

AN INVESTIGATION ON THE RESISTANCE OF RUBBERIZED ASPHALT MIXTURE TO AGING AND MOISTURE DAMAGE

AYMAN HASSAN AL-QUDAH¹, SUHANA KOTING^{1*}, MOHD RASDAN IBRAHIM¹,
MUNA M. ALIBRAHIM², NISHANTHINI JEGATHEESAN¹

¹Center for Transportation Research, Department of Civil Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

²Department of Architectural Engineering, Hijjawi Faculty of Engineering Technology, Yarmouk University, 21163 Irbid, Jordan

*Corresponding author: suhana_koting@um.edu.my

(Received: 26 September 2023; Accepted: 15 April 2024; Published online: 15 July 2024)

ABSTRACT: Asphalt pavements in Malaysia suffer severe deterioration, such as raveling and stripping, because the bonding and adhesion between asphalt and aggregate is poor. Heavy rains throughout the year are the main cause of deterioration or a contributing cause to accelerated failure of the pavement structure. Therefore, it is very important to inspect the moisture damage and permeability behavior of asphalt pavement, which can effectively help in a pre-preservation program for asphalt pavement. This study aims to evaluate the effect of adding crumb rubber (CR) on the pavement permeability and moisture damage in highly unfriendly environmental conditions. Laboratory investigation was employed to achieve this aim. The laboratory investigation involved the preparation of two different ACW 14 rubberized asphalt mixtures (unaged and aged). Each type of rubberized mixture contained four CR contents (0%, 5%, 10%, and 15%). The mixtures were tested for air voids, Marshall stability and flow, moisture susceptibility, permeability, and water absorption. The laboratory investigation showed that the CR was appropriate for use up to 10% in asphalt mixtures. There were improvements in the performance of the asphalt mixtures including the Marshall stability, stiffness, durability and resistance against moisture damage. Furthermore, the use of CR prompted better permeability and water absorption. ACW 14 mixture is considered a practically impervious mixture. In conclusion, the application of rubberized pavement can enhance various phases of pavement life and structure by improving the structural performance and reducing environmental impact and landfill issues in the future.

ABSTRAK: Turapan asfalt di Malaysia mengalami kemerosotan yang teruk seperti permukaan turapan jalan yang terpecah (rancak) dan berlubang (pelucutan) kerana ikatan dan lekatan antara asfalt dan agregat adalah lemah. Hujan lebat sepanjang tahun adalah punca utama kemerosotan atau penyumbang kepada struktur turapan rosak dengan cepat. Oleh itu, adalah sangat penting bagi memeriksa kerosakan disebabkan lembapan dan sifat kebolehtelapan turapan asfalt ini dapat membantu dengan berkesan dalam program prapemeliharaan turapan asfalt. Kajian makmal telah digunakan bagi mencapai tujuan ini. Kajian melibatkan penyediaan dua campuran asfalt bergetah ACW 14 yang berbeza (tidak berumur dan berumur). Setiap jenis campuran getah mengandungi empat kandungan CR (0%, 5%, 10%, dan 15%). Campuran telah diuji samada mempunyai lompong udara, kestabilan dan aliran Marshall, kerentanan lembapan, kebolehtelapan, dan penyerapan air. Kajian makmal menunjukkan CR sesuai digunakan sehingga 10% dalam campuran asfalt. Terdapat peningkatan dalam prestasi campuran asfalt termasuk kestabilan Marshall, kekakuan, ketahanan dan rintangan terhadap kerosakan lembapan. Tambahan pula, penggunaan CR mendorong kebolehtelapan dan penyerapan air. Campuran ACW 14 dianggap sebagai campuran praktikal tidak telap air. Kesimpulan, aplikasi turapan bergetah dapat meningkatkan

pelbagai fasa hayat dan struktur turapan dengan menambah baik prestasi struktur dan mengurangkan kesan alam sekitar dan isu tapak pelupusan pada masa hadapan.

KEYWORDS: *Crumb rubber modified bitumen, aged asphalt, dense-graded asphalt mix, rubberized asphalt mixture, moisture damage.*

1. INTRODUCTION

Roadways are an important part of any country's infrastructure systems and contribute significantly to economic growth by providing for the movement of commodities and freight, and social benefits and quality of life through access to services, work, and schools, general mobility, and leisure travel [1]. Based on the structural performance, road pavements are classified into two broad categories with numerous advantages and disadvantages, which are flexible and rigid pavements. Flexible pavements, commonly known asphalt pavements, are widely applied as highway, expressway, and airport pavements primarily owing to their flexibility, high riding quality, high resistance to skidding, and good serviceability [2]. Asphalt pavements are constructed with bituminous materials and require transverse joint-free characteristics that require less maintenance efforts resulting in lower construction and maintenance costs when compared to rigid pavements. In Malaysia, nearly 99% of paved roads are asphalt pavements. However, due to the rapid increase in traffic and extreme environmental factors, asphalt pavements are exposed to many distresses such as rutting, cracking, corrugation, shoving, and stripping after long-term operation, which can negatively affect the performance and service life of pavements. Unfortunately, even the best-designed asphalt pavements deteriorate over time due to axial wheel loads, moisture, and temperature.

Despite the fact that asphalt and aggregate materials used in the construction of asphalt pavements are relatively cheap materials [3] and perform good serviceability [4], the disruption to traffic and costs of maintenance and replacement of deteriorated pavement surfaces are an important issue, leading to a demand for more durable materials. Since asphalt is a temperature-sensitive material, it does not have sufficient resistance against pavement distresses that are caused by moisture and temperature [3]. Therefore, road engineers and designers must consider safety requirements, especially in wet conditions, along with economic aspects. To achieve this goal, four basic requirements must be considered when designing: construction cost, traffic loads, environmental factors, and the quality and availability of materials. Failure to comply with these requirements may result in economic losses resulting from maintenance and rehabilitation work or premature failure of the pavement. In Malaysia, asphalt pavements deteriorate rapidly and do not meet the anticipated design life due to heavy vehicle owners not adhering to the maximum permissible weights. Furthermore, asphalt pavements are very sensitive infrastructure elements, and the performance of the pavements are then affected by environmental and climatic factors such as moisture, temperature, heavy rains, and floods. Pavements are vulnerable to surface damage due to increased temperature, but more severe structural damage is caused by water damage arising from wetter winters and more frequent intense rainfall events [5].

Pavement permeability is a physical property, which is essential and crucial to characterizing the performance of pavement and its quality. Pavements with high permeability will rapidly deteriorate, and be exposed to oxidation (aging), raveling, and stripping due to air and water penetration, allowing the water to infiltrate the underlying layers [6]. The presence of water in pavement structure plays a very important role in accelerating pavement distress. Water damage occurs by breaking the bonds between the asphalt binder and the fine and coarse aggregates, thereby reducing durability and strength. A study by Omar et al. [7] showed that water causes a loss of adhesion between the asphalt and the aggregate interfaces (stripping).

