Evaluation of Mechanical Performance of Asphalt Emulsion Stabilized Base Course Using Asphaltenes or Cement

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

In
Civil (cross-disciplinary)

Department of Civil and Environmental Engineering
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Abstract

Civilization has become highly reliant on the road industry in recent years for both commercial and personal purposes. A typical road's function is to promote traffic flow comfortably and safely. The pavement is a structure made up of natural ground with varying layers on top that can distribute loads over many years and millions of traffic loads. Pavement requires a fundamental understanding of materials to be designed and constructed. Once it is open to traffic loads, it gradually deteriorates with time, repeated traffic load, and climate conditions. An asphalt pavement consists of different layers, which include subgrade, subbase, base, and surface courses. The base layer is the pavement's core structure that distributes most of the load on the pavement and reduces the wheel load stresses to levels that the subgrade can handle. For the base course, various soils or granular materials are available. Still, they may have inadequate properties resulting in significant pavement deformation and reduced pavement life. Besides, the integrity of the underlying soils has a significant impact on the long-term performance of pavement structures. These layers must be able to withstand permanent deformation, shear load and prevent excessive deflection that could cause fatigue cracking in the layers.

Generally, unbound aggregate bases are used as a base layer in the flexible pavements. The effect of unbound base layers on overall pavement efficiency will thus be determined by the layer's depth from the surface as well as the stiffness properties of the layers underneath. The addition of stabilizing agents to untreated granular aggregates improves the stability of unbound bases by increasing aggregate interlocks and facilitating load transfer. Asphalt emulsion stabilization is one the most technically reliable, cost-effective, and environmentally friendly methods to improve the properties of the base layer. However, these mixes have some drawbacks, such as weak early life mechanical properties and high porosity compared to hot mix asphalt. Some researchers discovered that adding 1-2 percent cement to the asphalt emulsion stabilized mixes greatly improves the early mechanical properties as well as the strength and toughness. Nonetheless, the application of these materials causes shrinkage cracking and early brittleness in pavement layers, particularly in cold climates. Other significant disadvantages of asphalt stabilization with cement include high rigidity of the mixture after stabilization, cracking due to shrinkage, and negative environmental effects. These major drawbacks of cement stabilization lead to more research into new materials that can be used as an alternative to cement.

The objective of this research is to evaluate and compare the performance properties of the stabilized base layer with asphalt emulsion and two different additives: 1) asphaltenes which is a waste material obtained from Alberta-oil sand with no significant use in the pavement industry; 2) cement which is a commonly used additive for this type of mixes. A mix design was created for determining the optimum emulsion content (OEC), considering the optimum moisture content (OMC) needed to compact the samples into maximum density. For mixture modification, different proportions of asphaltenes and cement contents were added to the mixture and physical and mechanical properties of the mixes were determined. To investigate the permanent deformation, moisture sensitivity, tensile strength, and low-temperature properties of the modified mixtures, Marshall stability, indirect tensile strength (ITS), Hamburg wheel tracking (HWT), and creep compliance and strength tests were performed on modified and unmodified mixtures. Additionally, in order to better understand the cracking resistance of adjusted mixtures, cracking tolerance (CT) of the samples was determined using the indirect tensile asphalt cracking test (IDEAL-CT).

Results from the study indicate that modification with asphaltenes and cement improved the performance of mixtures significantly compared to the control samples. Overall, compared to asphaltenes, cement was more effective in enhancing the rutting resistance and moisture sensitivity of the mixes. At the same time, it increased the cracking potential of the modified mixes at both intermediate and low temperatures.

Preface

All of the research discussed in this study was carried out at the University of Alberta's Asphalt and Binder Engineering Laboratory, under the supervision of Dr. Leila Hashemian. The introduction and literature review was performed by me based on previous academic findings in chapters 1 and 2.

A version of chapter 3 has been submitted and approved for publication as M. M. Uddin, F. Kamran, M. Basavarajappa, N. Bala, B. Corenblum, and L. Hashemian, “Mechanical Properties of Asphalt Emulsion Stabilized Base Course Modified Using Portland Cement or Asphaltenes.” in the American Society of Civil Engineers (ASCE) at the event of the International Airfield and Highway Pavement Conference will be held in June 2021.

A version of chapter 4 has been submitted for publication as M. M. Uddin, F. Kamran, L. Hashemian, “Evaluation of Asphalt Emulsion Stabilized Granular Base Modified with Cement or Asphaltenes.” in the Canadian Journal of Civil Engineering (CJCE).

Chapter 5 in this report gives the summary and conclusions of this study.

I was in charge of all major aspects of data collection, study, and interpretation, as well as manuscript preparation. In some parts of the project, Farshad Kamran assisted with data collection and analysis. Dr. Leila Hashemian assisted with manuscript revisions. Dr. Leila Hashemian was the study's supervisory author and was involved in idea development during the study.

Acknowledgements

I would like to give thanks, glory, praise, and adoration to almighty Allah.

This thesis is dedicated to my loving parents for their unwavering support, encouragement, and sacrifices. I'd also like to express my gratitude to Alberta Innovates for supporting this research with funding. Also, I'd like to express my gratitude to everyone who helped with the research materials: Asphalt emulsion was provided by Husky Energy; aggregates were provided by Lafarge Canada; and asphaltenes were provided by Nestor Zerpa and Value Development, Inc.

I would like to thank the following people, without whom I would not have been able to complete this research. Throughout this research, I have received a great deal of support and assistance.

My sincere gratitude to my supervisor, Dr. Leila Hashemian, for allowing me to join her team. Her knowledge was particularly useful in articulating the research subject and methodology. When I had a research issue, Dr. Leila Hashemian's door was always open, and she always pointed me in the right direction when she felt I needed it.

I'd like to express my gratitude to my colleagues for their unwavering support and assistance during my study. Farshad Kamran and Manju Basavarajappa deserve special thanks for assisting with laboratory research, data collection, and analysis. I also wish to thank my committee members, Dr. Alireza Bayat, Dr. Yaman Boluk and Dr. Maricor Arlos.

In addition, I'd like to express my gratitude to my parents for their sound advice. Finally, there are my friends, who have been a great help in debating our problems and conclusions, as well as providing a pleasant diversion from my study.

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Chapter 1 Introduction

1.1 Background

The road systems or network of any nation plays a significant role in its development through transportation of goods and services, a good road infrastructure is an essential component for both civilization and country developments [1]. Roads or pavements are generally designed to sustain traffic loads during their intended service life period. The ability of such pavements to resist temperature and transmit traffic loads depends entirely on their structure or layer quality.

The main categories of pavements used globally are rigid (concrete) and flexible (asphaltic) pavement [2]; however, the most commonly used type of pavement is flexible pavement due to its comparatively good resistance to temperature variations, good performance during its service life, high driving comfort, safety, low initial construction cost and easy maintenance [3]. Most countries in the world have an extensive network of paved roads, it was estimated that in the world's largest economies countries, in particular China and the United States of America, flexible pavements account for almost 95% of their pavement type [4]. Canada is one of the countries having an extensive network of paved roads, it was estimated that flexible pavements made of asphaltic materials represent 90% of the total paved road length in Canada. Flexible pavement consists of different layers that support it to resist temperature variation and transmit load. The main layers of flexible pavement are subgrade, subbase course layers, base course, and surface course layers. These layers are normally built on a suitable layer called subgrade, which finally receives and transmits traffic loadings. Amongst these layers, the base layer is an integral part of the pavement structure, which plays an important role in distributing the load to subgrade. Flexible pavements normally consist of an asphalt concrete layer placed over a base and/or a subbase layer which are supported by a compacted soil called subgrade [5].

Basically, a pavement base course is constructed with a dense graded aggregate structure, this gradation used can be made of crushed stone, crushed slag, or other untreated or stabilized materials. The major function of the base course is providing adequate load-support for the pavement [6]. A pavement base layer should be constructed in such a way as to have adequate resistance to deformations and fatigue cracking due to repeated application of loads or thermal cracking due to pavement exposure to low temperatures or extreme variations of temperature [7]. Furthermore, the base course layer under traffic loading most possesses adequate resistance against distortion effects and should be waterproofed to prevent damage due to water or moisture [7].

Seasonal changes in temperature, as well as traffic loading causes, distresses on flexible pavements. The prominent distresses for flexible pavements are rutting, cracking, and raveling [8]. These distresses affect the performance of pavement through deterioration without a proper program of maintenance measures; can cause a significant reduction in the service life of the asphalt pavement. In particular, cracked pavements are sensitive to continuous freeze and thaw cycles due to water ingression [9]. Maintenance and prevention plans play an important role in extending the service life of pavements, especially in cold regions such as Canada. As a result of this pavement distresses, governments and agencies spend huge amounts of money on pavement maintenance, reconstruction, or rehabilitation [1].

An increase in traffic loads in conjunction with intense climatic conditions has increased the rate of pavements deterioration around the world. Therefore, it has become necessary to improve pavement layers to prevent premature distresses in asphaltic pavements. A common method of mitigating pavement failures is the use of thicker pavement base courses or high-quality construction materials. These methods have some major drawbacks, such as negative environmental effects and an increase in pavement initial construction cost. Therefore, it is important to develop a method that can improve pavement performance and, at the same time, decreases the initial cost of construction. Several studies have found that base course stabilization could be a good alternative to overcome such problems [10–12].

The quality of the pavement base course layer can be improved through stabilization techniques. The two main techniques of base course stabilization are mechanical stabilization and chemical stabilization. Mechanical stabilization is a method of improving soil properties by grading the soil; this includes compressing and densification by using mechanical energy like rollers, rammers, and vibration techniques [11]. While, chemical stabilization involves the modification of soil properties by mixing or injecting chemically active compounds such as Portland cement, lime, fly ash, or viscoelastic materials [10,12]. Common materials used for chemical stabilization are asphalt emulsion and active fillers such as Portland cement.

Low-quality soil material mostly leads toward stabilization with cement, lime, and fly ash. Nevertheless, the application of these materials results in the development of shrinkage cracking and early brittleness in pavement layers, especially in cold climatic regions [9]. Other prominent drawbacks with cement stabilization are high rigidity of the mixture after stabilization, cracking due to shrinkage, adverse environmental effects. These major shortcomings associated with cement stabilization result in more investigations on new materials that can serve as an alternative, especially for application in cold climatic regions. Researchers considered the application of asphalt emulsion stabilization as a good alternative to cement stabilization in cold climatic zones [9,13]. Recently, the application of asphalt emulsion mixtures in the base course has become more popular due to its less energy consumption, fewer emissions, and high cost-effectiveness as it does not require heating [14].

Comparing asphalt emulsion with cement material, mixtures stabilized with asphalt emulsion are more flexible compared to cement stabilized mixes, also the application of asphalt emulsion treated aggregates in cold regions is more cost-effective. These benefits provide higher acceptance of using asphalt emulsion stabilization over cement stabilization by pavement construction industries [13]. Additionally, a large saving in energy consumption, as well as a reduction in the rate of pollution, are among the main reasons that encouraged pavement construction industries to employ the use of asphalt emulsion for stabilization [15,16]. Nevertheless, despite these benefits, some drawbacks are observed with asphalt emulsion stabilization.

