Evaluation of Mechanical Properties of Asphalt Emulsion Base Course Using Reclaimed Asphalt Pavement (RAP) and Asphaltenes

by

Nusrat Nazim Jhora

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Abstract

Road infrastructure significantly impacts the environment, and sustainability practices aim to minimize this impact. This includes reducing air and water pollution, preserving wildlife habitats, and reducing the consumption of natural resources. The goal is to minimize the impact of road development on the environment and natural resources while ensuring that the roads are safe, efficient, and meet the needs of communities. That is why there has been a growing trend toward using recycled materials in road construction in recent years. This is primarily driven by a desire to reduce road construction's environmental impact and conserve natural resources. Reclaimed asphalt pavement (RAP), made from recycled asphalt, can be used instead of traditional asphalt in road construction. RAP is created by milling or grinding up existing asphalt pavement that has been removed from roads, parking lots, or airport runways and is composed of asphalt binder and aggregate. Using RAP in pavement construction as a base course material helps to reduce the need for virgin aggregates and conserve natural resources. The use of RAP also offers several benefits, including reducing waste and reducing the environmental impact of road construction. But the quality of RAP can vary depending on its source and the process used to produce it for new pavement, making it essential to ensure proper quality control measures are in place.

The base layer of a road is one of the layers of the road structure and plays a crucial role in the overall performance and longevity of the road. Asphalt emulsions are used in road construction and maintenance to provide a more effective, efficient, and sustainable alternative to traditional asphalt binders with the possibility of enhancing the properties of the base layer. Therefore, asphalt emulsions are workable at low temperatures, making them a good option for road construction in cold climates; they can be used in reconstruction and rehabilitation techniques such as cold in place recycling (CIR). Using cold in-place recycling process, asphalt emulsion stabilized mixture produced with RAP and asphaltenes, is waste material from Alberta oil sand with no significant value and useful application in the pavement industry. Asphaltenes is the most polar component since it has a higher molecular weight than the other components and adding asphaltenes to an asphalt mixture makes it stiffer.

The objective of this research is to evaluate and compare the performance properties of the stabilized base course materials with different contents of RAP (50% RAP, 75% RAP and 100% RAP), asphalt emulsion with Asphaltenes. The impact of asphaltenes on the tensile strength and creep compliance performance of the recycled mixtures were investigated at the temperatures of -20, -10, and 0^{o}C and compared to the control mixture with no asphaltenes content.

A mix design was performed to determine the optimum emulsion content (OEC), considering the optimum moisture content (OMC) needed for the compaction with the maximum density of the samples. For mixture modification, a different proportion of Asphaltenes (0.5% and 1%) was added to the mixture to determine physical and mechanical properties. To determine the permanent deformation, tensile strength, and low-temperature properties and cracking tolerance of the modified mixtures, indirect tensile strength (ITS), and creep compliance, strength tests, Hamburg wheel tracking test (HWT) and the indirect tensile asphalt cracking test (IDEAL CT) were performed on modified and unmodified mixtures.

Results from the study indicate that modification of the mixtures with asphaltenes improved the performance of mixtures significantly compared to the control samples for mixtures with 50% RAP ,75% RAP and 100% RAP.The creep compliance analysis showed that modification of the mixture material with asphaltenes resulted in lower creep compliance values at below zero temperatures which consequently improves creep resistance in the modified mixtures for 50%

RAP, 75% RAP . On the other hand, asphaltenes-modified samples had higher tensile strength and fracture energy than the control sample at room temperature. It shows that the samples are more resistant to cracking. However, only for the sample with 50% and 75% RAP, the IDEAL CT-Index analysis shows that adding asphaltenes will increase the potential for crack propagation of asphaltenes-modified mixtures regardless of the RAP content. According to the Hamburg wheel tracking test and RRI results, Asphaltenes modified mixture showed a significant improvement in the rutting resistance compared to the unmodified mixtures.

Preface

All of the research held in this study was conducted at the University of Alberta's Asphalt and Binder Engineering Laboratory, under the supervision of Dr. Leila Hashemian. I conducted the introduction and literature review using the findings from chapters 1 and 2 of previous academic research.

A version of chapter 3 has been submitted and approved for publication as N.N.Jhora, F. Kamran, T.B.Moghaddam, and L. Hashemian, “Evaluation of Mechanical Performance of Asphalt Emulsion Base Course Comprised of Reclaimed Asphalt Pavement (RAP) and Asphaltenes.” in the Journal and Testing Evaluation (JTE).

Chapter 4 in this report gives the summary and conclusions of this study.

Dedicated to-

My supervisor and my parents, whose care, dedication, and efforts have enabled me to achieve such accomplishment and glory.

And to those who have consistently expressed their encouragement, their congratulations, and their guidance on the ideal path to take.

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Chapter1 : Introduction

1.1 Background

Through the transportation of goods and services, a country's road systems or network significantly contribute to its growth; hence, great road infrastructure is crucial for the development of both civilization and a nation [1]. It also helps create jobs and employment opportunities by enabling the transportation of people and resources. It is a critical infrastructure vital for modern society's functioning. Over the last ten years, the development of the global social economy has been largely boosted due to the pavement infrastructure [2]. Generally, roads and pavements are designed to resist traffic loads for the duration of their intended service life periods. Traffic load resistance is the ability of a road or pavement to withstand the stress and strains caused by the movement of vehicles over its surface. Traffic load resistance is an essential consideration in designing and constructing roads and pavements. To ensure that roads and pavements are resistant to traffic load, engineers use various design techniques and construction methods, such as designing the thickness of the pavement and using reinforcement materials like asphalt and concrete. Additionally, regular maintenance and repair can help to ensure that roads and pavements remain durable and resistant to traffic load over time. It was estimated that asphalt pavement covers more than 96% of the world's road network [1].

There are several benefits and drawbacks to both flexible and rigid pavement types, categorized based on design considerations [3]. Based on its relatively high resilience to temperature variations, improved performance throughout its service life, excellent driving comfort, safety, low initial construction cost, and ease of maintenance, flexible pavement is the most widely utilized type of pavement. [4]. The flexible pavement layers can support resisting temperature variations and carrying the load. The flexible pavement's basic layer is made up of surface course, base, sub-base and sub-grade course layers. The base layer, which distributes the load to the subgrade, is a crucial pavement construction component. Flexible pavements typically consist of an asphalt concrete layer placed over a base and a sub-base layer supported by a compacted soil layer known as a subgrade [5].

Increased traffic volume, severe weather, frequent traffic loads, and high tire pressure all contribute to the acute structural deterioration of pavements by creating excessive tensile stress concentrations at the bottom and top of the asphalt layer [6]. The quality of the layer or structure determines how well these pavements can resist temperature variations and transfer traffic loads. Each year, these highways receive billions of dollars in funding for maintenance, rehabilitation, and reconstruction [1]. Many studies have been undertaken recently to identify an effective solution for this suffering.

Pavement behaviour at low temperatures is an important consideration for designing and constructing roads and highways in regions where low temperatures are common. At low temperatures, the pavement materials become stiff and brittle, leading to cracking and other types of pavement damage. As a result, temperature variations result in the formation of tensile or compressive thermal strains. In particular, thermal stress more significant than the layer's tensile strength causes low-temperature cracking [7]. Transverse cracks that develop after a specific incident of rapid cooling combined with low temperatures or after multiple cooling cycles that eventually result in a large crack are the signs of this distress. Asphalt layers are generally prevented from shrinking or extending horizontally because of their vast lateral extent. The low-temperature properties of pavement materials are typically characterized using tests such as the thermal stress restrained specimen test (TSRST), which measures the material's tensile strength at low temperatures [8]. In colder climates, it is common to use unique pavement materials and designs specifically designed to withstand low temperatures. These may include the use of special aggregates and binders, the addition of antifreeze agents to the asphalt mix, and the use of thicker pavement layers. Proper pavement maintenance is also essential to prevent damage caused by low temperatures [9]. This may include filling in cracks and potholes, promptly removing snow and ice, and avoiding de-icing chemicals that can damage the pavement surface [10].

One of the construction materials most frequently utilized in asphalt pavement is reclaimed asphalt pavement (RAP). RAP production in the United States may be up to 41 million metric tonnes (45 million tonnes) annually, according to estimates based on incomplete data [11]. So it increases the use of virgin aggregate,landfill burden, higher energy and higher greenhouse emission. There are 82.2 million tons of reclaimed asphalt pavement (RAP) recycled in the US per year [12]. In 2018, the USA saved 4.1 million tonnes of virgin binder and 78 million tonnes of virgin aggregates by incorporating RAP material into new asphalt products [13]. As a results, using RAP in pavement industry reduces the use of virgin aggregate and lower greenhouse gas emission. Reclaimed asphalt pavement (RAP) is increasing as municipal, state, and federal transportation agencies make better use of their resources [14]. RAP is milled, excavated, or crushed asphalt pavement and is composed of asphalt binder and aggregates [15]. RAP recycling can be done on-site or in a central plant. Before applying a new overlay, milling is the technique most frequently used to recover RAP from existing pavements [16]. In the 1960s, Wirtgen in Germany invented the modern pavement milling technique [17]. Since then, due to its numerous benefits, milling of asphalt pavement layers has become a standard practice in pavement preservation projects worldwide. They include the capacity to preserve the geometry of highways, utility infrastructure, and bridge structures, in addition to the recovery of RAP [18]. Cold mix asphalt (CMA) has grown significantly within the pavement construction sector over the past few decades. Using asphalt emulsion, unheated aggregates are combined with or without reclaimed pavement (RAP) to create CMA [19]. Nowadays, people prefer using cold-mix asphalt emulsion mixtures over traditional hot-mix asphalt since they use less energy, have fewer emissions, and are more affordable because they don't require heat during the application process [20]. Cold recycling uses old asphalt pavement material to produce a new mixture for road construction [21]. Cold recycling is a cost-effective and environmentally friendly alternative to traditional hot mix asphalt production. It requires less energy, produces fewer emissions and reduces the need for virgin materials [22]. Several concentrations of recycled asphalt pavement (RAP) have been utilized in cold asphalt mixes, depending on the target and specifications of the design [23]. One of the most important sustainable development strategies for constructing and maintaining roads is cold mix asphalt with RAP [24]. Sustainability and cost reduction are the main reasons for incorporating materials into the modification of asphalt emulsion stabilized mixes. While constructing pavement, RAP establishes a cycle of material reuse that minimizes the use of natural resources.

Recently, it has become more common to use asphalt emulsion for activities including slurry seals, chip seals, micro-surfacing, fog seals, and tack coats in the building and preservation of pavements [25]. Asphalt emulsion is a mixture of asphalt cement, water, and an emulsifying agent that creates a stable suspension of asphalt particles. Asphalt mixtures containing RAP have been in practice since the 1930s [26]. An asphalt mixture's mechanical qualities (such as strength and durability) and field performance (such as resistance to cracking and deformation) are changed when RAP is added [14]. Asphalt emulsion improves RAP's flexibility, cohesiveness, and resistance to permanent deformation during cold recycling, although these materials may be more prone to rutting in slow-moving traffic [27]. Asphalt emulsion with RAP (Reclaimed Asphalt Pavement) is a sustainable and cost-effective way to construct or repair roads and pavements. However, some potential challenges are associated with using asphalt emulsion with RAP. For example, the quality of the RAP material can vary, impacting the final mix's performance. Additionally, there may be compatibility issues between the RAP and the emulsion, which could affect the stability and durability of the mix. Overall, using asphalt emulsion with RAP can provide a sustainable and cost-effective option for road construction and maintenance projects while reducing waste and conserving natural resources.

Cement has been included in asphalt emulsion mixtures to improve performance since the early 1970s [28]. Cement is made by heating limestone (calcium carbonate) with other materials, such as clay, to form a substance called clinker. This process is known as calcination and it releases CO2 as a byproduct [29]. In addition to calcination, the production of cement also involves the use of fossil fuels to power the kilns used in the calcination process. This combustion of fossil fuels also releases CO2 emissions [29]. The high demand for cement currently contributes to more than 7% of anthropogenic greenhouse gas (GHG) emissions despite being essential to many parts of the built environment [30].To keep global warming to 1.5°C over pre-industrial levels, all economic sectors must achieve net zero CO2 emissions before 2050 [30]. Since using asphaltenes as an additive instead of cement is still a relatively new and developing area of research. Asphaltenes have minimal value with no significant applications in the industry. Asphaltenes obtained through deasphalting are considered waste material from Alberta oil sand. Asphaltenes are complex, high molecular weight hydrocarbons found in crude oil and other petroleum products. They are solid at room temperature and are responsible for many of crude oil's physical and chemical properties, including its viscosity, density, and solubility. In oil sand bitumen refineries, asphaltenes are produced at a comparatively high rate. According to estimates, northern Albertan plants create asphaltenes at a much higher rate than average—about 17.5% of asphalts [31]. The addition of asphaltenes affects the mixture’s performance.

Asphaltenes increase the asphalt binder's stiffness and elasticity, significantly increasing the asphalt's resistance to permanent deformation [32].

Using Reclaimed Asphalt Pavement (RAP) and asphaltenes is to develop sustainable and cost-effective methods for producing and using asphalt mixes. RAP is a recycled material obtained from old asphalt pavements milled and crushed. Using RAP in new asphalt mixes can reduce the demand for virgin aggregates and binders, lowering the environmental impact and cost of asphalt production. Asphaltenes, on the other hand, are a fraction of crude oil that contains high molecular weight compounds that contribute to the stiffness and strength of asphalt binders. However, using RAP and asphaltenes in asphalt mixes can pose several challenges. For example, RAP can vary widely in its properties, depending on the age and condition of the original pavement, and its use in new mixes requires careful characterization and testing. Therefore, using RAP and asphaltenes is to develop strategies for optimizing the use of these materials in asphalt mixes while ensuring that the resulting mixtures meet the required performance specifications and are environmentally sustainable. This involves investigating their effects on asphalt mixes' mechanical and durability properties.

1.2 Research gaps

Reclaimed Asphalt Pavement (RAP) is a common recycled material used in road construction, and while there has been a significant amount of research conducted on its use but one research gap is the evaluate the long-term mechanical performance of RAP as a base materials in road construction. Many studies have evaluated the effect of different proportions of RAP on road performance, but there is no consensus on the ideal proportion that can be used as a base materials. Each year huge amount of RAP produced which also causes landfill burden, increase the use of virgin aggregates and binder, and generates carbon emission. That’s why, in this study, different content of RAP used as a base material to define its performance which will help to reduce landfill burden as well as use of virgin aggregates and binder. Cement is a commonly used additive in various industries, including construction, mining, and oil and gas. In the construction industry, cement is often added to concrete and mortar to improve their strength and durability, making it suitable for use in road construction and other infrastructure projects. But the production of cement is a highly energy-intensive process that generates a significant amount of carbon dioxide emissions. Cement production is responsible for around 7% of global greenhouse gas emissions, making it a significant contributor to climate change. Also, Cement production requires large amounts of natural resources such as limestone, clay, and other minerals. These resources are finite and non-renewable, and the high demand for cement can lead to their depletion over time. The production of cement can also pose health risks to workers and nearby communities. Exposure to cement dust can cause respiratory problems, and the use of certain additives in cement can also have toxic effects. Cement can be an expensive material, particularly in regions where it needs to be imported or where the demand for cement is high. This can make it challenging for some construction projects to stay within budget. In this regard, using asphaltenes as an additive in pavement construction makes a huge difference which is a waste material also improve the mixtures performance. Overall this research focused on uses RAP material with asphaltenes to improve mixtures performance which will focus on the sustainability and cost-effectiveness of road construction. Additionally, improving the performance of asphalt mixtures can help extend the lifespan of roads and reduce the need for frequent repairs and maintenance.

1.3 Objectives

The main objective of this research is to investigate and compare the performance of asphalt emulsion stabilized mixes modified using different content of recycled asphalt pavement (RAP) and asphaltenes derived from Alberta oil sand. The study's other particular objective includes the following:

- To investigate the impact of asphaltenes on the mix design of recycled mixes with different amounts of RAP and asphalt emulsion.
- To evaluate the performance properties of the designed mixes at low, intermediate and high temperatures.

1.4 Methodology

In order to achieve the objectives of this study, Different content of RAP and asphaltenes are used independently to stabilize asphalt emulsion mixtures, and results from various performance tests are used to compare the properties. The cationic slow setting (CSS-1H) asphalt emulsion was used in this study. Cracking resistance evaluation of asphalt emulsion stabilized mixes containing RAP and asphaltenes -25°C at temperatures was performed by conducting an indirect tensile strength (ITS) test under dry and wet conditions, compared with the control mixture. The cracking tolerance (CT) index, which is a measure that indicates intermediate-temperature cracking resistance of modified mixes, was obtained from load-deformation curves from ITS tests for 100% RAP, 50%RAP and 50% aggregate, 75% RAP and 25% aggregate. Also, to evaluate the cracking resistance of the asphalt emulsion stabilized mixes at low temperatures, indirect tensile strength and creep compliance (IDT) tests were conducted at 0°C, -10°C and -20°C.

Additionally, the moisture resistance of the stabilized mixes was evaluated by conditioning samples with freeze/thaw conditioning cycles. Evaluation of rutting resistance and moisture susceptibility at high temperatures of the asphalt emulsion stabilized mixtures containing asphaltenes with each content of RAP were performed using a Hamburg wheel tracking device (HWTD) test at a high temperature of 40°C.**Figure 1-1** shows the methodology flow chart.

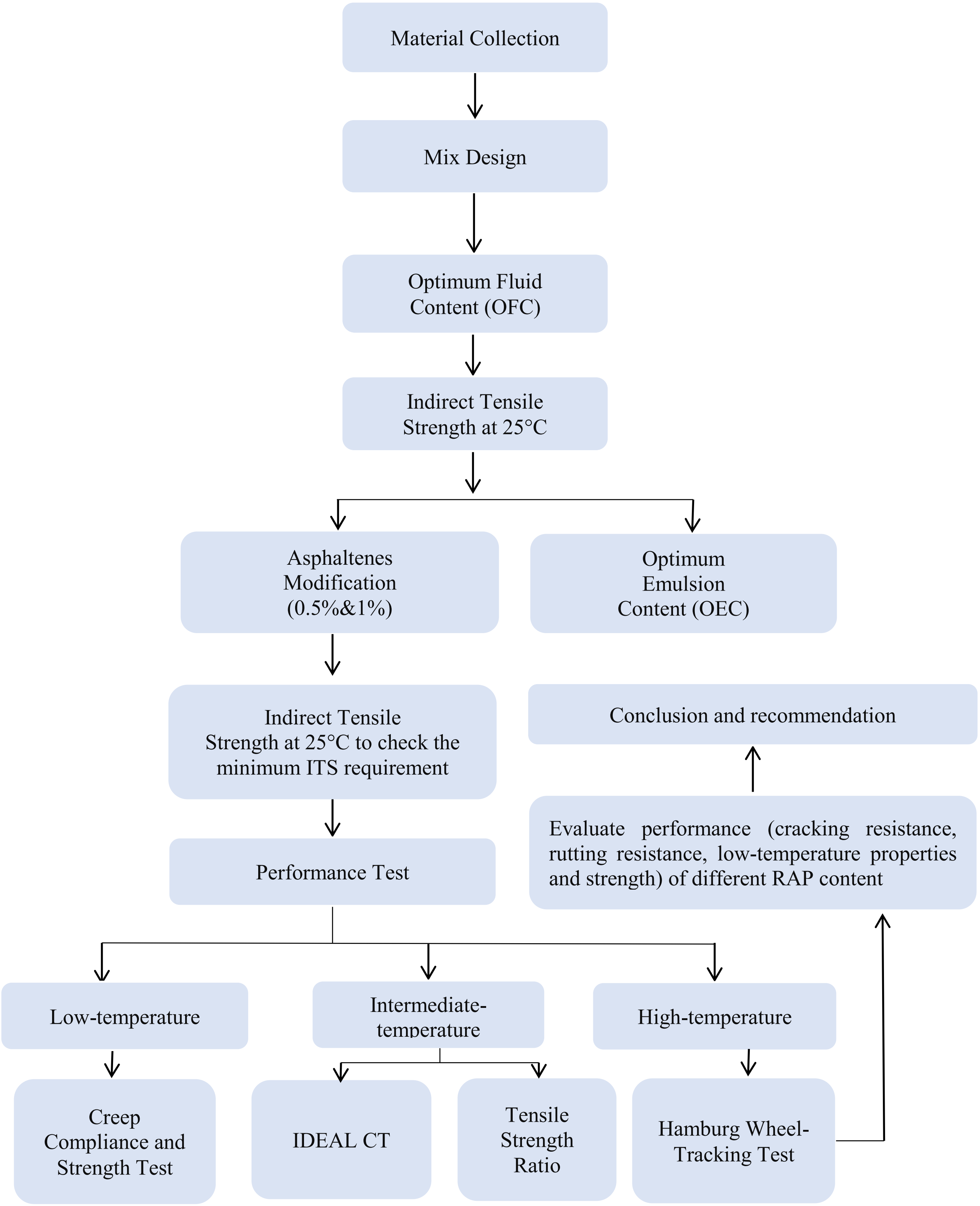
Material Collection
Mix Design
Optimum Fluid Content (OFC)
Indirect Tensile Strength at 25°C
Asphaltenes Modification (0.5%&1%)
Optimum Emulsion Content (OEC)
Indirect Tensile Strength at 25°C to check the minimum ITS requirement
Conclusion and recommendation
Performance Test
Evaluate performance (cracking resistance, rutting resistance, low-temperature properties and strength) of different RAP content
Low-temperature
Intermediate-temperature
High-temperature
Creep Compliance and Strength Test
IDEAL CT
Tensile Strength Ratio
Hamburg Wheel-Tracking Test

Figure 1-1: Methodology flow chart

1.5 Thesis outline

This thesis is organized into five chapters and presented as follows:

Chapter 1 – Introduction: In this chapter, a background or brief description of the complete research work is presented, along with the objectives, methodology and thesis structure.

Chapter 2 – Literature Review: This chapter provides a detailed review of the study's background. In this section, the relevant methodologies, benefits and drawbacks, and earlier research in the literature are reviewed and properly mentioned. Also, relevant case studies are provided.

Chapter 3 – Evaluation of Mechanical properties of asphalt emulsion stabilized base course modified with asphaltenes with different content of RAP: This chapter investigated and compared the impact of asphaltenes addition on asphalt emulsion stabilized mixes with RAP content in different temperature.