Referring to AL-Qudah [6], water deteriorates the underlying layers of roads. Accordingly, the maintenance of roads affected by wet tropical climatic conditions is a high percentage of the total road construction costs annually, i.e., in 2021, Malaysia was spent RM900 million on repairing roads damaged by rains and floods [8]. Therefore, pavement distresses prevent the optimal function of public road transport and are considered one of the largest factors contributing to fatal motor vehicle crashes.

In Malaysia, the design life of asphalt pavements is 15 years. Due to many advantages such as good strength and durability, adequate skid resistance, low permeability and low binder content, and applicability in any layer of pavement structure, the dense-graded asphalt mix is adopted as a wearing course intended for general use.

Statistics from Transport Ministry show that the number of road accidents in Malaysia is increasing almost annually. There were 370286 road accidents in 2021, and 545588 accidents in 2022, whereas approximately 1.1% of these accidents involved fatal accidents. According to a research study published by the Malaysian Institute of Road Safety in 2021, the design and condition of road infrastructure are one of the main causes of road accidents. Moreover, the pavements deteriorate over time due to traffic and environmental factors. This, in turn, requires regular road maintenance.

Overcoming the deficiencies in the performance of conventional asphalt pavements has resulted in a need for alternatives that can improve the performance of asphalt pavement mixtures. One viable alternative is rubberized asphalt mixture.

Several studies have been carried out to evaluate the use of CR in asphalt pavement mixtures. AL-Qudah [6] indicated that rubberized mixture is a term that refers to the blending of CR with an asphalt binder to enhance the durability characteristics of the following asphalt pavement mixture during service life. Wulandari and Tjandra [9] showed that the use of CR improved asphalt mixture strength and consistency. Sarsam and Hasan [10] evaluated the effect of water on asphalt mixtures containing CR based on the indirect tensile strength (ITS) test. Zhu et al. [11] assessed the performance of rubberized asphalt mixture containing reclaimed asphalt pavement. The penetration test, viscosity test, ductility test, softening test, compressive strength test, Marshal stability test, wheel tracking test, ITS test, dynamic creep, fatigue test, environmental impact were employed by different researchers [6, 12-15] to evaluate the performance evolution of crumb rubber modified bitumen (CRMB) binders and rubberized mixtures, respectively.

The existing studies have mainly evaluated the performance of rubberized mixtures through mechanical property tests, and there needs to be more research on the effect of CR on asphalt mixtures in terms of permeability behavior and water absorption before and after the aging process. To address this research gap in the body of knowledge, this study aims to investigate the effect of CR in asphalt mixtures to resist thermal oxidative aging and moisture damage. It also includes studying the effect of pavement permeability and moisture damage in unfriendly conditions.

Several influential factors affect pavement quality and permeability. The significant factors are aggregate, asphalt, temperature, moisture, and traffic load. Aggregate forms approximately 95% of the total weight of the mix and 85% of the volume. Thus, the properties of combined aggregates highly affect road quality, which offers the possibility of investment in these properties towards resisting varying ranges of challenging environmental and geotechnical conditions and externally applied loads. Aggregates used in pavements' asphalt layers (surface and binder) are constantly stressed due to traffic axial loads that cause wear and tear and premature crushing. For a high-quality pavement, grain particles should have good

resistance to withstand unnecessary rushing and stresses and influence pavements' traffic loading transfer capability to a greater extent. The suitability of aggregates for use in asphalt pavement mixtures is determined by several tests, including specific gravity, water absorption, soundness, abrasion, crushing value, flakiness, and elongation index. The type and size of aggregate are some of the most influential properties. Not only should the totals be strong, but they also require a proper size to make the pavement act monolithically. The aggregate size plays a crucial role in determining each property of pavement, such as durability, skid resistance, resilient modulus, indirect tensile fatigue, indirect tensile strength, stiffness, aging, stability, permeability, rutting, and resistance to moisture damage [3, 6, 16-18]. The aggregate size shall be in the allowable range to achieve strong mechanical interlocking in asphalt mixtures. Pavement containing high coarse aggregate content has high flexibility and porosity, and a faster rate of oxidation binder and loss of adhesion due to contact with water and air, and ultimately pits and exhibits some series of damage states such as raveling, stripping, and potholes. On the contrary, when the proportion of fine aggregate is high, the flexibility, porosity, and skid resistance of the pavement are low, consequently making the pavement more vulnerable to cracking, abrasion, and bleeding. Furthermore, the content of asphalt is mainly related to aggregate size. Not only does the size of the aggregate affect the quality of the pavement, but its shape also plays a very important role. The form of the aggregate may have angular, cubical, rounded, flaky, or elongated particles. Compared to angular, spherical, or cubical particles of the same aggregate, the flaky and elongated particles have less strength and durability. Pavement quality depends on the surface texture [7] and mineralogy of the aggregate [19]. The smoother the surface texture of the aggregate, the lower the absorption of the asphalt binder, and the lower the bond strength.

The type and content of asphalt are the second important consideration that affects the quality of the pavement. Asphalt properties vary over time and from one type to another, and are affected by weather (such as moisture, wind and air temperature) and pavement material parameters (such as physical and thermal properties). A binder serves two major functions; first, to hold the aggregates firmly (adhesion properties), and another function, to act as a sealant to water infiltration (waterproofing). Hence, the asphalt content and its properties significantly influence the pavement quality in terms of stiffness, strength, durability, raveling, rutting, fatigue life, and moisture damage [20]. Accordingly, the incorporation of solid waste materials to asphalt mixtures requires laboratory testing (such as Marshall stability and flow, volumetric properties, ITS, stiffness and Cantabro durability) to ensure that requirements are met. Several factors may contribute to asphalt deterioration, such as oxidation, volatilization, and polymerization, which are caused by moisture and temperature variations over time. Therefore, it is necessary to understand asphalt aging since the asphalt is fully observed under different temperature and moisture conditions. This study gives a quantitative measure for rubberized mixtures with and without oxidative aging.

The third factor that influences road quality is temperature. The viscous-elastic plastic characteristic of asphalt pavements varies with temperature. Therefore, the durability problem of the pavements is prominent because bituminous materials are a kind of temperature sensitive material [3]. Bituminous materials will contract as they fall in temperature and expand as they rise in temperature. Small amounts of expansion and contraction are typically accommodated without excessive damage, however extreme temperature variations cause severe to catastrophic failures. Small variations in the temperature have an unnoticeable effect on pavements. Asphalt pavements can suffer large transverse cracks due to excessive contraction in cold weather. On other hand, asphalt pavement is prone to permanent deformation (rutting) due to excessive expansion in hot weather [5]. Temperature and freeze-thaw cycling lead to acceleration of pavement distresses [21].

In addition, moisture is the main cause of deterioration or a contributing cause giving accelerated failure of the pavements [7] and can also lead to large economic and human losses. It is true that asphalt pavements are susceptible to surface damage due to temperature valuations, but more severe structural damage is caused by increased water damage arising from wetter winters and more frequent intense rainfall events. As a result, the presence of water inside the asphalt pavement structures causes premature failure and damage even with the absence of traffic loading, especially in humid-tropical regions that are subjected to high rainfall intensity and floods throughout the year. This would lead countries to spend millions of dollars on maintenance and rehabilitation of network roads; e.g. Malaysia spends millions each year on repairing road damage caused by rains and floods.