Studies have shown that for asphalt emulsion mixes to have adequate bonding properties comparable to that of asphalt mixtures, it generally takes a long time to cure [17]. The average time for asphalt emulsion mixes to have good strength has been estimated to spend almost three years time period [18,19]. This requirement by asphalt emulsion mixes of longer curing time leads to poor mechanical strength or low performance, especially at the early stages of construction [20]. To overcome these problems, we typically use active fillers like cement and lime. According to some researchers, adding 1% - 2% of cement to asphalt emulsion stabilized mixes significantly improves early mechanical properties, as well as strength and durability [21]. Nonetheless, in cold climates, the application of these materials causes shrinkage cracking and early brittleness in pavement layers [22]. Other significant disadvantages of asphalt stabilization with cement include high rigidity of the mixture after stabilization, cracking due to shrinkage, and negative environmental effects [23,24]. These major drawbacks of cement stabilization lead to more research into new materials that can be used as an alternative to cement.

Due to economic constraints as well as weather and traffic conditions, ongoing research has been performed to find alternative and innovative materials to enhance pavement base course performance. Researchers have employed the use of materials as alternatives to cement to improve asphalt emulsion mixes for base course application. Sustainability and increase in cost reduction are the major reasons for incorporating materials into the modification of asphalt emulsion stabilized mixes [25,26].

Asphaltenes obtained through the deasphalting process are considered as waste material from oil sand bitumen refineries; this material has a minimal value with no yet significant applications in the industry. Asphaltenes have a relatively high rate of production in oil sand bitumen refineries. It was estimated that in northern Alberta facilities, asphaltenes are produced at a significantly high rate of about 17.5% of asphalts [27]. Therefore, it is necessary to find efficient, practical as well as sustainable means of using asphaltenes in order to create value out of this material.

1.2 Objectives

The main objective of this research is to investigate and compare the performance of asphalt emulsion stabilized mixes modified using Portland cement or asphaltenes derived from Alberta oil sand. Other specific objectives of the study are as follows:

- To evaluate the performance of asphalt emulsion stabilized mixes containing Portland cement and asphaltenes using indirect tensile strength (ITS) at intermediate temperature of 25 °C and Marshall stability test.
- The load-displacement curve of the ITS test results was used to evaluate the cracking indices and fatigue resistance of modified asphalt emulsion mixtures using indirect tensile asphalt cracking test (IDEAL-CT) analysis.

- To evaluate the rutting deformation of the asphalt emulsion stabilized mixes containing Portland cement and asphaltenes based on wheel tracking tests at 40ºC temperature.

- To determine and compare moisture sensitivity of asphalt emulsion stabilized mixes containing Portland cement and asphaltenes using ITS test result after freeze/thaw conditioning of mixes and stripping inflection points (SIP)

- To evaluate asphalt emulsion stabilized mixes containing Portland cement and asphaltenes performance at low temperatures using the indirect tensile strength (IDT) test and creep compliance at 0°C and -10°C temperatures

1.3 Methodology

In order to achieve the objectives of this study, Portland cement and asphaltenes are used independently to stabilize asphalt emulsion mixtures and the result obtained from different performance tests are used for comparison of their properties. The asphalt emulsion used in this study is cationic slow setting (CSS-1H) asphalt emulsion. Cracking resistance evaluation of asphalt emulsion stabilized mixes containing Portland cement and asphaltenes at intermediate temperatures was performed by conducting an indirect tensile strength (ITS) test under dry conditions and then, compared with the control mixture. The cracking tolerance (CT) index, which is a measure that indicates low-temperature cracking resistance of modified mixes was obtained from load-deformation curves from ITS tests. Also, to evaluate the cracking resistance of the asphalt emulsion stabilized mixes at low temperatures, and indirect tensile strength and creep compliance (IDT) tests were conducted at temperatures of 0°C and -10°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 mixes containing Portland cement and asphaltenes were performed using a Hamburg wheel tracking device (HWTD) test at a high temperature of 40°C. Additionally, for moisture sensitivity analysis of the stabilized mixes, the stripping inflection point (SIP) was evaluated from the results and the rutting resistance was evaluated by calculating the total number of passes and the rut depth before failure as well as the rutting resistance index (RRI) of the mixes.

1.4 Thesis Outline

This thesis is organized in 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: In this chapter a detailed review on the background of the study was presented. The applicable procedures, advantages/disadvantages, and prior work in the literature are discussed and cited appropriately in this section. Additionally, relevant case studies are also presented.

Chapter 3 – Mechanical Properties of Asphalt Emulsion Stabilized Base Course Modified Using Portland Cement and Asphaltenes: This chapter evaluated the effects of adding Portland cement and asphaltenes to asphalt emulsion stabilized mixes were examined by conducting Marshall stability and indirect tensile strength test and compared between them.

Chapter 4 – Evaluation of asphalt emulsion stabilized granular base modified with cement and Asphaltene: This chapter investigated and compare the impact of Portland cement and asphaltenes addition on asphalt emulsion stabilized mixes.

Chapter 5 – Summary and Conclusions: In this chapter, differences in the performance of Portland cement and asphaltenes stabilized mixes are summarized and explained based on laboratory tests and observations. In addition, this chapter summarizes the idea, objectives, and scopes of the thesis.

Chapter 2 Literature review

2.1 Cold mix Asphalts and Stabilization Technique

The major important function of the base course layer in the pavement is providing load-supporting capacity through load distribution to the other pavement layers [28]. The pavement base course layer serves primarily as the load-carrying layer and this layer is the most structurally important layer for pavements [29]. This layer normally dampens the stress from traffic loading by transferring to subbase and subgrade layers.

This layer should have adequate resistance against permanent deformation, fatigue cracking caused by repeated loading, and thermal cracking when being exposed to low temperatures or intense temperature fluctuations [7]. Typically, the base course has a dense graded aggregate structure, which can be composed of crushed stone, crushed slag, or other untreated or stabilized materials [6]. Asphalt emulsion mixes are classified as cold mix asphalt mixture which was used for pavement construction especially in base layers. These types of mixes as the name implies composed of asphalt emulsion and unheated aggregates which are mixed and compacted at ambient temperature, that no heating is required for its preparation [30,31]. As this type of mix does not require heating, they offer various advantages over conventional hot mix asphalt mixes [31]. Cold mix asphalt has the advantage that, unlike hot mix asphalt, these types of mixes can be produced at both work site or in the plan, this benefit brings about a reduction in the cost of hauling as well as a significant reduction in energy consumption, these and other benefits makes this type of mixes a very cost-effective scenario [30]. Additionally, a large proportion of recycled asphalt pavement (RAP) can be used in the cold mix, these actions significantly reduce the cost of material for pavement construction [30]. The general application of cold mix asphalt mixes is mostly in a base course under conditions of low or medium traffic, other common applications of base course are in the construction of pavement wearing course/surface coat, and in maintenance works, application of cold mixes asphalt is more common in cold climatic regions [32,33]. Even though some benefits were recorded in the application of cold mixes, some challenges or drawbacks were also found to be associated with cold mixes, prominent among these drawbacks are the high porosity of the compacted mixture, longer curing time before achieving maximum strength, or weak early life strength.

In pavements especially asphaltic pavements, the repeated application of loading on unbounded granular base courses over a period of time results in densification which subsequently leads to deformations in the pavement [9,34,35]. Furthermore, if an unbound granular base course has low resistance to tensile load due to poor quality construction material, the pavement is affected by a tensile failure [36,37]. This direct impact indicates that a granular base course should be constructed with high-quality material to increase the resistance of the layer under loads conditions during service life. If a requirement of good quality construction materials cannot be achieved which may be due to the high cost of these materials, the suitable alternative is the application of stabilization to increase the strength of the layer.

The base material stabilization process is applied in the pavement construction for the purpose of increasing the stability, strength, bearing capacity as well as other performance properties of a base course layer [10–12]. Texas Department of Transportation [38], reported that the main performance properties that can be improved through base course material stabilization techniques are shear strength, stiffness, durability, and adequate resistance against moisture-induced damages.

The proper type of stabilizer and proper additive content for stabilization plays a significant role in determining improvements after application of stabilization. A different soil material requires a different stabilizing agent or additive for achieving the desired improvement as well as the reduction in distresses in the pavement layers. Different materials like asphalt in several forms such as asphalt emulsion, cutback asphalt, and foam asphalt can be applied for stabilization after careful consideration of various soil properties that require stabilization treatment [11,12]. Other materials such as active fillers are used for stabilization and these materials are added in various quantities. It was reported that a lime material is normally added between 1% and can be increased up to 4% of the total mix, Portland cement can be added between 1% to 3% of the total mix, and fly ash material can be added between 6% to 20% of coarse aggregates weight [10].

2.2 Asphalt Emulsion and Manufacture of Emulsion

An emulsion is a dispersion of small globules or droplets (0.001 to 0.01 mm) of one liquid into another [9]. One of the liquids is in the dispersed phase, while the other one is in the continuous phase. In particular, for cold recycling processes: asphalt is in the dispersed phase as they are seen as discrete droplets, and water is in the continuous phase where the droplets are suspended [9]. As asphalt is a petroleum product, it doesn’t mix well with water. In order to overcome this issue, an emulsifier material is used; the emulsifying agents assist with easily disintegrating into fine droplets. Asphalt emulsion is a combination of asphalt, water, and emulsifying agent mixed together.

The asphalt content in asphalt emulsion ranges in-between 30% to 70% of the total mix weight [9]. However, for cold recycling applications, it is recommended that the asphalt content does not exceed 60%. When the asphalt component is higher than 60% then the emulsion becomes too viscous, making it more difficult to pump and coat with the aggregate [9]. Most of the time emulsion content is composed of 60% residual asphalt, meaning 60% of the emulsion is made of asphalt dispersed in 40% of water. The important parameters for the application of asphalt emulsion are emulsion type (surfactants), residual asphalt, breaking time, and curing.

An important parameter for asphalt emulsion is the breaking time of the emulsion, this time is defined as the time required for an emulsion to break and set. The setting time of a particular asphalt emulsion depends on the chemical composition of that asphalt emulsion material. Generally, asphalt emulsion materials are prepared in such a way to have different setting times and this time depends particularly on the type of surfactants, their content, as well as the type of additives used [39]. Most often, asphalt emulsions are prepared such that when stored, they will remain in a stable suspension but when become in contact with aggregate surfaces, the emulsions break and form a layer of asphalt around aggregate particles [39]]. This becomes possible with the help of cations present in the aggregates which raise the OH- ions in emulsion and led to the setting. The breaking rate of an asphalt emulsion largely depends on the type of emulsifier used as well as the properties of the aggregates used [39].

Asphalt emulsion is processed or produced in a asphalt emulsion process plant as shown in Figure 2-1; this equipment consists of high-speed, high-shear mechanical devices, these devices share the asphalt into a tiny drop. In the production of asphalt emulsion, water is treated with an emulsifier inside the emulsifying solution tank and pumped to a colloid mill with asphalt [40]. The colloidal mill is responsible for breaking the asphalt into tiny droplets. The average diameter of these tiny droplets is approximately two microns.

