength and waterproof properties (Rozeveld et al., 1997). The binder in an asphalt mix has two main roles in a road pavement: 1. it holds the aggregates in contact and 2. it acts as a water sealant. However, due to some particular distress, such as fatigue failure, the performance and durability of the binder are greatly influenced by changes in its characteristics over time, which can result in pavement cracking (A Mahrez, 1999). Moreover, one of the most essential influences of an asphalt mix is the binder content. It is essential to use the right amount of binder for good performance of the asphalt mix. If there is not enough binder in the mix, it will be difficult to place, compact, and prone to fatigue cracking and other durability issues. On the other hand, too much binder will increase the cost of the mix and make it more prone to rutting and shoving. It is noticed that the 60/70 penetration grade bitumen is relatively good for road construction in tropical countries (Hussain & Yanjun, 2013). Since RAP contains aged binder, the more RAP is used in the asphalt mix, the less the amount of virgin binder will be required with a saving up to 63% (Han et al., 2019).

RAP is comprised of two majors: aged binder and aggregates. Aged binder typically undergoes physical and rheological changes during their service life. Asphalt binder loses its properties due to oxidation and becomes stiffer during its service life. Meanwhile, binder passes through two stages of aging: (1) short-term aging (construction time) and (2) long-term aging (service time). Figure 2.2 shows the long-term aging phenomena of binder (Moghaddam & Baaj, 2016). Natural phenomena such as oxidation, volatilization, polymerization, and synergism gradually enhance the viscosity of the binder during these two stages of aging, making it a stiff material (Al-Qadi et al., 2007). The composition of the base binder used during construction and the amount of aging throughout its service life are the two main factors for the intensity of the change in the properties of this aged binder (Zaumanis, 2014). The aged binder significantly impacts the new blend binder's properties. The mechanical performance of the RAP mix mainly depends on the aged binder properties. In particular, the aged binder had been shown in a laboratory study to affect the mechanical properties of the final binder blend because of its internal interaction (Noferini et al., 2017). For example, as the aged binder amount increased, the binder softening point, viscosity, and stiffness increased (Hussain & Yanjun, 2013; Noferini et al., 2017). The complex modulus could be increased by incorporating recyclable materials (Safi et al., 2019). Kennedy et al. (1998) investigated the rheological characteristics of various aged binder and virgin binder combinations and percentages and discovered that binder stiffness increased as the amount of aged binder increased. When the temperature is lowered, the rate of change of stiffness ($G^*/\sin\delta$) increased, as did the amount of RAP in the mix. However, restoring the properties of the aged asphalt binder is a major challenge to use high content RAP in an asphalt mix. Some studies showed that the rejuvenator is a high-performance additive that could help restore the properties of aged binders (Hill & Jennings, 2011; Randy C West & Copeland, 2015).

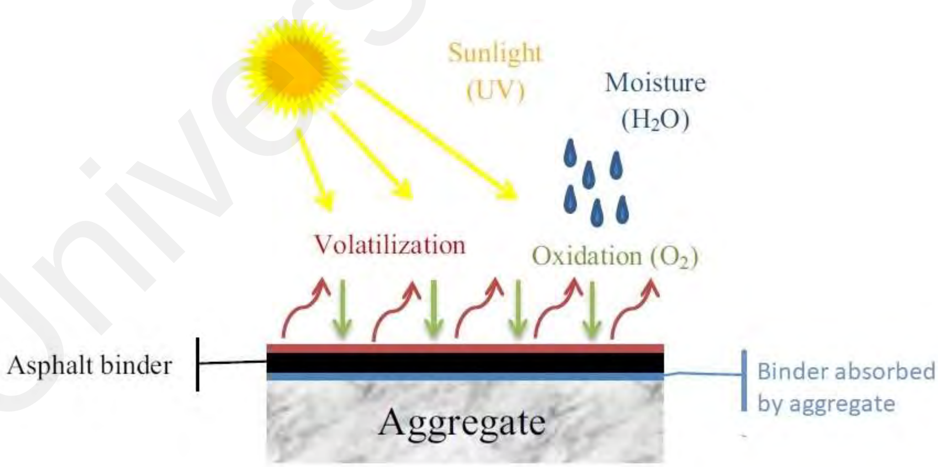

Figure 2.2: Aging phenomena of binder (Moghaddam & Baaj, 2016)

2.4 The Utilization of Crumb Rubber (CR) in Asphalt Binder

In response to the rapid economic and industrial growth, the number of vehicles on the road has increased worldwide. As a result, there is an unprecedented increase in waste tyre rubber. The poor management of these wastes would increase the risk of illegal dumping, excessive disposal costs, inadequate storage, and environmental damage. For instance, Malaysia produces about 10 million pieces of waste tyres a year that are not usually disposed of in an environmentally friendly way (Ibrahim et al., 2009; Nuha, 2016). Waste tyres are generally non-biodegradable and can occupy a large portion of land space. Heavy metals and chemicals are also found in waste tyres, which seep into the environment as they decompose. There are mainly two methods for recycling waste tyres: combustion fuel production and asphalt binder modifier. The latter is the best approach for recycling waste tyres (Nuha S, 2012). Waste tyres are shredded in a crack mill to make CR. It should be free from fibre and steel materials. The rubber particles are then sorted according to their form and size. CR is used as an asphalt binder modifier to improve the properties of the asphalt mix and provide an eco-friendly solution to the increasing waste tyres.

CR is one of the reinforcing material additives utilized in asphalt mixtures worldwide. Rubber from scrap tyres is used to make CR. It is a blend of synthetic and natural rubber, carbon black, antioxidant, filler, and extender-type oils. Integrating CR from ground tyres in asphalt binder under certain time and temperature conditions produces a CR-modified binder (Nuha S, 2012).

According to the Rubber Pavement Association, utilizing CR-modified binder in asphalt mixes can lower tire noise by up to 50%. Another benefit of utilizing a CR-modified binder in asphalt mix is extending the pavement's life. Jung et al. (2002); Presti (2013) described that CR-modified asphalt achieves low maintenance costs, low noise pollution, and good skid resistance due to the contrast of pavement and stripping.

Another study showed that the modified binder can extend the service life of pavements, which resulted in the modified binder becoming popular (Watson et al., 2018). In most of the applications evaluated, CR will be the best alternative to modified asphalt alternatives when considering the variability of the inputs, such as cost, estimated useful life, etc. (Hicks & Epps, 2003). As a result, the modified binder can provide real benefits for road construction and maintenance and good, durable, and affordable costs over the life of the road (Kumar & Garg, 2011). Furthermore, the advantages of using the CR-modified binder are listed below:

- provide higher resistance to susceptibility and higher fatigue resistance,
- increase the deformation resistance at a higher temperature,
- improve the properties of age resistance, and
- increase the adherence between the aggregate and binder.

Several studies have shown that CR serves an important role in asphalt production. The CR-modified binder would be more resistant to ageing than the unmodified binder because the CR-modified binder could reduce carbonyl and sulfoxide (Wang, Liu, Apostolidis, et al., 2020). The addition of CR prevents the asphalt binders from oxidation and volatilisation process, which is an essential aspect of the ageing process. CR would increase the efficiency and consistency of the binder (Majidifard et al., 2019), while the CR-modified binder would increase the stability and resistance to moisture as well as reduce the fatigue cracking of the asphalt mix (Majidifard et al., 2019; Mashaan et al., 2013b; Sun et al., 2020; Zaumanis & Mallick, 2015). Thus, CR would increase the binder's rheological properties. In addition, the stiffness of asphalt mixes with CR content is higher than samples without CR (Mashaan et al., 2013a, 2013b; Mashaan, Karim, et al., 2014). Moreover, the use of CR in the asphalt mix would improve the lifespan of the pavement in terms of fatigue performance (Wang, Liu, van de Ven, et al., 2020), moisture resistance (Izaks et al., 2015; Zaumanis & Mallick, 2015), stability (Mashaan et al., 2013b), and rutting performance (Ameri et al., 2020; Mashaan et al., 2013b). Moreover, CR is more resistant to low-temperature cracking than other modifiers (Babalghaith et al., 2016). The mix would become more stable with stronger adhesion through the addition of CR. Khalid (2005) showed that rubberized bitumen leads to longer fatigue life of the asphalt mix, better resistance to rutting, and findings that showed good fracture and fatigue cracking resistance.

Besides improving the durability of the asphalt pavement, the use of CR for the construction of pavements helps to reduce waste dumps. The suitable amount of CR content required to achieve the highest stability and rigidity was between 5 and 10% (Mashaan et al., 2013b). A separate study suggested that a smaller rubber dimension provided greater actual CR area, thus, achieving a more reactive binder (P. Li et al., 2018). Therefore, in this study, 80, mesh size CR was used. It was revealed that the addition of CR enhanced the performance, consistency, and moisture resistance of a high RAP mix (Majidifard et al., 2019).

2.5 The Use of Different Rejuvenators in Asphalt Mix

The two aging processes of the asphalt mix are short-term and long-term. Short-term aging occurs during production, while long-term aging occurs when asphalt mix is exposed to the atmosphere over their service life. During these two aging processes, the percentage of asphaltenes in the binder mainly increases due to volatilization and oxidation. The high percentage of asphaltenes in the binder stiffens it, resulting in cracks in the asphalt mix. Therefore, it is necessary to restore the aged binder properties.

In RAP mixes, rejuvenating agents restore the aged binder's physical and chemical properties. This is because rejuvenating agents are additives that can restore the aged binder's original rheological properties (Boyer & Engineer, 2000). Elkashef et al. (2017); Taherkhani and Noorian (2020); Randy C West and Copeland (2015) showed that rejuvenator is essential to produce a high-quality RAP mix because it serves as a principal catalyst to restore the aged binder properties. The rejuvenating agents are thought to diffuse the aged RAP binder up to a certain depth, restoring the original maltene to asphaltenes ratio and making the material less stiff or flexible (Zaumanis & Mallick, 2013). The rejuvenator facilitates the diffusion of the aged binder and restores the aged binder's physical and rheological properties. Therefore, the performance of the RAP mix is largely influenced by the rejuvenator's ability and rejuvenation process.

There are different types of recycling agents, such as rejuvenator and softer asphalt binder, that could restore the properties of aged binder in which the former was found to exhibit a high-performance additive characteristic (Hill & Jennings, 2011; Randy C West & Copeland, 2015). J. S. Chen et al. (2015) recycled the RAP mix obtained from the field using varied dosages of rejuvenators and a soft binder. They found that applying rejuvenators over a soft binder to reduce fatigue enhanced the performance of RAP mixes significantly. Shen et al. (2007) also found that the rejuvenator is more effective than the soft binder. They demonstrated the RAP mixes' indirect tensile strength (ITS) and rutting performance. Ding et al. (2016) used rejuvenators to investigate the effect of diffusion between virgin and aged binders. They discovered that adding a rejuvenator to an aged binder could boost recycling efficiency by speeding up the rate of inter-diffusion between the virgin and aged binder to the maximum level. The unique property of rejuvenator has attracted increasing interest for its application in asphalt technology.

There are different types of rejuvenators such as vegetable oils, waste oils, engineered products, and conventional and non-conventional refining base oils, all of which are rejuvenators. Im et al. (2014) investigated the effects of different rejuvenators on the performance of the RAP mix. The use of rejuvenators increased the RAP mix's cracking resistance, moisture sensitivity, and rutting resistance. They concluded that rejuvenator performance is influenced by the degree of blending between the aged and virgin binder, aggregates, and rejuvenator dosage. Zaumanis, Mallick, Poulikakos, et al. (2014) tested HMA mixes with 100% RAP with five generic rejuvenators at a 12% dosage (waste vegetable oil, waste vegetable grease, organic oil, distilled tall oil, and aromatic extract). Compared to virgin mixes, the mixes with all rejuvenators provided better rutting resistance and prolonged fatigue life. With three virgin binders at three aging states, Xiao et al. (2015) investigated the rheological properties of up to 50% of aged binders. It was observed that the rutting resistance of the binder improved by increasing the aged binder concentration but reducing the fatigue resistance. The RAP source influenced the performance characteristics of mixed asphalt binder.

Moreover, the performance of rejuvenators depends on the dosage and degree of blending between the aged binder and the virgin binder (Im et al., 2014). Table 2.1 shows different rejuvenators and their dosages used in different studies. The selection of proper dosage of rejuvenator is a critical issue (M. Chen, Leng, et al., 2014; Nayak & Sahoo, 2017; Reyes-Ortiz et al., 2012; Zaumanis, Mallick, & Frank, 2014) since the excessive incorporation of rejuvenators affects the stripping, adhesion, rutting, and heat cracking, while inadequate dosages can stiff the mix (Cong et al., 2016; Im et al., 2016). Because of this, several studies have indicated that the effective dosage of WEO was estimated at 15% by weight of the aged binder (Mamun & Al-Abdul Wahhab, 2018; Nurul Hidayah et al., 2014; Zaumanis et al., 2013). Meanwhile, the mixing approach is also crucial to the rejuvenation process. The most popular mixing method to apply a rejuvenator is by direct mixing at a mixing temperature of the RAP mix (Moghaddam & Baaj, 2016; Randy C West & Copeland, 2015; Zaumanis et al., 2020).