Finally, one of the primary functions of asphalt pavements is load distribution. However, traffic loads and environmental factors (heavy rains and temperature variations) deteriorate pavement over time. This deterioration begins very slowly and is cumulative, exacerbated by repeated traffic, aging, environmental factors, and construction deficiencies. Not knowing the quantification of all expected loads on the pavement under different vehicle weights and environmental conditions at any operational stage will fail. Various distresses such as rutting, fatigue cracking, and roughness would occur if the pavement cannot sustain stress due to frequent heavy wheel loads. Past studies have reported that various pavement distresses, such as severe depressions, potholes, and alligator cracks, are linked to excessive wheel loads.

2. MATERIAL AND EXPERIMENTAL PROGRAM

2.1. Materials

The materials used for the production of unaged and aged rubberized mixtures included aggregates, asphalt, filler, and ordinary Portland cement (OPC). At the same time, the CRMB binders were made from the use of CR and asphalt.

Granite aggregate supplied from Pens Industries, located in Kuala Perlis, Malaysia were used as coarse and fine aggregates. The dense-graded aggregate with a maximum nominal size of 14 mm (ACW 14) per JKR-2008 standard [22] was adopted. The basic physical properties of aggregates and the grain size distribution curve are presented in Table 1 and Fig. 1, respectively.

Table 1. Basic physical properties of aggregate

Property	Specification	Value	
		Coarse Aggregate	Fine Aggregate
Water absorption (%)	< 2	0.84	0.48
Bulk specific gravity	-	2.56	2.63
Apparent specific gravity	-	2.62	2.67
LA abrasion loss (%)	< 25	19.35	-

In Malaysia, asphalt PEN (60/70) is used to construct asphalt pavements because it is more resistant to traffic loads and heavy rainwater. The asphalt PEN (60/70) was used and sourced by Stolthaven Sdn. Bhd., which is located in Port Klang, Malaysia. Table 2 shows the physical and rheological properties of virgin asphalt.

2% of OPC with a specific gravity of 3.11 was added as an anti-stripping agent [22]. Moreover, CR used with a specific gravity of 1.10 was obtained through the mechanical shredding at ambient temperature, and collected from Gcycle Company located in Kedah,

Malaysia. The CR-sized 0.60-mm (30 mesh) originally produced from recycled vehicle tires was introduced as a reinforcing material.

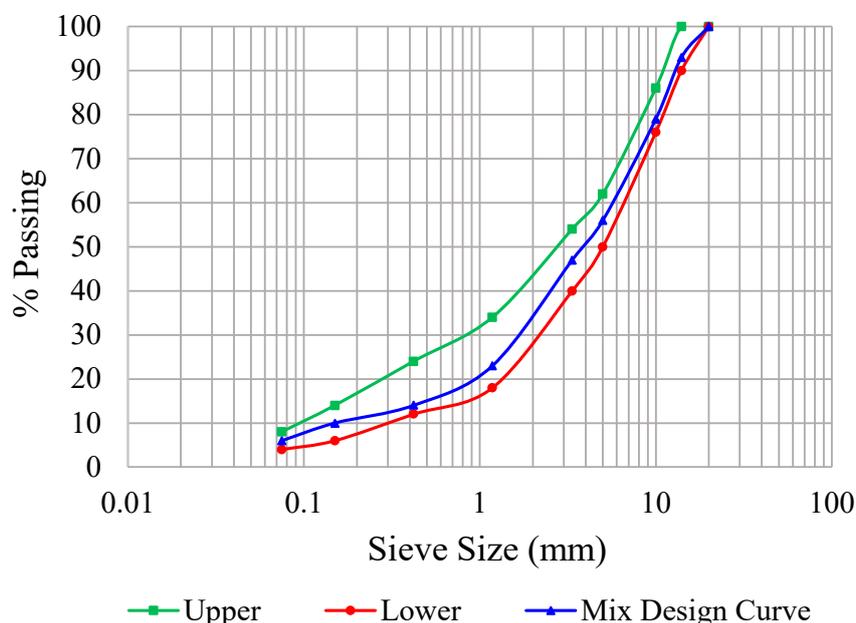


Figure 1. Mix design fractions of dense-graded aggregate (ACW 14).

Table 2. Physical properties of asphalt PEN (60/70)

Property	Specification	Value
Penetration at 25 °C (0.1mm)	60 - 70	63.2
Ductility at 25 °C (cm)	> 100	109.7
Softening Point (°C)	48 - 56	52.1
Specific Gravity at 25 °C	1.01 - 1.06	1.032
Viscosity at 135 °C (mPa.s)	-	491.3

2.2. Production of CRMB Binders

The CRMB binder comprises a bituminous material compound in which rubber in a proper form and proportion is incorporated using an appropriate technique. To this end, the wet process was adopted in this study to prepare CRMBs, where a suitable and effective dispersion of CR particles takes place in the asphalt binder phase. Unlike the wet process, in the dry process, the aggregate is directly mixed with CR before the asphalt binder is added to the asphalt mixture, which means that CRMBs and aged CRMBs cannot be used in the dry process. The CRMB binders were first produced by heating the virgin asphalt up to 180°C before adding the CR. The required amount of CR was slowly added to the heated asphalt, and then asphalt was blended with CR using a propeller blade mixer at a high speed of 4000 rpm for 60 min, as shown in Fig. 2. The mixing temperature was maintained at 180°C, following the same procedure reported by AL-Qudah et al. [3]. Four unaged CRMB binders were made, replacing virgin asphalt with the CR at 0%, 5%, 10%, and 15% of asphalt weight. These low CR replacement levels were adopted because the high replacement levels negatively affect the mechanical properties of the mixture by reducing the interfacial adhesion properties.

Asphalt, like any organic material, is susceptible to temperature fluctuations. Aging is one of the significant problems facing asphalt during the production and service life of pavements due to high temperatures. To evaluate the effect of temperature (aging), four different types of aged binders were produced, in which virgin asphalt and three CRMB binders were subjected to short-term simulation aging using a rolling thin film oven, representing the aging process during production. Eight different CRMB binders were produced and used to prepare eight different ACW 14 rubberized mixtures, and the contents of the binders and mixtures are summarized in Table 3.



Figure 2. Blending process of CR with virgin asphalt

Table 3. Contents of CRMB binders and rubberized mixtures

CR (%)	CR Weight (g)	Asphalt Weight (g)	Aging	CRMB Designation	Weight of Aggregates (g)	ACW 14 Rubberized Mixture	
						Acronym	No. of samples for each test
00	0.0	63.4	no	CRMB-00	1156.6	unaged CR-00	3
05	3.2	60.2	no	CRMB-05	1156.6	unaged CR-05	3
10	6.4	57.0	no	CRMB-10	1156.6	unaged CR-10	3
15	9.5	53.9	no	CRMB-15	1156.6	unaged CR-15	3
00	0.0	63.4	yes	aged CRMB-00	1156.6	aged CR-00	3
05	3.2	60.2	yes	aged CRMB-05	1156.6	aged CR-05	3
10	6.4	57.0	yes	aged CRMB-10	1156.6	aged CR-10	3
15	9.5	53.9	yes	aged CRMB-15	1156.6	aged CR-15	3

2.3. Preparation of Rubberized Asphalt Mixtures

Unaged and aged ACW 14 rubberized mixtures were designed by adhering to the Marshall mix design method [23] in conformity with JKR-2008 standard [22]. All ACW 14 varieties were produced from combined aggregates blended with asphalt at 5.2% (OBC). The mixing process continued until the binder coated all the aggregates. The mixing was done at a temperature of 150°C. Each sample was compacted by applying 75 blows per face at 45°C.