During emulsion production, a revolution of 1000 to 6000 rpm occurs by the high-speed rotor with a mill clearance settings of about 0.25 to 0.50mm and emulsion droplets of size between 0.001 to 0.010 m [21]. The process of emulsification involves heating the asphalt in the colloid mill to a low viscosity followed by adjusting the water temperature in the colloid mill for optimizing the emulsification. The selection of water temperature for the emulsification depends on the emulsification property as well as compatibility between the emulsifying agent and asphalt material. This optimization of temperature is based on the fact that very high-temperature asphalt emulsions are not suitable because the transferring process of emulsion from the colloid mill to the storage tank must be done at a temperature below the water boiling point. For keeping the emulsion produced in a state of uniform blending, mechanical agitation is required inside the storage tank [21].

A colloid mill can effectively disperse the asphalt by means of mechanical energy [40]. There are two feeder lines into the colloid mill: one for the asphalt and another for the emulsifying agent. With the aid of pumps through the air gap, the asphalt and emulsifier solution are mixed when it enters the mill. High shear and hydraulic forces were applied to the fluids through the air gap. The speed of the rotor and the size of the air gap in a colloid mill influence the forces to pump. The air gap allows the asphalt to be dispersed into the water in fine droplets, and the emulsifier minimizes the energy required for asphalt dispersion. It is crucial to monitor the viscosity by flow meter for asphalt to be able to disperse into the water. Generally, the viscosity needs to be relatively low, and the temperature at which the viscosity is obtained for asphalt dispersion is known as equiviscous temperature (EVT). Additionally, the temperature of the asphalt emulsion as it leaves the colloidal mill is also important for recording. If the emulsion exit temperature is at or above the minimum emulsion exit temperature (MEET), the stability of emulsion during manufacturing, cooling and storage is enhanced. MEET is equivalent to the temperature that provides a viscosity of about 20000 centipoises.

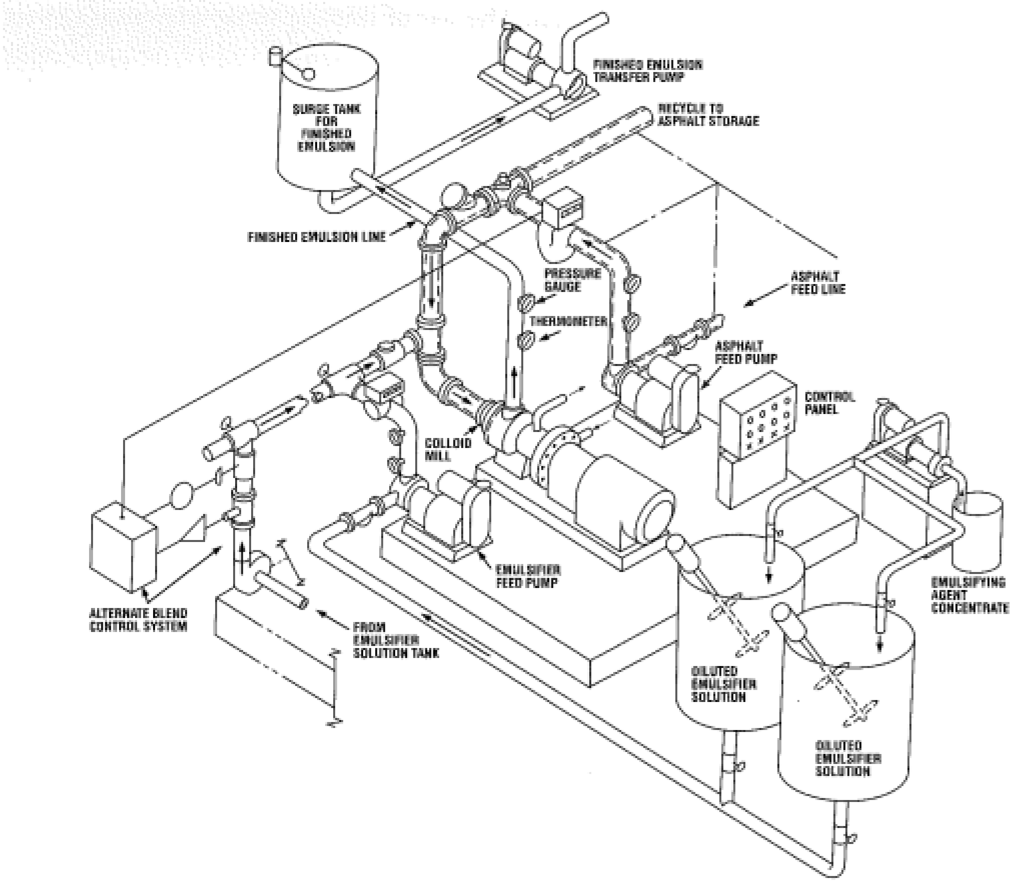


Figure 2-1 Schematic diagram of a typical asphalt emulsion manufacturing process [15]

2.3 Classes of Asphalt Emulsion

Currently, different classes of asphalt emulsion are produced from industries for various applications, the criteria for selecting an asphalt emulsion for a particular application depends upon the required performance properties needed for its application [15,41]. In general, there are three basic classes of asphalt emulsion namely anionic, cationic, and non-ionic. Anionic asphalt emulsifiers are generally fatty acids such as tall oils, rosins, and lignins [15]. In order for these emulsifiers to be active or workable, they react with sodium hydroxide in a saponification process and become negatively charged [9]. The cationic type of emulsifiers comprised of fatty amines such as diamines, imidazolines, and Amidoamines [15]. These emulsifiers become active or workable by effectively reacting with acids (typically, hydrochloric acid), and gain a positive charge to become cationic emulsion [9]. Anionic and cationic are the most readily available and widely used asphalt emulsions for pavement constructions. Finally, non-ionic emulsifiers are uncharged and not suitable for pavement applications.

As indicated above, amongst all the classes of asphalt emulsions, anionic and cationic are widely used for pavement construction and maintenance [9]. However, the cationic emulsion is preferred over anionic emulsion in pavement base course, this is due to the fact that cationic emulsions stabilize through their electrical charge, assisting with breaking the emulsion faster over mixing with an acidic and alkaline aggregate of road base, good quality of adherence with either acidic or alkaline types of aggregates, and effectiveness in all-weather [9]. On the other hand, the anionic emulsion breaks slowly with poor adhesion for acidic [9] aggregates, and the breaking rate is medium with good adhesion for alkaline aggregates. It is important to note that cationic emulsions are the best of recycling as they interact very well with both acidic and alkaline types of aggregates.

2.4 Breaking and Curing Time of Asphalt Emulsions

Apart from surface charge, emulsifiers are also classified based on breaking or setting time. Breaking is the separation of the water from asphalt emulsion and the coalescence of the asphalt droplets producing a continuous film of asphalt on the aggregate to enable coating with aggregates [9]. This process is due to the loss of water by evaporation. In this way, the asphalt droplets in dispersion adhere to the mineral aggregate surface after manufacturing, storage, transportation, and mixing. The time at which the breaking process occurs is also known as setting time. There are three types of asphalt emulsion based on setting time: rapid setting (RS), medium setting (MS), and slow setting (SS).

Normally, asphalt emulsions are manufactured to have four different setting properties, these setting properties are rapid setting (RS), medium setting (MS), slow setting (SS), and quick setting (QS). Rapid setting (RS) emulsions are emulsifiers that react quickly with aggregates to become asphalt concrete from the emulsion state and these types are normally used in the low surface of roads, specifically, chip seals and surface dressing [15]. For the medium setting (MS) emulsions, the evaporation process begins when fine dust of minerals is mixed with aggregate emulsion mix. They are used in open-graded cold asphalt-aggregate mixtures for plat mixes with a low surface area [40]. Slow setting (SS) emulsions are emulsifiers whose breaking time is extended between 30 minutes and 1.5 hours, sometimes even longer [9], and are generally used in dense graded aggregate bases, slurry seals, recycling asphalt, rut filling, micro-surfacing, and in-place mixes (recycling or stabilization) [15,40]. For cold-recycling applications, usually, medium and slow-setting asphalt emulsions are used [16]. Rapid setting asphalt emulsions are not preferable because they flocculate and coalesce rapidly in the presence of fine aggregates and active fillers, enabling balling of asphalt and poor coating.

In some cases, asphalt emulsions are modified and if modified some additional letter words are used to identify the emulsion, example of a modified emulsion is polymer-modified asphalt emulsions whereby a letter “P” is added in order to indicate the emulsion is polymer modified, similarly for latex modified emulsions a letter “L” is added at its end to indicate the emulsion is latex modified. Additionally, asphalt emulsions are also identified by using numbers 1 or 2, and letter (H) for hard emulsion or (S) for soft emulsion. The number “1” indicates low viscosity, and the number “2” indicates high viscosity, and “hard” (H) represents the high penetration base asphalt whereas “soft” (S) represents the lower penetration base asphalt [15,41].

Curing is the development of the rheological properties of asphalt cement. The full-strength gain depends on various factors such as field moisture content, emulsion and aggregate interaction, local climate (temperature, precipitation, humidity), and voids in the mix [9]. Ultimately, curing highlights the continuous cohesion film that holds the aggregates in place with a strong adhesive bond. The curing time of asphalt emulsion can range from 7 days to 14 days [17].

Several factors can affect the breaking and curing time of asphalt emulsion, however, Wirtgen's manual [9] emphasizes that these factors influence more the breaking and curing time. The factors are the rate of absorption of water by aggregate, moisture content, gradation of aggregates, void contents of the mix, type and quality of emulsion, mechanical forces caused by pumping, compaction, and traffic, mineral composition of the aggregate, the intensity of electrical charge on the aggregates with respect to the emulsion, the temperature of the aggregate and air temperature, and type and amount of active filler [9]. Usually, moisture content before mixing impacts the breaking time, while after compaction impacts the curing time.

2.5 Asphalt Emulsion: Advantages and disadvantages

Asphalt emulsion has considerably lower viscosities than asphalt itself, making it effective for application at reduced temperatures. The low-temperature characteristic not only minimizes emissions and energy consumptions but also prevents oxidation of asphalt. Additionally, emulsions are compatible with water and active fillers such as cement and lime to further improve the retained strength, provide resistance to moisture, and traffic accommodation [9]. Furthermore, for cold weather, it is recommended to implement cold recycling using the stabilizing agent for pavement maintenance.

The cold recycling process is advantageous as it reuses the existing asphalt pavement for maximum recovery without disturbing the structures below recycling [9]. Recycled asphalt pavement (RAP) stabilization utilizes emulsion to restore structural integrity, and enhance engineering properties such as strength, stiffness, durability while maintaining the riding quality [9]. Stabilizing with emulsion creates thicker pavement, reduces void compaction, resists crushing stresses due to inter-particle friction and repeated tensile stresses [9]. In order for an asphalt emulsion to be workable, it is crucial to consider the mix design such that optimum emulsion content is chosen for the appropriate thickness of the pavement layer with suitable aggregates [15]. A bituminous stabilized mixture is required to satisfy requirements such as stability, durability, fatigue behavior, tensile behavior, flexibility, and workability [42]. However, there are some disadvantages in the application of asphalt emulsion.