Table 2.1: Different types of rejuvenators and their dosages

Sl	Rejuvenator type	Dosage (%)	RAP content (%)	References
1	Composite rejuvenator (RRA)	10 of the aged binder's total weight	Binder aged in laboratory	Kuang et al. (2014)
2	Common rejuvenator (CRA)	10 of the aged binder's total weight	Binder aged in laboratory	Kuang et al. (2014)
3	Waste cooking oil (W)	5 of the aged binder's total weight	Extracted aged binder	M. Chen, Xiao, et al. (2014)
4	Commercial (oil type)	2–3 of the mixer's total weight	15-48	Shen et al. (2007)
5	SonneWarmix RJT	5.22 of the binder's total weight	40	Mogawer et al. (2013)
6	Organic blend	9 of the binder's total weight	50	Mogawer et al. (2015)
7	Aromatic oil	9 of the binder's total weight	50	Mogawer et al. (2015)
8	WV oil	12 of the binder's total weight	100	Zaumanis et al. (2015)
9	WV grease	12 of the binder's total weight	100	Zaumanis et al. (2015)
10	Waste engine oil	12 of the binder's total weight	100	Zaumanis et al. (2015)
11	Aromatic extract	12 of the binder's total weight	100	Zaumanis et al. (2015)
12	WEO	18.2 of the binder's total weight	100	Zaumanis et al. (2013)
13	WEO bottoms	>20 of the binder's total weight	100	Zaumanis et al. (2013)
14	Naphthenic flux oil	>20 of the binder's total weight	100	Zaumanis et al. (2013)
15	Paraffinic base oil	18.3 of the binder's total weight	100	Zaumanis et al. (2013)
16	Organic blend	11.2 of the binder's total weight	100	Zaumanis et al. (2013)

Rejuvenator is able to increase the maltenes-to-asphaltenes ratio in the aged binder, which is affected when high content RAP is used in asphalt mix and could reduce the viscosity and yield, leading to rutting problems. The rheological tests also showed that the waste oils would significantly soften the binder and achieve a lower $G^*/\sin\delta$ ($G^*/\sin\delta$ indicates elastic behaviour, where G^* is complex shear modulus and $\sin\delta$ is phase angle) (Bilema et al., 2021; DeDene, 2011), softening point temperature, and increase the penetration value (Villanueva et al., 2008). Silva et al. (2012) utilised WEO to restore aged binder from 14 dmm penetration value at 68°C softening point to the required penetration grade of 20/30 and softening point of less than 63°C. Furthermore, a rejuvenator potentially prevents thermal cracks and brittleness (Xie et al., 2017) and increases the durability of asphalt mixes (Bonicelli et al., 2017). Rejuvenators could also reduce the M_R (Izaks et al., 2015; Jia et al., 2015; Majidifard et al., 2019), moisture damage (Majidifard et al., 2019), optimum binder content (OBC) (Jia et al., 2015), and lead to limited changes in the prevention of fatigue (Jia et al., 2015; Zaumanis, Mallick, Poulikakos, et al., 2014). Moreover, the RAP mix with rejuvenator could improve the fatigue cracking resistance compared to the softer asphalt binder (J. S. Chen et al., 2015; Mogawer et al., 2016). However, CR is a widely used eco-friendly additive to support the shortcomings of rejuvenators (Crisman et al., 2020; Majidifard et al., 2019).

WEO is one of the common rejuvenators that restores and softens the aged binder (Hill & Jennings, 2011; H. Li et al., 2019; Tarsi et al., 2020; Randy C West & Copeland, 2015) and enhances the workability of RAP mixes (H. Li et al., 2019; Majidifard et al., 2019; Mangiafico et al., 2016). Moreover, it is available at a relatively low cost compared to other rejuvenators (Zaumanis, Mallick, Poulikakos, et al., 2014). Previous studies have shown that WEO acted as a key element that softened the aged binder and increased the fatigue life and workability (Jahanbakhsh et al., 2020; Joni et al., 2019; Abdelaziz Mahrez et al., 2009). Other studies showed that WEO has an active function in softening and rejuvenating the aged binder (Joni et al., 2019) and is also conveniently available and affordable compared to other rejuvenators (Zaumanis, Mallick, Poulikakos, et al., 2014). Although WEO can reduce the OBC (Jia et al., 2015), WEO has a lower percentage of volatile components since it is processed under high temperatures (above 220°C) (Jahanbakhsh et al., 2020), which partly contributes to binder hardening.

Despite its significant role as a rejuvenator, it is acknowledged that huge amounts of WEO are produced each year as a by-product across the global automotive industry. Improper disposal of WEO can cause environmental problems since they are usually disposed of in rivers left on open land (Dinh et al., 2018; Jahanbakhsh et al., 2020). As a result, WEO would enter the soil and water, consequently polluting the ecosystem (DeDene, 2011; Dominguez-Rosado et al., 2004).

2.6 Marshall Mix Design

The asphalt mix is designed to create a cost-effective mix and determine the aggregates' gradation. This creates a mix with adequate asphalt to ensure the pavement is durable and stable enough to meet traffic demand without distresses and the total compacted mix should have enough voids to allow for some more compaction under traffic and some asphalt expansion due to temperature variations without flushing, bleeding, or losing stability. Additional objectives of the asphalt mix design include achieving the highest void content to restrict the penetration of hazardous air and moisture into the asphalt and adequate workability to enable the proper placing of the asphalt without segregation. The ultimate goal of asphalt mix design is to get a uniquely designed binder content to provide a balance of all required attributes. When investigating the asphalt mix design, this can be used to determine the performance of the asphalt mix. The density, air voids in mix (VIM), voids in mineral aggregates (VMA), voids filled with binder (VFB), and OBC are the main focus of this investigation. These factors determine the asphalt mix's character, performance, and behaviour. Studying the listed attributes can estimate some indications of its possible durability and service performance.

2.7 Asphalt Mix Performance

Asphalt mix performance tests can help pavement engineers ensure the mix's performance under various materials, traffic, and environmental situations. There are two types of tests: volumetric and mechanical. Volumetric tests for asphalt samples include density measurement, VIM, VMA, and VFB. While mechanical performance testing includes Marshall stability, flow, M_R, fatigue, and moisture susceptibility tests.

The Marshall stability describes the maximum load-bearing capacity, while the Marshall flow denotes the asphalt's plasticity and flexibility property. The Marshall stability and flow ratio, known as the Marshall quotient (MQ), is used to measure asphalt's rutting or permanent deformation. A higher MQ value indicates a more rigid asphalt and vice versa (Geraldin & Makmur, 2020).

Several researchers have found that the durability and performance of pavement depend on the volumetric properties of the asphalt (Masad et al., 2006; Pellinen, 2003; Underwood & Kim, 2013; Yu et al., 2015). Hence, it is important to measure the asphalt's relative density (specific gravity) for long-term pavement performance (Asphalt Institute, 2014). One of the most crucial factors in determining future pavement performance is density. The durability of asphalt depends on the air void property of the asphalt. A higher amount of air void creates pathways that allow air and water to enter the asphalt. Rutting caused by a plastic flow can be avoided by using a properly designed compacted asphalt mix with enough VIM. The amount of VIM on the pavement should be adequate, not excessive, to prevent air and water penetration. However, VIM should also be high enough to prevent plastic flow after a few years of opening traffic (E. Brown, 1990). Furthermore, a significant parameter to determine pavement longevity is the VIM. A low VIM would result in a lesser permeable pavement and may cause bleeding, shoving, or rutting. On the other hand, a higher VIM would permit air and water to reach the pavement (Asphalt Institute, 2014). In the asphalt mix, VIM and density are correlated. Compaction, binder content, and/or filler material can be increased to achieve higher density. Although the density will increase as the VIM in the asphalt mix decreases, adding an excessive amount of binder or filler material to the asphalt mix will reduce the VIM, which will negatively affect the efficiency of the asphalt mix (Roberts et al., 1996).

Another relevant parameter to measure the pavement longevity is the thickness of the binder film, which largely depends on the number of VMA (Asphalt Institute, 2014). The value of VMA should constantly be high enough to ensure a sufficient binder film thickness, which leads to durable asphalt pavement. In contrast, asphalt below VMA values would have thinner binder films and exhibit a low-durability HMA pavement. Therefore, minimising the binder content by reducing the VMA would potentially result in poor and detrimental pavement performance. In this study, the VMA level in the HMA sample was set at a minimum of 14%, according to the Asphalt Institute requirement (Asphalt Institute, 2014).

The VFB is the percentage of intergranular void space between aggregate particles that have or are filled with an effective binder. As a result, VFB keeps the binder film on the asphalt to the proper thickness. The asphalt would be poorly sustainable if the VFB is too low. Conversely, the asphalt would be unstable if the VFB is too high (Asphalt Institute, 2014). In terms of the traffic level, the suitability of the VFB selection varies. Due to the greater need for asphalt strength and stability, higher traffic volume requires a lower VFB. In comparison, a low traffic volume requires a higher range of VFB to increase the HMA durability. However, an extremely high VFB level in the asphalt could cause bleeding. The air void level in the HMA sample was 70–80% in this study based on the PWD specification (2008) (Jabatan Kerja Raya, 2008).

A significant mechanical parameter for asphalt concrete is the elastic property, which is simply defined as the ratio of applied stress and the recoverable or “resilient” strain (the rate of strain change for the applied stress). The elastic property or modulus of elasticity specifies a gradually applied load, while the M_R specifies for repeated applied loads. The M_R value indicates the pavement system's response to traffic loading (E. R. Brown & Foo, 1989; Mokhtari & Nejad, 2012). Nowadays, design engineers use this parameter to design pavement layers (Mokhtari & Nejad, 2012). The M_R test is used to determine the elastic properties of the asphalt mix by calculating the stress-strain behaviour of the asphalt sample. This test is generally performed in many laboratories due to its simplicity and usefulness. The M_R of the asphalt mix depends largely on the softening point temperature of the binder. The M_R of the asphalt mix increases as the temperature decreases. The M_R results provide a fundamental relationship between pavement materials' stiffness and stress conditions used in pavement design techniques and structural analysis.

A pavement is exposed to moisture in various ways, especially in tropical regions. Different sources may cause the accumulation of water in the pavement. Due to an increase in the water pressure from the subgrade or side shoulder of the road, water may enter the pavement through cracks. Another explanation for the presence of water in the pavement may be the inadequate inclusive dryness of aggregates during the mixing process. Therefore, it is critical to assess the impact of moisture on pavement design. Moisture susceptibility refers to an asphalt mix's stripping tendency, which is determined by the bonding strength of the aggregate and binder. Therefore, it is important to design the mix properly. A mix that is adequately constructed but not thoroughly compacted, on the other hand, can be vulnerable to moisture damage. As a result, an HMA design should be evaluated in scenarios where moisture seeps into the mix's air voids. As a result, numerous studies were conducted using 7% air voids (Roberts et al., 1996). Stripping can be caused by a variety of reasons, including aggregate and binder qualities, the environment, construction procedures, drainage, and traffic. This test is not classified as a performance-based asphalt mix assessment, but it serves two functions. The first is to demonstrate binder and aggregate moisture susceptibility, and the second is to assess anti-stripping additive efficiency. A recent study showed that a 50 to 100% replacement ratio asphalt with RAP recorded a better performance than the virgin HMA if properly formulated (El-Maaty & Elmohr, 2015). It was also found that when RAP increased by 50%, the indirect tensile strength (ITS) was 106% more compared to the virgin mix, while the tensile strength ratio (TSR) was significantly improved. Thus, the moisture resistance of the asphalt mix with high content RAP would increase (El-Maaty & Elmohr, 2015; Mohammedreza Sabouri et al., 2015). In terms of the performance against moisture damage, Colbert and You (2012) showed that a 35% RAP mix performed better than a 50% RAP mix, although both mixes outperformed the control mix. In another study, Celauro et al. (2010) observed that a 50% RAP mix recorded a TSR value of nearly 95%, which indicated a low susceptibility against moisture damage.

Due to premature fatigue cracks, the lifespan of many in-service flexible pavements is severely limited. The mechanical design approach is chosen based on the tensile pressure (or strain) beneath the asphaltic layer to obtain the requisite fatigue life. These design methods assume that the tire-pavement contact causes fatigue fractures beneath the asphaltic layer that extend vertically toward the pavement surface (Roberts et al., 1996). The maximum horizontal tensile stress is found below the bounded layers, while the maximum horizontal compressive stress is found on the pavement's surface. If these fatigue cracks in the HMA are not repaired on time, these cracks can allow moisture to penetrate and lead to the problem of moisture damage (E. R. Brown et al., 2001).

There are two forms of controlled loading in a fatigue test: controlled-stress (or force) and controlled-strain (or displacement). The tension in controlled-stress testing remains constant, while the strain increases as the number of repeats increases. In controlled-strain testing, on the other hand, the strains are held constant, and the stress reduces as the cyclic strain is applied (Y. Huang, 2004). Controlled-stress loading simulates the behaviour of pavements with total thicknesses greater than six inches, whereas controlled-strain loading simulates the behaviour of thin pavements with total thicknesses less than two inches. Ghuzlan and Carpenter (2000) observed that the fatigue life obtained through controlled-stress testing was less than that obtained through controlled-strain testing. Because the same stress was applied throughout the test, damage occurred faster in controlled-stress testing than in controlled-strain testing, whereas it was reduced during controlled-strain testing. Increased void content reduces fatigue performance; changes in aggregate type or grading have a minor impact on fatigue response; and increasing mix stiffness does not always imply inferior fatigue behaviour, though sample heating and machine compliance may influence the results. Although rheology alone is insufficient to predict fatigue performance, the type of binder used can have a significant impact. Furthermore, aggregate type, grading, and mixing qualities have an impact on asphalt mix fatigue resistance. The angularity of the aggregates has a considerable impact on the initial stiffness, with up to a 25% increase in stiffness value (Carswell et al., 1997).