To prepare unaged asphalt mixtures, the unaged-CRMBs were used. Meanwhile, the aged mixtures were produced with aged CRMBs. Eight different rubberized mixtures were designed and divided into two equal groups: unaged and aged mixtures, as presented in Table 3.

2.4. Test Methods

2.4.1. Air Void Test

The air voids in the total mix (VTM) are important parameters because they permit the performance and properties of the mix to be predicted for the lifespan service of asphalt pavements. Eq. (1) was used to calculate the VTM for the ACW 14 rubberized mixtures in accordance with ASTM D3203 [24].

$$\text{VTM} = \left[1 - \frac{G_{mb}}{G_{mm}} \right] \times 100\% \quad (1)$$

where VTM is the voids in the total mix (%), G_{mb} is the bulk specific gravity of the compacted mix and G_{mm} is the maximum theoretical specific gravity of the paving mix.

2.4.2. Marshall Stability Test

Marshall stability and flow test was carried out as per ASTM D6927 [25], which involved determining the resistance and displacement of Marshall specimens in a direction perpendicular to the applied load at a deformation rate of 50 mm/min. The Marshall specimens were cured in a water bath for 30 min at 60°C before testing.

2.4.3. Moisture Susceptibility

The retained Marshall stability (RMS) was used to investigate the moisture susceptibility. In this test, the Marshall specimens were cured at 60°C for 1 day, and at 25°C for 28 days to achieve saturation levels up to 80 %. The RMS was measured by AASHTO T283 [26]. The load was applied until the specimen failure at a rate of 50.8 mm/min.

2.4.4. Permeability Test

The falling head permeability test was performed according to FM 5-565 standard [27]. Marshall specimens were immersed in water at 27°C for 2 hours before the test started. The permeability of the samples was calculated based on the falling head principle, as illustrated in Eq. (2).

$$k = \left(\frac{aL}{At} \right) \ln \left(\frac{h_1}{h_2} \right) \quad (2)$$

where, k is the coefficient of permeability (cm/sec), L is the height of the sample (cm), a is the pipe cross-sectional area (cm), A is the sample cross-sectional area, t is the time of flow between h_1 and h_2 (sec), and h_1 and h_2 are the initial and final head of water (cm), respectively.

2.4.5. Water Absorption Test

Water absorption before and after the aging process was evaluated as an important physical property of pavement more related to moisture-induced damages. The water absorption test was measured according to AASHTO T165 standard procedure [28]. The weights of dry samples were measured and recorded to the nearest 0.1g as W_{dry} . The samples were then immersed in water at 25°C for 28 days. Every 7 days, all the samples were taken out, wiped, and the SSD condition weights of the samples were measured and recorded as W_{SSD1} , W_{SSD2} ,

W_{SSD3} , W_{SSD4} after 7 days, 14 days, 21 days, and 28 days of immersion process, respectively. The average percentage of water absorption (P_{wa}) was calculated as given Eq. 3.

$$P_{wa} = \left[\frac{W_{SSDi} - W_{dry}}{W_{dry}} \right] \times 100\% \quad (3)$$

2.4.6. Durability Test of Optimal Rubberized Mixture

The durability performance of optimal rubberized mixture was tested for stiffness, Cantabro durability, ITS, and tensile strength ratio (TSR). The ratio of Marshall stability to Marshall flow is an indication of the stiffness of the asphalt mixture, and is also adopted as a standard by JKR [22]. It is well documented that stiffness is a measure of the material resistance to permanent deformations and shear stresses [3, 29].

The Cantabro durability is crucial to substantiate the production of a good quality wearing course by resisting crushing, and degradation. This test was conducted using a Los Angeles machine and without steel balls in accordance with EN 12697 standard [30].

As stipulated in AASHTO T283 [26], the purpose of the ITS test is to determine the durability of asphalt mixtures which depend on the cohesiveness of the asphalt films, and also to identify the sensitivity of the mix to moisture-induced damage by estimating the TSR for dry and wet conditioned specimens. This test was done by loading a compacted cylindrical specimen across its diametric vertical plane at a constant deformation rate of 50 mm/min. The ultimate load for each sample at failure was noted and utilized to estimate the tensile strength.

3. RESULTS AND DISCUSSION

3.1. Effect of Permeability

Permeability is the physical property that describes how water flows through a particular medium. The permeability is controlled by the size and shape distribution of aggregates and interconnections of the air voids. A study by Zaniewski and Yan [31] showed that the permeability of asphalt pavement is influenced by several factors including air voids, size and surface texture of aggregate, lift thickness and asphalt content. Air void content is the predominant factor that controls the permeability of pavement, where permeability increases when the air voids increase. This is due to the fact that increasing the void content leads to an increase in the interconnectivity of internal voids, which accelerates the process of infiltration and penetration of water into the pavement structure. Also, permeability increases with the increase of aggregate size. Conversely, when lift thickness increases and the potential for interconnected air void decreases, thus permeability decreases. Giompalo [32] reported that permeability decreases with increasing asphalt content because high asphalt content helps in reducing the interconnectivity of internal voids within the pavement, then decreasing the permeability. Some of the photos related to typical pavement distress due to moisture damage, one of Malaysia's main issues, are shown in Fig. 3 and Fig. 4.



Figure 3. Pavement distresses caused by moisture and traffic loads.

The high permeability of asphalt pavements causes thermo-oxidative aging, raveling, stripping, and rapid deterioration of the underlying layers. This occurs due to the penetration of air and water. As a result, pavement surfaces become less safe, less serviceable, and of lower riding quality. A correlation has been found between poor pavement surfaces and higher road crash rates (larger economic and human losses). Poor pavement surfaces contribute to fatal motor vehicle crashes [33] and are, therefore, a concern for road infrastructure owners and users. At this juncture, an important question arises: How can pavement surface conditions contribute to road accidents? The pavement surface can deteriorate to the level where it becomes dangerous. This includes broken asphalt concrete, sinkholes, uneven road surfaces, potholes, and road cracks. If a driver hits a pothole, the tire could burst, causing the vehicle to veer into another lane and collide. In addition, over time, the pavement surface becomes smoother, and thus, skid resistance decreases. This, in turn, increases road accidents, especially in wet conditions (rainy days).



Figure 4. Infiltration and penetration of water into pavement layers.