Although emulsion assists with stabilizing granular base, it has some drawbacks such as low early-stage strength, extended curing time, in-adequate resistance to moisture damage, and excessive rutting [21,43]. Therefore, it is recommended to use Portland cement, hydrated lime, and fly ash as active fillers for improving the performance of asphalt mixture with emulsions such as permanent deformation, strength, and moisture susceptibility [9]. Active filler chemically works as a second binder in gripping the aggregates and reacts within the mixture due to pre-existing water source forming hydration products to act as a catalyzer [40]. As a result, during the early stages, the trapped water is absorbed in the hydration process to assist with improving the mixture strength. The chemical composition of asphalt binder can have an impact on the properties of asphalt mixture [44].

2.6 Performance of Asphalt Emulsion Stabilized Mixes

Different studies compared the inclusion and exclusion of active fillers in cold recycling asphalt emulsion mixture to highlight an appropriate improvement in the performance properties of the mixture with the incorporation of active fillers [21,43,45–48]. While some studies mainly compared the effect of Portland cement, others also compared other active fillers such as hydrated lime (HL), hydrated lime slurry (HLS), and ground granulated blast furnace slag (GGBF) along with cement.

2.6.1 Portland Cement as Active filler

A study by Xu et al. [45] investigated the impact of 0.5%, 1.5%, and 2.5% cement contents on cold recycling asphalt mixtures with emulsion by performing various performance tests such as indirect tensile strength test (ITS) in both dry and wet condition to determine the moisture resistance ability, wheel tracking test to assess rut depth and dynamic stability for high-temperature stability, and bending beam test to evaluate low-temperature performance. Based on the ITS dry and wet tests, the ITS retained was higher with the higher amount of cement, which shows that after moisture subjection, cement plays a positive role in resisting moisture damage. From the wheel tracking test, it was evident that an optimum amount of cement exists, which 1.5% as it was provided the maximum value for dynamic stability and lowest rutting depth. The study further elaborates that specimen with 2.5% cement leads to poor workability due to excessive stiffness for compacting. Bending strength at failure and bending strain at failure are evaluated based on elementary beam theory from the three-point bending beam test. The results highlighted that bending strength at failure increased, while the bending strain at failure decreased with the increase in the amount of cement.

The study suggested that failure in cold recycled asphalt mixtures is due to excessive strain and high content of cement. An investigation by Terrell et al. [49] found that for the application of anionic emulsion under conditions of cold or moisture, the addition of small quantities of cement to asphalt emulsion enhances the curing rate of the emulsion mixture. Also, the study indicates that the ultimate resilient modulus of the asphalt emulsion mixture was improved by approximately 200% with the addition of 1% cement. Furthermore, the study shows that a cement content between 1% to 2% is the optimum cement content for significant improvement in performance properties of the mixes [21].

Furthermore, research by Jian et al., [45] revealed that the addition of cement to asphalt emulsion mixtures increases resistance to rutting deformation of the stabilized emulsion mixtures. Though the study indicates high cement content can result in adverse effects which leads to small or no improvement in rutting resistance of the mixes, the study found that cement addition of 1.5% is normally the optimum content for adequate improvement in performance. This effect is attributed to the high cement content which makes the stabilized mix to be very stiff and very hard to be compacted adequately.

In order to understand the role of 1%, 1.5%, and 2% cement in the early-age strength and long-term performance of asphalt emulsion cold recycled mixture, Yan et al. [46] conducted Hveem cohesion test, raveling test, immersion/ freeze-thaw IDT test, wheel track rutting test, and three-point bending test. Based on the experiments, it was discovered that the increase in the amount of cement results in higher cohesion force and lower raveling loss rate, which indicates that cement indeed positively contributes to the early-age strength. Furthermore, the higher content of cement also showed a trend in higher moisture susceptibility ratios for the immersion/freeze-thaw IDT test when compared to the sample without any cement. The wheel track rutting test results showed an increase in dynamic stability values with higher cement contents, suggesting that cement is advantageous for the high-temperature stability of asphalt emulsion cold recycling mixture. Lastly, the three-point bending beam test highlighted that at low temperature 1.5% cement is optimum since the failure strain percentage decreased after exceeding 1.5%. Therefore, although it is evident the addition of cement enhances the long-term performance of cold recycling asphalt emulsion mixtures when concerning about low-temperature effect, the cement content should not be greater than 1.5% according to this research.

2.6.2 Comparing Portland cement and other Active Fillers

A study by Niazi and Jalili [21] investigated the effect of active fillers such as 2% Portland cement, 2% hydrated lime slurry (HLS), and 2% hydrated lime (HL) and deduced that samples without the active fillers were sensitive to moisture damage. Upon performing ITS dry and wet tests, the tensile strength ratio (TSR) of the sample with the Portland HLS provided the best result followed by Portland cement and HL. The permanent deformation of the cold recycling asphalt mixtures was also improved with the introduction of active fillers as found from the dynamic creep test. It was discovered that the Portland cement, HLS, and HL resulted in a reduction of rutting depth by 40%, 30%, and 26% when compared to the sample without the additives. Furthermore, the wheel tracking test also emphasized a similar trend where Portland cement, HLS, and HL resulted in a decrease of rutting depth by 58%, 50%, and 38% when compared to the sample without any fillers. Based on the experiment, it is evident that either Portland cement or HLS could be highly effective for application in the cold recycling asphalt emulsion mixtures. Although both of these active fillers are beneficial, due to the difficulties in producing hydrated lime slurry the study reports that the use of Portland cement is recommended.

Additionally, Du [43] compared active fillers such as composite Portland cement (CPC) ranging from 1.5% to 3.5% in increments of 1%, 2.5% hydrated lime (HL), and 2.5% HL with 2.5% ground-granulated blast furnace slag (GGBF). Based on the soaked and freeze-thaw TSR and wheel tracking test, he recommended using 3.5% CPC or the combination of HL with GGBF as it provided the best value. However, according to the low temperature bending beam test, the fracture energy concept is developed which showed that 2.5% CPC is superior to both HL and its combination with GGBF. Although CPC provides desirable results, the higher amount of cement is prone to shrinkage and low-temperature cracking, in which case 2.5% CPC is optimum, and therefore is suggested to be used. Upon conducting the environmental scanning electron microscope test, he also emphasized that the hydration products of CPC enable it to perform better due to better cohesion with asphalt mastic, and adhesion strength between asphalt mastic and RAP.

2.7 Asphaltenes

Asphalt, a viscoelastic material is composed of saturates, aromatics, resins, and asphaltenes (SARA) [44]. The components can be further categorized as polar or nonpolar. Resins and asphaltenes comprise the polar fraction, while aromatics and saturates are the non-polar fraction [50]. Sultana and Bhasin [44] suggest that the usage of asphaltene can improve the rheological properties of asphalt mixture due to its polarity. Asphaltene is the most polar component due to its higher molecular weight compared to the other components and adding asphaltene in asphalt mixture increases the stiffness.

Asphaltenes can be obtained from different sources, however, the main sources of asphaltenes are oil sands, crude oil, asphaltite, tar sand, and bituminous coal [51]. For the separation of asphaltenes from their main source, different methods can be used to extract asphaltenes but the method of solvent extraction or solvent deasphalting is the most widely used for extraction of asphaltenes [52–55].

Asphaltenes obtained from refineries are considered as a waste, this material has minimal with no significant applications in the industry. Asphaltenes are a relatively produced higher rate in refineries. It was estimated that asphaltenes are produced at a high rate of 17.5% of bitumen in the refineries located in northern Alberta Province [27]. 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 for mixing. The asphaltenes produced from refineries is shown in Figure 2-2, the first picture shows asphaltenes in solid form while the second figure shows asphaltenes powdered form.

(a) **(b)**

Figure 2-2 Asphaltenes: (a) Solid Form; (b) Powder Form after Passing through No.100 Sieve

2.8 Design of Asphalt Emulsion Mixes

Asphalt emulsion mix design consists of different steps as well as testing protocols based on the requirement for a particular application and level of traffic load intended to be used [9]. Previously, the widely used mix design methods for asphalt emulsion mixes were the Hveem design method, which was used in California, and the Marshall mix design developed by the Illinois department of transportation [30]. However, in recent times, the widely used mix design method is using an asphalt manual from the Asphalt emulsion manufacturers association, specifically developed for cold mix asphalt applications [30].

Although there is no broadly accepted mix design currently available for asphalt emulsion cold mixes, a guideline based on empirical formulae, laboratory tests as well as previous experiences has been developed by various agencies such as Asphalt Institute [15]. According to the Asphalt Institute, the quantity of the asphalt emulsion to be used for a particular mix design is calculated based on the relationship shown in Equation 2-1, this relationship is used based on aggregate gradation type to be used for the mix.

$$\text{Base mixture: Asphalt Emulsion } \% = \frac{(0.06B + 0.01C)100}{A} \qquad [2-1]$$

Where:

A = Percentage of residue of asphalt emulsion remaining after distillation (as determined using ASTM D6997)

B = Percentage of dry aggregate passing through a No. 4 sieve

C = Percentage of dry aggregate retained on a No. 4 sieve.

According to the specification, the initial or approximate asphalt emulsion content obtained as per the above equation is used with the various combinations of asphalt emulsion and water content, these combinations are used to prepare samples for the determination of the optimum asphalt emulsion content.

For the optimum emulsion content, the specification recommends that samples with a minimum of three different emulsion contents should be prepared, and out of this, there must be at least one emulsion content below and above the approximate asphalt emulsion content determined from the above equation. However, during sample preparation, if the mixture appears very dry, it is recommended that the trial mixes should be started from approximate asphalt emulsion content. Similarly, if the asphalt emulsion mix is found to be rich in the coating, it is recommended to reduce the content for other levels with 1% of the normal difference between the emulsion contents [30].

2.9 Performance Evaluation of Asphalt Emulsion Mixes

Using the appropriate optimum asphalt emulsion content determined, different asphalt emulsion mixes are prepared and subjected to various testing protocols of asphalt emulsion to evaluate their resistance to rutting, fatigue, thermal cracking, low temperature cracking, and moisture-induced damages.

This chapter is presenting the theory of the Marshall stability test, indirect tensile strength test, IDEAL-CT analysis, Hamburg wheel tracking test, creep compliance, and IDT strength test.

2.9.1 Marshall Stability and Flow

Marshall stability and flow test are the most widely used method for mix design in many parts of the world, the parameters obtained from this test can also be used to evaluate the performance of the asphalt mixture [56]. It is well known that the Marshall stability and flow test is the most common test used for the development of an asphalt mixtures design based on main parameters which include stability, flow, density, and air voids. The significant benefit for the application of Marshall mix design for asphalt mixtures is that the method provides adequate attention to the density and void properties, and these parameters ensure good volumetric ratios for the asphalt mixes [56]. An additional benefit for the application of this method is that the test setup is simple the equipment for the test is portable and not expensive which makes it easy for remote quality control operations [56].

Marshall stability and flow test can be conducted in accordance with ASTM D6927-15 [57] specification using compacted specimens of 100mm in diameter and 60mm in height. Prior to the test the samples are prepared and compacted using a Marshall hammer. Marshall test is conducted using a load-deformation recorder together with a load cell and an automatic recording device which recorded both the stability and flow values of a sample. During the test, the maximum resistance load obtained during a constant rate of the deformation loading sequence is defined as the Marshall stability value of the sample. Marshall flow for the sample is defined as the maximum amount of deformation at the point of failure of the sample.