Tran et al. (2012) also studied the performance of 50% RAP mix with and without rejuvenator. The study reported that a 50% RAP mix with a rejuvenator increased the cracking resistance without compromising the moisture damage or permanent deformation resistance compared to a 50% RAP mix without a rejuvenator. It was also observed that using a rejuvenator slightly improved the TSR with no detrimental impact. Likewise, a study revealed that the best outcome for both fatigue and rutting resistance was achieved by combining 60% RAP and NA (El-Maaty & Elmohr, 2015). In addition, the compaction process is vital to achieving optimal rutting resistance through suitable interlocking aggregates (Polaczyk et al., 2021).

Al-Qadi et al. (2007) demonstrated that the use of RAP in a mix could improve the resilient efficiency and demonstrated the inconsistencies in fatigue and thermal performance. Some researchers have shown that high content RAP in HMA decreases the fatigue resistance (Izaks et al., 2015; Mohammadreza Sabouri, 2020). Since aged binders normally have higher brittleness, this may deteriorate the asphalt's fatigue resistance capacity. In some cases, the fatigue performance improved when RAP was used, particularly in modified polymer binders (Pasetto & Baldo, 2017). Soft bitumen or low penetration grade bitumen, on the other hand, can be added to prevent such problems (Miró et al., 2011; J. R. Oliveira et al., 2013; Silva et al., 2012; Valdés et al., 2011). At 10, 20, and 30% RAP content, B. Huang et al. (2004) investigated how stiffness, ITS, and fatigue resistance changed in asphalt mixes. When comparing stiffness, ITS, and fatigue resistance with 10% and 20% RAP content, the results showed that 30% RAP content significantly increased stiffness, ITS, and fatigue resistance.

According to Mogawer et al. (2016), the rejuvenators decrease the rutting resistance of asphalt by adding 50% RAP. However, this deterioration can be mitigated by incorporating polymer modified binder (PMB), while the fatigue cracking resistance of the same asphalt can be enhanced by rejuvenators. Therefore, it is recommended that a rejuvenator and a PMB be combined to produce a consistent high RAP mix. In light of the performance of the RAP mixes, Table 2.2 summarizes the performance of different asphalt mixes with various content of RAP obtained from different studies.

Table 2.2 Performance of various RAP mixes

References	RAP content	Performance results
El-Maaty and Elmohr (2015)	25, 50, 75, 100%	▪ Stability reduced by 15, 19, and 23% for 25, 50, and 75% RAP content, respectively, and increased by 10% for 100% RAP content. ▪ The mixes containing 50, 75, and 100% RAP showed a larger improvement in M_R. ▪ The TSR of the conditioned HMA increased for all RAP mixes, with the maximum TSR found with a 50% RAP content. ▪ The presence of RAP causes a reduction in mass loss percentage.
Idham and Hainin (2015)	20, 40, 60%	▪ The best quantity of RAP to add to the control mix to increase M_R, rutting resistance, and tensile strength was found to be 60%.
Han et al. (2019)	30, 40, 50%	▪ TSR first increased and then decreased. ▪ As the RAP content increased, the fatigue life of the RAP mix decreased.
Izaks et al. (2015)	30, 50%	▪ In terms of Marshal stability and flow and rut resistance, RAP has little effect on the volumetric and mechanical properties of recycled HMA. ▪ When compared to the reference mix, all recycled mixes have equivalent fatigue resistance. The use of RAP, particularly high RAP content in HMA, decreased fatigue resistance probably due to the high proportion of binder replacement that stiffens the asphalt mix, ▪ It is feasible to create high-quality HMA with up to 50% RAP while meeting volumetric and performance criteria.
Vargas-Nordcbeck (2007)	10, 20, 30%	▪ The stiffness of the binder blend rose as the RAP concentration increased, posing a greater risk of fatigue cracking. ▪ Increasing RAP content resulted in higher tensile strengths and a lower number of cycles to failure.
Ma et al. (2015)	30, 40, 50%	▪ RAP content showed significant effects on dynamic modulus and failure strain when RAP content increased by 40%. ▪ The mechanical properties of high modulus asphalt concrete (HMAC) are not adversely affected by RAP additions. HMAC's performance, on the other hand, deteriorated when RAP content increased.
Mohammadreza Sabouri (2020)	20, 40%	▪ Increasing the RAP content and/or lowering the binder content reduces fatigue resistance while improving the mix's rutting performance.
Randy Clark West et al. (2013)	0, 25, 40, 55%	▪ Mixes with a higher RAP percentage have lower fatigue resistance. ▪ Even though some RAP mixes do not fulfill the criteria, they are more moisture-resistant than virgin mixes.
J. Lee et al. (2015)	0, 15, 30, 60%	▪ Mixes with higher RAP content have lower fatigue resistance, which can be mitigated by utilizing a soft binder.
Silva et al. (2012)	100%	▪ The fatigue resistance of RAP mixes containing recycling agents is good. ▪ All of the mixes produced good results, however, the RAP mixture without the recycling agent is slightly more sensitive.

2.8 Chapter Summary

RAP is a good substitute for NA and binders. This is due to its potentiality to save energy, minimize mineral consumption, pollution, and prices while meeting a variety of performance requirements. Due to a lack of understanding and non-standard recycling standards, RAP implementation is still limited in many countries. As a result, a framework for using high-content RAP in HMA design needs to be developed.

Nevertheless, incorporating high content RAP into HMA design faces many challenges because the mechanical performance of RAP mixes mainly depends on the quality of aged pavement's ingredients, which are aged binder and aggregates. Because of its internal interaction, the aged binder was proven in a laboratory research to impact the mechanical properties of the final binder blend. Since the aged binder in RAP has already oxidized and hardened, when high RAP is utilized, the asphalt pavement becomes stiffer. So, rejuvenators or additives should be used to restore the properties of the aged binder into desired properties. WEO is the rejuvenator that could be softened and rejuvenated the aged binder. While the rejuvenator offers significant advantages, its drawback is that it could decrease the viscosity of the binder and increase the flow value and softness of the mix more than acceptable. Therefore, CR is one of the widely used environmentally friendly modifiers in contrast to rejuvenator's shortcomings. Moreover, CR is more resistant to low-temperature cracking compared to other modifiers. The modified binder with CR would be more resistant to ageing than an unmodified one. The unproven performance of 100% RAP mix and the lack of a consistent and logical approach to materials selection and mix design are the main impediments to the widespread adoption of 100% recycling. Therefore, it is necessary to optimise and introduce a standard guideline on the RAP content in HMA design.

Based on the above concepts, this study aimed to characterize the RAP content in the ACW14 mix design by investigating the mechanical performances through the Marshall stability, M_R, ITFT, moisture susceptibility, and ML tests. The high content RAP (from 30 to 50, 70, and 100%) was incorporated with two waste materials: CR as a binder modifier and WEO as a rejuvenator.

CHAPTER 3: RESEARCH MATERIALS AND METHODOLOGY

3.1 Introduction

This chapter describes the overall research framework of the study and detailed experimental procedures, including the selection and preparation of materials used throughout the study and every test method applied.

3.2 Research Framework

Figure 3.1 shows the flowchart for the experimental process in this study. Specifically, the investigation was performed using five different modified binder contents (4.5, 5.0, 5.5, 6.0, and 6.5%), four different RAP contents (30, 50, 70, and 100%), and a control mix that consists of NA only (0% RAP, denoted as R0). Each sample was prepared and analysed in triplicates to achieve an average and reliable result. The method consisted of six basic steps: materials selection and properties tests, modification of the virgin binder, quantification of the extracted aged binder, determination of OBC, and evaluation of the mechanical performance of the samples.

Based on PWD specifications (2008) (Jabatan Kerja Raya, 2008), five ACW14 mixes were selected for this study with wearing courses over 40 mm thickness. A 6% CR (by weight of virgin binder) was used as a binder modifier to enhance the rheological properties of the asphalt binder. Based on the research carried out by Mashaan et al. (2013b), it was found that, the proportion of CR should be between 5 to 10% to achieve maximum stability and rigidity. Based on the trial mix, and observation during the laboratory works, the 6% CR was used as a binder modifier to enhance the rheological properties of the asphalt binder. Furthermore, 15% of WEO was used (by weight of aged binder) as a rejuvenator to restore the properties of the aged binder. The dosage of WEO was selected based on the previous study (Mamun & Al-Abdul

Wahhab, 2018; Nurul Hidayah et al., 2014; Zaumanis et al., 2013). In addition, in this study it was examined how a 15% WEO soften/change the aged binder's properties.

In addition, the Marshall method was used to fix the OBC. Finally, the mechanical performance of the five ACW14 mixes was tested and analysed.

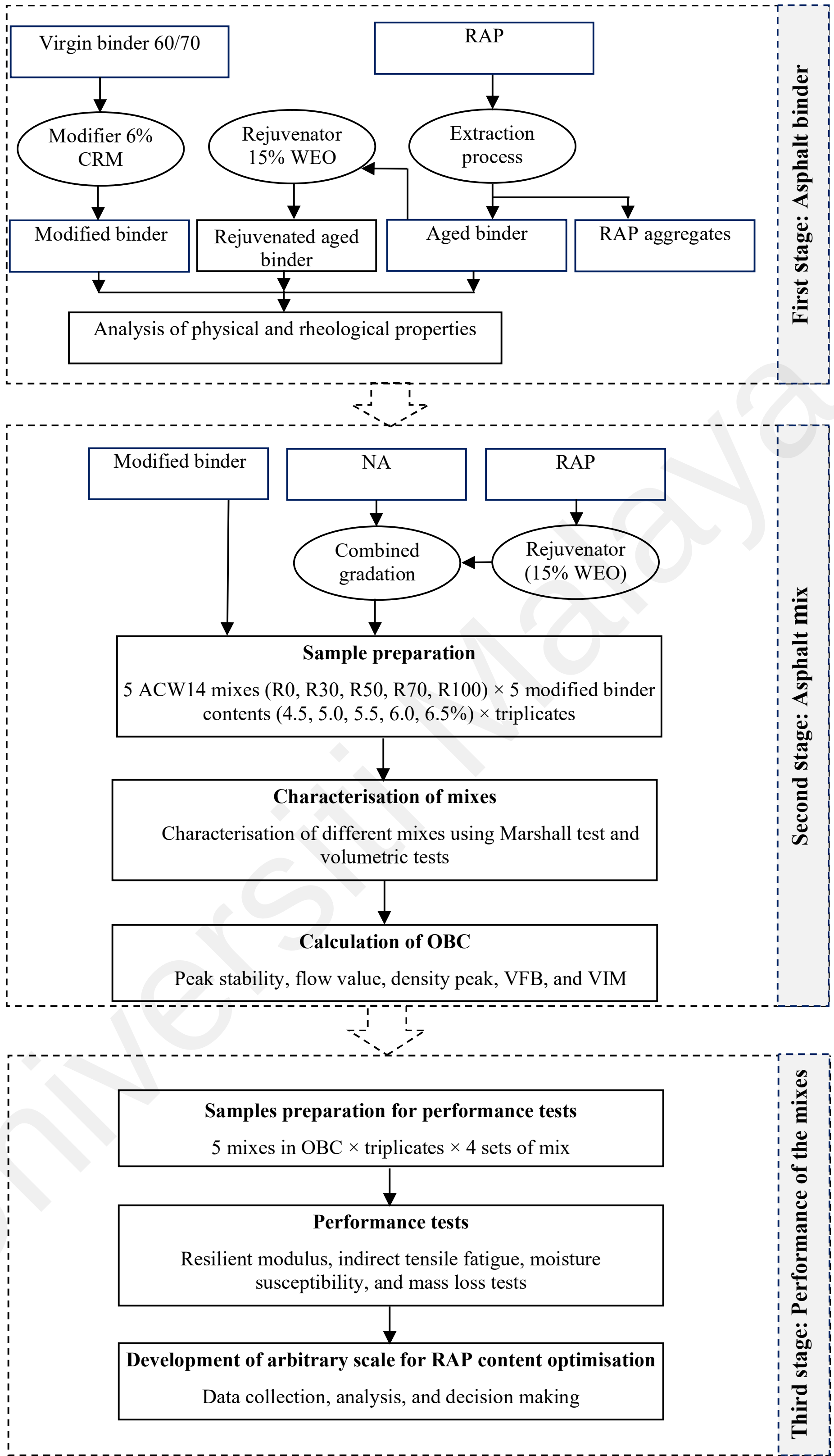

Figure 3.1: The experimental process in this study

3.3 Materials

This study used five primary materials to prepare the ACW14 mix samples, comprising RAP, NA, rejuvenator, binder, and binder modifier. The RAP was collected from Kuala Lumpur, Malaysia. Meanwhile, crushed granite was used as NA, while 1.5% ordinary Portland cement (by weight of total aggregate) was used as the active filler. The 60/70 penetration grade bitumen was used as the virgin binder and CR was used as binder modifier to improve the rheological properties of the virgin binder. WEO was used to serve as the rejuvenator to soften the aged binder. The RAP content varied from 30 to 50, 70, and 100% in terms of total aggregate mass. Figure 3.2 shows the relevant materials used in this study.

Figure 3.2: Components for the preparation of ACW14 mix samples

3.4 Sampling and Binder Extraction from RAP

RAP is often referred to as the recycling of aged asphalt pavement since RAP is a suitable replacement for NA and binder. The RAP was collected from a road located in Kuala Lumpur, Malaysia. At sampling time, the road was at the end of its service life as indicated by the visible signs of distress, such as cracking and rutting, on the road. The extraction test was conducted to quantify the aged binder from the RAP and determine the combined aggregate gradation. It was crucial to estimate the amount of aged binder latent in the RAP to calculate the total binder content (aged binder + modified binder). It was also important to characterise the aged binder to determine its properties.