3.2. Effect of Water Absorption

Water absorption is the process of absorbing water by materials either rapidly or gradually with the macromolecular structure of the materials. Water absorption is the major problem of asphalt pavements today because it is affected by direct rainfall intensity. The threat of the fluctuation in moisture is widely recognized as one of the main causes of long-term failure of pavement exposed to the atmosphere or in contact with an aqueous media. There are several recognized modes of water absorption problems, such as differential swelling related to concentration gradients, swelling linked to the degradation of the macromolecular structure of the material, and plasticization of the aggregate [34]. The main cause of the failure of asphalt pavement structure is its affinity with high water absorption, especially for underlying layers, which has serious consequences for its durability characteristics. Water damage to asphalt surface layers occurs by breaking the bonds between the asphalt binder and the fine and coarse

aggregates (stripping), leading to reduced durability and strength of pavements. Water below the asphalt layers is also an important issue. Poor drainage can saturate, swell, and deteriorate the supporting materials in the aggregate base and subgrade, allowing axial wheel loads to cause excess damage to the pavement structure.

3.3. Air Void Content

The VTM values of rubberized asphalt mixtures for different conditions are graphically drawn in Fig. 5. It is seen that the increment in the CR content led to the increment of the VTM values for unaged and aged asphalt mixtures. The unaged CR-15 and aged CR-15 mixtures possessed higher VTM values by 6.9% and 7.3%, respectively, in comparison to unaged CR-00 and aged CR-00 mixtures. This trend occurs because the point of contact between the aggregates is lower when the CR content is increased. The CR particles absorbed the oily components of the binder while the CR blended with the asphalt [6]. This resulted in increased CR mass (swelling CR), which is required to encapsulate the aggregate and subsequently fill the voids between the aggregate. Fig. 5 also shows that VTM, after the aging process, enhanced slightly. This behavior is related to the fact that when CRMB is subjected to aging, it becomes challenging to compact as its mass and stiffness increase. Furthermore, the swelling of CR particles continued to occur when they were placed in the oven. However, although the VTM of the mixtures increased as CR content increased, the VTM values were within the acceptable level (3-5%). Compared with control mixtures, the performance of rubberized varieties is better due to the increased VTM required to allow the pavement to undergo additional compaction under traffic loads while providing space for asphalt to flow without flushing onto the pavement surface.

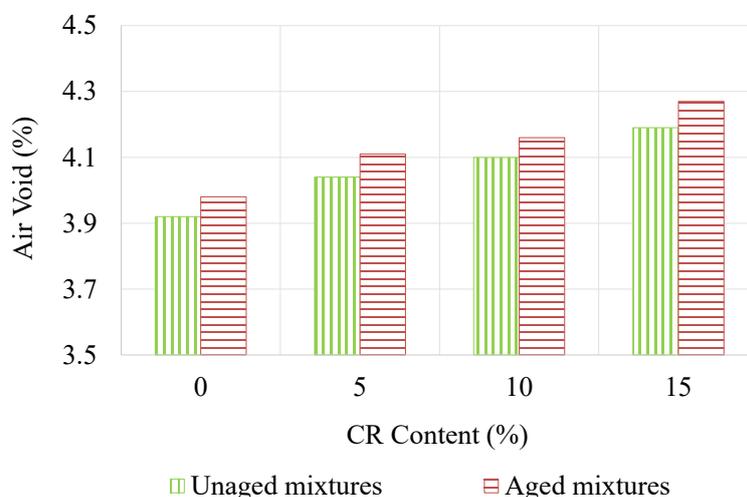


Figure 5. Air voids results before and after the aging process at different CR content

3.4. Marshall Stability

Fig. 6 shows the effect of CR on the stability of the unaged and aged mixtures. With the increase of CR in the asphalt, the stability of mixtures increased. The stability value before the aging process was at its maximum at 10% by 21.4% compared to that of control mixture. This occurs because the asphalt binder became more viscous with the addition of CR, thereby increasing the interfacial adhesion properties and stiffness [6]. The inclusion of more CR decreases the convenience adherence between the mixture compositions, thus deteriorating the stiffness performance. A high replacement level of asphalt with CR results in a brittle, stiff

mixture due to the loss of large volatiles from the binder at high temperatures, making the mixture more susceptible to cracking and abrasion. According to Izaks and Haritonovs [35], the combination of higher stiffness and more brittle behavior will likely lead to a shorter fatigue lifespan and a greater probability of thermal cracking occurring in the field.

As expected, the stability values of the mixtures with the aging process significantly increased due to the increased stiffness of aged mixtures. It can be explained that the binders lost the volatile materials and became more viscous after exposure to high temperatures. This strengthened the adhesion properties between the aggregate and the asphalt. All of the aged rubberized mixtures had higher stability values than that of the aged control mixture. The aged CR-15 mixture recorded the highest stability value of 29.6% compared to the aged CR-00 mixture. However, more than the stiffness alone is needed to give the complete picture because the ductility and brittleness of the mix will also affect its performance concerning cracking. Therefore, although the aged CR-15 mixture has the highest stability value after aging, this gives a negative indicator and reduces the potential resistance to thermal cracking in the field. Nevertheless, all asphalt mixtures with different CR levels exhibited higher values than the minimum allowable limit, i.e., 8 kN. This indicates that the CR can increase the rutting resistance under heavy traffic loads. Such a result agrees with findings study by Nashruddina, et al. [13].

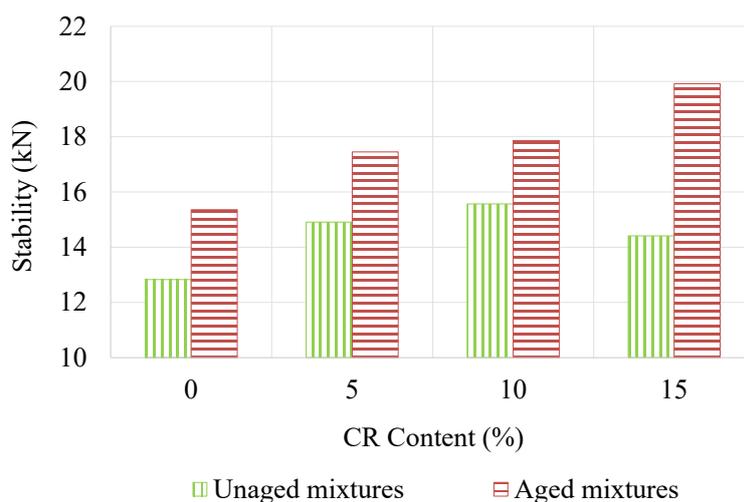


Figure 6. Results of Marshall stability before and after aging at different CR contents

3.5. Marshall Flow

The Marshall flow results at different CR contents with and without thermo-oxidative aging are presented in Fig. 7. The flow values of unaged mixtures decreased with the addition of CR to 10%, and then a noticeable increment in flow value was observed thereafter. After the aging process, there was an inconsistent trend in the relationship between the CR contents and the flow values. However, all the Marshall flow values were within the acceptable range of values (2-4 mm) recommended by JKR for ACW 14 [22]. Compared with unaged mixtures, the aged asphalt mixtures had lower flow values. This reduction could be related to the stiffer mixtures obtained and the decreased fluidity of the aged binders because the binders were very viscous due to the loss of the volatiles.