Chapter 4 – Summary and Conclusions: In this chapter, differences in the performance of RAP content and asphaltenes stabilized mixes are summarized and explained based on laboratory tests and observations. In addition, this chapter summarizes the thesis's idea, objectives, and scope.

Chapter2 : Literature Review

2.1 Flexible pavement

To sustain the traffic load and distribute it to the road surface, the sub-base, base course, and surface course that comprise the pavement structure are installed on a subgrade [33]. A sub-base layer may occasionally separate the base layer and the subgrade. The base layer increases the slab foundation's functional stiffness, and the base could be stabilized with cement or asphalt to improve its ability to perform better. The most structurally significant pavement layer is the base course layer, which mainly provides the load-bearing layer [34].

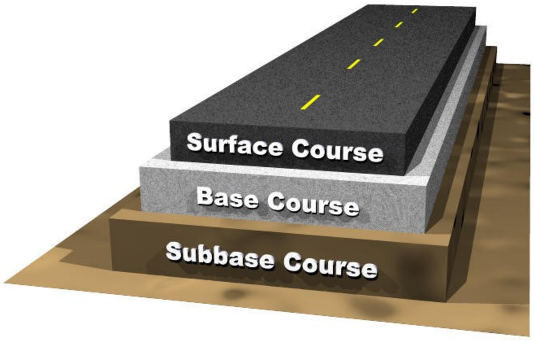

Figure 2-1: Pavement layers [35]

2.2 Pavement Cracking

Pavement cracking is a common problem in roads, highways, and other paved surfaces.One of the most typical pavement distresses is surface crack, which can spread with more traffic and result in moisture penetration and more serious road problems [36].

Figure 2-2: Cracks in Pavement [37]

There are several different types of pavement cracking, including:

Fatigue or Alligator Cracking: This type of cracking is caused by repeated traffic loading over time, which can result in the pavement's surface breaking into small pieces that resemble the scales on an alligator's skin.

Thermal Cracking: This type of cracking is caused by temperature changes that cause the pavement to expand and contract, leading to cracks.

Reflection Cracking: This type of cracking occurs when cracks in an underlying layer of pavement reflect through to the surface layer.

Longitudinal and Transverse Cracking: These types of cracking occur along the length and width of the pavement, respectively, and can be caused by a variety of factors such as heavy traffic loads or improper pavement design.

Pavement's performance and durability can be significantly impacted by its temperature. Cold temperatures may make the pavement more brittle, increasing the risk of cracking and other sorts of damage. Low-temperature cracking is a serious issue, especially in Northern US and Canada [38]. When the pavement is exposed to low temperatures, the tensile stresses propagate within the pavement structure and initiate thermal cracks. Due to freeze-thaw cycles and traffic loading, water can freely penetrate the pavement structure and accelerate the deterioration process. Thermal cracking has significant negative impacts on the performance of the pavement [38]. Pumping fines through such a crack could result in voids under the pavement, lowering its bearing capacity. As a result, low-temperature cracking could result in poor ride quality, reduced service life, and higher rehabilitation expenses [39].

2.3 Cold Mix Asphalt and Base Course Stabilization

Depending on the mixing procedure and utilized temperatures, the asphalt will be classified as hot mix asphalt or cold mix asphalt. Asphalt emulsion mixtures are classified as cold mix asphalt, which was used in base layers of pavement construction. The term "cold mix asphalt" refers to an asphalt mixture that is used in the construction of pavements but does not require heating before use [40]. Environmental awareness, including global warming and air pollution, has risen rapidly in recent years. Considering the road infrastructure, most energy consumption and environmental emissions occur during the construction phase of the roadways [41]. Most of the materials used in Cold Recycling (CR) can be recycled on-site, reducing the amount of material that needs to be transported to the construction site and reducing the requirement to heat the bituminous mixture to high temperatures. As a result, CR can decrease the amount of noise made by heavy machinery and equipment and the emission of greenhouse gases [42]. The cold recycled mix was primarily used in the base course or pavement surface of some low-volume, low-traffic roads in most of the world [43].

The history of cold recycling dates back to the 1960s and 1970s when the first studies on the use of cold recycling in road construction were carried out in Europe [44]. However, the widespread adoption of cold recycling only started in the 1980s, when the first commercial cold recycling plants were introduced [45]. Since then, technology has developed quickly and is now commonly used in many nations worldwide. [46]. There are several variations of cold recycling, including in-place recycling, central plant recycling, and full-depth reclamation. In-place recycling involves mixing the existing pavement with the binder in place and then compaction the mixture. Central plant recycling involves transporting the existing pavement materials to a central plant for processing and mixing. Full-depth reclamation involves pulverizing the entire pavement layer and mixing it with new materials to create a new pavement structure.

The term "cold in-place recycling"(CIR) refers to a rehabilitation approach in which the materials from the existing pavement are reused in place without the use of a heat [43]. Using cold mixes instead of hot mix asphalt mixtures has several benefits for the environment and is more economical [47]. However, compared to hot dense mixes, these mixtures have lower mechanical properties, including reduced earlier-life mechanical properties, excessive porosity, and the stability of their early-life properties [48]. Most CIR projects are built in the field without additional aggregates, and the work is done at room temperature. With pug mill mixers, cold mix asphalt can be generated both in a plant and on the worksite; this reduces hauling costs and energy consumption, making this mixture particularly cost-effective.

Similarly, by adding more reclaimed asphalt pavement (RAP) to the mix, cold mix asphalt (CMA) significantly lowers the cost of materials for paving [49]. The mechanical properties of the emulsified asphalt cold recycling mixture have recently improved considerably with the development and use of the modified emulsified asphalt, making it possible to utilize it to maintain the top layer of highway [50]. Even with the benefits of cold mix application, there are three significant drawbacks compared to hot mix application, such as the high degree of porosity of the compacted mixture, a lack of early life strength and a lengthy curing process necessary to reach maximum performance [51].

Cold recycling uses old asphalt pavement material to produce a new mixture for road construction. The process involves milling, mixing, stabilizing and compacting the existing asphalt pavement material with additives such as cement, bitumen emulsion, or foam bitumen [52]. This mixture is then placed and compacted to create a new pavement layer. Cold recycling is a cost-effective and environmentally friendly alternative to traditional hot mix asphalt production, as it requires less energy, produces fewer emissions and reduces the need for virgin materials [52, 53]

Despite its advantages, cold recycling also poses several challenges. One of the main challenges is the need for more understanding of the properties and behaviour of recycled materials, which can lead to suboptimal performance and reduced durability of the recycled mixture [46]. Additionally, the lack of standardization and harmonization of design and testing procedures has led to a lack of confidence in the quality and durability of cold recycled mixtures [45].To address these challenges, there is a need for further research and development in the field of cold recycling. Research should focus on improving our understanding of the properties and behaviour of recycled materials and developing standardized design and testing procedures for cold recycled mixtures [53, 44]. Additionally, there is a need for research on the sustainability and environmental impacts of cold recycling and the economic benefits and costs of the process

[52]. Cold recycling is a promising technology for road construction, offering many advantages over traditional hot-mix asphalt production. However, to fully realize its potential, further research and development are needed to address the challenges posed by the process and ensure the quality and durability of the recycled mixtures [44, 53].

2.4 Full-depth Reclamation

The Full Depth Reclamation (FDR) technology has increasingly gained popularity for rehabilitating existing flexible pavement. Most problems with ageing asphalt pavements can be resolved using cold technology known as full-depth reclamation. FDR is the technique of in-situ grinding and blending all layers of asphalt pavement and some or all of the underlying base materials to produce a homogenous material for application for a surface course. Using only the materials from the current pavement, the FDR process allows total reconstruction while solving grade, cross slope, and underlying pavement issues [54]. Using less virgin base course materials (virgin aggregates) and requiring less disposal of the old materials, FDR is a cost-effective technique for constructing or rehabilitating pavement. Full-depth reclamation increases a pavement's bearing capacity, structural strength and stability, extends lifetime and improves pavement conditions. Four processes comprise a standard FDR construction process: pulverizing the old pavement, stabilizing, shaping, and compacting. 250 to 300 mm is the average thickness of an FDR treatment. Such a layer is composed of recycled base material, reclaimed asphalt pavement (RAP), cement (2–6% by weight of all aggregates), and water (optimum content for compaction). RAP typically makes up less than 50% of the total aggregates in the mixture, depending on how thick the asphalt layer is.

2.5 Reclaimed asphalt pavement (RAP)

Existing asphalt pavement materials are typically removed during resurfacing, restoration, or reconstruction operations. The pavement material is removed and transformed into RAP, which contains important aggregate and asphalt binder. RAP aggregate properties can influence new mixtures' volumetric properties and performance, especially when a high amount of RAP is used [55]. In order to obtain the RAP aggregate properties, RAP fractions need to be separated using different methods, including ignition or solvent extraction methods. There are two binder recovery methods, namely: Abson method and the rotary evaporation method (Rotavapor method) [55].

Figure 2-3: Reclaimed Asphalt Pavement (RAP) [56]

Due to resource conservation efforts and reduced funding for pavement construction, the usage of recycled asphalt pavement has increased globally [57]. Recycling asphalt pavement and reusing materials in a cycle improves the use of natural resources. Because it reduces the demand for raw aggregate, reclaimed asphalt pavement (RAP) is a valuable substitute for virgin materials. Also, it lowers the amount of expensive new asphalt binder needed to produce asphalt paving mixtures. Many sources offer RAP. The most frequent method is pavement milling, usually known as "cold planning." RAP can also come from full-depth pavement demolition and excess asphalt plant mix, two other common sources. RAP is now being used as a valuable component in hot mix asphalt (HMA) by HMA producers due to rising demand and a shortage of aggregate and binder. As a result, there is an increased motivation to raise the proportion of RAP used in HMA. The two most essential elements that affect the utilization of RAP in asphalt pavement are financial savings and environmental advantages.

RAP is mainly made up of mineral aggregates (93 to 97 percent by weight). Hardened asphalt cement comprises a small portion of RAP (between 3 and 7 percent) [58]. There might be further materials. components of the RAP that require processing the material separately from other sources, such as particular types of aggregate, steel slag, or asphalt rubber; According to a Long-Term Pavement Performance (LTPP) programme evaluation of pavements with 30 percent RAP, the performance of pavements with up to 30 percent RAP is comparable to that of pavements made from virgin materials with no RAP [59]. A recent study comparing the performance of recycled versus virgin mixes utilizing Long-Term Pavement Performance (LTPP) data from 16 U.S. states and two Canadian provinces demonstrates that overlays containing at least 30% RAP performed on equal with overlays employing virgin mixtures [60].

Figure 2-4: RAP Properties

RAP was generally allowed in the subsurface, base, and shoulder combinations, but it might have been limited in surface/wearing courses. Few States permitted little to no RAP because of worries about performance [59]. Even though high levels of RAP were allowed, some states noted that contractors often needed to submit mix designs for amounts higher than 25% [59]. High RAP may impact the binder's characteristics, resulting in a mixture that is "overly stiff" and susceptible to low-temperature cracking. There was also a risk that a combination that was too rigid wouldn't be as durable and might crack too soon for pavements with significant deflections [59]. Running more excellent RAP contents could make you more competitive on some tasks, but higher RAP contents may also come with higher costs, such as higher RAP processing costs, higher materials testing costs, higher plant modification costs, and higher plant maintenance costs [60].In one study, two semi-dense mixtures (S-12 and S-20, according to Spanish standards) used for the rehabilitation of a highway segment were assessed. The mixtures had maximum aggregate sizes of 12 and 20 mm and contained 40% and 60% RAP, respectively. The results demonstrate that significant rates of recycled material may typically be included in bituminous mixes by properly characterizing and managing RAP stocks. In 2000, the Illinois

Department of Transportation permitted the use of RAP in SuperPaveTM HMA with a percentage ranging from 0 to 30%. For HMA shoulders and stabilized sub-bases, a maximum RAP percentage of 50% is permitted.

It was calculated that using recycled HMA pavement results in savings of between 14 and 34% for a RAP content ranging between 20 and 50% when considering material and construction expenses (Kandhal and Mallick 1997). Using RAP prevents the loss of non-renewable natural resources like virgin aggregate and asphalt binder while drastically reducing the quantity of construction waste that ends up in landfills. RAP is a helpful substitute for virgin materials since it lowers the amount of virgin aggregate and asphalt binder needed to produce HMA. Using RAP also helps preserve resources, save money on transportation needed to obtain high-quality virgin aggregate, and conserve energy. However, it has several drawbacks as well. When asphalt is reused, it usually degrades the original material's quality. As a result, it is less durable than new asphalt and is more prone to cracks and potholes. The amount of pavement supply materials determines quality. Sometimes when the material is being stored for recycling, trash and soil can get into the substance. The recycled asphalt loses its shine sooner than regular asphalt due to previous exposure to the sun and other weathering factors. In addition, the old asphalt's rich, black appearance fades more easily. As a result, it is not appropriate for high-traffic office areas.

It is critical to have a recycled asphalt driveway installed and maintained by a skilled contractor. This is because attempting to seal or repair the old asphalt can permanently damage the surface, and cleaning with strong chemicals can shorten its life expectancy. One issue with using recycled asphalt for paving is that in cold climates, using recycled asphalt may increase pavement cracking. This becomes more of a problem when virgin asphalt is combined with more than 25% recycled asphalt paving.

2.6 Asphalt emulsion in Pavement Industry

Asphalt cement, water, and an emulsifying agent are the components of asphalt emulsion. It is a widely used material in the pavement industry for various applications such as chip sealing, slurry sealing, micro-surfacing, and tack coating. The demand for a low-maintenance roadway motivates industries and government agencies to develop a cost-effective, simple-to-apply, and environmentally friendly preservation treatment technique [61]. Because quality raw materials are in short supply, it is necessary to use road materials efficiently and conservatively. This increases the usage of high-performance materials like modified emulsion and recycling. [61]. Asphalt emulsion is becoming increasingly popular for preservation treatment techniques due to its numerous advantages, including lower viscosity and application temperatures [62]. Emulsions were developed in the early 1900s and used in pavement applications in the 1920s. Emulsions were developed in the early 1900s and used in pavement applications in the 1920s. [61]. Because of the limited types of emulsion available and a lack of knowledge on how to involve in pavement construction, asphalt emulsions were initially limited to use only in spray applications and dust palliatives. [61]. However, roadway designers recommend using asphalt emulsions because of the increased traffic loads and volumes during World War II. [61].

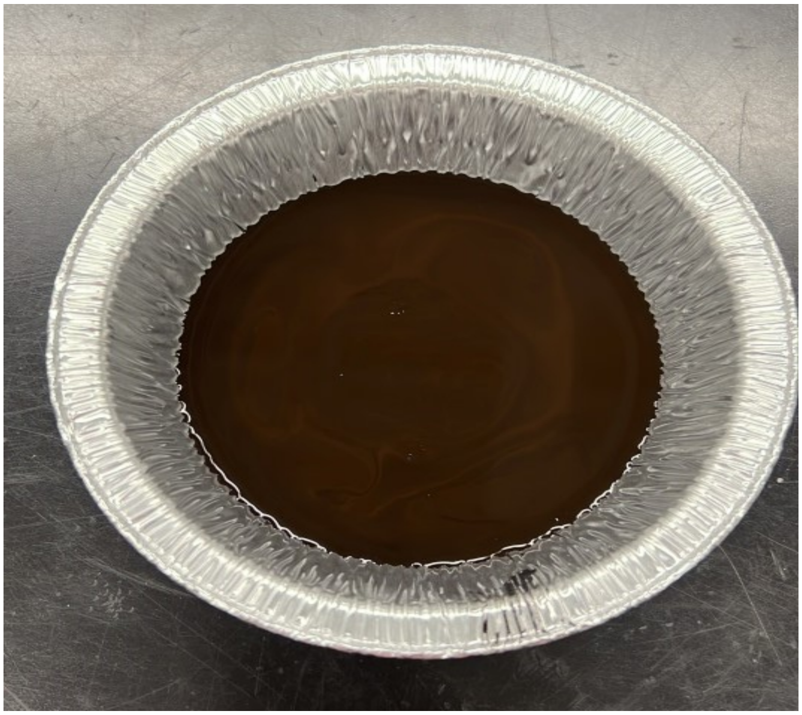

Figure 2-5: Asphalt emulsion

However, in addition to the above reasons, several of the causes listed below have increased the use of asphalt emulsions. The most crucial of these are the following. [61]. Asphalt emulsion emits very little or no hydrocarbons, which reduces atmospheric pollution. Since damp aggregates can be coated with asphalt emulsions, less fuel is needed to heat and dry the aggregates. The development of laboratory techniques to fulfil the accessibility of different asphalt emulsions aided design and construction requirements. Asphalt emulsions can also be used for preservation and treatment to prolong damaged pavements' life.

The world's largest emulsion manufacturer is in the United States [63]. Because of its lower viscosity, asphalt emulsion can be applied at lower temperatures [61]. Because of its road construction and maintenance applications, an asphalt emulsion is regarded as an environmentally friendly building material and is well-known as green technology. This low-temperature method lowers emissions and energy consumption while promoting a safer working environment and preventing the release of toxic gases. [61].

Because asphalt emulsion has a viscosity far lower than existing asphalt, it can be used in colder temperatures. The low-temperature property prevents asphalt oxidation and lowers emissions and energy use. Emulsions can also be used with water and active fillers like cement and lime to increase retained strength, provide moisture resistance, and accommodate traffic. Moreover, for pavement maintenance, cold recycling utilizing the stabilizing agent is advised during cold weather. The cold recycling method has an advantage in maximizing recovery by reusing the existing asphalt pavement without damaging the buildings below the recycling [64]. The emulsion stabilizes reclaimed asphalt pavement (RAP) to improve engineering properties, including strength, stiffness, and longevity, while maintaining the riding quality [64]. Emulsion stabilization increases pavement thickness, reduces void compaction, and protects against crushing loads brought on by inter-particle friction and constant tensile strains [64]. It is essential to consider the mix design so that the ideal emulsion content is chosen for the proper thickness of the pavement layer with acceptable aggregates for an asphalt emulsion to be workable [61]. To meet requirements for stability, durability, fatigue behaviour, tensile behaviour, flexibility, and workability, a bituminous stabilized combination is needed [41] .

Nonetheless, there are several drawbacks to applying asphalt emulsion. Overall, Pavement construction and maintenance can benefit from the versatility and sustainability of asphalt emulsion. In addition to lowering the environmental impact of conventional asphalt manufacture, it offers a practical and affordable alternative for repairing and maintaining pavements.

2.7 Classification and Manufacture of Asphalt Emulsion

Asphalt emulsions are classified based on several factors, including the type of emulsifying agent, the type of asphalt, and the application for which they are intended. Asphalt emulsions can be divided into three primary categories: anionic, cationic, and non-ionic. In general, fatty acids found in tall oils, rosins, and lignin serve as anionic asphalt emulsifiers. Anionic emulsions have negatively charged emulsifying agents and are typically used for applications like chip sealing and aggregate bonding. Cationic emulsions have positively charged emulsifying agents and are typically used for applications like cold mix paving and recycling of existing pavement. Pavement applications are not suited for non-ionic emulsifiers since they are uncharged. As previously mentioned, anionic and cationic asphalt emulsions are the most widely used for constructing and maintaining pavement. Also, Emulsifiers are categorized in addition to surface charge according to how quickly they break or set. In order to permit coating with aggregates, breaking is the separation of the water from the asphalt emulsion and the coalescence of the asphalt droplets, generating a continuous film of asphalt on the aggregate. Based on how quickly an asphalt emulsion sets, there are three different categories: rapid setting (RS), medium setting (MS), and slow setting (SS).Slow-Setting emulsions are designed to set slowly, allowing for better penetration into the pavement surface. Medium-Setting emulsions are designed to set at a medium rate and are commonly used for surface treatments and tack coats. Rapid-Setting emulsions set quickly and are typically used for patching and other small-scale repairs [65]. Emulsifiers with slow-setting (SS) emulsions have extended breaking times of between 30 minutes and 1.5 hours, occasionally much longer [66].

Asphalt emulsion process plant shown in **Figure 2-6**. These mechanical mechanisms divide the asphalt into a tiny drop and operate at high speeds and shears. Water is treated with an emulsifier in the emulsifying solution tank and pumped to a colloid mill with asphalt to create asphalt emulsion. Tiny droplets of asphalt are created by the colloidal mill. These tiny droplets have an average diameter of about two microns. The high-speed rotor rotates between 1000 and 6000 revolutions per minute (rpm) while producing emulsion droplets that range in size from 0.001 to 0.010 millimetres (m) [65]. As part of the emulsification process, the water temperature in the colloid mill is adjusted after the asphalt is heated in the mill to a low viscosity in order to achieve the best possible emulsification. The emulsification property as well as the compatibility between the emulsifying agent and asphalt material determine the choice of water temperature for emulsification. This temperature optimisation is based on the observation that very high-temperature asphalt emulsions are not practical because the emulsion must be transferred from the colloid mill to the storage tank at a temperature lower than the boiling point of water. Inside the storage tank, mechanical agitation is necessary to maintain the created emulsion in a state of uniform blending [65].