Meanwhile, the RAP was first crushed and air-dried. Then, the aged binder was extracted using the solvent extraction method following the standard of ASTM D 2172 (ASTM, 2011). Methylene chloride was used as the solution to extract the aged binder. Next, the aged binder was recovered using the Abson method (ASTM D 1856) (ASTM, 2009b) and later characterised. It was found that the RAP aggregates consisted of 4.1% aged binder (by weight of RAP aggregate). The RAP aggregates were then used to determine the combined aggregate gradation.

3.5 Rejuvenator and Rejuvenation

In this study, approximately 15% of WEO (by weight of aged binder) was used as the rejuvenator to restore the aged binder, with a penetration value of only 11 dmm. During the rejuvenation process, the extracted aged binder was first heated at 160°C for 1 h before the WEO was mixed using a propeller mixer at 800 rpm for 30 min. After the process was complete, the rejuvenated aged binder's physical and rheological properties (penetration, softening point, rotational viscosity, and dynamic shear rheometer (DSR)) were analysed. The specific gravity of the used WEO was 0.87, with a water content of 0.34%. Among the several types of rejuvenators used by various researchers, WEO is an efficient rejuvenator. Zaumanis, Mallick, Poulikakos, et al. (2014) tested HMA mixes with 100% RAP with WEO at specific dosage of 12% by weight of binder. WEO had a specific gravity of 0.872. Compared to virgin mixes, the mixes with WEO provided better rutting resistance and prolonged fatigue life. They suggested using WEO up to 25%. Another study by Nurul Hidayah et al. (2014) recommended using 15% WEO to improve the rutting resistance at high temperature performance.

3.5.1 Calculation of the RAP Stockpile's Weight

The RAP stockpile is equal to the total amount of RAP aggregates plus the amount of aged binder. Generally, the RAP stockpile is always greater than the amount of RAP aggregate. This is because the RAP stockpile contains the aged binder together with RAP aggregates. Therefore, it was important to deduct the amount of the aged binder.

$$RAP_{stockpile} = RAP_{aggregates} / (1 - RAP_{binder}) \tag{3.1}$$

Eq. 3.1 was used to calculate the RAP stockpile (i.e., how much RAP was used):

where,

$RAP_{stockpile}$ = Stockpile of the RAP including aged binder (g)

$RAP_{aggregates}$ = Amount of RAP aggregates without the aged binder (g)

RAP_{binder} = Aged binder latent in the RAP (%)

3.6 Aggregates

Crushed granite was used as the NA, while 1.5% ordinary Portland cement (by weight of total aggregate) was used as the active filler. The basic properties of the NA were evaluated according to the ASTM and AASHTO standards following the requirements stipulated by the PWD (2008).

3.7 Aggregate Gradation

Aggregate gradation has a key role in achieving an effective pavement performance, especially at higher percentages of the blend (Al-Qadi et al., 2007). Therefore, the sequential gradation of RAP mixes should be identical to the R0 to ensure that the effects of the overall differences in the aggregate gradation were eliminated, particularly the particle size distribution of the aggregates. According to the PWD (2008) and ASTM D 2419 standard, the amount of fine aggregate should not exceed 45% of the total aggregate (Aurangzeb et al., 2014; Jabatan Kerja Raya, 2008). The combination of

NA and RAP aggregate was calculated using the composite formula, as shown in Eq. 3.2:

$$N_i = \frac{(M_i - P_i \times a)}{(1 - a)} \quad (3.2)$$

where,

N_i = Percentage amount of NA required to be added to satisfy the gradation envelope

M_i = Percentage of aggregate as per the standard gradation envelope

P_i = Actual or field size of RAP aggregate

a = Desired proportion of RAP

i = Sieve size

3.8 Binder and Binder Modifier

A 60/70 penetration grade bitumen was used as the virgin binder, which CR modified. The modification was aimed to improve the rheological properties of the virgin binder. One batch of CR of 80 mesh size (0.177 mm) was collected from a local supplier and used throughout the experiment to maintain CR uniformity. Table 3.2 shows the physical properties of the CR used in this study.

Table 3.1: Physical properties of CR

Physical properties	Test standard	Unit	Values	Specification value
Passing	ASTM D 5644	%	80.0	-
Heat loss	ASTM D 1509	%	0.4	<1
Metal content	ASTM D 5603	%	0.1	<1
Fibre content	ASTM D 5603	%	0.1	<3

The virgin binder was modified by 6% CR (by weight of binder) of 80 mesh size using a propeller mixer at a speed of 200 rpm for 2 h at 160°C. The amount of virgin binder was based on previous studies that revealed the suitable CR content to achieve the highest stability and rigidity was 5–10% (Mashaan et al., 2013b). Moreover, other research suggested that a higher reactive binder was achieved using a smaller rubber dimension, which provided a greater actual CR area (P. Li et al., 2018). In another research, Majidifard et al. (2019) was used 12% CR by weight of virgin binder to evaluate the influence of CR in mixes with high RAP content. CR increased the moisture resistance of the RAP mixes, according to the researchers. The use of a rejuvenator in combination with CR in high RAP mixes improved their workability and compatibility.

3.9 Aggregate Tests

The NA used in this study was tested before being used to prepare the ACW14 mix samples. The following sections discuss the various physical properties tests of the NA according to the ASTM and AASHTO standards.

3.9.1 Los Angeles Abrasion (LAA)

The LAA test apparatus was used in this study to characterise the toughness and abrasion resistance of the aggregate. The overall lower pavement layers were used with higher corrosion losses because higher loads and pressures imposed by vehicles' wheels and heavy traffic have less impact than the sum of their upper layers, which are mostly near the pavement's surface and require more hardness and rigidity. The ASTM C 131 illustrates the standard procedure of the LAA test (ASTM, 2006).

3.9.2 Aggregate Impact Value (AIV)

The strength of the aggregate is an integral characteristic to withstand the impact of traffic loads. The BS 812-112 illustrates the standard procedure of the AIV test (British, 1990). The NA was placed inside the cylindrical cup and 15 blows were applied from a height of 380 ± 5 mm using a 13.5–14 kg heavy metal hammer.

3.9.3 Soundness Test

The soundness test measures the resistance of an aggregate towards disintegration by weathering. The typical soundness test involves the immersion of the aggregate sample repeatedly in a saturated sodium or magnesium sulphate solution. The maximum loss after five cycles of immersion was calculated in percentage. The AASHTO T 104 standard demonstrates the normal soundness test protocol (AASHTO, 2011). This study used magnesium sulphate ($MgSO_4$) as the immersion solution.

3.9.4 Flakiness and Elongation Index (FI and EI)

A major factor in the decay of aggregates in the HMA mix is the flat or elongated form of the aggregate particles. Flaky aggregates refer to an aggregate with an average thickness of fewer than 0.6 times than the average value, exhibit an adequate strength, and are smaller than cubic aggregates. In contrast to cubic aggregates, flaky aggregates do not have strong particles. Therefore, the flakiness test is used to determine the thin and flat properties of the aggregates in terms of length or width. The FI of the aggregate is defined as the percentage of the material tested by the mass of the flaky aggregates which pass a specific sieve. The ASTM D 4791 was used for the FI of the aggregate test (ASTM, 2010).

Besides the flaky aggregates, the elongation of aggregates indicates the length of the aggregate. The aggregates are considered long if the length of the aggregates is 1.8 times larger than the average value. In asphalt pavements, the maximum FI limit of the aggregate is 25%. Thus, the EI was measured according to the ASTM D 4791 standard.

3.9.5 Specific Gravity of Aggregates

The specific gravity analysis was conducted to evaluate the absorption rate and the water content of the NA. A separate analytical procedure was carried out for the fine aggregate and coarse aggregate. Generally, aggregates that are retained with a sieve size of 4.75 mm are classified as the coarse aggregate, while aggregates that passed through a sieve size of 4.75 mm and retained with a sieve size of 75 µm are classified as the fine aggregate.

The specific gravity of the aggregate is an effective parameter in converting the weight volume and calculating the volumetric properties of the compacted HMA. The tools and methods to determine the coarse and fine aggregates' specific gravity and water absorption were outlined in the ASTM C 127 and ASTM C 128 standards (ASTM, 2015a, 2015b). The specific gravity of the NA was measured under three separate sample conditions:

- Oven-dried (no water in the sample),
- Saturated surface dry (SSD) (water fills in the aggregate pores), and
- Submerged underwater.

The sample's apparent specific gravity, bulk specific gravity, and bulk SSD specific gravity, as well as the absorption, were measured using these three weight conditions and their relationships.

3.9.5.1 Basic Procedure to Determine the Specific Gravity of Aggregates

The procedure to determine the specific gravity is listed below:

(1) Approximately 2000 g of NA material was cleaned and dried in an oven at 110°C until a constant mass was achieved. After the NA was cooled to a suitable temperature for handling, the NA was immersed in water at room temperature around 15 to 19 h.

(2) The sample was dried until an SSD state was achieved. An effective approach to reducing the sample to an SSD state was to roll the NA into a towel and then shake and roll the NA from side to side. The mass of the sample was measured until no visible water film signs on the NA particle surfaces.

(3) The whole sample was placed in a bucket and the weight was measured underwater. The bucket should be pre-conditioned according to the temperature of the water bath. Before weighing, the container was shaken to release any air bubbles. To compensate for the water displaced by the sample, the overflowed container should be operated correctly.

(4) The NA was then removed from the water and dried in an oven at 110°C until a constant mass was obtained. The sample was left with all the water.

(5) The NA was cooled for 1 to 3 h at room temperature before the mass was measured.

(6) Three different masses were recorded during the test (A, B, and C) and the bulk specific gravity and absorption were calculated according to Eq. 3.3 and 3.4, respectively:

$$\text{Bulk Specific Gravity (G)} = \frac{A}{(B - C)} \quad (3.3)$$

$$\text{Absorption (in percent)} = \frac{(B - A)}{A} \times 100 \quad (3.4)$$

where,

A = Mass of oven-dried sample in the air (g)

B = Mass of SSD sample in the air (g)

C = Mass of sample in water (g)

3.10 Binder Tests

The physical and rheological properties of three types of a binder, comprising virgin binder, modified binder and extracted aged binder, were tested. The tests included penetration (ASTM D 5), softening point (ASTM D 36), ductility (ASTM D 113), flash and fire point (ASTM D 92), specific gravity (ASTM D 70), rotational viscosity (ASTM D 4402), and DSR (ASTM D 7175).

3.10.1 Penetration Test

The penetration test is a standard test to determine the hardness or softness of a semi-solid substance by measuring the depth in tenths of a millimetre, which is reached vertically in 5 s by a regular loaded needle. The penetration test was conducted on the different binders following the standardised ASTM D 5 (ASTM, 2013). A needle assembly of 100 g in total and a unit for release and locking in every position were included in the penetrometer. The temperature of the sample in the test was 25°C. In terms of room and instrument temperature, needle size, and weight on the needle, it was possible to note that the penetration values were mostly affected by the slightest imprecision. Under normal test conditions, a 60/70 binder grade indicates that the penetration value is 60–70.

3.10.2 Softening Point Test

The softening point refers to the temperature at which the asphalt binder reaches a particular degree of softening. In this study, the softening point was defined as the temperature at which a binder sample could not support the weight of a 3.5 g steel ball. The binder sample was covered with a steel ball and the distilled water was heated at a rate of 5 ± 0.5°C per minute. The binder material softened as the temperature rose, and the balls sank through the rings that carried some of the material. When the first binder-coated ball touched the bottom of the plate, the temperature was recorded. The test was carried out using the ring and ball system according to the ASTM D 36 standard (ASTM, 2014).

Similarly, the temperature was recorded when the second binder-coated ball touched the bottom of the plate. The recorded temperatures were then averaged. The difference between the temperatures was not more than 1°C.

3.10.3 Ductility Test

The ductility of the asphalt binder refers to its ability to elongate under traffic load without getting cracked during road construction works. The ductility test on the binder measures the length in centimetres to which it elongates before breaking off. The test followed the ASTM D 113 standard procedure (ASTM, 2017a). Firstly, the melted asphalt binder was spread in three regular briquette moulds and kept in a ductility test apparatus. The extended distance was then recorded when the breaking occurred. The test conditions were set at about 27°C and 5 cm/min speed. The ductility was considered an important elasticity characteristic of asphalt and shows the adhesiveness of the asphalt, which is similar to a binder's ability to withstand deformation at high temperatures.

3.10.4 Flash and Fire Point Test

Asphalt binder is a high-temperature flammable substance that can easily catch fire, making it a highly hazardous material if sufficient care is not taken in various phases of the mixing and construction process. Thus, it is crucial to sufficiently regulate the material's binder flash and fire point during the mixing and construction process. The flash point is the temperature in which the vapour of asphalt binder momentarily fires in flash form, while the fire point is defined as the lowest temperature in which the binder is inflamed and burned. The ASTM D 92 incorporates the standard method of determining flash and fire points (ASTM, 2016a).

3.10.5 Specific Gravity of Binder Test

In the laboratory experiment and paving jobs, classifying the specific gravity (relative density) is of great use. The specific gravity of the binder is defined as the ratio of the mass of a given volume of a binder of known content to the mass of an equal volume of water at 25°C. The chemical composition of the binder highly influences the specific gravity. A pycnometer was used to measure the specific gravity of the binder in a semi-solid or solid-state. ASTM D 70 standard procedure was followed for this test (ASTM, 2021).