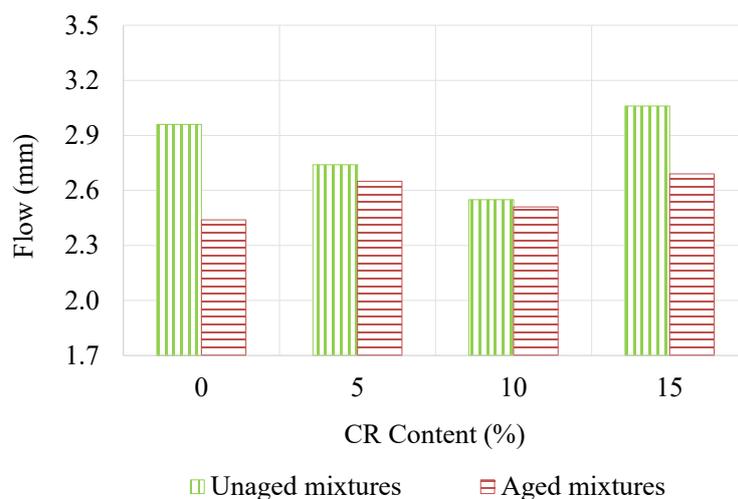


Figure 7. CR content and Marshall flow results before and after aging

3.6. Moisture Susceptibility

The results of RMS versus different conditions and aging for all ACW 14 mixtures are presented in Fig. 8. The RMS values of the rubberized mixtures appeared to be higher than those of the control mixtures. This signified that the mixtures replaced with CR had higher resistance to moisture damage than the control. This trend can be attributed to the increased viscosity of CRMBs because of exposure to high temperatures, which resulted in the formation of thick films of CRMB around the aggregate, reducing the effect of water on the bonding between materials. The RMS results showed that the mixtures with 10% CR without oxidative aging had higher RMS values at 1 and 28 days of curing by an increase of up to 37.7% and 38.2%, in comparison to those mixtures without CR under the same conditions. In the meantime, the highest RMS values for aged mixtures were at 15% and 10% of CR by 43.2% and 38.1% when compared to control mixtures at 1 and 28-day condition, respectively. This is an indication that the application of CR in the asphalt mixture can significantly improve the performance of asphalt pavement by improving the interfacial adhesion properties and reducing the degree of thermo-oxidative aging and moisture-induced damage. A similar trend was reported in past studies using CR as fine aggregate in asphalt mixtures [12, 36]. Water damage resistance varies greatly with the method of incorporating CR into asphalt. Similar to past studies, rubberized mixtures prepared using asphalt pre-blended with CR have greater resistance to water damage than mixtures prepared by directly blending CR with aggregates and then asphalt. The variation in water damage resistance values of rubberized mixtures is evidence that CRMB has good resistance to damage from aging and moisture.

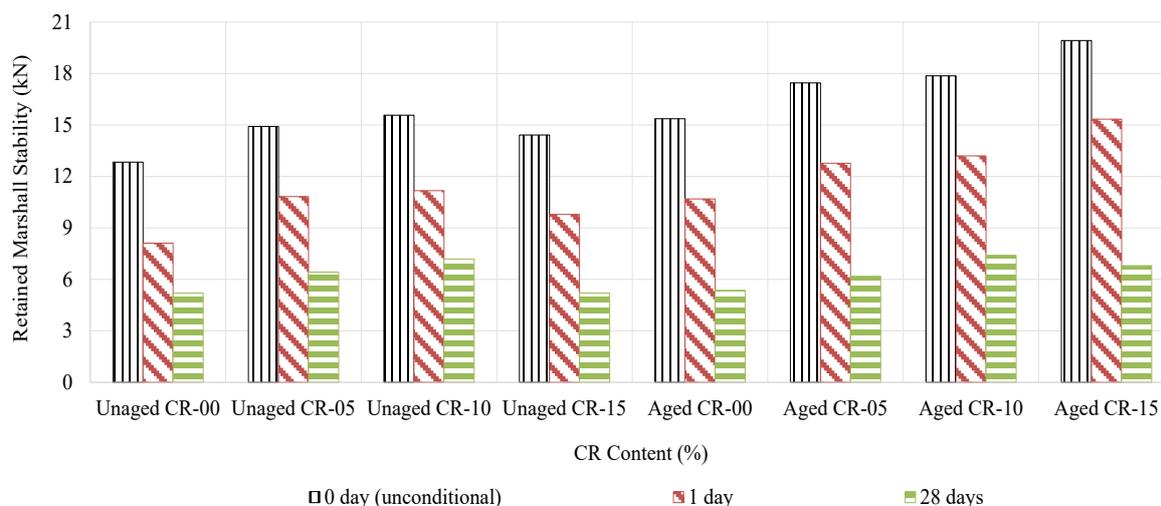


Figure 8. RMS results before and after aging versus CR content

3.7. Permeability

The permeability values of all the mixtures versus CR for different aging conditions are graphically presented in Fig. 9. With an increase in the CR replacement level, the permeability values of the mixtures increased, except for the unaged CR-05 mixture, which had the lowest value. This trend is due to increased VTM values of rubberized asphalt mixtures. The figure also depicts that the aging process causes a slight increase in the permeability values of the mixtures due to the increased VTM after the aging process, which is attributable to the explanation described earlier in section 4.3. Compared to the permeability values of control mixtures before and after aging, the mixtures with 15% CR achieved the highest increase values of 8.1% and 7.8%. Based on the results, the effect of CR on permeability was higher than that of aging. This behavior indicates that the physical and chemical properties of asphalt affected by adding CR were higher compared to the effect of temperature. In other words, the resistance of CRMBs to the impact of high temperature was improved. This proposed potential application of rubberized pavement will perform better than conventional pavement.

Depending on the permeability, asphalt mixtures are classified into several categories. According to the permeability scale proposed by Vardanega and Waters, all the mixtures with CR replacement are classified in category A. This category (A) confirms the mixtures have very low permeability. Moreover, Mullen's categorization indicates that the mixtures are classified as practically impervious mixtures [37]. However, when air voids increase, the permeability increases. Unlike the interconnected air voids, isolated air voids do not correlate with high permeability as there are no flow channels that allow water to penetrate. In other words, the pavement structure can be impervious even with some air voids within it.