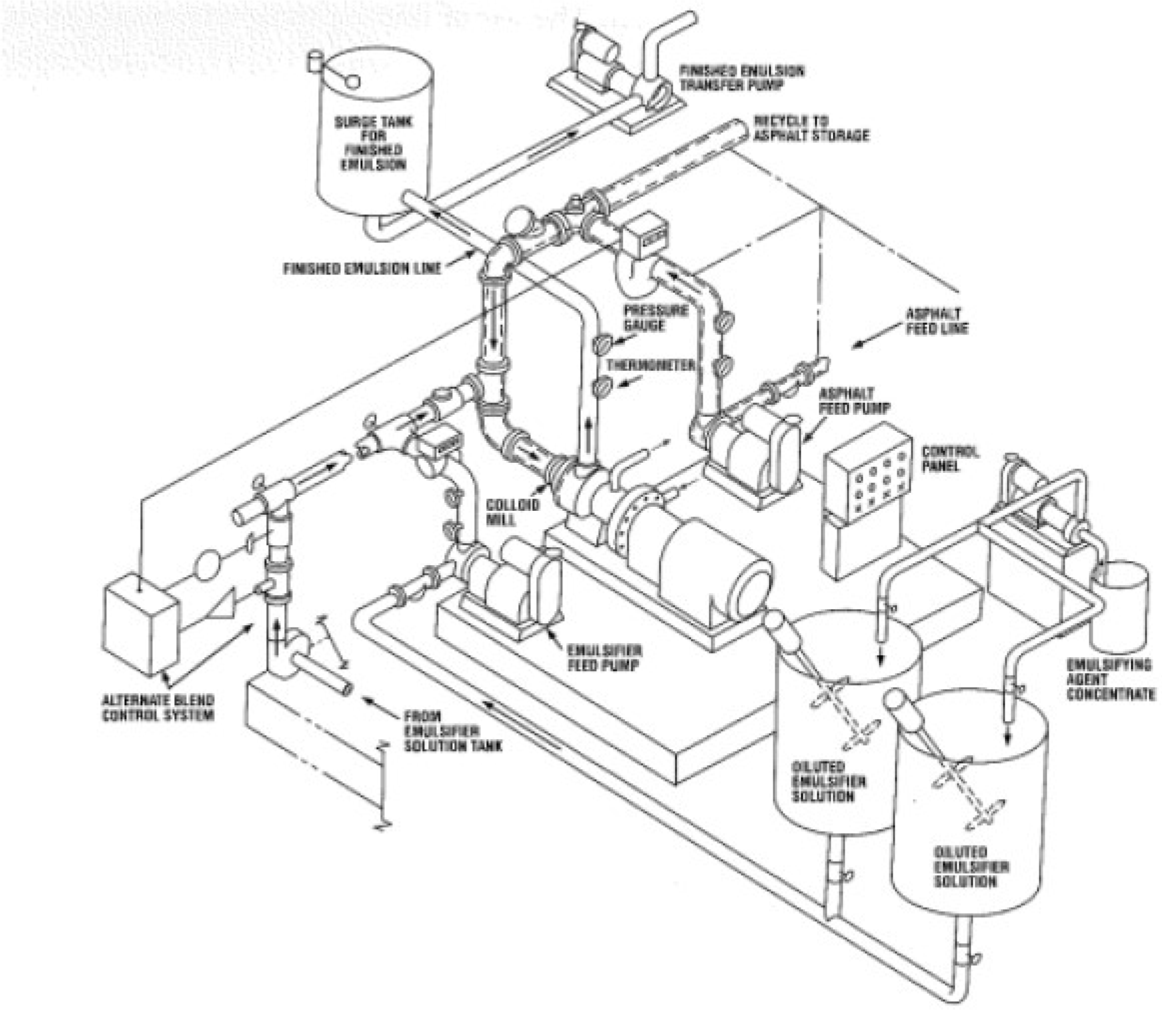

Figure 2-6: Schematic diagram of a typical asphalt emulsion manufacturing process [65]

The colloid mill has two feeder lines: one for the asphalt and one for the emulsifying agent. The asphalt and emulsifier solution is mixed as it enters the mill with the help of pumps that pass through the air gap. Through the air gap, the fluids were subjected to strong shear and hydraulic stresses. The forces to pump in a colloid mill depend on the rotor's speed and the size of the air gap. The emulsifier reduces the energy needed for asphalt dispersion, and the air gap enables the asphalt to dissolve into the water in tiny droplets. For asphalt to be able to disperse into the water, it is crucial to continuously measure the viscosity using a flow metre. The temperature at which the viscosity is obtained for asphalt dispersion is known as equiviscous temperature (EVT), and in general, the viscosity needs to be relatively low. The asphalt emulsion's temperature as it exits the colloidal mill is also crucial for recording. The stability of the emulsion during production, cooling, and storage is improved if the emulsion exit temperature is at or above the minimum emulsion exit temperature (MEET). MEET is the temperature at which a viscosity of around 20,000 centipoises is produced.

2.8 Asphaltenes in Pavement

In 3000 BC, the Sumerians became the first civilization to use asphalt as an adhesive for constructing statues, walls, and structures [67]. The first bitumen distillation was carried out in 1837 by French chemist M. Boussingault, who named the separated volatile liquid "petrolene" and the solid fraction "asphaltenes" (Because of the visual similarity to asphalt) [68]. Asphaltenes, a viscoelastic substance, comprise saturates, aromatics, resins, and asphalt (SARA) [69]. In the 1930s, asphaltenes were introduced as colloidal particles to increase oil viscosity. The polyaromatic component of crude oil known as asphaltenes has a wide variety of molecular masses recorded in the literature, from 700 to 40,000, to mention a few [70]. Also, 40,000 to 700, 10,000 to 7,500, >6,000, 3200 400, 800, and 300-1400 atomic mass units are a few of the reported statistics (AMU) [71]. The variety of oil sources and the asphaltenes molecules' propensity for self-aggregation are two other factors that contribute to the different outcomes and molecular weight ranges [72]. According to the SARA method, the molecular weight and chemical components recovered from one type of crude oil using two different solvents have different results. Asphaltenes are typically named for the n-alkane solvent precipitating them, like pentane or heptane [73]. Petroleum is not the only source of asphaltenes production. Virgin petroleum, tar sands, refinery bottoms, coal, shale oils, bitumen, oil shale, and coal extracts are among the sources of asphaltenes that come from fossil fuels. Asphaltenes are a group of heavy crude oil molecules that contain various substances with a high degree of polarisation and surface activity [72].

The components can also be divided into polar and nonpolar groups. The opposite portion is made up of resins and asphaltenes, whereas the non-polar fraction is made up of aromatics and saturates. Generally, the asphaltenes are the most polar and have the highest molecular weights. They also have the most propensity to self-associate and form agglomerates, and they are the component that reacts with oxygen the fastest [74]. Recent studies have shown that the polarity of asphaltenes can improve the rheological properties of an asphalt mixture. Due to its higher molecular weight than the other components, asphaltenes is the most polar component; adding asphaltenes to an asphalt mixture makes it stiffer.

Refineries manufacture asphaltenes at a significantly greater rate. It was projected that the refineries in northern Alberta Province create asphaltenes at a high rate of 17.5% of bitumen [40]. The solid asphaltenes were ground into powder form and sieved through a #100 sieve before being added to the mixture to make the mixing process more efficient and provide enough surface area.

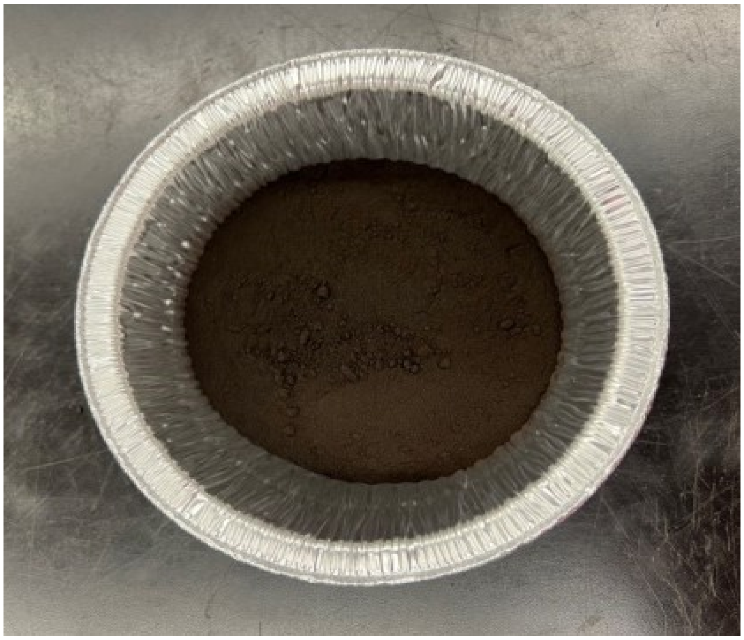

Figure 2-7: Asphaltenes (after sieving)

2.9 Composition of Mixture and Optimum Emulsion Content

In order to design the stabilized mixes using RAP, the Technical guideline for bitumen stabilized materials (TG2) [75] and the basic asphalt recycling manual prepared by the asphalt recycling and reclaiming association (ARRA) [76] were used. According to that, the proctor test was conducted for different content of RAP to calculate the Optimum Fluid Content (OFC) and, based on that, Optimum Moisture Content (OMC). After that, four different percentages of asphalt emulsion and water (1%, 1.5%, 2%, and 2.5%) were added to the mixtures with 0.5% intervals to determine the optimum emulsion content (OEC). An indirect tensile strength test was used to finalize Optimum Emulsion Content (OEC) with the dry and soaked condition at 25°C.

RAP and aggregate were ovens dried at 110°C for 24 hours to eliminate any remaining moisture. After that, the materials were removed from the oven to cool down at room temperature for a few hours. RAP and aggregates were mixed until the water mixed uniformly with the material. After that, Different content of asphalt emulsion was added with the uniformed materials and using a Marshall hammer; the mixture was compacted 50 blows on each side of the sample.

The Indirect Tensile Strength (ITS) test was conducted in accordance with the AASHTO T283 standard [77] for dry, wet, and freeze/thaw conditions. At each of the asphalt emulsion contents, nine samples (3 replicates for dry, three replicates for soaked, and three replicates for freeze/thaw) were prepared. The Marshall hammer was then used to compact the samples with 50 blows according to the previous process. Before testing, the dry samples were kept for three hours in an air chamber at 25°C. For wet samples, conditioning in a water bath for 24 hours at 25°C was done before using the AASHTO T283 [77] Freeze/thaw procedure. A similar method for loading followed as ITS and strength were calculated. Throughout the study, the asphaltenes-modified mixes were prepared using an OEC of 1.5% by weight of the total mixture. The control samples and the ones modified with asphaltenes were prepared similarly to the design samples for OEC. The RAP material was mixed with asphalt emulsion and water after being added with asphaltenes, dried at 110°C and cooled down to room temperature, according to the results of the mix design test. Before adding the asphalt emulsion, proportions of 0.5% and 1% asphaltenes by total mixture weight were also added to the RAP by previous research that suggested 1% as the ideal content for asphaltenes modification [32]. Three replicates were made for each asphaltenes content level (0.5% and 1%).

2.10 Performance Evaluation of the mixtures

2.10.1 Indirect Tensile Strength (ITS)

ITS test is used to determine the tensile strength properties of the asphalt mixture. ITS is also considered a cost-effective test as sample preparation and collection from the field, testing and analyzing the data is uncomplicated [78]. However, the tensile properties of the asphalt mixture are associated with the cracking properties; the higher ITS values correspond to a stronger cracking resistance [78]. Through the ITS test, the properties of asphalt mixtures, such as tensile strength, fatigue characteristics and permanent deformation, can be determined [79]. As mentioned earlier, the performance of the asphalt mixture to fatigue cracking depends on the tensile properties due to repeated traffic load on the pavement layers, which generates tensile stress and strains at the bottom of the pavement structure, leading to the fatigue failure of [79]. The stiffness of the asphalt mixture determines how much strain there will be. Hence, the ITS test results are used to measure the asphalt mixture's strength and resistance against fatigue failure, cracking, and rutting [79].

The tensile strength of the asphalt mixtures can be assessed using a Marshall specimen of approximately 100mm in diameter and 60mm thick by performing tests in a universal testing machine (UTM). The samples will be subjected to loading along a diametric plane with a constant compressive load at a rate of 50mm/min, acting parallel and along the vertical diametrical plane through two 13mm wide loading strips in both directions. This shows the sample testing and the sample after breaking. The compressive load applied to the sample will indirectly generate a tensile load along the horizontal axis of the sample [79]. The peak load recorded before the failure of the sample will be used to calculate the indirect tensile strength of the specimen using followed equation.

$$S_t = \frac{2000.P}{\pi.t.D}$$

where ,

S_t = indirect tensile strength (ITS), kPa

P = maximum load, N

t = average specimen thickness, mm

D = specimen diameter, mm

$$TSR = \frac{\mathbf{s1}}{\mathbf{S2}}$$

where,

TSR = Tensile strength ratio

S_1 = average tensile strength of the dry subset, kPa; and

S_2 = average tensile strength of the conditioned subset, kPa.

The indirect tensile strength test can be conducted using a universal testing machine (UTM) with Marshall Samples of dimensions approximately 100mm in diameter and 60mm in height. The dry samples can be tested directly at a 50 mm/min loading rate. For wet samples, it can be tested after 24 hours conditioned in a water bath.

The maximum load is recorded directly during testing, and the sample's indirect tensile strength is calculated. While for the freeze/thaw conditioning samples, the samples are preconditioned; the samples are first saturated, followed by plastic wrapping and frozen at a temperature of -18°C for approximately 16 hours; the samples are then placed inside a water bath at 60°C, the samples are then immediately removed from the plastic wrap and thawed at 60°C for 24±1 hour. After thaw conditioning, the specimens are transferred into a water bath at 25±0.5°C for 2 hours ±10 minutes. Finally, the samples are tested for indirect tensile strengths and the tensile strength ratio (TSR), which is a measure of resistance against moisture

2.10.2 IDEAL-CT Test

Asphalt pavement cracking is one of the main problems with asphalt mixture materials in North America and other parts of the world. In the past, different cracking tests for asphalt mixes have been developed to ascertain the cracking damage of an asphalt material; however, some of these tests are simple, practical, repeatable, efficient, and sensitive to asphalt mixtures [80]. The IDEAL-CT is considered one of the most cost-effective and time-efficient tests for cracking due to its simplicity, practicability, and repeatability. The IDEAL-CT has been designed as the ideal cracking test to determine the cracking resistance of asphalt material. The IDEAL-CT test is similar to the traditional indirect tensile strength test, where the test is run at 50 mm/min and room temperature using Marshall specimens (100 mm or 4 in diameter) or Superpave (150 mm or 6 in) samples with different thicknesses (38, 50, 62, 75 mm, etc.). Samples from the laboratory are generally prepared to have air voids of 7±0.5 percent. The cracking tolerance (CT-Index) is a parameter derived from the load-displacement curve of the samples after testing, and it is used to determine sample resistance against fatigue cracking. For the cracking resistance, the higher the CT index value of the sample, the higher the fatigue resistance of the sample [81]. The cracking tolerance of an asphalt sample depends largely on some parameters, which include the aggregate gradation used for the mix and air voids. If an additive is used, the additive type also affects the mix's CT-Index. Using the following equation, the CT-Index of a sample can be calculated.

$$\text{CT Index} = \frac{t}{62} * \frac{l75}{D} * \frac{Gf}{|m75|} * 10^{6}$$

where,

CT Index = cracking tolerance index

G_f = fracture energy, joules/m2

|m75| = absolute value of the post-peak slope, N/m

l_{75} = displacement at 75% of post-peak slope, mm

D = specimen diameter, mm

t = thickness of specimen, mm

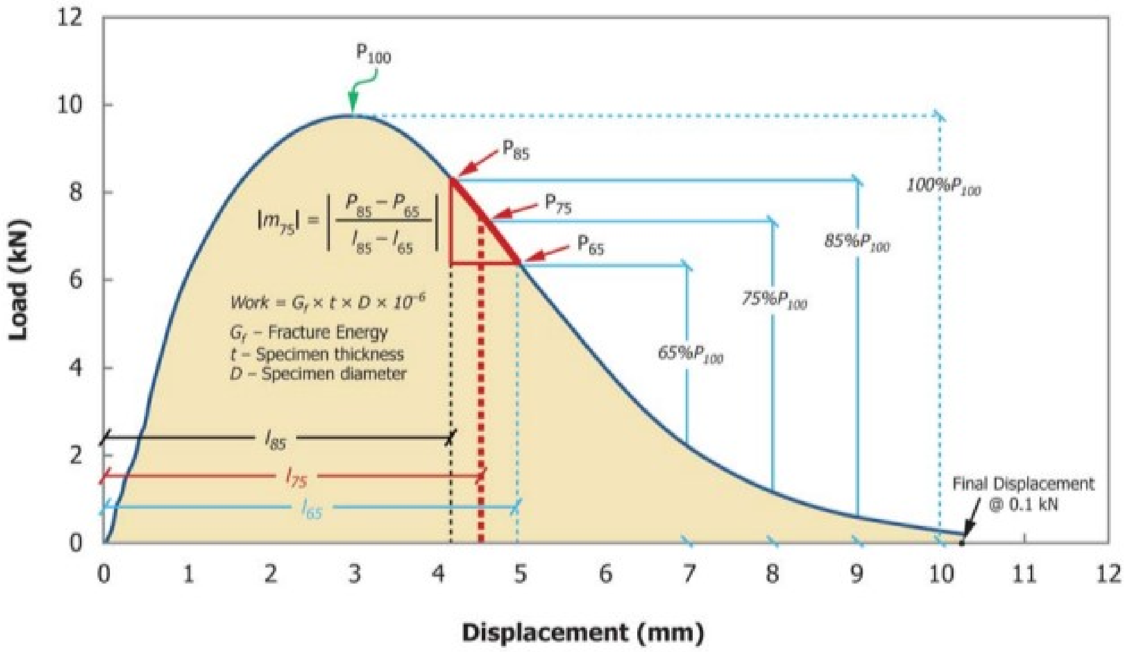

Figure 2-8: Recorded Load (P) versus Load-Line Displacement (l) Curve [82]

2.10.3 Creep Compliance and Indirect Tensile Test (IDT)

Creep compliance and indirect tensile tests (IDT) were developed to determine the resistance of asphalt mixtures to thermal cracking and have since proven to be the most accurate tool for predicting low-temperature results [83]. The rate at which strain increases for a continuous application of time-dependent strain per unit stress is measured by creep compliance.

AASHTO T322-07 [84] was used to evaluate the creep compliance and strength of the mixtures using an indirect tensile test setup to compare the low-temperature properties of different content of RAP samples with asphaltenes content. This test has demonstrated the effectiveness of the mixtures at low temperatures. For each of the RAP and asphaltenes contents, Marshall Samples with three replicates were prepared.

However, in this case, the samples' surface was cut to a height of 38 to 50mm. Considering the base layer and Performance grading (PG) of the binder used to prepare the asphalt emulsion, the test temperatures used in this analysis were 0°C, -10°C and -20°C. Before the inspection, samples were conditioned for 3±1 hours in an air chamber. The specimens were subjected to a fixed static load for 100±2 seconds, with LVDTs recording deformation in both the horizontal and vertical axes. After the creep test, the samples were subjected to an indirect tensile test at a rate of 12.5mm per minute before the failure point was reached. **Figure 2-9** depicts the test setup and test samples before and after processing. The load-deformation values obtained from the test were used to measure the samples' fracture energy and indirect tensile strength for both temperatures. Each asphalt mix's creep compliance [D (t)], tensile strength, and fracture energy were calculated.

The creep compliance was calculated as per Equation 2-3. The maximum load is used to determine tensile strength, which is then "adjusted" to indicate the "actual" tensile strength [83], using the following equation:

$$\mathbf{D_t = \frac{\Delta X_{tm,t} \times D_{avg} \times b_{avg}}{P_{avg} \times GL} \times C_{cmpl}}$$

where:

D_t = Creep compliance at time t (kPa),

GL = Gauge length in meters 25 × 10 $^{-3}$ for 100 mm diameter specimens),

D_{avg} = Average diameters (mm),

b_{avg} = Average thickness (mm),

P_{avg} = Average force (kN),

$\Delta X_{tm,t}$ = Trimmed mean of the $\Delta X_{i,t}$ arrays, (where the i = 6 arrays are sorted according to the sorting order from two faces data from each sample)

$$[0.704-(0.213*(\frac{bavg}{Davg}))] \leq C_{cmpl} \leq [1.556-(0.195*(\frac{bavg}{Davg})]$$

C_{cmpl} = Creep compliance correction factor, which is:

$$C_{cmpl} = 0.6345 \text{ X } (\frac{X}{Y})^{-1} -0.332$$

where,

$(\frac{X}{Y})$ = absolute value of the ratio of the normalized, trimmed mean of horizontal deformations to the normalized, trimmed mean of vertical deformations at time corresponding to half the total creep test time (typically 100 seconds) for all specimen faces.

$$S_{t,n} = \frac{2xpf}{\pi xbnxDn}$$

Tensile strength= $(0.78xS_{t,n})+38$(for psi)

Tensile strength= $(0.78xS_{t,n})+0.262$(for MPa)

where,

$S_{t,n}$ = “uncorrected” tensile strength of specimen, n

$P_{f,n}$ = maximum load observed for specimen, n

b_n = thickness of specimen, n

D_n = diameter of specimen, n

Figure 2-9: IDT test setup

2.10.4 Hamburg wheel tracking test (HWTT)

The Hamburg Wheel Tracking Test (HWTT) is a commonly used laboratory test to evaluate the resistance of asphalt mixes to rutting caused by repeated wheel loading. The HWTT is considered a reliable and repeatable test for evaluating the rutting resistance of asphalt mixes, and it is often used in research and quality control applications. The test measures the number of wheel passes required to cause a specified deformation or rutting in the specimen. The rutting test can be carried out in accordance with AASHTO T324-16 [85] specification using a cylindrical or slab sample; the test contains a small steel rolling wheel device of 705 ± 4.5 N, 47 mm wide, which rolls at a frequency of 52 ± 2 passes per minute and a maximum speed of 0.305 m/s at midpoint with an approximate distance of 230 mm across a submerged sample. The compacted air void content for the samples is 7.0 ± 0.5 percent. The test is carried out at a predetermined temperature, with the device set to track for 20,000 passes or until the sample reaches a rutting depth of 12 mm, whichever shows up first.

The Hamburg wheel tracking test, like the indirect tensile strength test, compares the moisture content of asphalt materials. A graph of rut depth versus the number of passes is plotted, which provides valuable information about the asphalt material's susceptibility to moisture damage by obtaining the stripping inflection point (SIP) as shown in Error! Reference source not found. which indicates the point at which moisture damage starts to take effect on the sample. The rutting resistance index (RRI) was determined by multiplying the number of passes by one subtracted by the rut depth in inches. The stripping inflection point (SIP) was determined to assess the mixtures' rutting potential and moisture damage susceptibility.