2.9.2 Indirect Tensile Strength

The tensile strength properties of an asphaltic material are determined by performing indirect tensile strength test. The tensile properties of an asphaltic material are highly related with the cracking properties of the material. It well established that the higher the ITS value of a sample the higher the cracking resistance of the sample [58]. The performance of the asphalt mixture to fatigue cracking is dependent on the tensile properties, as mentioned earlier due to repeated traffic load on the pavement layers which generates tensile stress and strains at the bottom of the pavement structure, these stresses generated leads pavements to fatigue failure during service life [59]. The stiffness of an asphaltic material determined the magnitude of the strain of a sample. Based on this the ITS test can be used as a good indicator of strength as well as adherence against fatigue failure, cracking and rutting of the asphalt mixture [59]. The effects of saturation and accelerated water conditioning, along with freeze-thaw cycle of an asphaltic material can also be evaluated through indirect tensile strength test. For ITS test, samples can be prepared and conditioned in accordance with AASHTO T 283-14 [60] specification which is also known as Lottman procedure.

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 height. For unconditioned samples, the dry samples can be tested directly at a loading rate of 50 mm/min. during testings, the maximum load is recorded directly, and the indirect tensile strength of the sample is calculated in accordance to the equation 2-2. While for the freeze/thaw conditioning samples, the samples are preconditioned, the samples are first saturated, followed by plastic wrapping and frozen at temperature of -18°C for an approximately 16 hours, the samples are then placed inside 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 then conditioned by transferring in to 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 ratios (TSR) which is a measure of resistance against moisture is calculated using equation 2-3. NCHRP Report 673 [61] suggests that the TSR of an asphaltic material should be beyond 70% in order to have adequate resistance against stripping and moisture damage.

$$S_t = \frac{2000P}{\pi t D} \qquad [2-2]$$

Where,

S_t = indirect tensile strength (ITS), kPa

P = maximum load, N

t = average specimen thickness, mm

D = specimen diameter, mm

$$TSR = \frac{S_1}{S_2} \qquad [2-3]$$

Where:

TSR = tensile strength ratio

S1 = average tensile strength of the dry subset, kPa; and

S2 = average tensile strength of the conditioned subset, kPa.

2.9.3 IDEAL-CT Test

One of the major distresses of asphaltic material in North America and other parts of the world is the cracking of asphalt pavement. 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 [62]. The IDEAL-CT has been developed as the ideal cracking test to be used for estimating 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 at 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.). IDEAL-CT test can also be conducted with field cores. Samples from the laboratory are normally 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 [63]. 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 cracking tolerance of an asphalt sample depends largely on some parameters which include the aggregate gradation used for the mix, air-voids and if additive is used, the type of additive also affects the CT-Index of the mix. The CT-Index of a sample can be calculated using Equation 2-4 [64].

$$CT_{Index} = \frac{t}{62} * \frac{l_{75}}{D} * \frac{G_f}{|m_{75}|} * 10^6 \qquad [2-4]$$

where,

CT_{Index} = cracking tolerance index

G_f = fracture energy, joules/m^2

$|m_{75}|$ = 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

2.9.4 Hamburg wheel tracking test

The Hamburg wheel tracking equipment is used to evaluate the rutting resistance of asphalt mixes, Rutting test can be performed In accordance with AASHTO T324-16 [65] 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 samples for the test are compacted to an air void of 7.0 ± 0.5 percent. The test is conducted at a predefined temperature and the device is set to tracks for 20,000 passes or until the sample reaches a rutting depth of 12-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. A graph of rut depth versus the number of passes is plotted which provides valuable information about the asphalt material susceptibility to moisture damage by obtaining the stripping inflection point (SIP) as shown in Figure 2-3, which indicates the point at which moisture damage starts to take effect on the sample. It was suggested that, if an asphalt material SIP occurred at less than 10,000 load cycles passes, the sample may be highly susceptible to moisture-induced damages [66]. The consolidation point is regarded as the rut depth achieved in the sample within the first 1,000 loading cycles passes due to post-compaction consolidation.

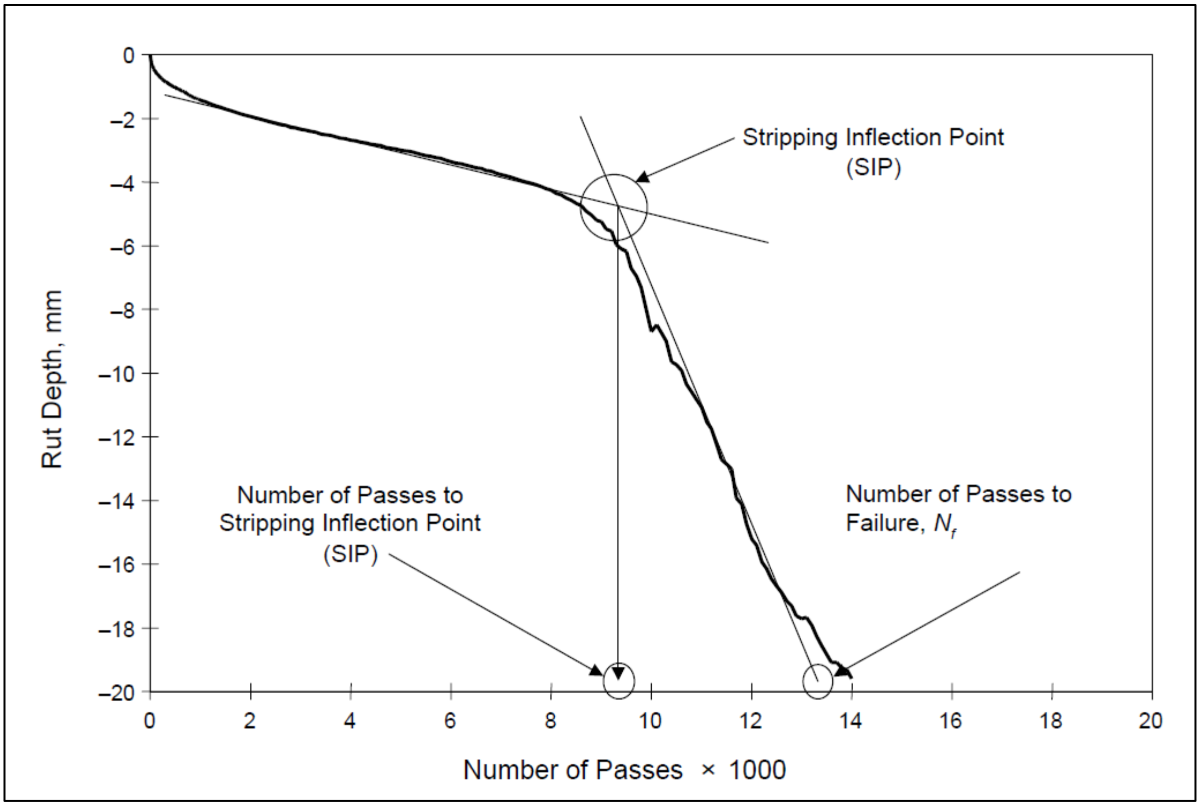


Figure 2-3 Key parameters of the wheel tracking test analysis [65]

2.9.5 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 [67]. Creep compliance is the rate at which strain increases for a constant application of stress time-dependent strain per unit stress, while indirect tensile strength is the strength of the mixture under tension.

AASHTO T322-07 [68] was used to assess the creep compliance and strength of the mixtures using an indirect tensile test setup to compare the low-temperature properties of samples adjusted with asphaltenes or cement. The efficiency of the mixtures at low temperatures is demonstrated in this test. For each of the emulsion contents, a Marshall sample with three replicates was prepared.

In this case, however, the surface of the samples was cut to a height of 38 to 50mm. Considering the base layer and PG grading of the binder used to prepare the asphalt emulsion, the test temperatures used in this analysis were 0°C and -10°C. Prior to 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 2-4 depicts the test setup as well as test samples before and after processing. The load-deformation values obtained from the test were used to measure the fracture energy and indirect tensile strength of samples for both temperatures. Each asphalt mix's creep compliance [D(t)], tensile strength, and fracture energy were measured.

The creep compliance was calculated as per Equation 2-5. While tensile strength is calculated as a function of the maximum load and then "corrected" to its "true" tensile strength [67], using Equation 2-6.

$$D(t) = \frac{\Delta Xtm,t \times Davg \times bavg}{Pavg \times GL} \times Ccmpl \tag{2-5}$$

where:

D(t) = creep compliance at time t (kPa)-1

GL = gauge length in meters

Davg = average diameter of all specimens

bavg = average thickness of all specimens

Pavg = average creep load

Xtm,t = trimmed mean of the normalized, horizontal deformations of all specimen faces at time t

$$C_{cmpl} = correction\ factor = 0.6354 \times \left(\frac{X}{Y}\right)^{-1} - 0.332$$

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 50 seconds) for all specimen faces.

$$S_{t,n} = \frac{2\times P_{f,n}}{\pi\times b_n\times D_n} \quad [2\text{-}6]$$

$$Tensile\ strength = \left(0.78 \times S_{t,n}\right) + 38 \quad (for\ psi)$$

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

where:

St,n = “uncorrected” tensile strength of specimen, n

Pf,n = maximum load observed for specimen, n

bn = thickness of specimen, n

Dn = diameter of specimen, n

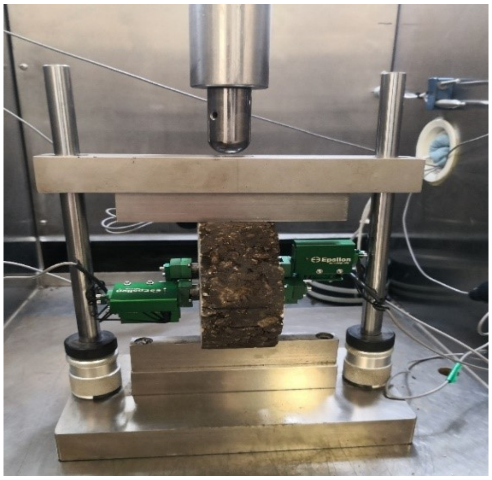


Figure 2-4 IDT test setup

Chapter 3 Mechanical Properties of Asphalt Emulsion Stabilized Base Course Modified Using Portland Cement and Asphaltenes.

3.1 Abstract

Base course quality has a significant impact on the pavement load-bearing capacity and the layer strength could be improved using stabilization techniques. Asphalt emulsion is one of the commonly used materials for base course stabilization. Cement is usually added as an active filler to enhance the mix properties. Asphaltenes is a waste material derived from Alberta oil-sands bitumen with no significant application in the industry. This study compares the impact of asphalt emulsion stabilized layers modified by asphaltenes and cement separately. For this purpose, asphaltenes and cement modified mixes with 1% and 2% by the mixes total weight were prepared. Both mixes mechanical properties were investigated through Marshall stability, indirect tensile strength (ITS), tensile strength ratio (TSR). IDEAL-CT test was also used to evaluate the cracking resistance of the mixes. From the results, it was concluded that asphaltenes had a greater impact on increasing the Marshall stability, tensile strength, and cracking resistance of the mixes compared to cement. However, asphaltenes-modified samples were found to be more susceptible to moisture damages.