3.10.6 Viscosity Test

The viscosity refers to the measure of flow resistance of the liquid bituminous elements. The strength of the large paving mixes at the temperature of application is influenced by the viscosity. The fluid's internal resistance to flow is calculated as the dynamic viscosity or absolute viscosity. The standard Brookfield viscometer test was used in this study following the ASTM D 4402 standard (ASTM, 2015c). The rotational viscometer is one of the most common instruments to measure dynamic viscosity. A probe in the liquid sample is rotated in the instrument in which a 27-number spindle was used at 20 rpm. At high production and construction temperatures (usually above 135°C), the viscosity of the asphalt binder is critical because it can regulate permeability, mixability, and workability.

3.10.6.1 Determination of the Mixing and Compaction Temperatures

The rotational viscosity was obtained to determine the mixing and compaction temperatures of the modified binder. The viscosity of the samples was tested at 135°C and 165°C to determine the mixing and compaction temperatures. The relationship between the viscosity and the temperature was then plotted. Based on the plotted graph in Figure 3.3, the mixing and compaction temperature of the modified binder was measured to withstand 0.17 ± 0.02 Pa·s and 0.28 ± 0.03 Pa·s for HMA mixing and compaction, respectively (ASTM, 2009a; Randy C West et al., 2010; Z.-q. Zhang et al., 2009). Figure 3.3 also shows that the mixing and compaction temperatures were 167 ± 1°C and 160 ± 2°C, respectively.

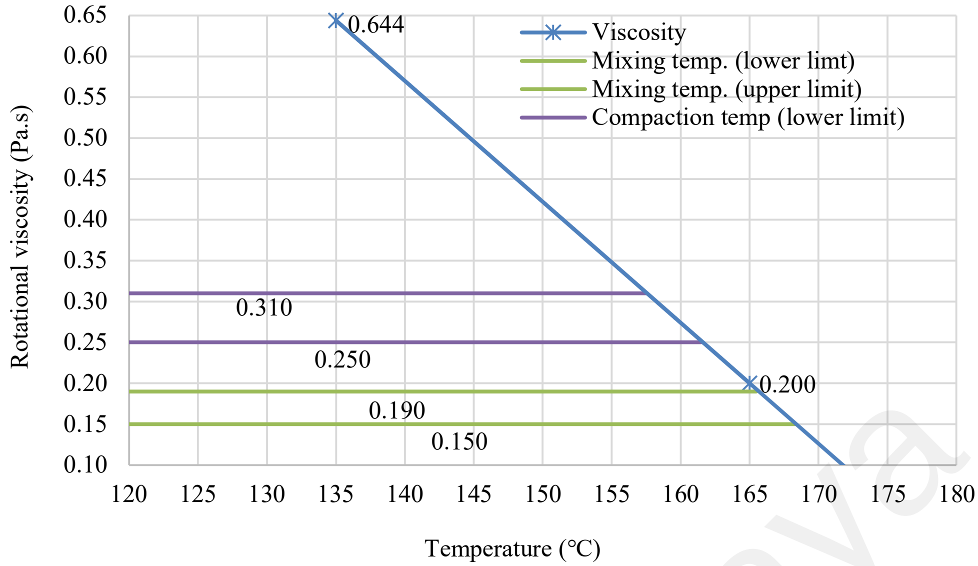

Figure 3.3: Viscosity analysis for the determining mixing and compaction temperature

3.10.7 Dynamic Shear Rheometer (DSR) Test

The DSR is used to determine asphalt binders' viscous and elastic performance at medium to high temperatures. The ASTM D 7175 standard was used to determine the DSR (ASTM, 2008). A thin asphalt binder sample (1 mm) sandwiched between two circular plates was used in the simple DSR test. The amplitude sweep was performed at 10 rad/s (1.59 Hz) where the lower plate was positioned when the upper plate oscillates back and forth through the sample to generate a shear action. The test was carried out at a high-test temperature of 58°C to 70°C, with a temperature range of 6°C. The DSR test was performed on unaged and aged asphalt binder samples and was regulated mainly by Rheowin software.

3.11 Mix Design

The main purpose of mix design is to accurately determine the combination of binder and aggregates to ensure the long-lasting performance of the pavement structure. This includes determining the type and quantity of the binder and selecting the appropriate aggregate gradation. Marshall mix design was used to distinguish the relationship between the mix parameters (Marshall stability and flow) and to determine the OBC. In this study, OBC was determined by analysing the Marshall stability, Marshall flow, and volumetric properties for a single selected aggregate gradation and five different modified binder contents (4.5, 5.0, 5.5, 6.0, and 6.5%) for the four different RAPs (30, 50, 70, and 100%), and a controlled RAP.

3.11.1 Different ACW14 Mix Types

Table 3.3 shows the various types of asphalt mixes and their composition. In this study, the ACW14 mix was selected according to the PWD (2008) (Jabatan Kerja Raya, 2008). The control mix consisted of NA only and no RAP was added, hence it was labelled as the R0 mix. In contrast, the label R30 mix indicates that 30% of RAP was combined with 70% of NA, while the label R100 mix indicates that 100% of RAP was alternatively used without any NA. Table 3.3 also shows the amount of modified binder in gram per kilogram of mix. It shows that the amount of modified binder drastically decreased with the increment of RAP content since RAP had an aged binder of 4.1%. The amount of modified binder (M_B) was calculated using the procedure on the following page:

T_A = Total aggregate mass to make a sample [For example, 1000 g of T_A is used]

V_A = virgin aggregate mass = (T_A* V_A%) g [For R50, V_A = 1000 g * 50% = 500 g]

RAP_{agg} = RAP aggregate mass = T_A* RAP_{agg}% [For R50, RAP_{agg}=1000g * 50%=500g]

RAP_B = RAP binder (aged binder) = 4.07% for this study

RAP_{stock} = RAP stockpile mass = RAP_{agg}/ (1- RAP_B%)

[For R50, RAP_{stock} = 500 g / (1-4.07%) = 521.21 g]

V_B% = Virgin binder content in %

M_B = Modified binder mass = [(T_A* V_B) - (RAP_{stock}* RAP_B%)] g

[For R50 at 6% binder, 1000*6% - 521.21*4.07% = 38.78g]

Table 3.2: The composition of each mix

Mix type	Aggregates (%)		Modified binder content (g/kg)				
	RAP	NA	4.5%	5.0%	5.5%	6.0%	6.5%
R0 (control mix)	0	100	45.0	50.0	55.0	60.0	65.0
R30	30	70	32.3	37.2	42.3	47.3	52.3
R50	50	50	23.8	28.8	33.8	38.8	43.8
R70	70	30	15.3	20.3	25.3	30.3	35.3
R100	100	0	2.6	7.6	12.5	17.6	22.6

Note: RAP consists of a 4.1% aged binder.

3.11.2 ACW14 Mixes Preparation

The ACW14 mix samples were prepared for the Marshall stability and flow test following ASTM D 6926 (ASTM, 2016b). According to standard procedure, the NA, RAP, and modified binder were first heated separately in the oven to 170°C for 1 h. For the preparation of R0, the modified binder was mixed with the heated NA. On the other hand, WEO (15 % of aged binder mass) for the RAP mixes was directly mixed with the heated RAP, allowing WEO to contact the preheated RAP for proper diffusion. Then, NA were added and followed by the modified binder. This process would stimulate diffusion, consequently activating the aged binder (Zaumanis et al., 2019; Zaumanis et al., 2020). The mixing and compaction temperatures were 167 ± 1°C and 160 ± 2°C, respectively (Figure 3.3). The asphalt mix was then placed in a mould and compacted at 75-blow/face. The size of each sample was 101.6 ± 0.1 mm in diameter and 63.0 ± 1.0 mm in depth.

The Marshall stability and flow were tested following ASTM D 6927 (ASTM, 2015d). Tests were performed in triplicates for each sample. The sample's stability and flow measurements were carried out by immersing each sample in a water bath at 60 ± 1℃ for 30 to 40 minutes. It was put within the grips of the Marshall apparatus after extracting the sample from the water bath. The loading was carried out at the 50.8 mm/min standard rate. The resulting stability and flow values were documented. Table 3.4 shows the standard requirement of the Marshall and volumetric properties.

3.12 Volumetric Analysis

The volumetric properties such as VIM, VMA, and VFB were measured according to the ASTM D 3203 standard (ASTM, 2005) while the mix bulk specific gravity was measured following the ASTM D 2726 standard (ASTM, 2017b).

3.12.1 Bulk Specific Gravity

A basic element of an asphalt mix design is to determine the bulk specific gravity (G_{mb}) of the sample. The mass of the sample divided by its volume multiplied by one unit of mass of water is the basic calculation of gravity. In this study, the mass comprises the aggregate mass and the binder mass. The volume includes the effective volume in a compacted sample of the aggregates, binder, and VIM. The bulk specific gravity of the samples was determined using Eq. 3.3, as provided in section 3.9.5.1.

3.12.2 Air Voids in Mix (VIM)

The tiny pockets of air between the asphalt-coated aggregate particles are known as the VIM. For additional compression under traffic due to the increase in temperature and for a small amount of asphalt expansion, a certain VIM percentage at an HMA is needed. The air void level in the HMA sample was approximately 3–5% in this study, according to the PWD specification (2008) (Jabatan Kerja Raya, 2008). The VIM was determined based on the Eq. 3.5, Eq. 3.6, and Eq. 3.7:

$$\text{Volume of Binder (k)} = [\text{h} \times \text{G}_{\text{mb}} \div \text{G}_{\text{bb}}] \tag{3.5}$$

$$\text{Volume of Aggregates (l)} = [(100 - \text{h}) \times \text{G}_{\text{mb}} \div \text{G}_{\text{ab}}] \tag{3.6}$$

$$\text{Air voids (VIM)} = [100 - (\text{k} + \text{l})] \tag{3.7}$$

where,

k = Volume of binder in a compacted sample (%)

h = Binder content used to prepare a sample (%)

l = Volume of aggregates in a compacted sample (%)

G_{ab} = Bulk-specific gravity of the aggregate.

G_{bb} = Bulk-specific gravity of the binder.

G_{mb} = Bulk-specific gravity of compacted materials or samples.

3.12.3 Voids in Mineral Aggregates (VMA)

VMA is the amount of interstitial space between the aggregate particles of a compacted paving mixture. It contains VIM and the amount of asphalt binder that is not absorbed in the aggregate. In this study, the VMA level in the HMA sample was set at a minimum of 14% according to the Asphalt Institute requirement (Asphalt Institute, 2014). The VMA was expressed as a percentage of the total volume of the mix, as shown in Eq. 3.8:

$$\mathrm{VMA} = 100 - \mathrm{l} \tag{3.8}$$

where,

l = Volume of aggregates in a compacted sample (%) from Eq. 3.6

3.12.4 Voids Filled with Binder (VFB)

The percentage of inter-granular void space between the aggregate particles containing or filled with an effective binder is represented by the VFB. In view of this, VFB is used to maintain the correct thickness of the binder film in the asphalt. The air void level in the HMA sample was 70–80% in this study based on the PWD specification (2008) (Jabatan Kerja Raya, 2008). VFB is expressed as the percentage of the volume of the voids in the mineral aggregates, as shown in Eq. 3.9:

$$\mathrm{VFB} = [100 \times \mathrm{k} \div \mathrm{VMA}] \tag{3.9}$$

where,

k = Volume of binder in a compacted sample (%) from Eq. 3.5

Table 3.3: Standard value of Marshall and volumetric properties

Parameter	Test standard	Standard requirements	Standard
Stability (kN)	ASTM D 6927	≥ 8.0 [1]	[1] PWD standard (Jabatan Kerja Raya, 2008)
Flow (mm)		2.0 - 4.0 [1]	
MQ (kN/mm)		≥ 2.0 [1]	
VIM (%)	ASTM D 3203	3 – 5 [1]	[2] Asphalt Institute standard (Asphalt Institute, 2014)
VFB (%)		70 – 80 [1]	
VMA (%)		≥ 14 [2]	
Bulk specific gravity	ASTM D 2726	-	

3.13 Optimum Binder Content (OBC)

The OBCs for five different mixes (R0 and four RAP mixes) were determined based on the Marshall mix design method and PWD specification (2008). The mean OBC was calculated by averaging the five corresponding binders' content values of the following parameters: (i) the peak stability; (ii) the flow equals 3 mm; (iii) the specific gravity peak; (iv) VFB equals 75%, and (v) VIM equals 4.0%.

3.14 Analysis of Variance (ANOVA)

The various binder and RAP contents used to prepare the five ACW14 mixes were statistically tested to examine the effect of the amount of binder and RAP on the mix design's stability, flow, and volumetric properties. In addition, the variance of the five mixes for the M_R, moisture susceptibility, ITFT, and ML tests was also statistically tested using ANOVA.

A two-factor ANOVA without replication was performed to determine the significant effect of the binder and RAP on the ACW14 mix. The null hypothesis (H_o) indicates that the changes in the amount of binder and RAP do not affect the Marshall stability, flow, and volumetric properties of the ACW14 mix design. The significance level (α) was assumed to be 0.05.

Additionally, a single-factor ANOVA was performed to identify the significant difference between the five mixes of the M_R, moisture susceptibility, ITFT, and ML tests based on the standard value or R0. A H_o indicates that the ML differences between the five mixes are not significant. The significance level (α) was assumed to be 0.05.