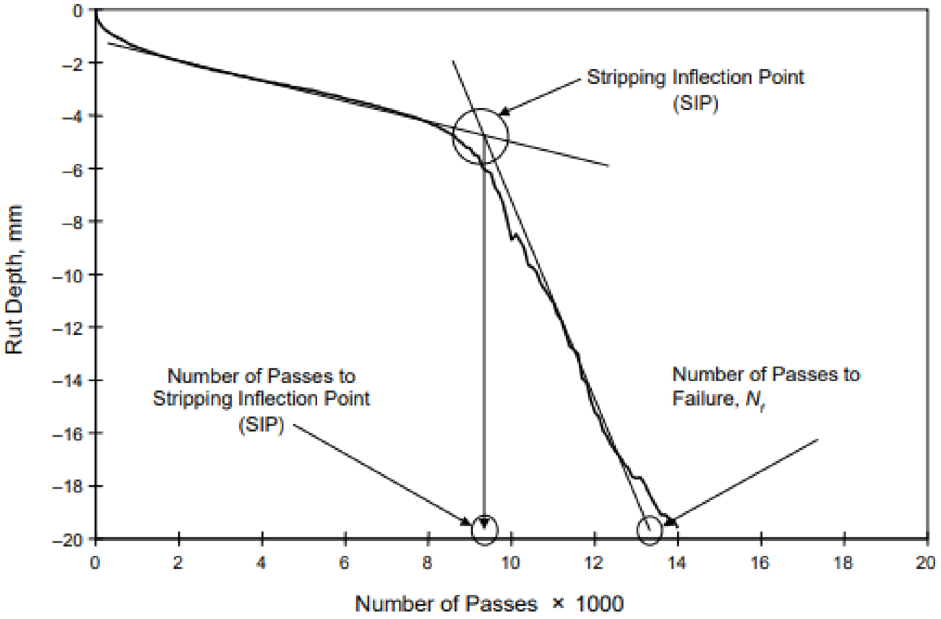

Figure 2-10: Hamburg Curve with Test Parameters [85]

It has been recommended that if an asphalt material SIP occurs at less than 10,000 load cycles, the sample may be highly susceptible to moisture-induced damage [86]. The consolidation point is defined as the rut depth attained in the sample during the first 1,000 loading cycle passes due to post-compaction consolidation. **Figure 2-11** presents the Hamburg wheel tracking test setup.

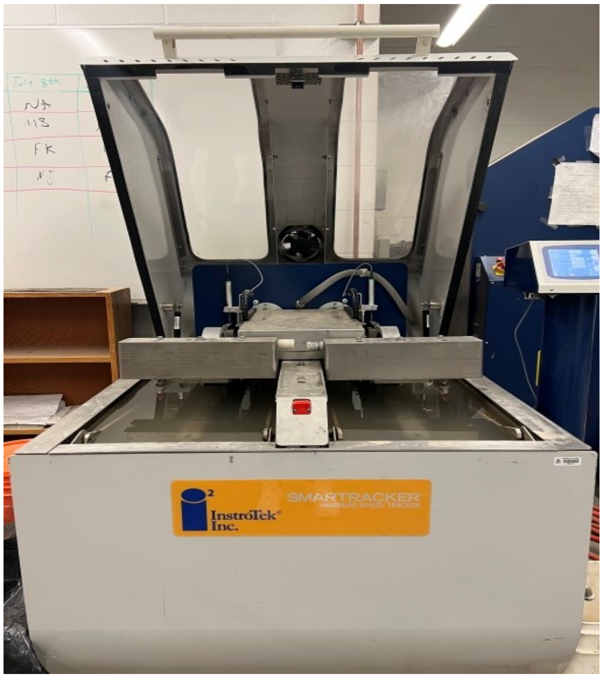

Figure 2-11: Hamburg wheel tracking test setup

Chapter3 : Evaluation of Mechanical Performance of Asphalt Emulsion Base Course Comprised of Reclaimed Asphalt Pavement (RAP) and Asphaltenes

3.1 Abstract

Reclaimed asphalt pavement (RAP) is a material that is produced by grinding up old asphalt pavement which can be mixed with virgin asphalt binder and aggregates to fabricate a recycled asphalt mixture. The use of reclaimed asphalt pavement is an important practice that promotes sustainability and reduces pavement construction costs. In this study, asphaltenes, which is a waste material collected from oil sands, was added as modifier to recycled mixtures fabricated with different contents of RAP. Proctor test was conducted to determine the optimum fluid content (OFC). Mix design was performed with asphalt emulsion and different asphaltenes contents in addition to the 50% RAP,75% RAP and 100% RAP. Mechanical properties of the modified mixtures were evaluated by conducting the indirect tensile strength test, creep compliance and strength test, indirect tensile cracking test (IDEAL-CT), and Hamburg wheel tracking test. Optimum emulsion content (OEC) was determined 1.5% based on sample performance using the indirect tensile strength test (ITS). The results obtained indicates that asphaltenes improves the strength up to design-specified limits, with the asphaltenes-modified samples showing lower creep compliance compared to the unmodified sample indicated better low-temperature performance. In addition, the fracture energy is found to be lower in the asphaltenes-modified mixtures resulted samples are more prone to cracking. Also, that asphaltenes-modified mixtures had better cracking resistance at intermediate temperature (25℃) and better rutting performance at high temperature (40 ℃) compared to the unmodified mixture. Overall, the 100% RAP mix with 1% asphaltenes had the best tensile strength, cracking resistance, rutting resistance performance.

3.2 Keywords

Pavement recycling; Cold asphalt mixture; Mixture performance; Cracking resistance; Permanent deformation.

3.3 Introduction

One of the most typical pavement distresses is a surface crack, which can spread with traffic loading and after moisture penetration causing more serious road problems [87]. As pavement ages, it loses its flexibility and becomes more prone to cracking [88]. This is especially true for asphalt pavements, which can become brittle over time. Pavements expand and contract with temperature changes, which can cause thermal cracking. Cracking such as alligator cracking, longitudinal cracking, block cracking, and edge cracking can lead to reduced pavement life, safety hazards, and increased maintenance costs [89].

Low-temperature cracking in asphalt pavement is a serious issue, especially in regions with extreme low-temperature weather conditions, such as the northern United States and Canada [38] [90]. At lower temperatures, tensile stresses build up within the pavement structure, leading to the initiation of thermal cracks [91]. In addition, the continuous traffic load on the distressed pavement and freeze/thaw dynamics during the spring season make the asphalt pavement structure more susceptible to further distress [38]. As a result, the pavement's durability and service life are significantly reduced [90]. In recent years, various research studies have been conducted to find a suitable solution to these challenges.

The cost of pavement construction can be significantly influenced by factors, such as the type of pavement material used, the size and scope of the project, and the availability of resources and labor [38]. The use of reclaimed asphalt pavement (RAP) is among the construction materials most frequently used in asphalt pavements [92]. The use of RAP is a potential solution that also helps the environment by reducing the carbon footprint of pavement construction. RAP material is typically generated from the milling or removal of old asphalt pavement from roadways, parking lots, or other paved surfaces [93]. The history of asphalt pavement recycling dates to the early-20th century [59], although the use of RAP in the asphalt paving industry became particularly popular in the United States in the 1970s during the oil embargo, when the cost of crude oil had skyrocketed [16], RAP is a suitable alternative to virgin materials because it reduces the use of virgin aggregate and the amount of virgin asphalt binder required in the production of asphalt mixes [94], Using RAP in pavement construction has become a relatively common practice, as it is both an environmentally and an economically attractive approach [94], In fact, the use of RAP in new asphalt pavement is considered to be an environmentally sustainable practice [94]. However, the use of RAP does require proper processing and handling to ensure that the resulting pavement meets the desired quality and performance requirements [95].

RAP has gained popularity also because of its ability to significantly reduce the pollution caused by pavement Cold recycling (CR) is a method of rehabilitation of flexible pavements in need of repair due to structural defects [96]. The cold in situ recycling process is a more efficient method than hot recycling, as the CR process is more environmentally friendly [97]. Furthermore, CR technology has proved to be significantly beneficial to the construction process in terms of safety, technical, and economic aspects [96]. Most of the materials used in CR can be recycled on site, resulting in less hauling of material to the construction site, and the bituminous mixture does not need to be heated to a high temperature. As a result, the use of CR can reduce the emission of greenhouse gas and lower the noise level produced by heavy vehicles and equipment [96].

The use of RAP in asphalt mixtures at different percentages ranging from 10% to 100% has been investigated in previous studies [98]. RAP concentrations typically depend on the gradation, the properties of the extracted aggregates, and the properties of the recovered binders [99]. For instance, using a high RAP content may alter the properties of the blended binder, resulting in an overly stiff mix that may be vulnerable to low-temperature cracking. A further concern is that an overly stiff mix will not be as durable and may lead to premature crack propagation in pavements with significant deflections [16]. With regard to the economic aspect, the use of high concentrations of RAP in asphalt mixtures can drive up project costs due to the need for additional material testing, higher processing costs, the need for plant modifications, and increased plant maintenance costs [94]. RAP normally makes up less than 50% of the total aggregates in the mixture, depending on the thickness of the asphalt layer [95].

For the rehabilitation of existing flexible pavement, the Full Depth Reclamation (FDR) technology has been gaining popularity [100]. Most of the issues associated with aging asphalt pavements can be resolved through the use of FDR technology [101]. FDR is the technique of in-situ grinding and blending of all the layers of an asphalt pavement, as well as some or all of the underlying base materials, to produce a homogenous material for surface course applications [102]. Given that it uses less virgin base course materials (virgin aggregates), thereby necessitating less disposal of materials, FDR is a cost-effective technique for constructing or rehabilitating pavement [103]. Full-depth reclamation increases a pavement's bearing capacity and structural strength and stability, extends its service life, and improves pavement service life [104]. Such a layer is typically composed of RAP, recycled base material, cement (2% to 6% by weight of total aggregates), and water (optimum content for compaction).

In recent years, the use of asphalt emulsion in pavement construction and preservation treatment tasks such as slurry seals, chip seals, micro-surfacing, fog seals, and tack coats has also gained popularity [65]. Asphalt emulsions have a stable dispersion under storage, mixing, and pumping, where the emulsion breaks down and forms an asphalt layer around the aggregate particles when it comes into contact with them [105] [106]. Today, more than 8 million tons of asphalt emulsion are produced worldwide each year [107]. AAs noted above, over the years, researchers have conducted experiments to evaluate asphalt emulsions containing different content levels of RAP [108]. In the CIR process, an asphalt emulsion is typically used as a binding agent to help mix the recycled materials together and create a new asphalt mixture. The recycled materials, which typically include RAP and any existing base materials, are first milled or pulverized in place to create a new aggregate base. Asphalt emulsion is then added to the recycled material to bind it together and create a new pavement layer. The asphalt emulsion used in CIR typically contains a high level of recycled materials and other additives, such as polymers or rejuvenators, which help improve the performance and durability of the new pavement [109]. The emulsion is typically sprayed onto the recycled material in a controlled manner to ensure that the right amount of emulsion is added to the mixture. The use of asphalt emulsion in CIR can provide several benefits, including reduced costs, improved environmental sustainability, and the preservation of natural resources [110]. Additionally, the use of asphalt emulsion in CIR can help improve the overall quality of the new pavement, as the emulsion can help create more stable and durable pavement layers [96]. Also, asphalt emulsion improves RAP's flexibility, cohesiveness, and resistance to permanent deformation during cold recycling, although these materials may be more prone to rutting in slow-moving traffic. One of the notable benefits of asphalt emulsions is that they significantly reduce the viscosity of asphalt at lower temperatures.

Saturates, asphaltenes, resins, and aromatics, referred to collectively with the acronym "SARA", are the four primary fractions that constitute asphalt binder [106]. Asphalt binder is further categorized into polar and non-polar components, the polar fractions being resins and asphaltenes, and the non-polar fractions being aromatics and saturates [111]. Asphaltenes are a complex mixture of organic compounds that are found in crude oil, bitumen, and other petroleum products. They are a heavy, high-molecular-weight fraction of the petroleum distillate that is insoluble in n-heptane, but soluble in aromatic solvents such as toluene, xylene, and benzene [112]. Asphaltenes are known for their complex and varied chemical structures, which include a range of fused-ring polycyclic aromatic hydrocarbons (PAHs), heteroatom-containing compounds (such as nitrogen, sulfur, and oxygen), and other functional groups [113]. Additionally, asphaltenes can affect the performance and properties of asphalt binders used in pavement construction. The amount and type of asphaltenes in asphalt binders can affect the binder's viscosity, stiffness, and durability, which can, in turn affect the overall performance and lifespan of the pavement [114]. Asphaltenes are produced in the process of deasphalting bitumen and are considered a waste material with no significant application in current practice [115].

RAP is a valuable resource in pavement construction, but its use can impact the properties of asphalt mixtures, including stiffness, fatigue resistance, and rutting potential. Asphaltenes are also known to impact the properties and performance of asphalt binders, however their effects on asphalt mixtures are not fully understood. Therefore, the aim of this study is designing cold asphalt mixtures with different RAP concentrations (recycled asphalt mixtures) using asphalt emulsion and asphaltenes followed by evaluating the performances of the designed mixtures through different mechanical tests. The low-temperature, intermediate temperature and high temperature properties of the designed mixtures were compared to the unmodified (control) mixtures by conducting indirect tensile strength (ITS), creep compliance and strength tests, indirect tensile cracking test (IDEAL-CT) and Hamburg wheel tracking test.

3.4 Methodology

This experimental study was conducted in three stages. The first phase involved choosing the aggregate gradation, and determining the optimum emulsion content (OEC), and optimum moisture content (OMC) for compaction. In the second stage, ITS was performed to evaluate the strength and stability of the mixtures prepared. In the third stage of the study, TSR tests for both, saturated and freeze/thaw (F/T) samples, IDEAL CT- Index as well as Hamburg wheel tracking tests, were conducted in order to evaluate the performance properties of the mixtures. **Figure 3-1** shows the flow-chart for the experimental program.

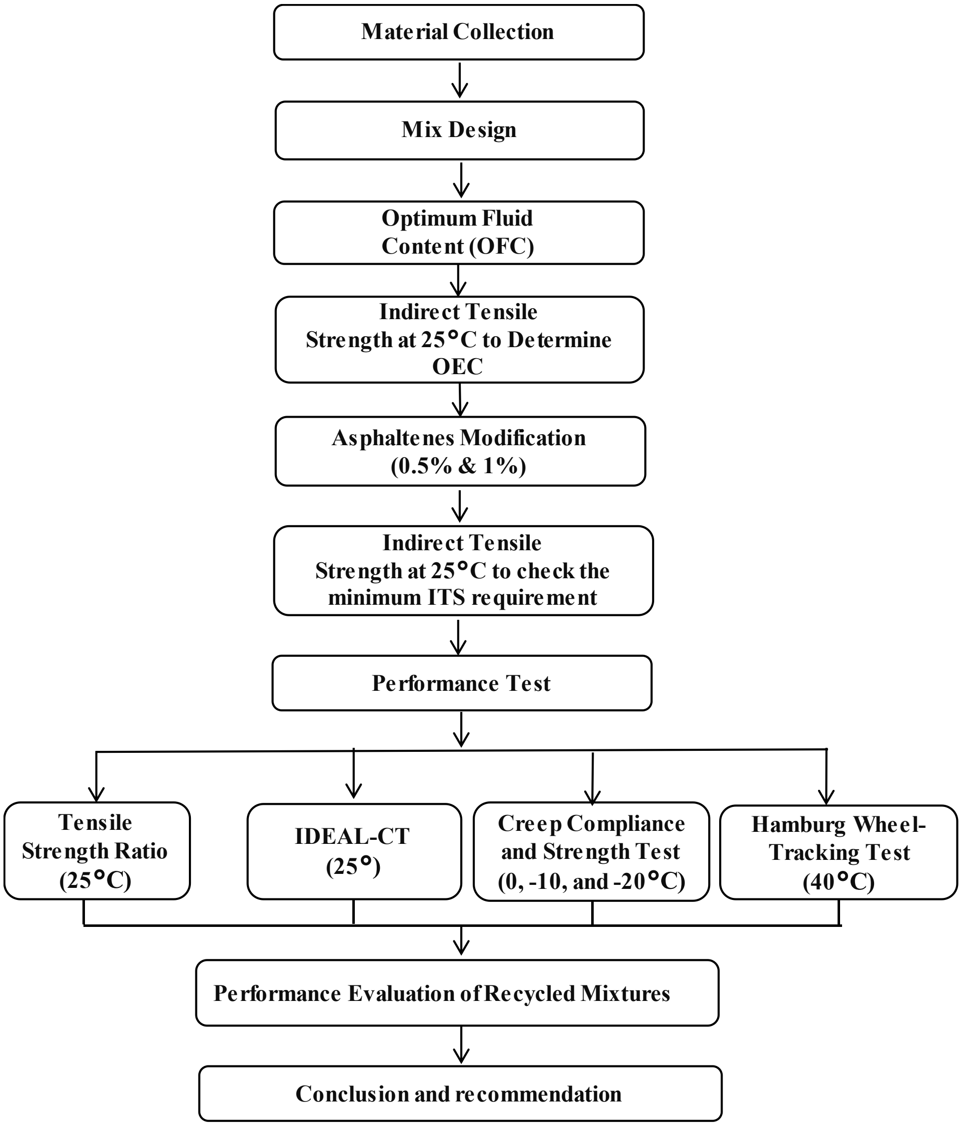

Figure 3-1: Flow-chart of the experimental program

3.5 Materials and methods

3.5.1 Aggregates

The aggregate selected for the laboratory work is single sourced which was obtained from Lafarge Canada. The selected aggregate gradation was within the Wirtgen Cold Recycling Manual [66] and City of Edmonton [116]recommended envelopes. The requirements were met by selecting a well-graded aggregate gradation. Aggregate gradation and the physical properties of the aggregates are shown in **Table 3-1**. The optimal moisture content was determined before mixing using the proctor test in accordance with ASTM D698 [117].

Table 3-1: Aggregate Properties

Characteristics	**Test Methods**		**Value**	**Limit**
	ASTM[1]	**AASHTO**[2]		
Amount of material finer than 75-µm (No. 200) sieve in aggregate	C117	T11	6%	2-9%
Specific gravity and water absorption of fine aggregates	C128	T84	2.604 0.624%	-
Specific gravity and absorption of coarse aggregates	C127	T85	2.598 0.870%	-
Los Angeles abrasion of coarse aggregates	C131	T96	23%	Max 40%
Compactability test (Proctor test)	Modified D1 557	Modified T180	6.3% water	-
			15.4 max. dry Density	-

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[1] American Society for Testing and Materials (ASTM)

[2] American Association of Highway and Transportation Officials (AASHTO)

3.5.2 Reclaimed Asphalt Pavement (RAP)

The RAP material was collected from the Acheson stockpile. The extracted binder is analyzed using a dynamic shear rheometer (DSR) in original, rolling thin film oven aged (RTFO), and pressure ageing vessel (PAV) conditions, as well as specific gravity and penetration tests. Binder and aggregates tests were performed on the provided material, and the results are provided in

Table 3-2. The grain size distributions for mixtures with 100%, 75%, and 50% RAP replacement are shown in **Figure 3-2.**

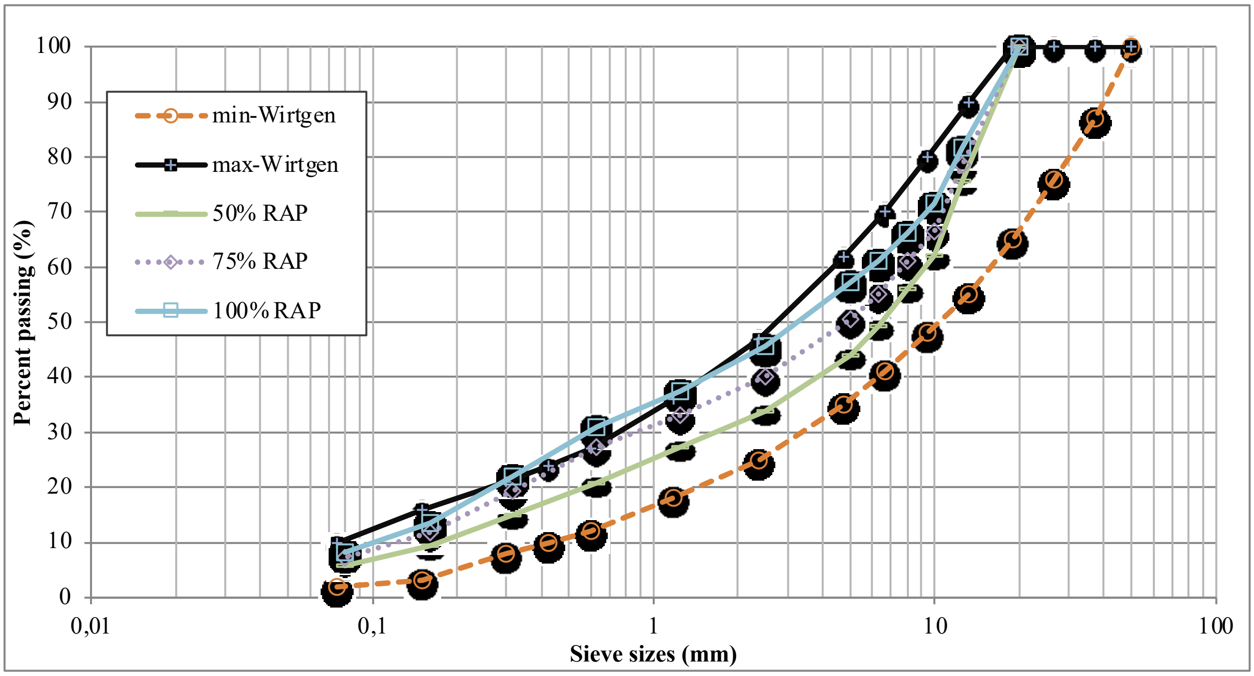


Figure 3-2: Gradation size distribution of the recycled mixes with RAP

Table 3-2: RAP binder properties

Test Name	**AASTHO**	**ASTM**	**Test Temperature (°C)**	**Test Result**	**Unit**	**Pass/Fail**
Original RAP Binder						
Specific Gravity	T228	D70	25	1.05		
			15	1.05		
Penetration	T49	D5	25	53.6	mm/10	
RTFO Residue						
Dynamic Shear Rheometer	T315	D7175	76	2.7	kPa	Pass
			82	1.4	kPa	Fail
Predicted Failure Temp				77.8	℃	
PAV Residue						
Aging Temperature	R28	D6521		100	℃	
Dynamic Shear Rheometer	T315	D7175	19	4049.3	kPa	Pass
			16	5084.2	kPa	Fail
Predicted Failure Temp				16.2	℃	
Bending Beam Rheometer (Creep)	T313	D6648	-18	142.0	MPa	Pass
			-24	322.0	MPa	Fail
Predicted Failure Temp				-33.5	℃	
Bending Beam Rheometer (Slope)	T313	D6648	-18	0.3		Pass
			-24	0.2		Fail
Predicted Failure Temp				-28.5	℃	
Performance Grade (PG)				76-28	℃	

3.5.3 Asphalt Emulsion

The asphalt emulsion used for base stabilization in this research is a cationic slow setting (CSS), (which contains 61% asphalt and 39% water) according to Wirtgen Cold Recycling Manual [66], as it requires the least amount of time for mixing and placing the base layer as well as the aggregates charge. According to ASTM D6937 [118], the emulsion has a specific gravity of 1.02 and a viscosity of 22 Saybolt Furol seconds (SFS), at 25°C. Table 3 provided the physical properties of asphalt emulsion. **Table 3-3** provided the physical properties of asphalt emulsion.