3.2 Introduction

As an integral part of flexible pavements, the base layer plays an important role in transferring the traffic load to the subgrade. Major distresses associated with asphalt pavements are rutting, cracking, and ravelling [8]. Such distresses influence pavement performance through deterioration and reduction in pavement service life. In particular, cracked pavements are very sensitive to continuous freeze and thaw cycle due to water seepage in pavements [9]. Therefore, it is essential to carefully design and construct granular base layers to inhibit cracking. Generally, unlike conventional HMA, which requires high amounts of energy for its production [69], a mixture of aggregates, asphalt emulsion, and water is prevailing against climate change [70], in particular, cold in-place recycling. Cold mix asphalt contributes to energy savings of 95% compared to HMA [47], and asphalt emulsion is the most popular type of cold mix asphalt [31].

Asphalt emulsion has considerably lower viscosities than asphalt itself, making it effective for application at reduced temperatures [71]. The low-temperature characteristic not only minimizes emissions and energy consumptions but also prevents oxidation of asphalt. Additionally, emulsions are compatible with water and active fillers such as Portland cement and lime to improve the retained strength, provide resistance to moisture, and higher traffic resistance [9]. Furthermore, it is recommended for cold weathers to implement cold recycling using stabilizing agents for pavement maintenance. Recycled asphalt pavement (RAP) stabilization utilizes emulsion to restore structural integrity and enhance engineering properties such as strength, stiffness, durability while maintaining the riding quality [9]. Although asphalt emulsion helps stabilize the granular base, it has some drawbacks such as low early-stage strength, extended curing time, inadequate resistance to moisture damage, and excessive rutting [21,43]. Therefore, it is recommended to use Portland cement, hydrated lime, and fly ash as additives for improving the performance of stabilized mixes with asphalt emulsion such as permanent deformation, strength, and moisture susceptibility [9]. Additives chemically work as a second binder in gripping the aggregates and react within the mixture due to pre-existing water source, forming hydration products to act as a catalyzer [72]. As a result, during the early stages, the trapped water is absorbed in the hydration process to improve the mixture strength. The chemical composition of asphalt binder can impact the properties of asphalt mixture [44].

Several researchers compared the inclusion of active fillers in cold recycling asphalt emulsion mixture to highlight an apparent improvement in the mixture's performance properties' performance properties. Xu et al. [45] studied the impact of the addition of 0.5%, 1.5%, and 2.5% Portland cement to cold recycled asphalt mixtures with emulsion by conducting various performance tests such as indirect tensile strength test (ITS) in both dry and wet condition to determine the moisture resistance of the mixes. Based on the results, the ITS was found to be higher for wet samples and was increased with increasing the amount of Portland cement. This showed after moisture conditioning, Portland cement played a positive role in preventing moisture damage. The study suggested that failure in asphalt emulsion stabilized mixes are due to excessive strain and high content of Portland cement.

Niazi and Jalili [21] investigated the effect of Portland cement, hydrated lime slurry (HLS), and hydrated lime (HL) at 2% content. They deduced that samples without the active fillers were sensitive to moisture damage. The permanent deformation of the mixtures was also improved with the introduction of active fillers according to the dynamic creep test. It was discovered that the Portland cement, HLS, and HL resulted in a reduction of rutting depth by 40%, 30%, and 26%, respectively, when compared to the sample without the additives. Furthermore, the wheel tracking test also emphasized a similar trend where Portland cement, HLS, and HL resulted in a decrease of rutting depth by 58%, 50%, and 38%. It was concluded that both Portland cement and HLS could be highly effective for application in the cold recycling asphalt emulsion mixtures. Although both of these active fillers are beneficial, due to the difficulties in producing hydrated lime slurry, the study reports that the use of Portland cement is recommended. Du [43] compared the composite Portland cement (CPC) ranging from 1.5% to 3.5% in increments of 1%, 2.5% hydrated lime (HL), and 2.5% HL with 2.5% ground-granulated blast furnace slag (GGBF). Based on the soaked and freeze/thaw TSR and wheel tracking test, the study recommended the use of 3.5% CPC or the combination of HL with GGBF as it provided the best value. Although CPC provides desirable results, the higher amount of Portland cement is prone to shrinkage and low temperature cracking, in which case 2.5% CPC is optimum, and suggested to be used. In contrast, previous studies concluded that ordinary Portland cement (OPC) and other additives improved the mechanical properties of cold asphalt emulsion mixture, but they have demerits too, which are environmental and economic impacts.

From literatures discussed, it is evident that Portland cement is widely used, and improves the performance of asphalt emulsion stabilized courses. Although there have been research investigating the effect of Portland cement, hydrated lime, and ground-granulated furnace slag on stabilization, there have been limited studies investigating the application of asphaltenes as an additive to improve the performance of asphalt emulsion stabilized mixes.

Asphalt binder composed of saturates, aromatics, resins and asphaltenes often abbreviated as (SARA). Asphalt is further categorized into polar and non-polar components, the polar fractions are resins and asphaltenes, the non-polar fractions are aromatics and saturates [50]. Sultana and Bhasin [44] suggests that the application of asphaltenes can improve the rheological properties of asphalt mixture due to its polarity. Asphaltenes is the most polar component due to its higher molecular weight compared to the other components and adding asphaltenes in asphalt mixture increases the stiffness. Although there have not been studies on asphaltenes application with asphalt emulsion from previous studies, it is expected that asphaltenes can potentially improve the performance properties of asphalt emulsion stabilized mixes.

3.3 Objectives

The objective of this study is to compare the mechanical performance of a well-graded granular base course stabilized with a slow setting (CSS-1H) asphalt emulsion modified with Portland cement and asphaltenes derived from Alberta oil sands bitumen. Marshall stability, ITS tests were used to compare the compressive and tensile strength of the mixes, respectively. To investigate moisture sensitivity of the mixes, TSR after saturating the mixes by water and also freeze-thaw conditions was evaluated. To compare cracking resistance of the mixes, IDEAL-CT test was conducted.

3.4 Materials

3.4.1 Aggregates

The aggregates used were supplied by Lafarge Canada. A well-graded aggregate gradation was selected in accordance with Wirtgen Cold Recycling Manual [9], City of Edmonton [73] and Alberta transportation [74]. Aggregate gradation has been shown in Table 3-1 and the physical properties of the aggregates are shown in Table 3-2. The bulk specific gravity of the aggregates ($G_{sb\text{-}agg}$) was also determined to be 2.601. The amount of filler used in stabilization of the granular base layer and Los Angles abrasion test results of aggregates are found to satisfy the specification of Wirtgen Cold Recycling Manual [9] and city of Edmonton [73] standards. Optimum moisture content has been determined prior to mixture testing, using proctor test in accordance with ASTM D698 [75] specification for the aggregate gradation and the result is also presented in Table 3-2.

Table 3-1 Selected aggregate gradation.

Sieve size (mm)	20	12.5	10	8	6.3	5	2.5	1.25	0.63	0.315	0.16	0.08	Filler (Pan)
% Passing	100	75.17	61.23	55	48	42.73	32.08	25.61	18.93	13	9	6	0
% Retain	0	24.83	13.94	6.23	7	5.27	10.65	6.47	6.68	5.93	4	3	6
Coarse-fine	57.27%						42.73%						

Table 3-2 Physical properties of aggregates.

Description	**Result**	**Standard**	**Limitation**
Amount of material finer than 75-µm (No. 200) sieve in aggregate (%)	6	ASTM C117	2-9
Specific gravity of fine aggregates (G_{fa})	2.604	ASTM C128	
Absorption of water of fine aggregates (%)	0.624		
Specific gravity of coarse aggregates (G_{ca})	2.598	ASTM C127	
Absorption of water of coarse aggregates (%)	0.87		
Abrasion of coarse aggregates (%)	23	ASTM C131	Max 40
Optimum Moisture Content, OMC (%)	6.3	ASTM D698	
Dry Density (kN/m^3)	15.4 max.	(Modified D1557)	

3.4.2 Asphalt Emulsion

According to Wirtgen Cold Recycle Manual [9], the typical asphalt emulsion used for base stabilization is a cationic slow setting (CSS), as it requires the minimum time for mixing and laying the base layer as well as the aggregates charge. In this study, a Cationic slow setting (CSS-1H) consisting of 61% asphalt and 39% water was used. The asphalt binder used for the preparation of the asphalt emulsion is 80/100 penetration grade asphalt. The specific gravity of emulsion determined using ASTM D6937 [76] to be 1.02 and viscosity at 25˚C is 22. Settlement in 24 hours was 0.5% by the mass, and particle charges were positive due to the cationic origin of the asphalt emulsion. Penetration of asphalt residue at 25ºC 95, ductility is >40cm, and solubility in Trichloroethylene of Asphalt residue is >97.5%. (Husky energy 2018)

3.4.3 Portland cement

ASTM C1157 [77]/ CSA A3000 [78] type GU Portland cement was used in this study. The basic properties of cement are shown in Table 3-3.

Table 3-3 Basic properties of cement

Initial setting time (min)	45	ASTM 1157
Final setting time (min)	420	ASTM 1157
Compressive strength at 3d (Mpa)	13	ASTM 1157
Compressive strength at 7d (Mpa)	20	ASTM 1157
Compressive strength at 28d (Mpa)	28	ASTM 1157

3.4.4 Asphaltenes

In this study, asphaltenes derived from Alberta oil-sand bitumen was used. It was obtained in solid form and crushed into a powder form. The asphaltenes sieved through a No. 100 sieve, and those passed through the sieve are used for modification with the aim of achieving uniform dispersion during the mixing. Figure 3-1 shows solid asphaltenes and crushed powdered asphaltenes after sieving through No. 100 sieve. According to the SARA test, the asphaltenes content in the sample was determined to be 79.62%, while saturates, aromatics, and resins are 6.85%, 9.68%, and 3.84%, respectively.

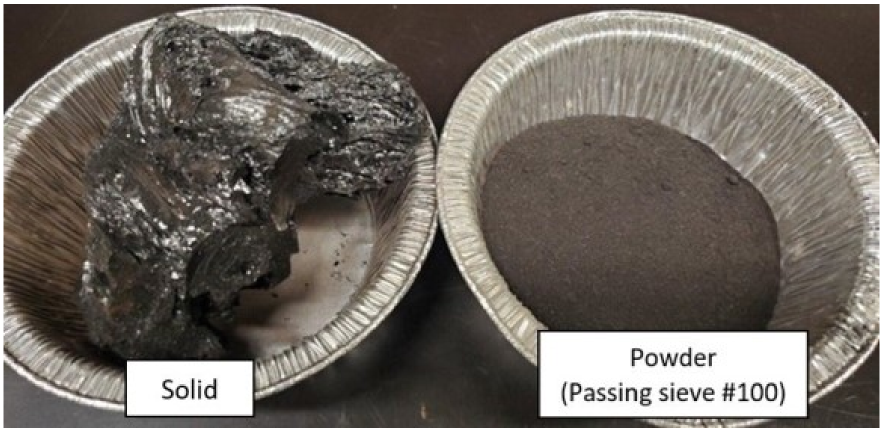


Figure 3-1 Asphaltenes used in the mixtures.