3.15 Mixes Performance Tests

Other sets of ACW14 mixes were prepared for each RAP content based on the OBC. The mechanical performance tests were conducted, namely, resilient modulus (M_R), moisture susceptibility, indirect tensile fatigue test (ITFT), and mass loss (ML) tests. The following sections describe these performance tests in more detail.

3.15.1 Resilient Modulus (M_R)

In this study, the M_R test was used to assess the extreme energy of the pavement, which is the highest ability of the pavement to withstand an applied stress without any permanent distortion (resistance of the pavement to elastic deformation). The M_R was performed on all five types of asphalt mixes (four RAP mixes and R0) using the universal material testing apparatus (UMATTA) according to the AASHTO T 342 (AASHTO, 2015). The samples were kept at 25°C for 4 h before the test. The M_R test conditions included the application of haversine loading shape, 1000 N peak loading, 10 Hz frequency, 0.1 s loading time, and 3.0 s pulse repetition period.

The sample was placed in the test jig and kept inside a temperature-controlled chamber at a certain temperature until the test temperature was obtained at the core of the sample. The sample was loosely fitted to the loading machine and the loading strips were centred in parallel and vertical diametric planes. The displacement transducer yoke (LVDT: linear variable differential transformer) was mounted. The sample was tightly tightened to fix the yoke to the central peripheral and two loose clamps. The level monitor was used to adjust the LVDT transducer mechanically to function within the electrical range. The load was applied vertically in the vertical dimension plan of the sample cylindrical specimen.

To determine the M_R values, the resulting horizontal deformation of the sample was calculated with an assumed Poisson's ratio. A pulse compressive force was applied to the sample and the resulting total recoverable strain was determined by the LVDT transducer. The ITFT was then initiated. Each sample was evaluated on a diametric plane four times the equivalent distances and an average of four readings was considered.

3.15.2 Moisture Susceptibility Test

A wet-versus-dry moisture conditioning test is widely used to evaluate moisture susceptibility (Nejad et al., 2012; Özen, 2011). The TSR is the indicator of the resistance capacity of the sample to moisture damage and was measured according to the AASHTO T 283 standard (AASHTO, 2007), commonly known as the modified Lottman test. The TSR is defined as the ratio of the indirect ITS of the samples under wet and dry conditions ($\mathrm{TSR} = \frac{\mathrm{ITS_{wet}}}{\mathrm{ITS_{dry}}}$). In general, a higher TSR value indicates a higher resistance to moisture damage. The minimum requirement of TSR was 0.80 (AASHTO, 2007; Jabatan Kerja Raya, 2008).

Two sets of samples with a height of 63.0 ± 1.0 mm and a 101.6 ± 0.1 mm diameter were prepared with 7 ± 0.5% VIM. The first set of samples (3 out of 6 samples) was classified as the controlled (dry) subset, while the remaining was classified as the conditioned (wet) subset. The dry subset was immersed in water at 25 ± 0.5°C for 2 h ± 10 min. Conversely, the wet subset was immersed in a hot water bath at 60 ± 1°C for 24 ± 1 h and then kept in another water bath for 2 h ± 10 min to maintain the temperature at 25 ± 0.5°C.

All samples were tested using the Marshall apparatus to determine the ITS value at a given distortion rate of 50 mm/min at 25°C. The peak load at failure was recorded. The

ITS of both conditioned samples was calculated using Eq. 3.10. Finally, the TSR was calculated following the Eq. 3.11.

$$ITS = (2.\ F_{max}) / (\pi.h.d)\ [N/mm^2] \quad (3.10)$$

where,

ITS = Indirect tensile strength (N/mm^2)

F = Failure Load (kN)

h = Thickness of sample (mm)

d = Diameter of sample (mm)

$$TSR = \frac{ITS_{wet}}{ITS_{dry}} \quad (3.11)$$

where,

TSR= Tensile strength ratio in %

ITS_{wet}= Indirect tensile strength of wet (conditioned) specimen

ITS_{dry}= Indirect tensile strength of the dry (unconditioned) specimen

3.15.3 Indirect Tensile Fatigue Test (ITFT)

The fatigue characteristic of pavement materials is also a crucial parameter that should be determined because fatigue failure is one of the major asphalt distresses due to excessive traffic loading and the environmental impact (Jahangiri et al., 2019). The fatigue performance of the HMA mix is directly proportional to the pavement's service life. This would also lead to substantially lower durability of the asphalt pavements. In this way, predicting an early pavement failure due to fatigue would enable a simpler and swift approach to redesigning the pavement. There are three types of laboratory tests to measure the fatigue life of HMA, which include four-point bending, direct tension-compression, and indirect tensile testing. Among these tests, ITFT is an effective method, which can be performed in two ways: controlled stress (more acceptable for thick pavement layers) and control strain (more acceptable for thin pavement layers).

In this study, the controlled stress (while the strain values were changeable) was used according to the BS EN 12697-24:2018 standard (British, 2012). The test was conducted using the UMATTA machine under a sinusoidal loading on a compact asphalt sample. Eventually, the relative application of a compressive load pulse in the vertical diameter resulted in the permanent deformation and induced tensile stresses was necessary to break the sample into two sections.

Fatigue Life (Nf) is the sum of the cycles of asphalt failure. The lifespan of fatigue is defined as the number of cycle loads causing the splitting or permanent vertical distortion. The fatigue testing was used to assess the fatigue resistance of the asphalt and evaluate the relative performance of the asphalt. The major test conditions included the temperature, loading force, loading shape, loading time, and rest time at 25°C, 2600 N, haversine, 0.1 s, and 0.4 s, respectively.

3.15.4 Mass Loss (ML) Test

The ML test is a reliable approach to determining compact asphalt mixes' durability (Cox et al., 2017; Doyle & Howard, 2011). The durability performance test procedure for ML was based on the ASTM C 131 method (ASTM, 2006). The LAA machine was used to conduct the test without any steel ball. It was necessary to fix 300 revolutions at 25 ± 1°C and the speed from 30 to 33 rpm. A higher ML indicates lower resistance to ravelling. The percentage of ML was calculated by following Eq. 3.12:

where,

$$P = \frac{(P_1 - P_2)}{P_1} \times 100 \tag{3.12}$$

P = ML (%)

P_1 = Mass before the test, P_2 = Mass after the test

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

High-quality asphalt mixes require high-quality materials, including appropriate ranges of aggregate durability and other requirements. The binder often plays a major role in the performance of the asphalt mixes. Therefore, each asphalt material comprising aggregates, binders, and RAP was evaluated through the respective test. The test results were then compared with the minimum criteria outlined in the relevant standards. The OBC determination was performed following the PWD standard (2008). (Jabatan Kerja Raya, 2008).

The performance results of ACW14 mixes containing five RAP percentages were discussed in this chapter. All the samples discussed were subjected to the M_R test, moisture susceptibility test, ITFT, and ML test. The results were tabulated and compared. Finally, the development of the arbitrary scale was presented as a different perspective towards evaluating the performance test results in this study.

4.2 Summary of Natural Aggregates (NA) Test Results

Aggregate quality is a critical determinant for asphalt mix performance. This is because high-quality asphalt mixes require adequate quality aggregates in durability, angularity, and other quality parameters. The quality of the aggregate mix also has a significant effect on the effectiveness of the asphalt mix. Size, shape, strength, and gradation are added attributes that significantly impact the performance of asphalt mixes and should therefore be evaluated and tested. The test results of all of the selected aggregates were compared to the minimum requirements stated in the applicable standards to assess their quality. The LAA test was carried out according to ASTM C131 standards (ASTM, 2006). The aggregate value, according to PWD should not exceed 25% (2008) (Jabatan Kerja Raya, 2008). As Table 4.1 shows, the measured value of LAA for the granite aggregate was 25% - an acceptable value based on PWD requirements (2008) (Jabatan Kerja Raya, 2008). According to PWD (2008) (Jabatan Kerja Raya, 2008), the maximum allowed value of a soundness test is 18%. The soundness value of granite was measured according to AASHTO T 104 (AASHTO, 2011), and the results are shown in Table 4.1. As can be seen from the table, a 0.8% value was generated in the soundness test for granite material, which is below the maximum 18% limit set by the relevant value. FI test was also carried out following ASTM D 4791(ASTM, 2010). The results for the flakiness of the granite materials are shown in Table 4.1. According to the PWD standard (2008) (Jabatan Kerja Raya, 2008), the maximum allowable value for aggregate flakiness is 25%. The calculated values for the granite materials met this standard. The normal specific gravity and water absorption values of the granite aggregates were 2.60 and 1.2% respectively, the results of which are shown in Table 4.1. Based on the results of this test, the aggregates used in this study met the standard requirements and were therefore suitable for use in pavement construction.

Table 4.1: Properties of NA

Test	Test standard	NA	PWD requirement (2008)
Los Angeles abrasion (LAA)	ASTM C 131	25%	≤ 25%
Flakiness index	ASTM D 4791	7.3%	≤ 25%
Soundness test ($MgSO_4$)	AASHTO T 104	0.8%	≤ 18%
Sp. gr. coarse aggregate	ASTM C 127	2.61	-
Sp. gr. fine aggregate	ASTM C 128	2.58	-
Sp. gr. filler		3.02	-
Sp. gr. combined aggregate	ASTM C 127	2.60	-
Water absorption (combined aggregate)	MS 30	1.2%	≤ 2%

Note: LAA = Los Angeles abrasion; FI = Flakiness index; Sp. gr. = Specific gravity.

4.3 Aggregate Gradation

This study used the PWD standard (2008) for aggregate gradation to design the ACW14 mix. Table 4.2 shows the fusion of NA and RAP aggregates using Eq. 3.2 to meet the standard design gradation of the PWD (Jabatan Kerja Raya, 2008). From Table 4.2 it can be shown that the fine aggregate sizes (5 mm to 1.18 mm downgraded) of the RAP was 24% more compared to the virgin aggregate. In contrast, coarse aggregate sizes (20 mm to 10 mm) were 65% smaller than virgin aggregates.

Table 4.2: Fusion of NA and RAP aggregates

BS Sieve size (mm)	Design gradation, M_i (%)	Real size of RAP, P_i (%)	Amount of NA needed to adjust gradation envelope				
			N_i (%) a=0% (R0)	N_i (%) If a=30%	N_i (%) If a=50%	N_i (%) If a=70%	N_i (%) If a=100%
20	0	0.0	0	0.0	0.0	0.0	0.0
14	10	3.6	10	12.7	16.4	24.9	6.4
10	14	12.2	14	14.8	15.8	18.2	1.8
5	19	22.8	19	17.4	15.2	10.1	-3.8
3.35	9	10.1	9	8.5	7.9	6.4	-1.1
1.18	15	20.4	15	12.7	9.6	2.4	-5.4
0.425	13	12.5	13	13.2	13.5	14.2	0.5
0.15	9	7.5	9	9.6	10.5	12.5	1.5
0.075	5.5	5.0	5.5	5.7	6.0	6.7	0.5
Pan	4	5.9	4	3.2	2.1	-0.4	-1.9
Filler	1.5	0.0	1.5	2.1	3.0	5.0	1.5
	100.0	100.0	100.0	100.0	100.0	100.0	0.0

Note: 1. If N is negative, it is necessary to recalculate the percentage aggregate of NA properly. **2.** No adjustment was made in this study for 100% RAP. **3.** BS = British Standard.

4.4 Summary of Binders Test Results

A modified binder with 60/70 penetration grade bitumen and 6% CR was used in this study. This section describes quality control for virgin binders, modified binders, aged binders, and rejuvenated ones. The physical and rheological properties of the virgin binder were tested and compared with the PWD requirements (2008). Table 4.3 shows the results of these tests.

4.4.1 Virgin and Modified Binders Test Results

Following ASTM D5, the virgin binder's penetration test was performed. The test results are shown in Table 4.3. This binder met the penetration test as its 65 dmm value was within the usual range for a 60/70 penetration grade binder. After modifying the virgin binder, its penetration was tested and the penetration value of 58dmm was found. The softening points of the virgin and modified binders were tested following ASTM D36. The binders passed the softening point test as their values of 50 and 53 were within the standard range (48-56). Binders with higher softening points generally work best on HMA pavements. Values of 50 and 53, were acceptable in this case and met the requirements. The virgin and modified binders were tested for flash points in accordance with ASTM D92 (Table 4.3). The estimated figures reveal that this binder can be heated to temperatures of 235°C and 215°C without igniting. The ductility properties of the virgin and modified binders were also tested in accordance with ASTM D113. Table 4.3 shows that the virgin binder values were greater than 100 cm, while the modified binder values were 34.2 cm.

The average viscosity values were 366 cP at 135°C and 144 cP at 165°C of the virgin binder and 644 cP at 135°C and 200 cP at 165°C of the modified binder, that was reasonable for a binder as a viscoelastic material. It implies that at service temperature, the material will have a high stiffness modulus and will be able to cover the aggregates with a thin layer of asphalt binder. The rutting resistance factor (G*/sinδ) of the virgin binders at temperatures of 58, 64, and 70°C is 2.2, 1.0, and 0.5 kPa, whereas the modified binder at the same temperature was 3.8, 1.8 and 0.5 kPa respectively.

Based on the results, the rheological properties of the modified binder increased compared to that of the virgin binder. For instance, the rotational viscosity at 135°C and the rutting resistance factor (G*/sinδ) values at 58°C of the modified binder were higher at 644 cP and 3.8 kPa, respectively, compared to those of the virgin binder at 366 cP and 2.2 kPa, respectively. On the other hand, certain physical properties (penetration, ductility, flash point, and fire point) decreased slightly after modified virgin binder. Mashaan et al. (2013a, 2013b); Mashaan, Karim, et al. (2014) showed similar results to this study. They demonstrated that CR would increase the binder's rheological properties. In addition, the stiffness of asphalt mixes with CR content is higher compared to samples without CR.