Table 3-3: Physical properties of asphalt emulsion [119]

Property	Standard ASTM/AASHTO	Specification		Typical Analyses
		Minimum	Maximum	
Tests on asphalt emulsion				
Specific gravity (Density) at 15.6˚C, kg/L	D6937/T59	-	-	1.020
Residue by distillation, % by mass	D6997/T59	57	-	61
Viscosity at 25˚C, S.F.S	D7496/T59	20	100	22
Oversized particles (sieve), % by mass	D6933/T59	-	0.3	0.008
Settlement (24 hours), % by mass	D6930/T59	-	1.0	0.5
Particle charge test	D7402	Positive	Positive	
Tests on residue				
Penetration at 25˚C (100 g, 5 s), d_{mm}	D5/T49	40	125	95
Ductility at 25˚C (5 cm/min), cm	D113/T51	40	-	>40
Solubility in Trichloroethylene, % by mass	D2042/T44	97.5	-	>97.5

3.5.4 Asphaltenes

Asphaltenes derived from Alberta oil-sand bitumen was used in this study. It was obtained in the powder form. Asphaltenes were sieved through a No. 100 sieve to achieve equal dispersion during the mixing process. The asphaltenes content of the sample was 79.62%, while the contents of saturates, aromatics, and resins were 6.85%, 9.68%, and 3.84%, respectively, according to the SARA test [120].Properties of asphaltenes provided in the **Table 3-4.**

Table 3-4: Properties of Asphaltenes [121]

Property	Standard	Typical analysis (Values)
Origin of Sample	-	Cold Lake bitumen
Bulk Density, kg/m³	-	403.6
True Density, kg/m³	-	1135
Gross Calorific Value, MJ/kg	ASTM D5865	38.6
Net Calorific Value, MJ/kg	-	36.4
MCR (Micro Carbon Residue), Wt%	ASTM D4530	37.2

3.6 Mix Design Procedure

3.6.1 Determining Optimum Fluid Content Using Proctor Test

The Proctor test was performed in accordance with ASTM D1557-12 [122] to determine the optimum fluid content (OFC) of the mixtures. After cooling down RAP and aggregates to room temperature from an overnight oven-drying at 110˚C, different water contents were added to mixtures with 100%, 75%, and 50% RAP. In a Proctor test mould, mixtures were compacted in 5 layers with 56 blows of compaction on each layer. Based on the specifications, a modified Proctor test hammer with a standard mass of 4.5 kg was used. **Table 3-5** shows the OFC value at which maximum dry density (MDD) was achieved.

Table 3-5: Proctor test results for different RAP content

RAP Content	Optimum fluid content (OFC) (%)	Maximum dry density(kN/m^3)
50%	5.1	21.20
75%	5.0	18.69
100%	4.9	17.46

3.6.2 RAP and Aggregate Mix Design Procedure

Technical guideline (TG2) [123] was adopted to design the stabilized mixtures with RAP and aggregate. The amount of asphalt emulsion added to the mixtures was determined using the OFC from the Proctor test. Different emulsion concentrations (1%, 1.5%, 2%, and 2.5%) were added to mixtures fabricated with various RAP contents, and the optimum emulsion content (OEC) was determined based on sample performance using the indirect tensile strength test (ITS). Materials were oven-dried overnight at 110°C and then cooled down to room temperature before mixing. The mixing process was initiated by adding water and asphalt emulsion to the mix of RAP and aggregates. Samples were mixed until the asphalt emulsion was uniformly distributed. Then, the mixture was compacted using 50 blows of a Marshall hammer on each side of the sample. Compacted samples were cured in an oven for 48 hours at 60°C and then removed from the moulds.

3.6.3 Indirect Tensile Strength (ITS)

AASHTO T283 [124] was followed for conducting the ITS test for determining optimum emulsion content. Three replicates for the dry sample and three replicates for wet samples were prepared to determine ITS with each content of asphalt emulsion. After mixing the samples, they were cured for 48 hours at 60℃ according to Asphalt Recycling and Reclaiming Association (ARRA) [76]. Three dry samples were subjected to conditioning at a controlled temperature which was 25℃ for three hours in an environmental chamber, and three wet samples were soaked at 25℃ in the water bath for 24 hours. After conditioning, the samples were tested together with vertical monotonic load with a loading rate of 50 mm/min. To determine the ITS, the maximum load that was applied to the samples prior to failure was recorded. Using following equation, the ITS for each sample was then calculated.

$$S_t = \frac{2000.P}{\pi.t.D}$$

where: S_t = Indirect tensile strength (kPa), P = Maximum applied load (N), t = Average height of the specimen (mm), D = Diameter of the specimen (mm).

3.6.4 Asphaltenes Modification and Samples Preparation

Throughout the study, the asphaltenes-modified mixes were prepared using an OEC of 1.5% by weight of the total mixture. The control samples and the ones modified with asphaltenes were prepared similarly to the design samples for OEC. A similar process for the preparation of the mixture was followed as a mix design process with the difference of adding the asphaltenes to the mixtures before adding water and emulsion. The compaction, mixing, and curing processes were similar to the process explained before in RAP and aggregate mixing design. The RAP material was mixed with asphalt emulsion and water after being added with asphaltenes and dried at 110°C and cooled down to room temperature, according to the results of the mix design test. Before adding the asphalt emulsion, proportions of 0.5% and 1% asphaltenes by total mixture weight were also added to the RAP in accordance with previous research that suggested 1% as the ideal content for asphaltenes modification [125]. For each asphaltenes content level (0.5% and 1%), three replicates were made.

ITS test has been conducted on all six samples in dry and wet conditions. This dry and wet samples were cured at 60 ˚C for 48 hours and wet samples were conditioned for 24 hours in water bath before testing. Three extra samples for Freeze/ Thaw were prepared for control (no asphaltenes) and modified samples by conditioning them in a water bath at 25˚C for 24 hours and then transferring them to a freezer for a minimum of 16 hours at -18±3˚C inside a plastic bag. Following the freezing process, samples were moved to another water bath at 60±1˚C for 24 hours and finally conditioned in a different water bath at 25℃ for 2hrs before testing. Samples were labelled as EX-AY, "E" indicates the asphalt emulsion, "X" is the percentage of emulsion added, "A" indicates asphaltenes and "Y" is the percentage of the asphaltenes added to the mix. For example, E1.5-A0.5 means emulsion content were 1.5% and asphaltenes content were 0.5%.

3.7 Testing Program

3.7.1 Tensile Strength Ratio (TSR)

The ITS test was conducted in accordance with the AASHTO T283 standard [124] for dry, wet, and freeze/thaw conditions. At each of the asphalt emulsion contents, nine replicates of the samples (3 replicates for dry, 3 replicates for wet, and 3 replicates for freeze/thaw) were made. The Marshall hammer was then used to compact the samples with 50 blows according to the same process as previously. Prior to testing, the dry samples were kept for three hours in an air chamber at 25°C. For soaked samples, conditioning in a water bath for 24 hours at 25°C was done before using the AASHTO T283's [124] freeze/thaw procedure. The freeze–thaw conditioning was carried out by storing the samples in a freezer at −18°C for 16 hours after saturation in water for 24 hours at 25°C and then conditioning them in a water bath at 60°C for 24 hours. A similar method for loading followed as ITS and strength were calculated. TSR was calculated using the following equation.

where:

$$TSR = \frac{S_1}{S_2}$$

TSR = Tensile strength ratio

S_1 = average tensile strength of the conditioned subset, kPa; and

S_2 = average tensile strength of the dry subset, kPa.

3.7.2 CREEP COMPLIANCE AND INDIRECT TENSILE TEST

According to AASHTO T 322 [126] creep compliance is defined as the time-dependent strain divided by the applied stress. Creep compliance and ITS are the two main inputs to the low-temperature or thermal cracking module. For this experiment, the AASHTO T 322 [126] test procedure was used as a reference. This test simulates the low-temperature performance of mixtures by recording the constant load applied and the corresponding horizontal and vertical deformation of the samples for a given period of time. Given the performance grading of the binder used to prepare the asphalt emulsion in this study (i.e., PG 76-28), the test temperatures used were 0 °C, -10°C, and -20°C. Nine Marshall samples (3 replicates for each test temperature) for each of the asphaltenes content levels were prepared with different concentrations of RAP. The compacted samples were surface-cut to the height range of 38 mm and 50 mm. According to the standard, the samples were conditioned in an environmental chamber for 3±1 hours to bring them to the selected test temperature prior to testing. Four Linear Variable Differential Transducers (LVDTs) were used to record the vertical and horizontal creep displacements for 100 ± 2.5 s. Once the creep test had been completed at each test temperature, the tensile strength test was conducted by applying a compressive load to the specimen at a rate of 12.5 mm of ram (vertical) movement per minute. The ITS, fracture energy (FE), creep compliance, and Poisson ratio values were then calculated. Creep compliance was calculated using the following equation.

$$D_t = \frac{\Delta X_{tm,t} \times D_{avg} \times b_{avg}}{P_{avg} \times GL} \times C_{cmpl}$$

where:

D_t = Creep compliance at time *t* (kPa),

GL = Gauge length in meters 25×10^{-3} for a 100 mm diameter specimens),

D_{avg} = Average diameters (mm),

b_{avg} = Average thickness (mm),

P_{avg} = Average force (kN),

$\Delta X_{tm,t}$ = Trimmed mean of the $\Delta X_{i,t}$ arrays, (where the i = 6 arrays are sorted according to the sorting order from two faces data from each sample)

C_{cmpl} = Creep compliance correction factor, which is:

$$C_{cmpl} = 0.6345 \times \left(\frac{X}{Y}\right)^{-1} - 0.332$$

$$\left[0.704 - 0.213\left(\frac{bavg}{Davg}\right)\right] \leq C_{cmpl} \leq \left[1.556 - 0.195\left(\frac{bavg}{Davg}\right)\right]$$

where $\left(\frac{X}{Y}\right)$ = absolute value of the ratio of the normalized, trimmed mean of horizontal deformations to the normalized, trimmed mean of vertical deformations at the time corresponding to half the total creep test time (typically 100 s) for all specimen faces.

$$S_{t,n} = \frac{2.P_{f,n}}{\pi.b_n.D_n}$$

Tensile strength = $(0.78 \times S_{t,n}) + 0.262$ (for MPa)

where:

$S_{t,n}$ = "uncorrected" tensile strength of specimen, n (kPa)

$P_{f,n}$ = maximum load observed for specimen, n (N)

b_n = thickness of specimen, n (mm)

D_n = diameter of specimen, n (mm)

The load–displacement graph could then be generated based on the ITS data. An object's resistance to crack growth, or toughness, it should be noted in this regard, is dependent on the energy absorbed as the crack advances, i.e., the FE (represented as G_f in Eq. 6). FE (in J/m^2) was determined from the ratio of the area under the load versus the displacement curve using the following equation:

$$G_f = \frac{W_f}{D.t} \times 10^6$$

where:

G_f = failure energy (J/m^2),

W_f = work of failure (J),

D = specimen diameter (mm), and

t = specimen thickness (mm).

3.7.3 IDEAL-CT Analysis

The IDEAL-CT was analyzed for both control and asphaltenes-modified mixes based on ASTM D8225-19 [82] standard. This specification was also used to calculate the cracking tolerance index (CT-Index) based on the fracture energy theory. The CT-Index was calculated from fracture energy (G_f), which has a proportional relationship to the CT Index.

$$CT_{Index} = \frac{t}{62} \times \frac{L_{75}}{D} \times \frac{G_f}{|m_{75}|} \times 10^6$$

where:

CT-Index = Cracking tolerance index;

G_f = Failure energy (Joules/m^2);

$|m_{75}|$ = Absolute value of the post-peak slope m75 (N/m);

L_{75} = Displacement at 75% post-peak load (mm);

D = Specimen diameter (mm);

t = Specimen thickness (mm);

The fracture energy provides an indication of the crack propagation within asphalt pavement at low service temperatures. The work of fracture (W_f) is estimated as the area under the load-displacement curve. The fracture energy (G_f) is calculated by dividing the W_f by the cross area of the specimen (D multiplied by t).

$$G_f = \frac{W_f}{G_f} \times 10^6$$

where:

G_f = failure energy (Joules/m^2),

W_f = work of failure (Joules),

D = specimen diameter (mm), and

t = specimen thickness (mm).

3.7.4 Hamburg Wheel Track Test

The Hamburg wheel tracking test is used to determine the rutting resistance of asphalt mixes. Rutting test can be performed in accordance with AASHTO T324-19 [85] specification using a cylindrical or slab sample (Dimensions of 400 mm (length), 300 mm (width), and 80 mm (height) for the current mix), the test contains a steel rolling wheel device of 705 ± 4.5 N, 47 mm-wide which rolls at a frequency of 52 ± 2 passes per minute and a maximum speed of 0.305 m/s at midpoint with an approximate distance of 230 mm across a submerged sample. The test is conducted at a predefined temperature, and the device is set to track for 20,000 passes or until the sample reaches a rutting depth of 12.5 mm, whichever is achieved first. Similar to the indirect tensile strength test, the Hamburg wheel tracking test is also used for comparative moisture evaluation of asphalt materials.

3.8 Result and Discussion

3.8.1 Determining Optimum Emulsion Content (OEC)

After considering the findings from both the ITS dry and ITS wet tests, optimum 1.5% asphalt emulsion per weight of the total mixture for OEC was selected. According to the technical guideline (TG2) [123], the lower limit for asphalt emulsion-stabilized material was determined to have a minimum value of 225 kPa and 125 kPa for ITS dry and ITS wet, respectively. Based on the higher value of the ITS dry and ITS wet with the lowest amount of asphalt emulsion, OEC was selected. In accordance with the TG2 [123] and Wirtgen cold recycling guidelines [66], the tensile strength ratio (TSR) was also adjusted. In **Table 3-6** ITS dry and wet results presented for each RAP content.

Table 3-6: ITS dry and wet results for each content of RAP

RAP Content	Asphalt emulsion content (%)	ITS dry (kPa)	ITS wet (kPa)	Standard deviation (ITS dry)	Standard deviation (ITS wet)
50%	1	194.63	161.76	4.06	6.36
	1.5	207.67	191.11	6.40	6.97
	2	210.43	199.03	11.42	11.01
	2.5	189.60	179.11	3.00	11.20
75%	1	141.73	109.94	6.56	5.16
	1.5	137.81	133.58	9.27	9.96
	2	135.06	115.93	4.16	11.65
	2.5	139.92	132.39	14.22	3.69
100%	1	125.51	100.01	6.12	4.64
	1.5	143.23	110.13	5.29	1.33
	2	138.91	156.44	0.78	7.49
	2.5	137.03	166.01	4.97	0.25

3.8.2 Indirect Tensile Strength (ITS) test results

Table 3-7 presents the ITS test results showing a significant improvement in the strength of the samples modified with asphaltenes, resulting in them passing the minimum limits for the design. Both 50% with 0.5 and 1% asphaltenes samples pass the design limits, and asphaltenes increase the strength by about 38% and 35% compared to the control samples, respectively. This increase for the 75% RAP with 0.5 and 1% asphaltenes were 54% and 63% compared to the control samples. For 100% RAP, an increase of 48% and 57% were seen compared to the control samples, respectively.

Wet TSR results for the control samples of the 50%, 75%, and 100% RAP were reported to be 92%, 96.9%, and 76.9%, respectively. These values decrease for 0.5% asphaltenes compared to their control samples in each RAP content to 76.7%, 77.9%, and 68.5%, respectively. However, there was a sharp increase of 1% asphaltenes compared to the control samples in each RAP content to 89.9%, 97%, and 92.3%, respectively. All of the saturated TSR values passed the 50% threshold, with the lowest being 68.5%, which shows that samples are not susceptible to moisture damage based on this test, but further analysis using other moisture tests like the Hamburg wheel tracking test is required. Freeze and thaw conditioned samples value about 36.1%, 50.4%, and 61.1% for control samples of the 50%, 75%, and 100% RAP. However, adding asphaltenes had some improvement in the freeze and thaw conditioned of 50% RAP materials. This value increased to 41.4% and 59.4% of the control sample for 0.5% and 1% asphaltenes. For 75% RAP, there was a decrease to 48.4% and 42.5% for 0.5% and 1% asphaltenes. 100% RAP mixtures had a decrease in TSR freeze and thaw values for 49.7% and 49.3% for both 0.5% and 1% asphaltenes.

Table 3-7: ITS and TSR test results for different content of RAP

RAP content	Sample ID	ITS Dry (kPa)	ITS wet (kPa)	ITS F/T (kPa)	TSR Saturated	TSR Freeze/Thaw
50%	E1.5	207.6	191.1	74.9	0.92	0.36
	E1.5-A0.5	287.2	220.3	118.8	0.77	0.41
	E1.5-A1	280.4	252.2	166.7	0.90	0.59
75%	E1.5	137.8	133.5	69.4	0.97	0.50
	E1.5-A0.5	212.7	165.7	102.9	0.78	0.48
	E1.5-A1	224.9	217.4	96.1	0.97	0.42
100%	E1.5	143.2	110.1	87.5	0.76	0.61
	E1.5-A0.5	212.3	145.3	105.4	0.68	0.49
	E1.5-A1	225.1	207.9	207.9	0.92	0.49

3.8.3 CREEP COMPLIANCE AND STRENGTH TEST

Creep compliance is a fundamental property that determines the strain or stress development in flexible pavements or damage evolution in asphalt mixtures. Creep compliance captures the extent to which a material will deform over time under a constant load and predicts the time to failure of a material under long-term loading. This can affect the long-term performance of materials used in low-temperature applications in cold regions. In the present study, creep compliance tests were conducted in accordance with AASTHO T-322 [126] at temperatures of 0°C, -10°C, and -20°C for both modified and unmodified mixtures with each RAP content. The ITS and FE values calculated using the load–deformation graphs for the samples at different temperatures presented in the **Table 3-8** and **Table 3-9**.

Table 3-8: Tensile strength for creep samples

RAP content	**Sample ID**	**ITS (kPa)**			**Standard deviation**		
		0 °C	**−10 °C**	**−20 °C**	**0 °C**	**−10 °C**	**−20 °C**
50%	E1.5	681.54	934.68	862.84	37.5	108.6	80.8
	E1.5-A0.5	776.24	940.73	983.83	12.5	49.6	84.8
	E1.5-A1	741.58	807.93	914.51	48.0	57.1	135.8
75%	E1.5	611.00	753.80	849.42	24.1	6.2	205.6
	E1.5-A0.5	680.75	749.83	893.56	43.8	131.4	46.6
	E1.5-A1	712.90	805.03	838.50	57.5	56.5	15.2
100%	E1.5	N/A	611.72	711.09	N/A	53.5	187.2
	E1.5-A0.5	585.80	648.31	745.27	15.4	211.0	16.6
	E1.5-A1	606.37	646.17	761.18	42.5	2.79	112.4

Table 3-9: Fracture energy results for creep samples

RAP Content	Sample ID	Fracture Energy(J/m^2)			Standard deviation		
		0 °C	−10 °C	−20 °C	0 °C	−10 °C	−20 °C
50%	E1.5	1,345.82	2,166.54	2,189.06	195.9	267.1	243.
	E1.5-A0.5	1,499.58	1,501.86	1,483.03	22.0	199.6	351.0
	E1.5-A1	1,618.18	1,361.01	1,383.71	186.0	121.1	329.4
75%	E1.5	1,237.77	2,055.51	1,990.79	199.1	82.1	204.5
	E1.5-A0.5	1,362.58	1,867.15	1,289.28	124.1	227.0	166.0
	E1.5-A1	1,608.74	1,961.02	1,391.07	99.8	642.7	60.1
100%	E1.5	N/A	1718.69	1738.46	N/A	265.4	127.5
	E1.5-A0.5	1622.39	2441.85	1702.17	204.5	483.8	157.8
	E1.5-A1	1030.24	1053.51	1298.66	134.2	87.2	117.8

Looking at the ITS results at 0 °C, it can be observed that the maximum failure load and FE increased slightly for both mixtures (50% RAP content and 75% RAP content) also for 100% RAP, control samples underwent the creep test at 0°C has failed under the loading before starting the strength test, there was no data reported for 100% RAP with no asphaltenes. Increases in tensile strength of 14% and 9% and increases in FE of 11% and 17% were observed in the unmodified 50% RAP samples with 0.5% and 1% asphaltenes, respectively. This finding suggests that, in some cases, asphaltenes-modified samples are more resistant to cracking, given the higher FE at 0°C for 50% RAP, in the case of the modified mixture compared to the control mixture. However, for the 75% RAP, the results indicate that asphaltenes had a more adverse effect on the cracking resistance of modified asphalt emulsion-stabilized mixtures than on that the control samples. For 100% RAP with 0.5% asphaltenes had higher fracture energy at -10°C.

Figure 3-3 to Figure 3-5 present the load-displacement graphs for each RAP content for a specific temperature at -20°C. The rate of load- displacement or the slope of the graph after the peak load shows how rapidly the initiated crack is propagating in each sample. It can be seen that the control samples had the lowest slope in the case of the 50% RAP, followed by the 0.5% and 1% asphaltenes, indicating that the addition of asphaltenes improve the load capacity of the mixture since adding asphaltenes increased the elasticity of the samples compared to control samples On the other hand, for the 75% RAP and 100% RAP, the slope of the load–displacement graphs at −20 °C were followed the same trend like 50% RAP, meaning that asphaltenes had an effect on crack propagation in this case. Overall, the slopes of the graphs after failure for the samples with asphaltenes are steeper compared to those of the control samples, and this is indicative of rapid crack propagation.