3.5 Methodology

3.5.1 Mix Design

According to Asphalt Institute [15], well-graded granular aggregates was selected and asphalt emulsion content was calculated accordingly. The amount of asphalt emulsion to be used in this method has been calculated as per the relationship provided in Equation 3-1. Value of A, which is the amount of the material retained after distillation was found to be 61%.

$$\text{Base mixture: Asphalt Emulsion percentage} = \frac{(0.06\text{B} + 0.01\text{C}) * 100}{\text{A}} \qquad [3-1]$$

where:

A = Percentage of residue of asphalt emulsion remaining after distillation (as determined using ASTM D6997 [79]); B = Percentage of dry aggregate passing through a No. 4 sieve; C = Percentage of dry aggregate retained on a No. 4 sieve.

The approximate asphalt emulsion content determined using the relationship was found to be 4.89% per total weight of the mixture. Using this as a base asphalt emulsion content and adding OMC to the aggregates, the Marshall stability and ITS test were conducted to determine the optimum emulsion content (OEC) with four different contents of asphalt emulsion 1% intervals. Samples were compacted using a Marshall hammer with 50 blows per face and were cured inside an oven at 60 ^{o}C for 48 hours. The cured samples were kept outside the oven for a minimum of two hours to cool down before extracting the specimens from the mould. Three specimens were prepared for each of the emulsion contents. Before Marshall stability test, the samples were conditioned for at least 2 hours at 25^{o}C in the air chamber. For ITS test, samples were conditioned at 25^{o}C in the air chamber three hours before testing. To evaluate the tensile strength of the specimens, the test was conducted by applying load at a rate of 50mm/min, and recorded the maximum applied load until failure point of the samples. The tensile strength of the samples was calculated using Equation 3-2.

$$S_t = \frac{2000 * P}{\pi * t * D} \qquad [3-2]$$

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).

3.5.2 Indirect Tensile Strength and Tensile Strength Ratio

The ITS test was conducted in accordance with AASHTO T283 [60] specifications. A set of three replicate samples for each of Portland cement and asphaltenes were prepared and tested for ITS. The same numbers of samples were tested after conditioning according to the standard for determining the TSR for saturated and freeze-thaw samples. For conditioning, the samples were saturated in a water bath at 25^{o}C for 24 hours. Afterwards, the sample were tested for ITS and TSR determined using Equation 3.

$$TSR = \frac{S_2}{S_1} \qquad [3-3]$$

Where:

S_1 = Average tensile strength of the dry subset (kPa)

S_2 = Average tensile strength of the conditioned subset (kPa)

For freeze-thaw conditioning, a set of three samples was saturated under water for 24 hours and were sealed using a plastic bag. The sealed samples were stored in a freezer at -18 ^{o}C for 16 hours. Before ITS testing, the samples were placed in a water bath at 25^{o}C for 2hr. TSR value determined using Equation 3-3.

3.5.3 IDEAL-CT analysis

The IDEAL-CT was analyzed for both cement and asphaltenes modified mixes based on ASTM D8225-19 [64] 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. The relationship used to determine the CT Index is shown in Equation 3-4.

$$\mathrm{CT_{Index}} = \frac{\mathrm{t}}{62} * \frac{\mathrm{l_{75}}}{\mathrm{D}} * \frac{\mathrm{G_f}}{|\mathrm{m_{75}}|} * 10^6 \qquad [3-4]$$

Where:

CT-Index = Cracking tolerance index; G_f = Failure energy (Joules/m^2);

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

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

D = Specimen diameter (mm); t = Specimen thickness (mm);

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).

3.5.4 Preparation of mixtures with Portland cement or asphaltenes

Optimum asphaltenes content was selected based on the previous study conducted by Kamran F. et al. [80] on the same material. In this study, 0.5%, 1%, 2% and 3% of asphaltenes (by the total weight of the mix) were added to the stabilized mixes. The optimum asphaltenes content was calculated to be 1% by the weight of total mix based on mixes mechanical properties including permanent deformation, tensile strength, and low-temperature cracking resistance. In this research, the same amount of cement was used for mixes preparation to compare the impact of cement with asphaltenes on the mixes properties. According to a previous study by Issa et al. [81] and Basic Asphalt Recycling Manual [82] the optimum cement content for stabilized mixes using asphalt emulsion in typically between 1% and 2% by the weight of the mixes.

Cement was mixed with oven-dried aggregates and water was added into the mixture to optimum moisture content of 6.3% and mixed until a uniform mix was achieved. Asphalt emulsion was added and the specimens were compacted using Marshall hammer with 50 blows per side of the samples. The compacted samples were cured in molds for 48hours at 60ºC as per specification given by the Asphalt Institute. Asphaltenes was mixed with the asphalt emulsion manually and was added to the mix of aggregate and water. The same procedure was followed for compaction and curing as cement modified samples. Previous studies revealed that the ITS values and curing time of the asphalt emulsion stabilized mixes modified with cement increases linearly [45].

However, in order to keep the similar condition to compare the results of asphaltenes and cement, curing process were kept uniform.

3.6 Results and discussion

3.6.1 Optimum Emulsion Content Determination

Marshall stability and density test results for OEC determination are shown in Figure 3-2(a) and Figure 3-2(b), respectively. Marshall stability test results indicate that 3.70% asphalt emulsion content per total weight of the mix provided the highest stability for the mixtures. Also, considering the trend of density presented in Figure 3-2(b), a maximum density occurs at an asphalt emulsion content of 3.7%. Considering both Marshall stability and density results, a value of 3.7% of asphalt emulsion content (per total mix) was selected as the optimum emulsion content of the mix.

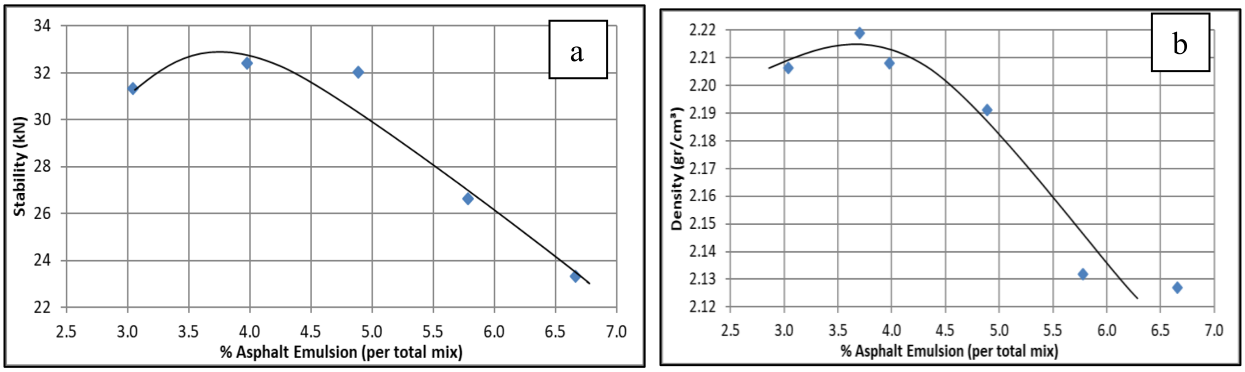


Figure 3-2 Stability (a) and density (b) values with respect to asphalt emulsion content

presents results from ITS test for determining the OEC. The results show that the maximum ITS value was achieved with 3.7% asphalt emulsion content. Therefore, based on results obtained from ITS and Marshall stability test, it was confirmed that the optimum emulsion content is 3.7% by weight of the total mix.

Table 3-4 Design matrix for asphaltenes modification

Emulsion content (% per total mix)	3.04	3.70	3.98	4.89	5.78
ITS (kPa)	288	298	284	270	276

3.6.2 Marshall Stability Test Results

Marshall stability test results were compared to evaluate the effect of asphaltenes and cement on asphalt emulsion stabilized mixes. Figure 3-3 presents the Marshall stability test results for control, asphaltenes-modified and Portland cement-modified mixtures. It can be seen that both asphaltenes and Portland cement modified mixtures have higher stability compared to the control mixture. Compared to unmodified samples, the addition of 1% and 2% asphaltenes increased the stability by 48.7% and 97.4%, respectively. In addition, the addition of 1% and 2% cement has increased the stability of the mixes by of 47% and 89.6%, respectively. Comparing the results, it was found that the Marshall stability of the modified mixes increased with the addition of more additives. Increasing the additives from 1% to 2% increased the stability by 32.7% and 29% for asphaltenes and cement, respectively. Marshall quotient (MQ) was calculated as the ratio of Marshall stability by flow number. All the modified samples had a higher Marshall quotient (MQ) compared to the unmodified samples, which indicates higher resistance of the samples to rutting. However, comparing the samples including asphaltenes and cement with the same quantities, it was found that cement provides more stiffness compared with asphaltenes. Also, unlike cement, 2% asphaltenes sample has a decrease in stiffness compared to the 1% content.

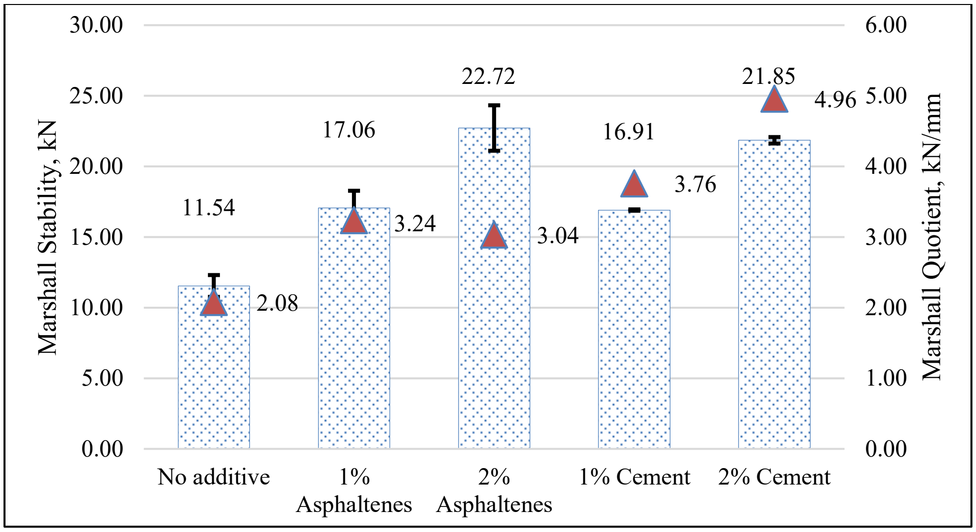


Figure 3-3 Marshall Stability and Marshall Quotient of the modified mixtures

3.6.3 Indirect Tensile Strength Test Results

Figure 3-4 represents the results of ITS test for control, asphaltenes and cement modified mixes. It can be observed that the dry ITS values of all modified mixes are significantly higher than the control sample. It can be seen that asphaltenes is more effective in increasing the tensile strength of the mixes compared to cement. Asphaltenes modified mixes show the greatest improvement in tensile strength of 106% and 193% at contents of 1% and 2%, respectively. The improvements in cement modified mixes are 51% and 88% for 1% and 2% cement, respectively.