4.4.2 Extracted Aged Binder and Rejuvenated Aged Binder Test Results

The extracted aged binder's penetration, softening point, viscosity, and DSR tests were tested. Then, 15% WEO was mixed with the aged binder as a rejuvenator to soften the aged binder properties. After the rejuvenation process, penetration, softening point, viscosity, and DSR tests of the rejuvenated aged binder were tested and examined. Some experiments, such as ductility, flash point, and specific gravity, were not performed due to a lack of extracted aged binder. Table 4.3 shows the properties of the aged binder and the changes in properties of the aged binder with the incorporation of 15% WEO. The addition of WEO increased the penetration value of the aged binder but decreased the viscosity and softening point. WEO restored the penetration value of the aged binder to 45 dmm, which was only 11 dmm before rejuvenation. The softening point of the aged binder was 71°C which was 65°C after rejuvenation. The results imply that the WEO was able to soften the aged binder. Furthermore, the rotational viscosity test at 135°C and 165°C of the aged binder were 3513 and 632, respectively, which decreased to 918 and 195, respectively, after rejuvenation. Hence, the addition of WEO reduced the viscosity of the rejuvenated aged binder due to the softening effect of WEO on the aged binder. Table 4.3 also shows that the value of the G*/sinδ decreased with the addition of the WEO and increased with temperature. The rheological property in terms of G*/sinδ of the aged binder was restored to 5.0 kPa at 70°C with 15% of

WEO. Bilema et al. (2021); DeDene (2011) also showed that the waste oils would significantly soften the binder and achieve a lower G*/sinδ. Therefore, WEO is one of the common rejuvenators that restores and softens the aged binder (Hill & Jennings, 2011; H. Li et al., 2019; Tarsi et al., 2020; Randy C West & Copeland, 2015).

Table 4.3: Properties of virgin, modified, extracted, and rejuvenated aged binders

Property	Test temp. (°C)	Test standard	Virgin binder	Specification for the virgin binder	Modified binder (6% CR)	Extracted aged binder	Rejuvenated aged binder (15% WEO)
Penetration (100g, 5sec., dmm)	25	ASTM D5	65	60-70	58	11.0	45
Softening point (˚C)	-	ASTM D36	50	48-56	53	71	65
Ductility (cm)	27	ASTM D113	>100	>100	34.2	-	-
Flash point (°C)	-	ASTM D92	235	Min. 230	215	-	-
Specific gravity	25	ASTM D70	1.029	1.0-1.06	1.031	-	-
Rotational viscosity (20 rpm, cP)	135	ASTM D4402	366	-	644	3513	918
	165		144	-	200	632	195
G*/sinδ (10 rad/s, kPa)	58	ASTM D7175	2.2	Min. 1.0 kPa	3.8	95.9	21.7
	64		1.0		1.8	42.0	10.7
	70		0.5		0.9	22.1	5.0

Note: Penetration was measured in decimillimetre (dmm) or in units of 0.1 mm; G* = complex modulus; δ = phase angle; cP = centipoise; G*/sinδ = Rutting resistance factor.

4.5 Optimum Binder Content (OBC) Determination

The OBC of the five mixes were calculated by averaging the five corresponding binders' content values of the following parameters: (i) the peak stability; (ii) the flow equals 3 mm; (iii) the specific gravity peak; (iv) VFB equals 75%, and (v) VIM equals 4.0%. Marshall and volumetric test results for the five mixes concerning five separate binder contents are plotted in graphs and shown in Appendix B. Table 4.4 summarises the OBC and binder amount in percentages for the five mixes. Overall, the OBC for RAP mixes was lower than that of R0 in which the OBC of RAP mixes gradually decreased as the RAP content increased. This was probably due to the increment in the percentage of fine particles and the amount of WEO in the mix. However, the differences in OBC for all the mixes were relatively small. For example, the OBC for the R100 mix was roughly 8% lower than that of R0, which was in agreement with other studies that reported a similar trend (Arshad et al., 2017; Esfahani & Khatayi, 2020; Mamun & Al-Abdul Wahhab, 2018, 2020; Taherkhani & Noorian, 2019).

In addition, the amount of binder used in RAP mixes was drastically reduced. For instance, only 22.2% of binder was used to prepare the R100 mix, which was 79.7% lower than the amount of binder used to prepare R0 samples. It was anticipated that high content RAP in the asphalt mixes would lead to a significant economic gain in the related pavement construction field. Therefore, the use of high content RAP successfully reduced the use of NA and virgin binder, which provides a significant advantage for practical application. This was probably due to the combination of WEO and CR in which the WEO not only softened and rejuvenated the aged binder but also enhanced the workability of the RAP mix (Jia et al., 2015; Joni et al., 2019; Majidifard et al., 2019; Mangiafico et al., 2016), while the CR enhanced the stability, efficiency, and consistency of the asphalt (Majidifard et al., 2019; Mashaan et al., 2013b). Moreover, the inclusion of RAP influenced the Marshall properties.

Table 4.4: Percentage of OBC and binder

Component	Mix type				
	R0	R30	R50	R70	R100
OBC (%)	5.9	5.8	5.6	5.5	5.5
Modified binder used (%)	100.0	78.2	62.0	45.9	22.2
Binder amount saving (%)	0.0	23.2	41.7	57.4	79.7

4.6 Marshall Parameters in the OBC of the Five Mixes

Table 4.5 provides an overview of the changes in the Marshall parameters for R0 and RAP mixes in OBC. All mixes met the minimum 8 kN stability criteria for high-volume traffic roads based on the results. Specifically, the stability of RAP mixes improved from 32% to 48% compared to the standard PWD (2008) value of 8 kN (Jabatan Kerja Raya, 2008). The highest improvement in the stability value was achieved by the 30% RAP mix, which showed a 16.7% increase from that of the R0. The results indicated that WEO was an efficient rejuvenator that effectively enhanced the properties of the aged binder (Hill & Jennings, 2011; Joni et al., 2019; Randy C West & Copeland, 2015). Given that the CR could improve the mechanical performance of binders (Majidifard et al., 2019), the addition of CR into the mix was assumed to improve the stability.

Furthermore, all mixes followed a 2–4 mm flow standard. The flow of the mixes increased with the increment of RAP content due to the use of WEO in RAP mixes, which allowed aggregates to float in the mix. The asphalt with 100% RAP mix, which was 33.3% above the R0, reflects the maximum increase in flow that made it more plastic and easier to deform than other mixes. In addition, the amount of WEO increased with the increment of RAP content, in which the WEO was able to soften the aged binder and increase the workability of the asphalt mix. Moreover, the inclusion of CR in the mix enhanced its flow value (A Mahrez, 1999; Majidifard et al., 2019; Mashaan et al., 2013b).

Given that the value of MQ was seen to decrease, consequently, the effects of stability and flow on MQ could have influenced the outcome. Therefore, it was unlikely that all the mixes suffered any damage as all MQ values were higher than the standard value. Furthermore, the MQ value decreased with the increment of RAP content, indicating an inverse relationship between the two parameters, which was probably due to the effectiveness of the rutting or permanent deformations of the mixes (Geraldin & Makmur, 2020). The bulk specific gravity values showed an increasing trend up to 70% in the RAP mix, but the result was slightly lower for the 100% RAP mix. But all mixes obtained higher values compared to that of the R0. This could be due to the filling in the voids of the aggregate particles that blended more compactly with the binder, resulting in an increment of mass at a similar volume. Since a higher specific gravity of an asphalt mix indicates better long-term performance (Asphalt Institute, 2014), the RAP mixes would likely be as durable as the R0.

In addition, Table 4.5 includes the results of the volumetric properties (VIM, VMA, and VFB) for R0 and RAP mixes. Since the value of VIM of all mixes met the PWD standard (2008) of 3–5%, their permeability properties were considered substantial. Furthermore, it was relatively necessary to maintain the minimum 14% VMA standard set by the Asphalt Institute to adopt the binder film within the mix (Asphalt Institute, 2014). According to the result, the VMA values of all RAP mixes were above the minimum limit, while the VFB values of all RAP mixes were within the threshold limit (70–80%). It was also observed that VFB decreased with the increase in the amount of RAP. Therefore, the volumetric properties indicated that all RAP mixes were likely to be sustainable and durable.

Table 4.5: The value of Marshall Parameters in the OBC of the five mixes

Mix types	OBC (%)	Marshall parameters						
		Stability (kN)	Flow (mm)	MQ (kN/mm)	Bulk sp. gr.	VIM (%)	VMA (%)	VFB (%)
R0	5.9	10.2	3.0	3.4	2.28	4.3	17.4	75.0
R30	5.8	11.9	3.1	3.9	2.30	3.6	16.5	78.5
R50	5.6	11.1	3.4	3.3	2.31	3.6	16.1	78.0
R70	5.5	10.4	3.4	3.1	2.31	3.6	16.0	77.0
R100	5.5	10.2	4.0	2.6	2.30	4.6	16.7	72.9
Standard	-	≥8.0[1]	2-4[1]	≥2.0[1]	-	3-5[1]	≥4.0[2]	70-80[1]

Note: [1] PWD standard (Jabatan Kerja Raya, 2008); [2] Asphalt Institute standard (Asphalt Institute, 2014); Sp. Gr. = Specific gravity.

4.7 Statistical Analysis (ANOVA)

Table 4.6 summarises the statistical analysis of the relationship between the binder percentages and RAP percentages through various mechanical properties tests. According to the ANOVA results, it was found that all the *p*-values for all tested parameters were smaller than α (0.05) and all F-statistics were larger than the F-critical values (F > F_{crit} and $p < 0.05$). Hence, the H_o was rejected, indicating that the changes in the amount of RAP and binder significantly affected the performances of the ACW14 mixes.

In addition, the ANOVA results on the Marshall properties and volumetric properties showed that the binder and RAP content were significant factors in OBC optimisation. Overall, the ANOVA results indicated that the two factors (variations in the binder and RAP contents) played important roles in the Marshall stability, flow, quotient, and volumetric properties of the five ACW14 mixes.

Table 4.6: ANOVA summary (two-factor without replication)

Test	Source of variation (%)	F	*p*-value	F_{crit}	Effect
Stability	Binder	17.531660	0.000011	3.006917	Significant
	RAP	8.609671	0.000663	3.006917	Significant
Flow	Binder	16.63945	1.48E-05	3.006917	Significant
	RAP	8.726804	0.000618	3.006917	Significant
MQ	Binder	10.24726	0.000261	3.006917	Significant
	RAP	19.87519	4.75E-06	3.006917	Significant
Specific gravity	Binder	14.75419	3.12E-05	3.006917	Significant
	RAP	7.673141	0.00119	3.006917	Significant
VIM	Binder	69.41357	6.65E-10	3.006917	Significant
	RAP	7.720219	0.001154	3.006917	Significant
VFB	Binder	135.7838	3.94E-12	3.006917	Significant
	RAP	7.936527	0.001005	3.006917	Significant
VMA	Binder	3.648729	0.026945	3.006917	Significant
	RAP	7.634963	0.00122	3.006917	Significant

4.8 Performance Test Results

4.8.1 Resilient Modulus (M_R)

Figure 4.1 shows the average values of M_R results for R0 and RAP mixes. The M_R value indicates how the pavement system reacts to traffic loading (E. R. Brown & Foo, 1989; Mokhtari & Nejad, 2012). According to the results, it can be seen that the M_R increased with the increment in RAP content. This finding demonstrates that when the amount of RAP in the fresh mix increases, the M_R increases, and it is conceivable to use 100% of RAP. Idham and Hainin (2015) claim is similar to this result. Mixes with higher M_R were assumed to be more resistant against deformation, given that the higher presence of the aged binder from the high RAP content was able to increase the elastic component of the viscoelastic HMA mix (Han et al., 2019).

Moreover, incorporating CR, which has exceptional viscoelastic properties, increased the elastic recovery value. Nonetheless, the use of WEO reduced the M_R, as demonstrated by the slow growth rate of M_R value by some 25% with the R100 mix compared to the R0. This occurrence may be associated with the change in the binder's rheological properties. Thus, it can be concluded that the combined use of WEO and CR was effective to obtain a balanced M_R value.

A single-factor statistical analysis was performed to determine the significance in M_R between the five mixes for R0. A H_o refers to an insignificant M_R difference between the five mixes, while the significance level (α) was assumed to be 0.05. Based on the statistical analysis in Table 4.7, the ANOVA outcomes revealed that *p*-value > 0.05 and $F < F_{crit}$. Hence, the H_o was accepted, implying no significant differences in M_R between the five mixes.