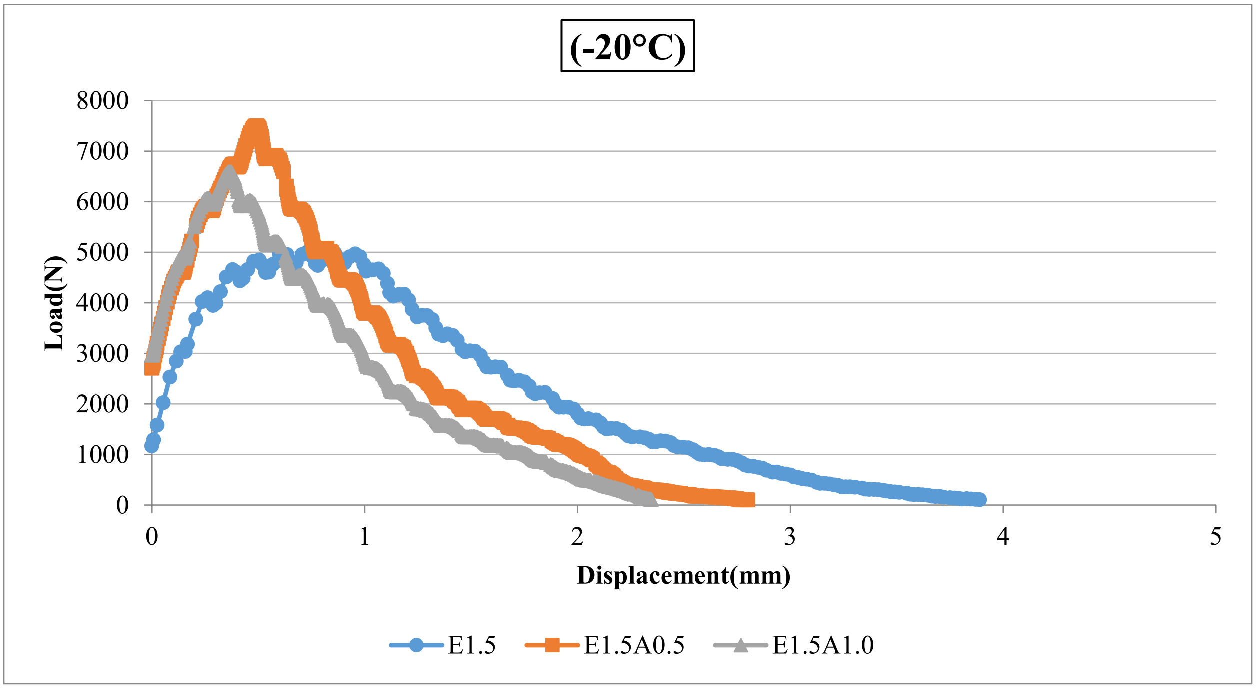


Figure 3-3: Load-displacement graph for 50% RAP and 50% aggregate

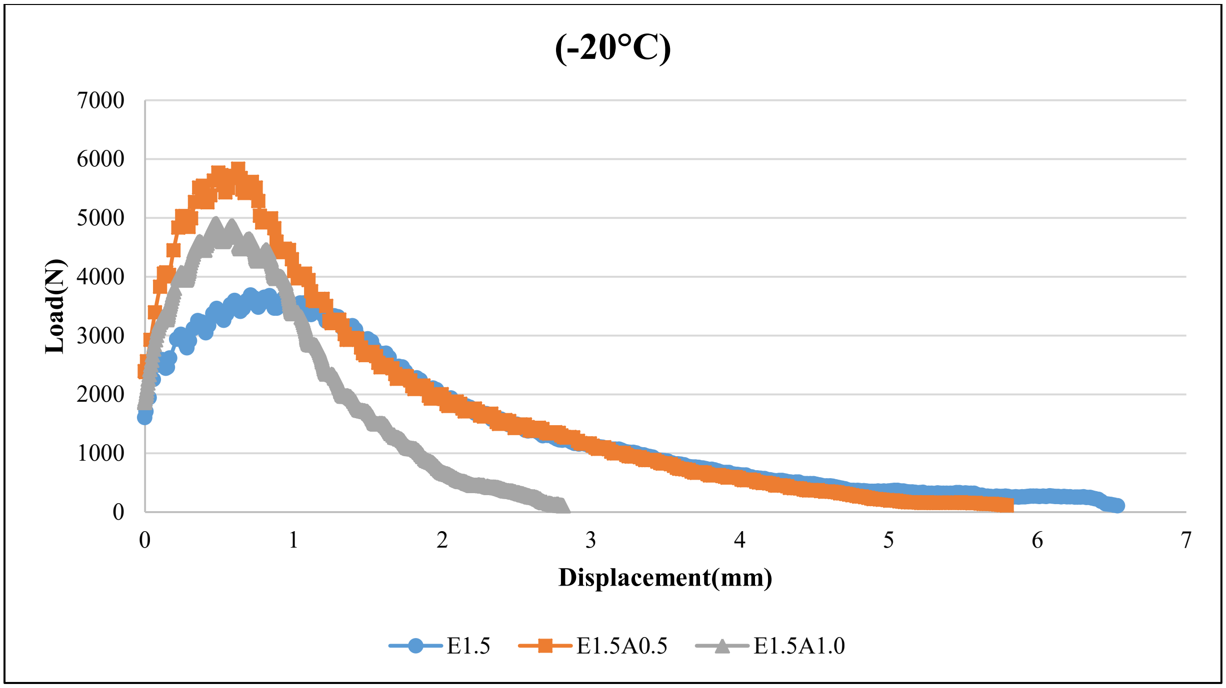


Figure 3-4: Load-displacement graph for 75% RAP and 25% aggregate

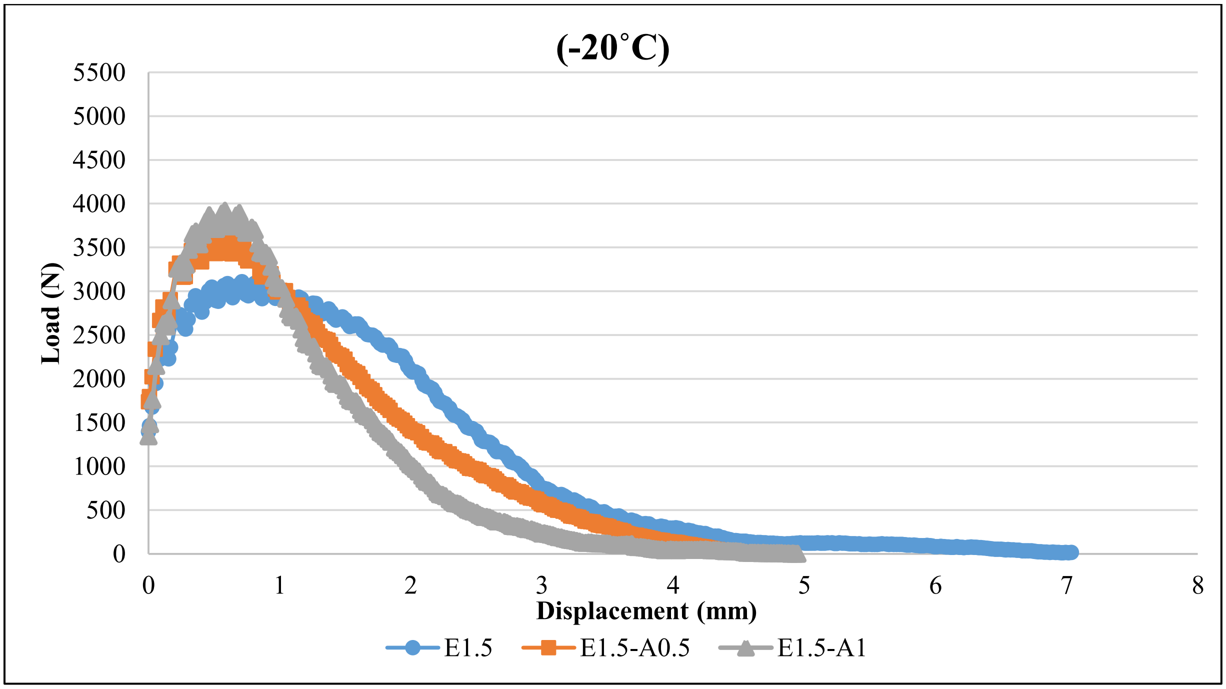


Figure 3-5: Load-displacement graph for 100% RAP

Table 3-10: Creep Compliance results for 50 s

RAP content	Sample ID	Creep Compliance (0°C) (1/kPa)	Creep Compliance (−10°C) (1/kPa)	Creep Compliance (−20°C) (1/kPa)
50%	E1.5	4.20E-06	1.11E-06	8.47E-07
	E1.5-A0.5	8.00E-07	4.32E-07	4.06E-07
	E1.5-A1	8.21E-07	4.66E-07	4.41E-07
75%	E1.5	6.17E-06	2.30E-06	1.45E-06
	E1.5-A0.5	2.56E-06	1.01E-06	8.62E-07
	E1.5-A1	1.27E-06	8.30E-07	7.81E-07
100%	E1.5	N/A	3.39E-06	2.59E-06
	E1.5-A0.5	2.72E-06	1.06E-06	2.19E-06
	E1.5-A1	2.43E-06	1.08E-06	1.32E-06

Table 3-10 provides the creep compliance results for the 50s for all temperatures. **Figure 3-6** present the creep compliance-time results for each RAP content with a specific temperature at -10°C since for 0°C and -20°C followed the same trend (Table 10). Creep compliance results at different temperatures over a period of 100 s were recorded. For better comparison, creep compliance values were calculated for 1s, 2s, 10s, 20s, 50s and 100s and showed it to the **Figure 3-6** for each RAP content**.** For the 50% RAP at -10°C, the creep compliance values decreased significantly as a result of asphaltenes modification, indicating the better low-temperature performance of asphaltenes-modified mixtures to creep loading compared to control samples. The reduction in creep compliance was about 81% and 80% for the mixtures modified with 0.5% and 1% asphaltenes, respectively. For 75% RAP and 100% RAP with addition of asphaltenes creep compliance values decreased significantly. However, it indicates that with addition of asphaltenes samples had better low-temperature performance.

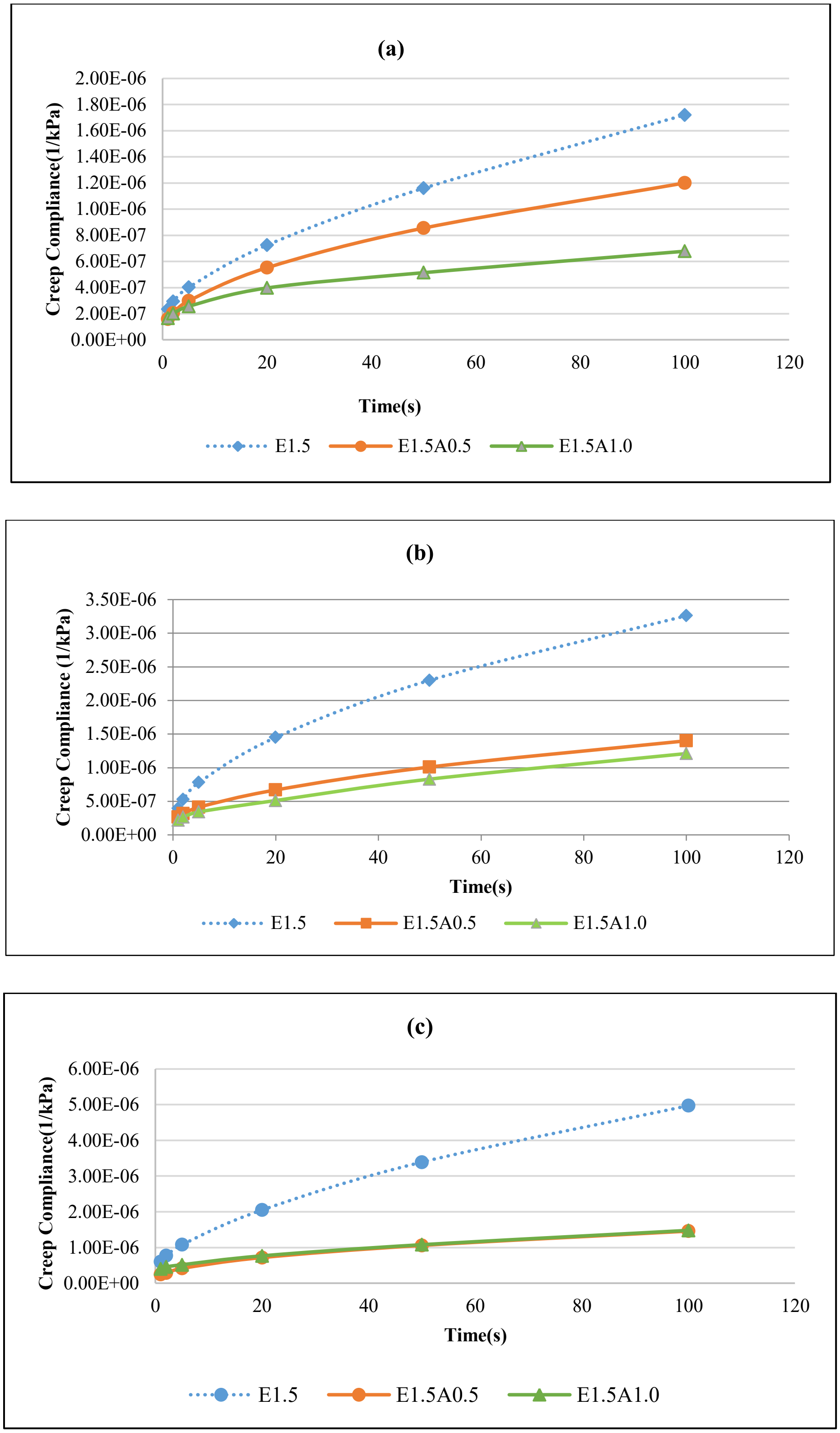


Figure 3-6: Creep compliance–time results at -10°C: (a) 50% RAP; (b) 75% RAP; (c)100% RAP

3.8.4 IDEAL-CT test results

The CT Index is a cracking resistance performance indicator for asphalt mixtures. The indirect tensile cracking test is used to evaluate the cracking resistance of asphalt mixtures at an intermediate temperature, which can range from 5°C to 35°C depending on the local climate. Crack initiation and propagation is the main phase of cracking mechanism. Therefore, the lower CT-Index value, the stiffer the mix, the faster the crack growth, and the higher the load reduction resulting in low cracking resistance. On the other hand, the larger the tolerable strain, the slower the crack growth and load reduction and, consequently, higher cracking resistance [82]. In this observation, the cracking tolerance index (CT-Index) was calculated from load-displacement graphs presented in **Table 3-11** using followed equation according to the ASTM D8225 [82] standard.

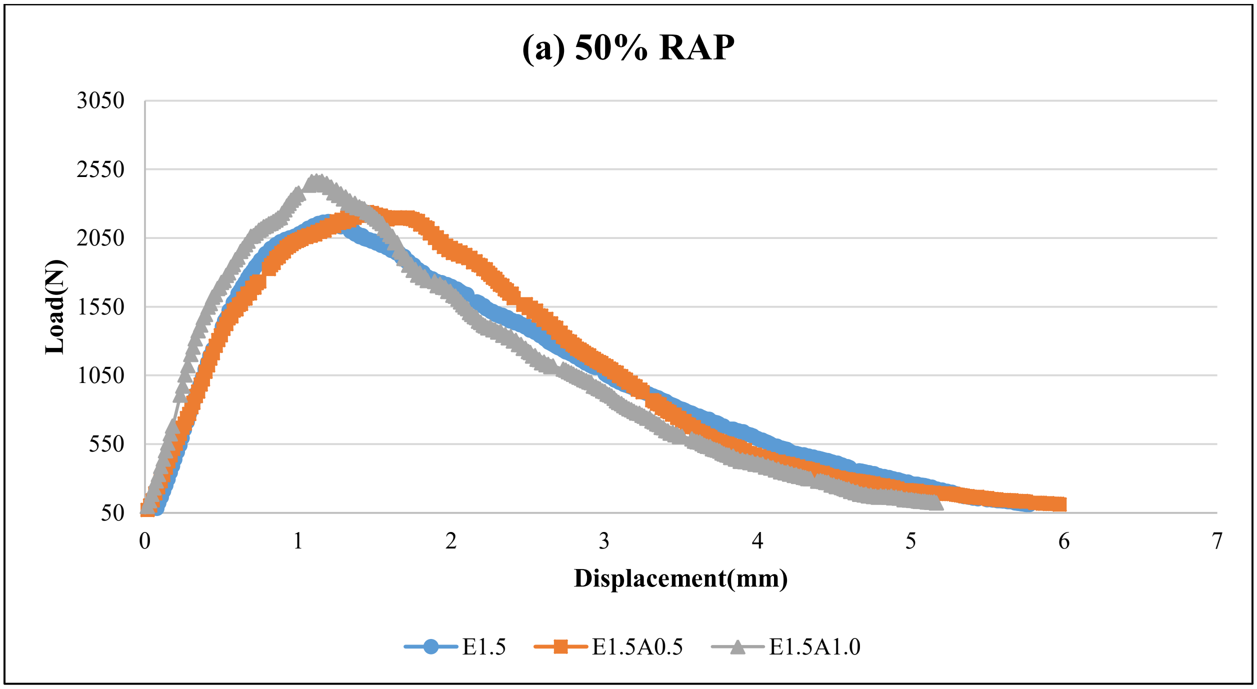
$$G_f = \frac{W_f}{D * t} \times 10^6$$

Table 3-11: Fracture energy and CT-Index values for different content of RAP

RAP Content	**Samples ID**	**Fracture Energy (Joules/m^2)**	**CT-Index**
50%	E1.5	945.27	33.79
	E1.5A0.5	992.78	29.45
	E1.5A1.0	1100.28	17.91
75%	E1.5	831.98	71.34
	E1.5A0.5	1254.76	67.70
	E1.5A1.0	1510.13	82.05
100%	E1.5	589.83	46.19
	E1.5A0.5	1364.09	134.02
	E1.5A1.0	1479.58	120.37

As can be observed from the **Table 3-11**, the samples prepared with the 100% RAP displayed an increase in CT Index with 0.5% asphaltenes exhibiting the highest value of 124.49 (almost twice that of the 75% RAP) and 1% asphaltenes displaying approximately 119.23 in second place. It can be said that 100% RAP with 0.5% asphaltenes provides the highest resistance to cracking than all the RAP contents. The 50% RAP has the lowest CT Index values compared to RAP content with the addition of 0.5% and 1% Asphaltenes which is 29.45 and 17.91, respectively. For 50% RAP control samples had the highest CT Index value, which is 74.07, but with the addition of 0.5% and 1% Asphaltenes, it decreased which is 72.84 and 58.37.

The result also shows that for 50% RAP, the addition of 0.5% and 1% asphaltenes decreases the CT Index by 12.84% and 47%, and the addition of 0.5% and 1% asphaltenes reduces the CT index by 1.66% and 20.93%, respectively for 75% RAP. However, for 100% RAP, it showed the opposite trend. With the addition of 0.5% and 1%, Asphaltenes CT-Index values increased which is about 41.85% and 35.86%. The rate of displacement or the slope of the graph after the peak load shows how fast the initiated crack is propagating in 50% RAP and 75% RAP. It can be seen that the control sample has the lowest slope for each RAP contents.



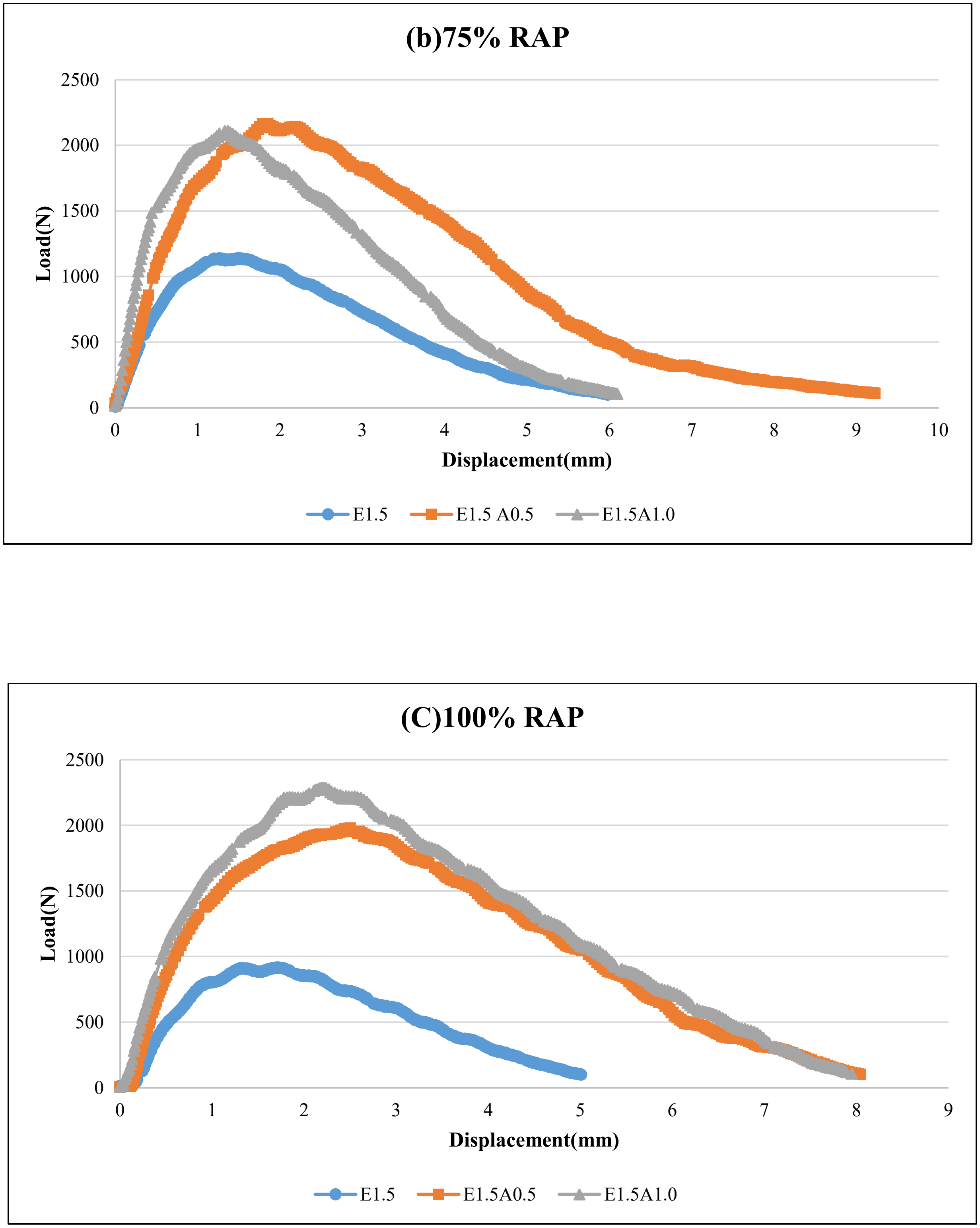


Figure 3-7: Load-displacement graphs for different contents of RAP: (a) 50%; (b) 75%; and (c) 100%

Figure 3-7 presents the load-displacement graphs of the samples for each content of RAP, where the slope of the plot or displacement rate after the peak load is indicative of how rapidly a crack, once initiated, will propagate in each of the mixtures. As can be seen, for 50% RAP, the slope after the peak point is almost similar for control and modified samples with 0.5% Asphaltenes. However, with the addition of 1%, Asphaltenes has the steeper slope compared to control samples with 50% RAP. Modified samples has the steeper slope than the control samples, indicating more rapid crack propagation with the addition of Asphaltenes for 75% RAP. 100% RAP with the addition of Asphaltenes has the steeper slope (almost similar for both content of Asphaltenes) compared to control samples. It can also be observed that the graph of the control sample is flatter than that of the asphaltenes-modified sample. Overall, cracking resistance has been improved.