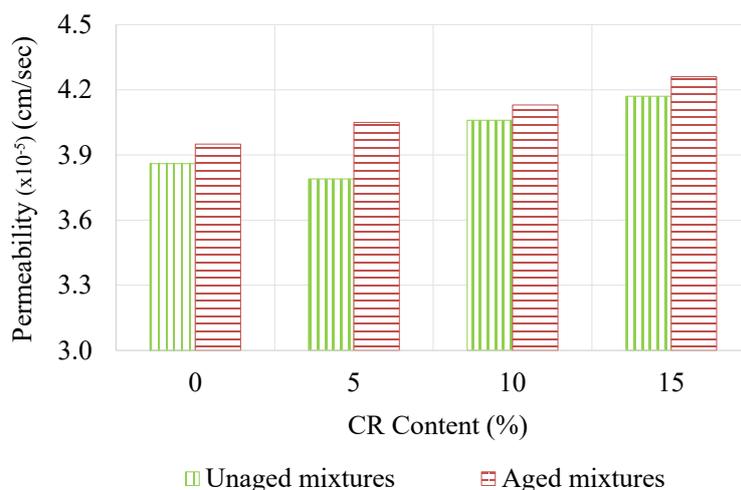


Figure 9. CR content and permeability relationship before and after aging

3.8. Water Absorption

The presence of water in asphalt pavements is unavoidable. The water absorption values of the mixtures versus the CR for oxidative aging conditions are graphically drawn in Fig. 10. The results showed that the CR content affected the water absorption of the mixtures and had a similar trend and that, for any aging condition, the water absorption values of the compacted mixture specimens increased with an increase in the CR replacement level. Moreover, all the rubberized mixtures had higher water absorption values than the control mixtures because of the higher VTM of rubberized mixtures with and without aging conditions. This confirms that VTM plays an important role in the water infiltration and absorption of pavements, which results in moisture damage and loss of interface adhesion, thereby affecting the strength and durability of pavement. However, CR has a significant role in reducing the degree of oxidative aging and leads to a good coat, subsequently decreasing the water absorption by aggregate in asphalt mixtures in the long run and during its service life.

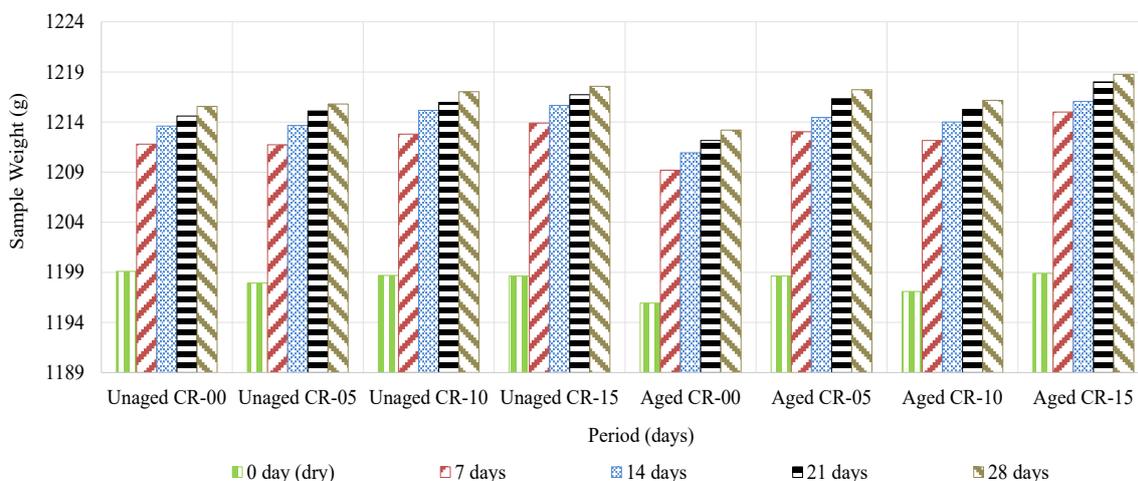


Figure 10. Weights of unaged and aged rubberized mixtures affected by water content

3.9. Durability of Optimal Rubberized Mixture

Asphalt mixtures will undergo thermo-oxidative aging during production and service life. Therefore, compared to mixtures without aging, the performance investigation of asphalt mixtures after aging is the most important consideration. The laboratory investigation for the aged mixtures revealed that the aged mixture with an additional 10% CR (aged CR-10) appeared to have the best performance properties compared to other aged mixtures. The analysis results of the durability of the aged CR-10 mixture are given in Table 4. The results show the stiffness of the aged CR-10 mixture is superior to the aged-control mixture by up to 15.43% and is greater than the JKR requirement (2 kN/mm) [22].

As shown in Table 4, the aged mixture with 10% CR had a higher Cantabro durability value than the control mixture. This is caused by the addition of CR, which made the mixture stiffer and brittle due to the volatile loss of the asphalt components. The increased loss of Cantabro durability can also be attributed to the increased VTM with the addition of CR. The Cantabro loss requirement must be less than or equal to 15% [22], and the results showed that all fulfilled this requirement.

Table 4. Durability characteristics of aged mixtures

Mixture	Stiffness (kN/m)	Cantabro loss (%)	ITS (kPa)	TSR (%)
Aged CR-00	6.35	5.41	1236.1	84.21
Aged CR-10	7.33	6.56	1304.8	86.07

The average values of ITS and TSR for the two aged mixtures are also attached in Table 4. The aged rubberized samples in a diametric strength direction perform similarly, as shown for the Marshall stability. Compared with the aged CR-00 mixture, the ITS of the aged CR-10 mixture increased up to 5.6%, mainly due to the more viscous CRMB resulting from the thermo-oxidative aging process. This in turn led to the formation of thick films of the CRMB around the aggregates, thus strengthening the interfacial adhesion properties. Moreover, the TSR of the aged CR minus 10 mixture was higher than TSR of the aged CR-00 mixture, indicating sufficient resistance against moisture damage. Besides, all the aged mixtures were above the minimum required value (80%) of TSR prescribed by AASHTO T283 [26].

4. CONCLUSION

This study investigated the effect of CR in asphalt mixtures to resist thermal oxidative aging and moisture damage. Moreover, the causes and effect of pavement permeability and moisture damage in unfriendly conditions was examined. Based on the results and analysis, the following conclusions can be drawn:

1. The permeability and water absorption values of the mixtures with and without aging increased when CR content increased due to the increased VTM. The ACW 14 rubberized mixture is considered a practically impervious mixture if designed properly.
2. Asphalt mixture with CR had high resistance to aging and moisture damage due to the improved adhesion properties. Therefore, rubberized asphalt pavement can enhance various phases of pavement life and structure by improving structural performance and reducing moisture and temperature (aging).
3. The permeability and water penetration of asphalt pavements increases over time because of the failure caused by wheel loads and severe environmental factors. A high permeability of asphalt pavement causes thermo-oxidative aging, raveling, stripping, and

rapid deterioration of the underlying layers, which have serious consequences for its durability characteristics.

ACKNOWLEDGEMENT

The authors would like to acknowledge University of Malaya, Malaysia, for providing support to this research paper through the KW IPPP-Research Maintenance Fee (RMF) Individual (no. RMF0476-2021).