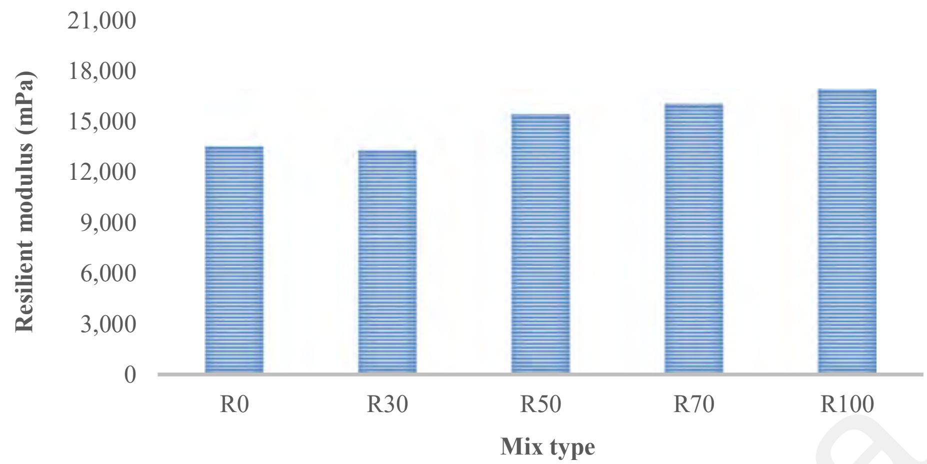

Figure 4.1: M_R for the five mixes

Table 4.7: ANOVA-single factor results for M_R

Source of variation	df	F	*p*-value	F_{crit}
Between groups (Mix types)	4	0.5788146	0.691839	5.192167

4.8.2 Moisture Susceptibility Test

The TSR value was determined using wet versus dry moisture conditioning to assess moisture susceptibility. It indicates the resistance capacity of the sample to moisture damage. Figure 4.2 illustrates the TSR values of the five mixes. The TSR values of all RAP mixes were above that of the R0 (0.89) and the standard value (0.80). The highest TSR value was recorded for the R100 mix (0.97), approximately 10% higher than that of R0.

Interestingly, the TSR value increased as the RAP content increased except for the R50 mix (0.93) where the TSR value was only 1.8% less than that of the R30 mix. Thus, the addition of RAP was very significant towards the sample's resistance capacity to moisture damage, as represented by the TSR value. Although the substitution of 100% RAP in the HMA mixture could affect the moisture performance of the HMA, the TSR values obtained show that the increasing trend of TSR was reasonable, since all the measured values were above the standard requirement.

Furthermore, the TSR value is commonly associated with higher stiffness in RAP mixes. The moisture susceptibility is mainly characterised by the adhesive resistance between the aggregate and binder and the cohesive resistance of the binder particles. Since RAP aggregates were already covered with the aged binder, the RAP mixes were generally less susceptible to damage than the virgin mix. The TSR value indicates the stripping tendency of an asphalt mix. Because the TSR values of the RAP mixes are higher than the standard value, all of the mixes can be said to have anti-stripping additive efficacy. The utilisation of a rejuvenator in this study successfully restored the properties of the aged binder (Zhu et al., 2021). Moreover, the rheological properties of the extracted aged binder were also significantly higher (Table 4.3). Therefore, the combined use of WEO and CR was effective in applying a high content RAP in the HMA mix design. It can be concluded that the use of RAP mixes for pavement construction prevents the likelihood of unfavourable pavement moisture damage.

A single-factor statistical analysis was performed to determine the significance in TSR between the five mixes based on the standard value. A H_o refers to an insignificant TSR difference between the five mixes, while the significance level (α) was assumed to be 0.05. Based on the statistical analysis in Table 4.8, the ANOVA outcomes revealed that p-value > 0.05 and $F < F_{crit}$. Hence, the H_o was accepted, implying no significant differences in TSR between the five mixes.

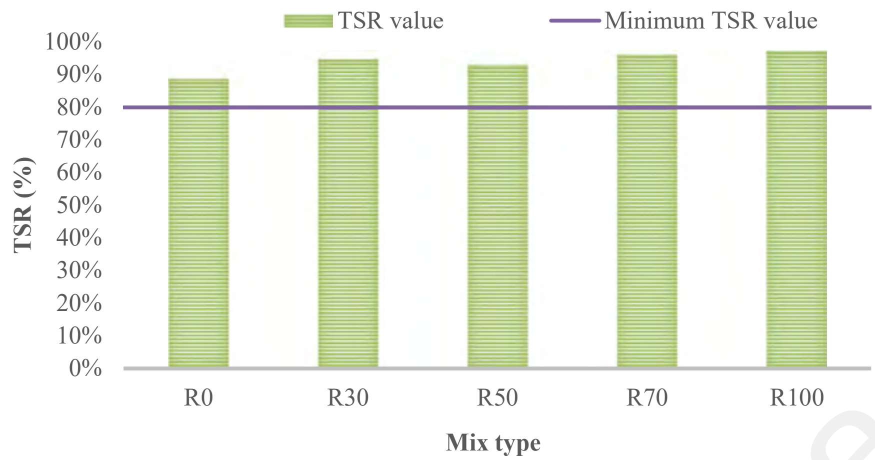

Figure 4.2: TSR values for the five mixes

Table 4.8: ANOVA-single factor results for Moisture Susceptibility

Source of variation	df	F	*p*-value	F_{crit}
Between groups (Mix types)	4	0.055644	0.992389	5.192167

4.8.3 Indirect Tensile Fatigue Test (ITFT)

According to the EN 12697-24 standard, the fracture life corresponds to the total cycle, resulting in the sample's complete rupture (British, 2012). The fractured life measures the ability of the asphalt to withstand repeated tensile forces during its service life for an extended period. Based on the number of failure cycles of the five mixes (R0 and RAP mixes) in Figure 4.3, the R50 mix recorded the highest fatigue resistance, followed by the R30 and R70 RAP mixes. This study's highest findings (R50) is 10% lower than the previous research findings of (El-Maaty & Elmohr, 2015). In contrast, the R100 mix was approximately 5% less resistant to fatigue cracking compared to that of R0. Al-Qadi et al. (2007) also demonstrated the inconsistencies in fatigue performance. Some researchers have shown that high content RAP in HMA decreased fatigue resistance (Izaks et al., 2015; Mohammadreza Sabouri, 2020). This is most likely owing to the high proportion of binder replacement in the asphalt mix, which stiffens it. In some cases, the fatigue performance improved when RAP was used, particularly in modified polymer binders (Pasetto & Baldo, 2017). The decrease in fatigue cracking may be due to the inadequate blending and diffusion between WEO and aged binders, which could shorten the fatigue life.

The fatigue life of a high content RAP mix is largely influenced by the quality of blending and diffusion between the rejuvenator, virgin, and aged binders. In addition, the use of CR prolonged the fatigue life, as shown in many studies (Kocak & Kutay, 2017; Pasetto & Baldo, 2017; Wang, Liu, van de Ven, et al., 2020). Therefore, the results showed that the fatigue performance improved with a modified binder, while WEO contributed limited improvements in fatigue prevention (Jia et al., 2015; Zaumanis, Mallick, Poulikakos, et al., 2014). Since the fatigue value of all RAP mixes was close to or higher than that of the R0 value, this study suggested that the integration of WEO and CR was effective.

A single-factor statistical analysis was performed to determine the significance in ITFT between the five mixes based on the standard value. A H_o refers to an insignificant ITFT difference between the five mixes, while the significance level (α) was assumed to be 0.05. Based on the statistical analysis in Table 4.9, the ANOVA outcomes revealed that p-value > 0.05 and $F < F_{crit}$. Hence, the H_o was accepted, implying no significant differences in ITFT between the five mixes.

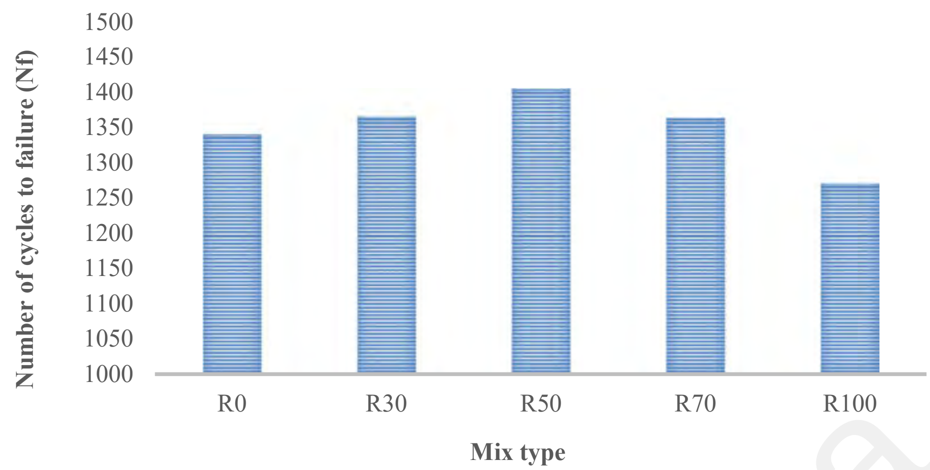

Figure 4.3: Fatigue results for the five mixes

Table 4.9: ANOVA-single factor results for ITFT

Source of variation	df	F	*p*-value	F_{crit}
Between groups (Mix types)	4	1.205029	0.411977	5.192167

4.8.4 Mass Loss (ML) Test

Figure 4.4 shows the comparison of ML of the five mixes obtained through Eq. 3.12. According to the results, all ML values of the five mixes were well below the 15% standard limit, as required by PWD (2008) (Jabatan Kerja Raya, 2008). Moreover, the R50 mix achieved the highest ML value of 3.5%, which was well below the acceptable limit.

A single-factor statistical analysis was performed to determine the significance of ML between the five mixes based on the standard value. A H_o refers to an insignificant ML difference between the five mixes, while the significance level (α) was assumed to be 0.05. Based on the statistical analysis in Table 4.10, the ANOVA outcomes revealed that p-value > 0.05 and $F < F_{crit}$. Hence, the H_o was accepted, implying no significant differences in ML between the five mixes.

Therefore, all mixes demonstrated promising results, which indicated that they were highly resistant to ravelling. Furthermore, the ML test indicated the possible impact of such improvements on mix disintegration resistance, linked to the mixed durability and abrasion resistance (Ruiz et al., 1990). Hence, CR and WEO reduced the ML considerably, and all mixes were highly durable (Cox et al., 2017; Doyle & Howard, 2011).

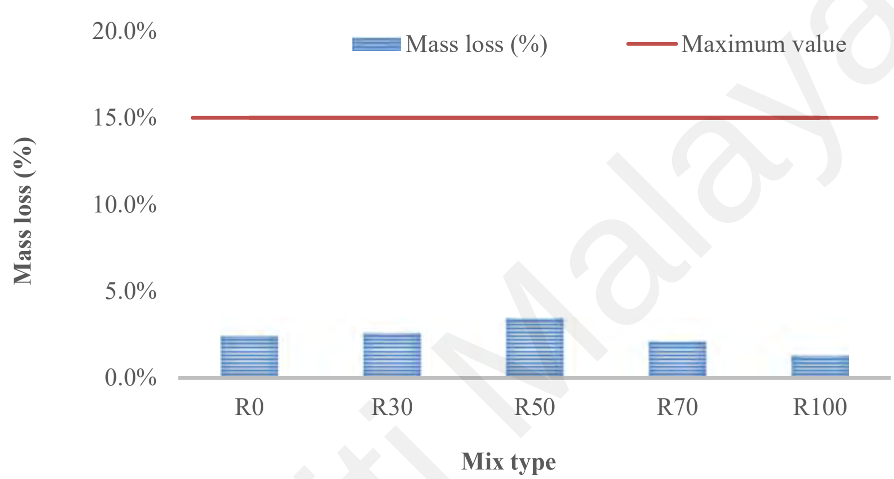

Figure 4.4: ML testing result for the five mixes

Table 4.10: ANOVA-single factor results for ML

Source of variation	df	F	*p*-value	F_{crit}
Between groups (Mix types)	4	0.003771	0.999961	5.192168

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusions

This study characterized the ACW14 mixes using high content RAP and waste materials (WEO and CR) with the following conclusions:

1. The addition of WEO increased the penetration values of the extracted aged binder while decreasing the softening point, viscosity, and G*/sinδ values.
2. The stability of all RAP mixes was higher than the standard limits (8.0 kN). The increment of RAP content was found to increase the flow. The findings also showed that all RAP mixes satisfied the Marshall stability, flow, and volumetric properties criteria. The findings demonstrated that OBC values gradually decreased as RAP content increased. Statistically, the amount of RAP and binder content significantly affected the Marshall stability, flow, and volumetric properties of the ACW14 mix design.
3. The value of M_R increased with the increment in RAP content. All RAP mixes were more resilient than the R0 except for the R30 mix in which the M_R value obtained was 1.6% lower than that of the R0. The TSR values of all RAP mixes were above the standard requirement (80%). In terms of fatigue performance, the R30, R50, and R70 mixes produced a higher fatigue resistance than the R0. The R100 mix was approximately 5% less resistant to fatigue cracking than the R0. The lower threshold value (15%) of all mixes from the ML test showed promising results. The results indicated that the mixes were highly resistant to ravelling and sufficiently durable.

5.2 Recommendations

Based on the findings in this study, the following recommendations are made:

1. It is recommended to investigate RAP from different sources using the method proposed in this study.
2. To establish the most cost-effective type and dosage of rejuvenator, extensive research should be done with various types and dosages of rejuvenator.
3. To compare the performance of HMA mix with 100% RAP, they can be tested both with and without rejuvenators. So that specifications can be established for the use of mixes with a high RAP content.
4. This study was conducted using only 60/70 penetration grade bitumen. Future research should focus on different grades of bitumen.
5. The DSR test was performed only to reveal the properties of the binder used in this study. In the future, researchers will try to perform extensive analyses using DSR machines, such as isothermal curve, isochronal curve, complex modulus and phase angle master curves, black diagram, storage, and loss moduli, SHRP fatigue parameter, and more.
6. It is also recommended to conduct chemical and morphological tests of the binders (virgin, modified, aged, and blend binder).

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LIST OF PUBLICATIONS

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