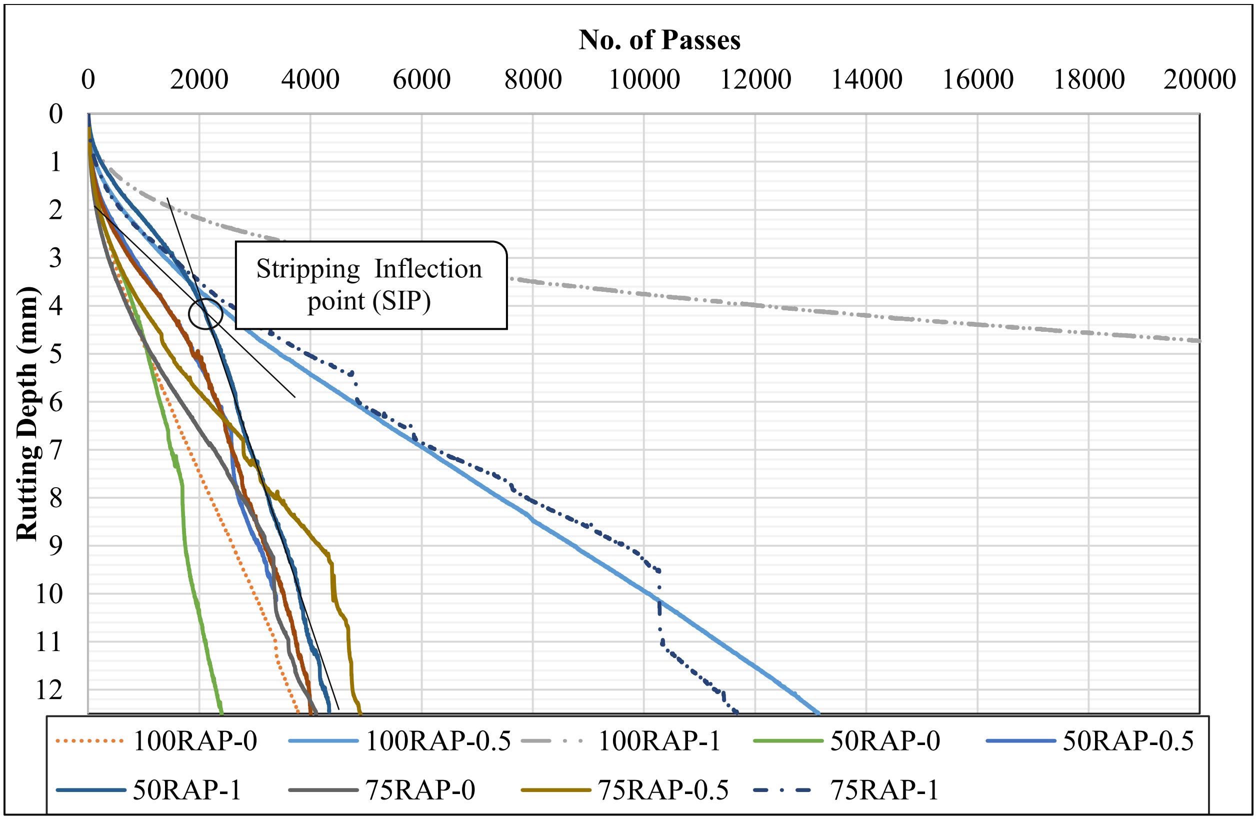
3.8.5 Hamburg Wheel track Result

The Hamburg wheel tracking test evaluates the potential for moisture damage effects because the specimen is submerged in temperature-controlled water during test. This method also measures the rut depths and the number of passes to failure. The striping inflection point (SIP) is the intersection point of the creep slope and stripping slope, in an actual number of passes at that point. A stripping slope is an inverse rate of deformation that continues through the test's end after the stripping inflection point. SIP was determined to evaluate the rutting potential and susceptibility of the mixtures to moisture damage. The rutting resistance index (RRI) was calculated by multiplying the number of passes by one inch subtracted by rut depth in inches. **Figure 3-8** presents the rutting depth versus number of passes for each specimen. **Table 3-12** also lists the SIP and RRI values. According to these results, the number of passes is increasing for all the modified samples compared to the unmodified samples. For 75% and 100% RAP, mixtures with 1% asphaltenes had a higher number of passes than mixtures with 0.5% asphaltenes at the time of failure however, an increase in the number of passes for 50% RAP was more for mixtures with 0.5% asphaltenes than 1%. RRI values for the samples showed an improvement for the modified samples too. An increase of 80.3% and 66.3% for mixtures with 0.5% and 1% asphaltenes in 50% RAP samples were observed compared to 50%RAP and this improvement for 75% RAP was about 19.6% and 185.2% compared to 75%RAP, respectively. RRI improvement for 100% RAP samples was significant, about 246.6% and 744.7% for both

0.5% and 1% asphaltenes compared to the 100%RAP. It can be seen that for 50% RAP, SIP for the control sample did not record while adding the asphaltenes increased the SIP at both asphaltenes concentrations (0.5% and 1%). However, with the addition of asphaltenes, it had an increase in SIP, compared to control samples. In addition, no SIP has been detected for the 100% RAP mixture, which means samples are not susceptible to moisture damage. All samples started to have concaved graphs before failure, and except 75 RAP-E1.5-A1, all of them were susceptible to moisture damage due to concaved portion happening before 10,000 passes. The SIP value under the 10,000 passes indicated the moisture susceptibility of the samples [122]. As a result of this test, it can be concluded that asphaltenes modification significantly increased the permanent deformation resistance in the modified samples compared to control samples because it makes the mixture stiffer.

Table 3-12: Hamburg wheel tracking test results

RAP Content	Sample ID	SIP	Maximum Rutting Depth (mm)	Number of Passes at 12.5 mm	RRI
50%	E1.5	-	12.5	2406	1221.9
	E1.5A0.5	2249	12.5	4338	2203.2
	E1.5A1.0	2207	12.5	4006	2034.5
75%	E1.5	2980	12.5	4102	2083.3
	E1.5A0.5	4226	12.5	4904	2490.6
	E1.5A1.0	10132	12.5	11698	5941.1
100%	E1.5	-	12.5	3792	1925.9
	E1.5A0.5	-	12.5	13142	6674.5
	E1.5A1.0	-	4.74	-	16267.7



[3][4][5]**Figure 3-8: Hamburg Wheel track Test Results**

ANALYSIS OF VARIANCE

To understand if there is statistically significant difference in the ITS, CT-Index, and RRI values after asphaltenes modification, Analysis of Variance (ANOVA) was conducted on the values obtained for the recycled mixtures with different RAP and asphaltenes contents. The significance level (α) of 0.05 was considered. The ANOVA outputs (P-values, F-values and F-critical) are calculated and provided in **Table 3-13**. As can be observed from this table, both the asphaltenes content and RAP content had significant impacts on the ITS Dry and ITS wet values where the F-values are larger than F-critical, and P-values are smaller than 0.05, although they did not have significant impacts on the ITS F/T and RRI. In addition, unlike the asphaltenes modification, the RAP content significantly influenced the CT-Index values. ANOVA analysis also showed that

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[3] 100 RAP-0 means 100% RAP with 0% asphaltenes

[4] 100 RAP-0.5 means 100% RAP with 0.5% asphaltenes

[5] 100 RAP-1 means 100% RAP with 1% asphaltenes

the asphaltenes and RAP contents can both affect the creep compliance results at low temperatures significantly although their impacts depend on the test temperature.

Table 3-13: ANOVA Two-Factor without Replication Outputs

Property	**Asphaltenes content**			**RAP content**		
	F-value	**P-value**	**F-crit**	**F-value**	**P-value**	**F-crit**
ITS Dry	178.8665	0.000122	6.944272	128.1231	0.000236	6.944272
ITS Wet	50.53247	0.001449	6.944272	36.39134	0.002714	6.944272
ITS F/T	5.291042	0.075246	6.944272	1.682424	0.294980	6.944272
Creep compliance (-10°C)	9.024763	0.032910	6.944272	4.477236	0.095341	6.944272
Creep compliance (-20°C)	6.229411	0.059064	6.944272	22.607	0.006606	6.944272
CT-Index	0.502035	0.638959	6.944272	24.37167	0.005752	6.944272
RRI	2.345315	0.211845	6.944272	2.525352	0.195324	6.944272

3.9 Conclusions

The main focus of this research study is to investigate and compare the impact of the addition of asphaltenes to asphalt emulsion stabilized mixes for base course applications with different contents of RAP (50% RAP, 75% RAP and 100% RAP). Asphaltenes were added separately into the asphalt emulsion, and samples were subjected to various standard test methods. The samples were tested for their low-temperature performance, rutting resistance, moisture susceptibility, and cracking resistance. Based on the test results and analysis performed on the control and asphaltenes-modified asphalt emulsion stabilized mixes, the following conclusions have been drawn:

- The strength value improved greatly at the lower temperature with the addition of asphaltenes for each RAP content. The TSR results showed that the addition of asphaltenes made the mixture more sensitive to the moisture damage compared to the control samples.

- Indirect tensile test results showed that modification of asphaltenes resulted in lower FE values with lower temperature and consequently, an increase in the samples' brittleness at lower temperatures which made samples more prone to cracking.
- The creep compliance analysis showed that modification of the RAP and aggregate mix material with asphaltenes resulted in lower creep compliance values indicating the better low-temperature performances since it decreases the deformation of the samples.
- With intermediate temperature, the addition of asphaltenes improved the tensile strength of dry and wet samples to the design limits for RAP mixtures.
- With the addition of asphaltenes, each content of asphaltenes had higher fracture energy at intermediate temperature compared to control samples thereby, it indicates mixes are more resistant to crack propagation. Also, CT-Index analysis shows that asphaltenes-modified samples had an increased cracking resistance compared to control samples.
- Permanent deformation test results using a Hamburg wheel tracker showed that the addition of asphaltenes improved both rutting resistance and moisture sensitivity of the modified mixture compared to the unmodified mixtures. Overall, rutting resistance was higher in 100% RAP mixtures.
- ANOVA analysis showed that the asphaltenes content and RAP content had significant impacts on the ITS Dry, ITS Saturated and Creep Compliance values, although they did not have a significant influence on the ITS F/T and RRI. In addition, only the RAP content significantly influenced the CT-Index values.
- In conclusion, 100% RAP had better tensile strength, cracking resistance, rutting resistance and low-temperature performance compared to other RAP content. Also

asphaltenes is a promising additive for recycled mixture since it is improving tensile strength, cracking resistance, rutting resistance and low-temperature performance.

In this research, the experimental work was limited to the Hamburg wheel tracking test and IDEAL CT-Index tests at 40°C and 25°C. To better understand the behaviour of the mixes, further steps will involve conducting analysis on critical pavement temperature.

Chapter4 : Summary and Conclusion

The popularity of RAP is driven by a combination of cost-effectiveness, sustainability, and improved performance. RAP has been found to improve the performance of asphalt pavements, particularly in terms of durability and resistance to cracking. Also, using RAP promotes sustainability, as it reduces the need for new asphalt material and saves natural resources. Recently, sustainability has become a popular topic within the world. People prefer sustainability for a variety of reasons, ranging from environmental concerns and social responsibility to economic benefits and health considerations. Sustainability ultimately provides a way to improve the future for ourselves, our communities, and the world. So, using RAP in the pavement industry opens the door to rebuilding our future. As asphalt emulsion mixes have been used in base courses for more than ten years, high-performance asphalt emulsion stabilized mixes with various additives are required to address their drawbacks and increase the lifespan of pavements. This provides an opportunity to investigate the benefits of asphaltenes to improve the performance of asphalt emulsion mixes.

The major goals of this study are to investigate the performance of base course mixes stabilized with asphalt emulsions that contain different amounts of RAP (50, 75, and 100%) and different amounts of asphaltenes (0.5% and 1%). Different tests based on AASHTO/ASTM standards were performed to determine several mechanical properties of the mixture. At high, intermediate, and low temperatures, the samples were tested for their resistance to rutting, moisture resistance, and cracking.

Several testing of modified asphalt emulsion stabilized mixtures using RAP and asphaltenes were carried out, and the study's findings are summed up as follows:

- The sample tensile strength results showed that 1.5% asphalt emulsion is the best emulsion content to use in all mixtures. The addition of asphaltenes increased the tensile strength of dry and soaked samples to the design limits for RAP mixtures.
- Modification with 0.5% and 1% asphaltenes increases tensile strength compared to the control samples. By comparing these performances of the asphaltenes-modified mixes to the control samples, it can be concluded that the asphaltenes-modified mixes are more effective at improving the tensile strength of the mixes. Overall, 100% RAP with 1% asphaltenes had the higher strength values.

- Asphaltenes modified mixtures are considerably more prone to moisture damage than control mixes, according to the TSR results for both saturated and F/T samples. It is concluded that mixes modified with asphaltenes are more susceptible to moisture damage.
- According to the analysis of the IDEAL-CT data, the CT-Index for samples modified with asphaltenes decreased for 50% RAP and 75% RAP and increased for 100% RAP compared to control samples, even though the addition of asphaltenes increased fracture energy. Overall, it is concluded that the addition of asphaltenes will improve the mix's cracking resistance in comparison to control samples of mixes stabilized with asphalt emulsion.
- When wheel tracking test data were used to compare rutting resistance to the control mix, it was found that the asphaltenes-modified mixture performed significantly better than the unmodified mixtures.
- The ITS results at 0°C showed that, compared to the control samples, the tensile strength of changed samples was slightly increased after the addition of asphaltenes, according to IDT low-temperature results analysis. The creep compliance analysis showed that modification of the RAP and aggregate mix material with asphaltenes resulted in lower creep compliance values, consequently improving low-temperature performance in the modified mixtures for each RAP content. Therefore, the additions of 0.5% and 1% asphaltenes increased the strength and decreased the fracture energy of the mixtures in some cases. In summary, mixes modified with asphaltenes were prone to low-temperature cracking than control mixes and mixes with lower RAP content were weaker compared to high RAP content.
- When all of the findings are taken into account, it is clear that adding asphaltenes to the mixture increases its strength; however, asphaltenes-modified mixes show better cracking resistance, but for both 50% RAP and 75% RAP, the CT index shows crack propagation is faster compared to 100% RAP. In contrast, rutting resistance and moisture sensitivity of the mixes for respective RAP concentrations were improved more successfully by asphaltenes-modified samples as compared to control samples. Moreover, asphaltenes, a

cheap and environmentally beneficial waste product, can be added to enhance asphalt emulsion stabilized base course mixes.

References

[1] M. N. Borhan, . F. Suja, . A. Ismail and . R. A. Rahmat, "Used Cylinder Oil Modified Cold-Mix Asphalt Concrete," *Journal of Applied Sciences,* vol. 22, p. 3485–91., 2007.

[2] J. Chen, H. Dan and et al, "New innovations in pavement materials and engineering: A review on pavement engineering research 2021," *Journal of Traffic and Transportation Engineering,* 2021.

[3] S. Zarei and J. Ouyang, "Experimental analysis of semi-flexible pavement by using an appropriate cement asphalt emulsion paste," *Construction and Building Materials,* 2020.

[4] T. Delft , " Annual Report about Flexible and Rigid PavemenT," Delft University of Technology, Road Department: Delft, 2012.

[5] P. AT and M. EA., Pavement design and materials., 2008, p. 544.

[6] A. Seitllari, . I. Boz, . J. Habbouche and S. Diefende, "Assessment of cracking performance indices of asphalt mixtures at intermediate temperatures," *International Journal of Pavement Engineering,* 2020.

[7] Q. F. Adam, E. Levenberg and et al, "Modeling the use of an electrical heating system to actively protect asphalt pavements against low-temperature cracking," *Cold Regions Science and Technology,* 2023.

[8] M. Pszczola, D. Rys and et al., "Field Evaluation of High Modulus Asphalt Concrete Resistance to Low-Temperature Cracking," *MDPI,* 2022.

[9] J. L. O. L. Júnior, L. F. A. L. Babadopulos and et al, "Effect of aggregate shape properties and binder's adhesiveness to aggregate on results of compression and tension/compression

tests on hot mix asphalt," *Materials and Structures,* 2020.

[10] T. Ahmad and H. Khawaja, "Review of Low-Temperature Crack (LTC) Developments in Asphalt Pavements," *The International Journal of Multiphysics,* 2018.

[11] J. Sulivan, "Pavement Recycling Executive Summary and Report," Federal Highway Administration, Washington, DC, 1996.

[12] K. Diouri, A. De and et al, "Effect of aging and temperature on milling-induced stresses and cracks in Hot Mix Asphalt (HMA) pavements," *Construction and Building Materials,* 2021.

[13] G. Tarsi, . P. Tatarann and C. Sangiorgi, "The Challenges of Using Reclaimed Asphalt Pavement for New Asphalt Mixtures: A Review," *Materials (Basel),* 2020.

[14] J. S. Daniel and . A. Lachance, "Mechanistic and Volumetric Properties of Asphalt Mixtures with Recycled Asphalt Pavement," *Journal of the Transportation Research Board,* pp. 28-36, 2005.

[15] W. Chesner, . R. Collins and Mackay, "User Guidelines for Waste and Byproduct Materials in Pavement construction," Federal Highway Administration(FHWA), 2002.

[16] R. C.West, "Best Practices for RAP And RAS Management.," NATIONAL ASPHALT PAVEMENT ASSOCIATION (NAPA)., 2015.

[17] H.-J. Volk, "Wirtgen Drives the Development of Surface Mining," *Procedia Engineering,* pp. 30-39, 2016.

[18] R. Mallick and P. Kandhal, "Pavement Recycling Guidelines for State and Local Governments.," Federal Highway Administration Publication, Washington D.C., USA., 1997.

[19] T. A. Tedla, D. Singh and et al, "Effects of air voids on comprehensive laboratory performance of cold mix containing recycled asphalt pavement," *Construction and Building Materials,* 2023.

[20] S. Du, "Interaction mechanism of cement and asphalt emulsion in asphalt emulsion mixtures," *Materials and Structures,* pp. 1149-1159, 2014.

[21] J. L. Gaunt and . J. Lehmann, "Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production," pp. 42(11):4152-8, 2008.

[22] R.-H. Kim, S. Lee, J.-H. Lee, Y.-M. Kim and J.-Y. Suh, "Developing Technologies for Rainwater Utilization in Urbanized Area," pp. 401-410, 2010.

[23] B. Mishra, "A study on use of reclaimed asphalt pavement (RAP) materials in flexible pavements," 2015.

[24] A. Grilli, F. Cardone and et al, "Mechanical behaviour of cement-bitumen treated materials containing different amounts of reclaimed asphalt," *European Journal of Environmental and Civil Engineering,* 2018.

[25] The Asphalt Pro, "Basic Asphalt Emulsion manual," The Asphalt Institute., Washington D.C., 1979.

[26] Z. Xie, A. J. Taylor, N. Tran and . S. Kim, "Evaluation of Different VMA Estimation Methods for Asphalt Mixtures Containing RAP," *Journal of Materials in Civil Engineering,* vol. 32, no. 7, 2020.

[27] A. Kavussi and A. Modarres, "A model for resilient modulus determination of recycled mixes with bitumen emulsion and cement from ITS testing results," *Construction and Building Materials,* vol. 24, no. 11, pp. 2252-2259, 2010.

[28] J. Xu, S. Huang and et al, "The impact of cement contents on the properties of asphalt emulsion stabilized cold recycling mixtures," pp. 48-55, 2011.

[29] A. Hasanbeigi, . L. Price and . E. Lin, "Emerging energy-efficiency and CO2 emission-reduction technologies for cement and concrete production: A technical review," *Renewable and Sustainable Energy Reviews,* vol. 16, no. 8, pp. 6220-6238, 2012.

[30] . A. M. Sabbie , G. Habert and et al, "Achieving net zero greenhouse gas emissions in the cement industry via value chain mitigation strategies," vol. 4, no. 10, pp. 1398-1411, 2021.

[31] A. Meisen, "Bitumen Beyond Combustion (BBC) Project Phase 1 Report," Alberta Innovates, 2017.

[32] A. Ghasemirad, N. Bala and L. Hashemian, "High-Temperature Performance Evaluation of Asphaltenes-Modified Asphalt Binders," *Materials Science, Engineering,* 22 July 2020.