REFERENCES

- [1] Administration, FH. (2018) Sustainable Pavement Program. U.S. Department of Transportation, Washington, USA.
- [2] Hassani A, Taghipoor M, Karimi MM. (2020) A state of the art of semi-flexible pavements: Introduction, design, and performance. *Construction and Building Materials*, 253: p. 119196.
- [3] AL-Qudah A, Abdul Rahim M, Ghazaly ZM, et al. (2018) Effect of aged crumb rubber bitumen on performance dense graded mix in Malaysia. *International Journal of Civil Engineering and Technology*, 9(4): p. 1356-1369.
- [4] Zhang H, Chen Z, Zhu C, Wei C. (2020) An innovative and smart road construction material: thermochromic asphalt binder, in *New Materials in Civil Engineering*, Editors. Butterworth-Heinemann. p. 691-716.
- [5] Qiao Y. (2015) Flexible pavements and climate change: impact of climate change on the performance, maintenance, and life-cycle costs of flexible pavements. University of Nottingham.
- [6] AL-Qudah AH. (2018) Mechanical Properties of Asphaltic Concrete Mixture with Crumb Rubber and Aged Binder. School of Environmental Engineering, Universiti Maaysia Perlis, Malaysia.
- [7] Omar HA, Yusoff NIM, Mubaraki M, Ceylan H. (2020) Effects of moisture damage on asphalt mixtures. *Journal of Traffic and Transportation Engineering (English Edition)*, 7(5): p. 600-628.
- [8] New Strait Times Agency. (2021) Flood-damaged road repairs to cost RM900 million. Kuala Lumpur, Malaysia.
- [9] Wulandari PS, Tjandra D. (2017) Use of crumb rubber as an additive in asphalt concrete mixture. *Procedia engineering*, 171: p. 1384-1389.
- [10] Sarsam SI, Hasan EA. (2017) Evaluating Water Damage Resistance of Recycled Asphalt Concrete Mixtures. *Journal of Engineering*, 23(1): p. 156-168.
- [11] Zhu J, Ma T, Dong Z. (2020) Evaluation of optimum mixing conditions for rubberized asphalt mixture containing reclaimed asphalt pavement. *Construction and Building Materials*, 234: p. 117426.
- [12] Mashaan N. (2016) Use of waste tyre rubber in enhancing the mechanical properties of stone mastic asphalt mix. Civil Engineering Department, University of Malaya, Malaysia.
- [13] Nashruddin TF, Ramadhansyah PJ, Norhidayah AH, et al. (2014) Evaluation of Binder Absorption in Asphalt Mixture with Various Aging Conditions Using Rice Method. *Jurnal Teknologi (Sciences & Engineering)*, 71(3): p. 53-56.
- [14] Bansal S, Misra AK, Bajpai P. (2017) Evaluation of modified bituminous concrete mix developed using rubber and plastic waste materials. *International Journal of Sustainable Built Environment*, 6(2): p. 442-448.
- [15] Wangn T, Xiao F, Zhu X, Huang B, Wang J, Amirkhanian S. (2018) Energy consumption and environmental impact of rubberized asphalt pavement. *Journal of Cleaner Production*, 180: p. 139-158.
- [16] Pouranian MR, Haddock JE. (2020) Effect of aggregate gradation on asphalt mixture compaction parameters. *Journal of Materials in Civil Engineering*, 32(9): p. 04020244.
- [17] Garcia VM, Barros L, Garibay J, Abdallah I, Nazarian S. (2020) Effect of aggregate gradation on performance of asphalt concrete mixtures. *Journal of Materials in Civil Engineering*, 32(5): p. 04020102.

- [18] Bharath G, Reddy KS, Tandon V, Reddy MA. (2021) Aggregate gradation effect on the fatigue performance of recycled asphalt mixtures. *Road Materials and Pavement Design*, 22(1): p. 165-184.
- [19] Shivakumara SN, Mallesh SK, Anjum MI. (2015) Effect of particle shape on the workability and properties of conventional bituminous mixes. *Int. J. Res. Eng. Technol*, 4(4): p. 50-54.
- [20] Asghar MAA. (2015) Evaluation of strength characteristics of recycled bituminous pavement materials, in *School of Civil Engineering & Surveying*. University of Southern Queensland.
- [21] Din IM, Mir MS, Farooq MA. (2020) Effect of freeze-thaw cycles on the properties of asphalt pavements in cold regions: a review. *Transportation Research Procedia*, 48: p. 3634-3641.
- [22] Malaysian Standards. (2008) Standard Specification for Road Works, Section 4, Flexible Pavement. *Jabatan Kerja Raya (JKR)*, Kuala Lumpur, Malaysia.
- [23] Annual Book of ASTM Standards. (2002) Standard Test Method for Preparation of Bituminous Mixtures Using Marshall Apparatus, in ASTM D1559, American Society for Testing and Materials (ASTM) International: West Conshohocken, PA, US.
- [24] Annual Book of ASTM Standards. (2005) Standard Test Method for Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures, in ASTM D3203, American Society for Testing and Materials (ASTM) International: West Conshohocken, PA, US.
- [25] Annual Book of ASTM Standards. (2005) Standard Test Method for Marshall Stability and Flow of Bituminous Mixtures, in ASTM D6927 American Society for Testing and Materials (ASTM) International: West Conshohocken, PA, US.
- [26] Annual Book of AASHTO Standards. (2007) Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage, in AASHTO T283, American Association of State and Highway Transportation Officials (AASHTO): Washington, US.
- [27] Florida Standards. (2004) Florida Method of Test for Measurement of Water Permeability of Compacted Asphalt Paving Mixtures, in FM5-565, Florida Department of Transportation: Gainesville, Florida, US.
- [28] Annual Book of AASHTO Standards. (2002) Standard Method of Test for Effect of Water on Cohesion of Compacted Bituminous Mixtures, in AASHTO T165, American Association of State and Highway Transportation Officials (AASHTO): Washington, US.
- [29] Babalghaith AM. (2021) Development of Stone Mastic Asphalt Pavement Design with Palm Oil Clinker as Fine Aggregate Replacement, in *Civil Engineering*. University of Malaya. Malaysia.
- [30] Annual Book of EN Standards. (2017) Standard Test Method for Particle loss of porous asphalt specimens, Bituminous mixtures, in European Standards (EN) 12697, British Standards (BS) Institution: London, UK.
- [31] Zaniewski JP, Yan Y. (2013) Hot Mix Asphalt Concrete Density, Bulk Specific Gravity, and Permeability.
- [32] Giompalo JA. (2010) Permeability of hot mix asphalt concrete as affected by binder content. West Virginia University.
- [33] Mkwata R, Chong EEM. (2022) Effect of pavement surface conditions on road traffic accident-A Review. in *E3S Web of Conferences*. EDP Sciences.
- [34] Fadhil TH, Mohammed HA, Ahmed TY. (2015) An empirical relationship between asphalt and water absorption of coarse aggregates in HMA. *Journal of Engineering and Sustainable Development*, 19(1): p. 132-146.
- [35] Izaks R, Haritonovs V, Klasa I, Zaumanis M. (2015) Hot Mix Asphalt with High RAP Content. *Procedia Engineering*, 114: p. 676-684.
- [36] Cao W. (2007) Study on properties of recycled tire rubber modified asphalt mixtures using dry process. *Construction and building materials*, 21(5): p. 1011-1015.
- [37] Vardanega P, Waters T. (2011) Analysis of asphalt concrete permeability data using representative pore size. *Journal of Materials in Civil Engineering*, 23(2): p. 169-176.