[33] C. Barry R. , C. Schwart and R. Boudreau, "Geotechnical aspects of pavements," ederal Highway Administration, United States, 2006.

[34] J. Speight, Aspahlt Materials Science and Technology., 2015.

[35] Pavement Interactive, "Pavement Structure," [Online]. Available: https://pavementinteractive.org/reference-desk/design/structural-design/pavement-structure.

[36] F. Guo, Y. Qian and et al, "Pavement crack detection based on transformer network," *Automation in Construction,* vol. 145, 2023.

[37] TIBBS, "TIBBS Paving," [Online]. Available: https://www.tibbspaving.com/what-are-the-common-causes-behind-pavement-cracking.

[38] K. H. Moon, "Comparison of Thermal Stresses Calculated from Asphalt Binder and Asphalt Mixture Creep Compliance Data," The University of Minnesota, 2012.

[39] P. K. Das, Y. Tasdemi and B. Birgissona, "Low temperature cracking performance of WMA with the use of the Superpave indirect tensile test," *Construction and building materials,* vol. 30, pp. 643-649, 2012.

[40] J. Jiang, F. Ni, J. Zheng, Y. Han and J. Xuan, "Improving the high-temperature performance of cold recycled mixtures by polymer-modified asphalt emulsion," pp. 41-48, 2018.

[41] N. Bueche, "Warm asphalt bituminous mixture with regards to energy, emissions and performance.," Young researchers seminer(YRS), Torino, 2009.

[42] M. Piratheepan, Designing Cold Mix Asphalt (CMA) and Cold-In-Place Recycling (CIR) using SUPERPAVE Gyratory Compactor, Texas: University of Nevada, 2011.

[43] A. Modarres and P. Ayar, "Coal waste application in recycled asphalt mixtures with bitumen emulsion," vol. 83, pp. 263-272, 2014.

[44] . J. Alfarra and M. Rüdiger, "Cold recycling of asphalt pavements: A review.n," *Journal of Cleaner Production,* pp. 42-54, 2016.

[45] M. Rüdiger, T. Bauer and M. Putz, "Cold recycling in situ - Mobile plants.," *Waste Management,* pp. 1267-1275, 2006.

[46] H. Li, Y. Li and X. Chen, "Durability evaluation of asphalt pavement using the JPCP test," *International Journal of Pavement Engineering,* pp. 333-338, 2009.

[47] S. Al-Busaltan, . H. Al Nageim, W. Atherton and G. Sharples, "Mechanical Properties of an Upgrading Cold-Mix Asphalt Using Waste Materials," vol. 24, no. 12, 2012.

[48] j. Read, The Shell Bitumen Handbook, 2003.

[49] M. Piratheepan, "Designing Cold Mix Asphalt (CMA) and Cold-In-Place Recycling (CIR) Using SUPERPAVE Gyratory Compactor," University of Nevada, 2011.

[50] M. Ahmed, "Emulsified asphalt residue recovery and characterization: combined use of moisture analyzer balance and dynamic shear rheometer," *Journal of the Transportation Research Board ,* pp. 88-96, 2014.

[51] N. A. Thanaya, "Review and Recommendation of Cold Asphalt Emulsion Mixtures Caems Design," *Civil Engineering Dimension,* pp. 49-56, 2007.

[52] J. Jungklaus and H. Braess, "Energy balance and CO2 emissions of cold in-situ recycling and hot asphalt production," *Journal of Cleaner Production,* pp. 1519-1527., 2006.

[53] J. Lee and J. Kim, "A review of cold in-place recycling techniques," *Waste Management,* pp. 883-890, 2010.

[54] E. J. Kearney and . J. E. Huffman, "Full-Depth Reclamation Process," *Transportation Research Record: Journal of the Transportation Research Board,* vol. 1684, no. 1, 1999.

[55] T. B. Moghaddam and H. Baaj, "The use of rejuvenating agents in production of recycled hot mix asphalt: A systematic review," *Construction and Building Materials,* pp. 805-816, 2016.

[56] D. T. G. Townsend, "UNDERSTANDING THE ENVIRONMENTAL IMPACTS OF RECLAIMED ASPHALT PAVEMENT," [Online]. Available: https://faculty.eng.ufl.edu/timothy-townsend/research/beneficial-use-of-waste-materials/understanding-the-environmental-impacts-of-reclaimed-asphalt-pavement/.

[57] M. A. Wasemiller and K. B. Hoddinott, Testing soil mixed with waste or recycled

materials, 1997.

[58] B. Kallas, Kallas, B. F. Flexible Pavement Mixture Design Using Reclaimed Asphalt Concrete, FHWA/RD-84/088, 1984.

[59] A. Copeland, "”Reclaimed Asphalt Pavement in AsphaltMixtures: State of the Practice”," 2011.

[60] R. C. West, ” Best Practices for RAP and RAS Management”, 2011.

[61] The Asphalt Institute, A Basic Asphalt Emulsion Manual. 4th ed: Asphalt Emulsion, 4th ed., 2008.

[62] B. Ashley, . I. Pinto and G. Minas , "Enhancing the Fundamental Knowledge and Use of Asphalt Emulsions Using Systematic Scientific and Engineering Approaches: Final Report," Midwest Transportation Center., 2018.

[63] James A., "Overview of asphalt emulsion.," Asphalt Emulsion Technology, 2006.

[64] "Wirtgen Cold Recycling Manual.," Windhagen, Germany., 2012.

[65] The Asphalt Institute, MS-19 Basic Asphalt Emulsion Manual, Third ed., The Asphalt Institute, 2019.

[66] Wirtgen Cold Recycling Manual, Wirtgen Cold Recycling Manual, 1st ed., Windhagen, Germany: Wirtgen GmbH, 2012.

[67] H. Abraham , "Asphalts and Allied Substances: Their Occurrence, Modes of Production, Uses in the Arts and Methods of Testing," 1918.

[68] M. Boussingault, XCI. On the constitution of bitumens, 1836.

[69] B. A. Sultana S, " Effect of chemical composition on rheology and mechanical properties of asphalt binder.," *Construction and Building Materials.,* pp. 48-55, 2014.

[70] A. Ratovskaya, "Determination of the molecular weight of asphaltenes by the thermoelectric technique," *Chem Technology Fuels Oils,* 1968.

[71] D. Li and . M. Greenfield, "High internal energies of proposed asphaltene structures," 2011.

[72] M. Hassanzadeh and M. Abdouss, "Essential role of structure, architecture, and intermolecular interactions of asphaltene molecules on properties (self-association and surface activity)," *Chemical Engineering,* 2022.

[73] A. Soleymanzadeh, M. Yousef and et al, "A review on methods of determining onset of asphaltene precipitation," *Journal of Petroleum Exploration and Production Technology,* 2018.

[74] M. Mousavi, F. Pahlavan and et al, "Multiscale investigation of oxidative aging in biomodified asphalt binder," *Applied optical materials,* 2016.

[75] TG2, "Technical guideline: Bitumen stabilized materials. A Guideline for the Design and Construction of Bitumen Emulsion and Foamed Bitumen Stabilised Materials (3 ed.)," Howard place,South Africa, 2020.

[76] ARRA, "Basic asphalt recycling manual. Association, Asphalt Recycling and Reclaiming (ARRA).," Federal Highway administration, 2001.

[77] AASTHO T283, "Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage," American Association of State Highway and Transportation Officials, Washington, D.C, 2017.

[78] M. Islam and M. Hossain , "A study of asphalt aging using Indirect Tensile Strength test.," *Construction and Building Materials,* pp. 218-23, 2015.

[79] Technology CUoSa, Indirect tensile strength characteristics, Cochin University of Science and Technology, 2014.

[80] F. Zhou, D. Newcomb , C. Gurganus and S. Banihashemrad , "Experimental design for field validation of laboratory tests to assess cracking resistance of asphalt mixture," NCHRP Project, 2016.

[81] F. Zhou , "Development of an IDEAL Cracking Test for Asphalt Mix Design , Quality Control and Quality Assurance Final Report for NCHRP IDEA Project," NCHRP Project, 2019.

[82] ASTM D8225 − 19, "Standard Test Method forDetermination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature," American Society for Testing and Materials., West Conshohocken, PA, 2019.

[83] D. Christensen and R. Bonaquist, "Evaluation of Indirect Tensile Test (IDT) Procedures for Low-Temperature Performance of Hot Mix Asphalt," *Transportation Research Board,* 2014.

[84] AASHTO T 322, "Standard Method of Test for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device," American Association of State Highway and Transportation Officials, Washington, D.C, 2007.

[85] AASHTO T 324-19, "Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures.AASHTO provisional standards.," American Association of State Highway and Transportation Officials., Washington, D.C., 2011.

[86] T. Aschenbrener, "Evaluation of Hamburg wheel-tracking device to predict moisture

damage in hot-mix asphalt," Transportation Research Record, Colorado, 1995.

[87] L. Sun, M. Kamaliardakani and Y. Zhang, "Weighted Neighborhood Pixels Segmentation Method for Automated Detection of Cracks on Pavement Surface Images," *Journal of Computing in Civil Engineering,* August 2015.

[88] A. Shams, W. Nazimuddin M and L. N. Mohammad, "Evaluation of bio-based and petroleum-based rejuvenator based on cracking susceptibility of hot mix asphalt with high RAP content," *Construction and Building Materials,* vol. 371, no. 0, p. 130725, 2023.

[89] J. Zhong, J. Huyan and et al, "A deeper generative adversarial network for grooved cement concrete pavement crack detection," *Engineering Applications of Artificial Intelligence,* 2023.

[90] T. Aschenbrener, "Investigation of Low Temperature Thermal Cracking in Hot Mix Asphalt," Colorado Department of Transportation, 1995.

[91] D. Jung and T. Vinson, "Low-Temperature Cracking:Test selection.," Stratagic Highway Research Program., Washington,DC:, 1994.

[92] L. Kirby, "The Use of Recycled and Innovative Materials in Asphalt Concrete Pavements," Bradley University, 2017.

[93] . W. H. Chesner, R. J. Collins and et al., "User Guidelines for Waste and Byproduct Materials in Pavement Construction," Federal Highway Administration Research and Technology, 2002.

[94] . S.-C. Huang and H. Benedetto, Advances in Asphalt Materials. Road and Pavement Construction., 2015.

[95] P. Caputo , S. Eskandarsefat and et al, "Effect and Mechanism of Rejuvenation of Field-

Aged Bitumen Extracted from Reclaimed Asphalt Pavement," *Transportation Research Procedia,* 2023.

[96] F. Xiao, . S. Yao, . J. Wang, X. Li and et al, "A literature review on cold recycling technology of asphalt pavement.," *Construction and Building Materials,* 2018.

[97] S. Miliutenko, A. Björklund and et al, " Opportunities for environmentally improved asphalt recycling: the example of Sweden.," *Journal of cleaner production,* pp. 43-156, 2013.

[98] R. Taha, A. Al-Harthy and et al, "Cement Stabilization of Reclaimed Asphalt Pavement Aggregate for Road Bases and Subbases.," *Journal of Materials in Civil Engineering,,* 2002.

[99] T. Pradyumna, A. Mittal and J. PK, "Characterization of Reclaimed Asphalt Pavement (RAP) for Use in Bituminous Road Construction.," *Agra, India: 2nd Conference of Transportation Research Group of India (2nd CTRG).,* 2013.

[100] . J. Kwon, Y. Seo and et al, "Field and numerical investigation of full depth reclamation with Portland cement in Georgia.," vol. 27, 2020.

[101] W. Fedrigo, W. Peres Núñez and A. T. Visser, "A review of full-depth reclamation of pavements with Portland cement: Brazil and abroad.," *Construction and Building Materials,,* vol. 262, 2020.

[102] The AsphaltPro, "Best Practices of Full Depth Reclamation," Asphalt Pro Magazine, 2019.

[103] F. Kaseer, E. Arámbula-Mercado and et al, "Full-depth reclamation (FDR) mix design: Proposed revisions to the indirect tensile strength thresholds.," *Construction and Building Materials,* vol. 254, 2020.

[104] A. Ghanizadeh, M. Rahrovan and et al, "The effect of cement and reclaimed asphalt pavement on the mechanical properties of stabilized base via full-depth reclamation.," *Construction and Building Materials,* pp. 165-174, 2018.

[105] A. Buss, I. Pinto and et al, "ENHANCING THE FUNDAMENTAL KNOWLEDGE AND USE OF ASPHALT EMULSIONS USING SYSTEMATIC SCIENTIFIC AND ENGINEERING APPROACHES.," *Institute for Transportation.,* 2018.

[106] M. Marasteanu and T. Clyne, "Rheological Characterization of Asphalt Emulsions Residues.," *Journal of Materials in Civil Engineering,* 2006.

[107] D. Salomon, "Asphalt Emulsion Technology," Transportation Research Board, Washington, DC, 2006.

[108] Z. Xie, A. J. Taylor, N. Tran and S. Kim, "Evaluation of Different VMA Estimation Methods for Asphalt Mixtures Containing RAP," *Journal of Materials in Civil Engineering,* vol. 32, no. 7, 2020.

[109] AI, Basic Asphalt Emulsion Manual, Asphalt Institute and Asphalt Emulsion, 2008.

[110] AI, "Basic Asphalt Emulsion manual," The Asphalt Institute, Washington D.C., 1979.

[111] Y. Xu, . E. Zhang and L. Shan, "Effect of SARA on Rheological Properties of Asphalt Binders," *Journal of Materials in Civil Engineering,* 2019.

[112] S. Ashoori, M. Sharifi and et al, "The relationship between SARA fractions and crude oil stability," *Egyptian Journal of Petroleum,* 2017.

[113] Y. Tian, B. Jiang and et al, "Characterisation by ESI FT-ICR MS of heteroatomic compounds in catalytic hydropyrolysates released from marine crude oil asphaltenes," *Organic Geochemistry,* 2022.

[114] A. Ghassemirad , N. Bala and et al, "Application of asphaltenes in high modulus asphalt concrete," *Construction and Building Materials,* 2021.

[115] N. Turuga, "EFFECT OF SOLVENT DEASPHALTING PROCESS ON THE PROPERTIES OF DEASPHALTED OIL AND ASPHALTENES FROM BITUMEN.," University of Alberta., Edmonton, 2017.

[116] City of Edmonton, "Design and Construction Standards.," 2015.

[117] ASTM International, "ASTM D698-12 Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort," American Society for Testing and Materials, West Conshohocken, PA, 2003.

[118] ASTM D6937 -16, "Standard Test Method for Determining Density of Emulsified Asphalt.," American Society for Testing and Materials., West Conshohocken, PA, 2016.

[119] Husky oil, "Specification and Typical analysis of Asphalt Emulsion.," 2018.

[120] F. Kamran, M. Basavarajappa, . N. Bala and L. Hashemian, "Laboratory evaluation of stabilized base course using asphalt emulsion and asphaltenes derived from Alberta oil sands," *Construction and Building Materials,* 2021.

[121] Value Creation Inc, "Summary of Key Tests on Asphaltenes.," Value Creation Inc, Calgary,AB,Canada., 2006.

[122] ASTM D1557-12, "Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3 (2,700 kN-m/m3))," ASTM International, West Conshohocken, PA, 2021.

[123] TG2, A Guideline for the Design and Construction of Bitumen Emulsion and Foamed Bitumen Stabilised Materials., 3rd ed., Southern African Bitumen Association (Sabita),

2020.

[124] AASHTO T283-21, "Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage," American Association of State Highway and Transportation Officials, Washington, D.C., 2021.

[125] F. Kamran, M. Basavarajappa, N. Bala and L. Hashemian, "Performance Evaluation of Stabilized Base Course using Asphalt Emulsion and Asphaltenes Derived from Alberta Oil Sands.," *Transportation Research Record: Journal of the Transportation Research Board,* 2021.

[126] AASHTO T 322-07, "Standard Method of Test for Determining the Creep Compliance and Strength of Hot-Mix Asphalt (HMA) Using the Indirect Tensile Test Device," American Association of State and Highway Transportation Officials, 2020.

[127] L. Kirby, "The Use of Recycled and Innovative Materials in Asphalt Concrete Pavements.," Bradley University., 2017.

[128] M. Martínez-Echevarría, M. Rubio and et al, The reuse of waste from road resurfacingl:cold in-place recycling of bituminous pavement, an environmentally friendly alternative to conventional pavement rehabilitation methods, vol. 109, WIT Transactions on Ecology and the Environment., 2008.

[129] . Y. Qiao, E. Dave and et al, "Life Cycle Costs Analysis of Reclaimed Asphalt Pavement (RAP) Under Future Climate.," *Sustainabilty,* 2019.

[130] M. Zaumanis, R. Mallick and R. Frank, "100% recycled hot mix asphalt: A review and analysis," *Resources, Conservation & Recycling Advances,* vol. 92, pp. 230-245., 2014.

[131] X. A. Sanchez-Castillo, "Effect of Reclaimed Asphalt Pavement on Ontario Hot Mix

Asphalt Performance," University of Waterloo, Waterloo,Ontario, 2014.

[132] G. Tarsi, . P. Tataranni and C. Sa, "The Challenges of Using Reclaimed Asphalt Pavement for New Asphalt Mixtures: A Review.," 2020.

[133] E. Arámbula-Mercado, S. Chavarro-Muñoz and S. Hu, "Performance of Hot and Cold Recycled Mixtures with High Reclaimed Asphalt Pavement Content.," Transportation Research Board, 2020.

[134] C. López, A. González, G. Thenoux, G. Sandoval and J. Marcobal, "Stabilized emulsions to produce warm asphalt mixtures with reclaimed asphalt pavements," *Journal of Cleaner Production,* vol. 209, pp. 1461-1472, 2019.

[135] City of Edmonton, Design and construction standards, vol. 2, Edmonton: City of Edmonton, 2015.

[136] TG2, Technical guideline: Bitumen stabilized materials. A Guideline for the Design and Construction of Bitumen Emulsion and Foamed Bitumen Stabilised Materials, 3 ed., Howard place, South Africa: Southern African Bitumen Association (Sabita), 2020.

[137] K. H. Moon, "Comparison of Thermal Stresses Calculated from Asphalt Binder and Asphalt Mixture Creep Compliance Data," The University of Minnesota, 2010.

[138]

[139] D. Needham, "Developments in bitumen emulsion mixture for roads," University of Nottingham, 1996.

[140] AASTHO T283, "Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage," American Association of State Highway and Transportation Officials, Washington, D.C., 2021.

[141] Qiao, Yaning; Dave, Eshan;et al., "Life Cycle Costs Analysis of Reclaimed Asphalt Pavement (RAP) Under Future Climate," *Sustainabilty,* vol. 11, no. 19, 2019.

[142] S. Miliutenko, A. Björklund and et al., "Opportunities for environmentally improved asphalt recycling: the example of Sweden," *Journal of cleaner production,* vol. 65, pp. 43-156, 2013.

[143] Wirtgen Cold Recycling Manual., "Wirtgen Cold Recycling Manual.," Wirtgen GmbH, Windhagen, Germany, 2012.

[144] Soliman, H., Shalaby, A., & Kass, S., "Overview of Specifications for Unbound Granular Base Materials in Selected Canadian Provinces and Neighbouring States. InTransportation 2014: Past, Present, Future-2014," 2014.

[145] AASHTO T11, "Standard Method of Test for Materials Finer Than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing," American Association of State Highway and Transportation Officials, Washington, D.C., 2021.

[146] AASHTO T44, "Standard Method of Test for Solubility of Bituminous Materials," American Association of State Highway and Transportation Officials, Washington, D.C., 2021.

[147] AASHTO T49, "Standard Method of Test for Penetration of Bituminous Materials," American Association of State Highway and Transportation Officials, Washington, D.C., 2021.

[148] AASHTO T51, "Standard Method of Test for Ductility of Asphalt Materials," American Association of State Highway and Transportation Officials, Washington, D.C., 2021.

[149] AASHTO T59, "Standard Method of Test for Emulsified Asphalts," American Association of State Highway and Transportation Officials, Washington, D.C., 2021.

[150] AASHTO T84, "Standard Method of Test for Specific Gravity and Absorption of Fine Aggregate," American Association of State Highway and Transportation Officials, Washington, D.C., 2021.

[151] AASHTO T85, "Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate," American Association of State Highway and Transportation Officials, Washington, D.C., 2021.

[152] AASHTO T96, "Standard Method of Test for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine," American Association of State Highway and Transportation Officials, Washington, D.C., 2019.

[153] AASHTO T180, "Standard Method of Test for Moisture–Density Relations of Soils Using a 4.54-kg (10-lb) Rammer and a 457-mm (18-in.) Drop," American Association of State Highway and Transportation Officials, Washington, D.C., 2021.

[154] S. Arafat, . N. M. Wasiuddin and et al., "Evaluation of bio-based and petroleum-based rejuvenator based on cracking susceptibility of hot mix asphalt with high RAP content," *Construction and Building Materials,* 2023.

[155] D. A. Obeng and Y. A. Tuffour, "Prospects of alternative funding sourcing for maintenance of road networks in developing countries," *Transportation Research Interdisciplinary Perspectives,* 2020.

[156] H. Ziari and M. Hajiloo, "The effect of mix design method on performance of asphalt mixtures containing reclaimed asphalt pavement and recycling agents: Superpave versus balanced mix design," *Case Studies in Construction Materials,* 2023.

[157] Z. Liu , . L. Sun and et al, "A review of design methods for cold in-place recycling asphalt mixtures: Design processes, key parameters, and evaluation," *Journal of Cleaner*

Production, 2022.

[158] V. Antunes , A. Freire and et al, "A review on the effect of RAP recycling on bituminous mixtures properties and the viability of multi-recycling," *Construction and Building Materials,* pp. 453-469, 2019.

[159] AASHTO T 324-19, "Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures.AASHTO provisional standards.," American Association of State Highway and Transportation Officials., Washington, D.C., 2019.

[160] F. Zhou, "Development of an IDEAL Cracking Test for Asphalt Mix Design, Quality Control and Quality Assurance," *Transport Research Board,* 2019.

[161] M. Uddin, "Performance Comparison of Asphalt Emulsion Stabilized Granular Base Modified with Cement or Asphaltenes," Canadian Journal of Civil Engineering, 2021.

[162] L. Sun, M. Kamaliardakani and et al, "Weighted Neighborhood Pixels Segmentation Method for Automated Detection of Cracks on Pavement Surface Images," *Journal of Computing in Civil Engineering,* 2016.