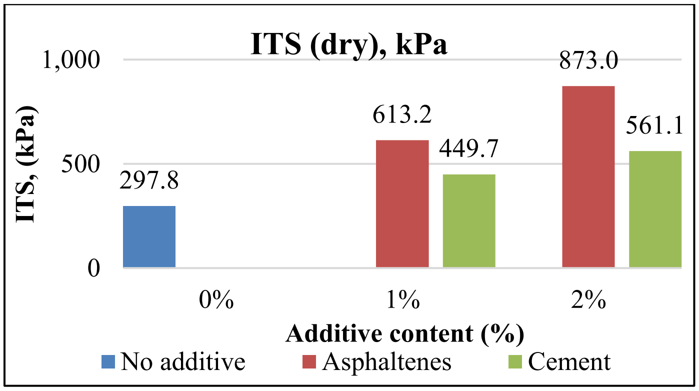


Figure 3-4 ITS of the modified mixtures

Figure 3-5 represents the ITS test results for control, asphaltenes and cement modified mixes conditioned underwater and a freeze-thaw cycle. It can be seen that in both cases, the ITS values of all modified mixes are significantly higher than that of the control sample. Similar to dry ITS, It can be concluded that asphaltenes is more effective in increasing the tensile strength of the mixes compared to cement. The TSR test results for both saturated and freeze-thaw conditioned control and modified samples are presented in Figure 3-6. It can be seen that from figure 6 the modified mixes using asphaltenes have lower TSR values than the control sample. However, the cement modified mixes showing no sensitivity to moisture after saturation and freeze and thaw conditioning. This indicates these mixes will be more resistant to moisture-induced damages.

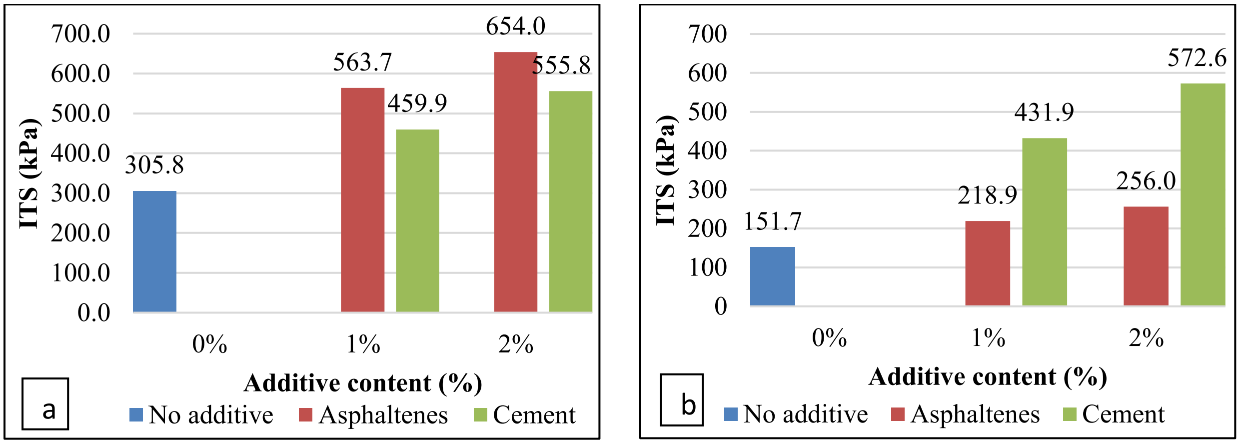


Figure 3-5 Comparison of ITS value of asphaltenes and Portland cement (a) Saturated (b) Freeze and thaw

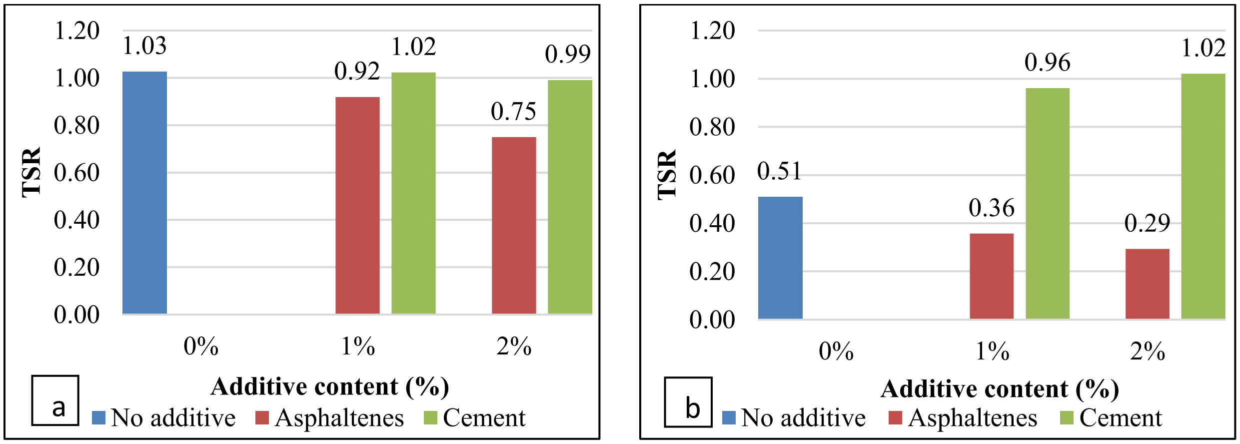


Figure 3-6 Comparison of TSR values of asphaltenes and Portland cement modified samples (a) saturated (b) freeze and thaw.

3.6.4 IDEAL-CT analysis

The cracking tolerance index (CT-Index) was calculated from load-displacement graphs of ITS test for dry samples presented in Figure 3-7. Table 3-5 presents the CT-Index values for the samples according to the ASTM D8225 [64] standard.

Table 3-5 Fracture energy and CT-Index values of Asphaltene and Portland Cement

Test Description	Control	1% Asphaltenes	2% Asphaltenes	1% Cement	2% Cement
Fracture Energy	1,056.4	1,716.8	2,176.4	944.2	961.7
CT-Index	22.7	8.2	6.8	7.6	4.4

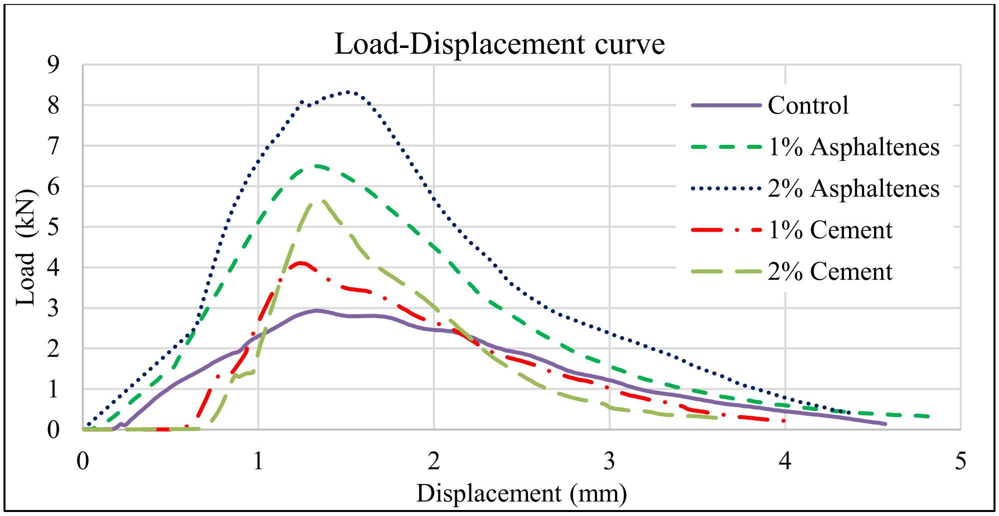


Figure 3-7 Load displacement curve

Table 3-5 shows the addition of 1% and 2% asphaltenes decreases the CT-index by 64% and 70%, and the addition of 1% and 2% cement reduces the CT-index by 67% and 81%, respectively. In conclusion, cement has more adverse impacts on cracking resistance and potentially fatigue resistance of asphalt emulsion stabilized mixes than asphaltenes. Figure 7 shows load-displacement relationship. The rate of displacement or the slope of the graph after the pick load shows how fast the initiated crack is propagating in each sample. It can be seen that the control sample has the lowest slope followed by 1% and 2% of each additive.

3.7 Conclusions

Based on performance test results and analysis performed on the asphaltenes-modified and cement-modified asphalt emulsion stabilized mixes, the following conclusions have been drawn:

- Asphaltenes was found to be more effective in increasing the tensile strength and Marshall stability of the mixtures compared to cement. The addition of 1% and 2% asphaltenes improved the tensile strength by 106% and 193%, respectively. However, the addition of the same amount of cement resulted in less than 90% improvement.
- The MQ results shows that the addition of both cement and asphaltenes increases mixture stiffness and decreases rutting susceptibility.
- TSR results show that the addition of asphaltenes slightly increases the moisture sensitivity of mixes, while the addition of cement improves the moisture resistance of the asphalt emulsion stabilized mixes.
- CT-Index analysis shows that both asphaltenes and cement will increase the cracking potential of asphalt-emulsion stabilized mixes. However, asphaltenes modified samples are more resistant to cracking compared to cement modified mixes.

Chapter 4 Evaluation of Asphalt emulsion stabilized granular base modified with cement or asphaltenes.

4.1 Abstract

Pavement layers, specifically the base course, play a critical role in improving the pavement service life. The quality of the base course layer can be improved through the technique of stabilization. Asphalt emulsion is a common material used for stabilization, and various materials such as active fillers can be added to further improve the stability of asphalt emulsion mixtures. This investigation compares the impact of cement and asphaltenes as additives to asphalt emulsion-stabilized layers. The asphaltenes used is a waste by product derived from the processing of Alberta oil-sands bitumen. For the purpose of comparing the performance properties, cement- and asphaltenes-modified mixtures are prepared at two concentrations—1% and 2% by the total weight of the mixtures. The performance properties of the modified mixtures are investigated by conducting a series of tests including Marshall stability, indirect tensile strength, IDEAL-CT, and tensile strength ratio. In addition, to evaluate low-temperature cracking resistance of the mixtures, creep compliance and strength tests are conducted at 0 °C and −10 °C. The results and analysis show that asphaltenes-modified mixtures have higher Marshall stability, tensile strength, and intermediate- and low-temperature cracking resistance compared to mixtures modified with cement. However, the moisture sensitivity analysis indicates that mixtures modified with asphaltenes are more prone to moisture-induced damage compared to cement-modified mixtures.

4.2 Introduction

Pavements are generally designed to sustain traffic loads during their designed service life, where the integrity of the underlying soils has a significant impact on the long-term performance of pavement structures [10]. The pavement structure consists of the surface, base, and sub-base layers, normally built on a suitable subgrade. These layers receive and distribute the traffic load downwards to the subgrade [28]. Among these layers, the base layer is an integral part of the pavement structure, playing an important role in distributing the load to the subgrade. Generally, the base courses are prepared with high-quality aggregates, such as crushed stone, gravel, and sand [28]. The performance of the pavement layers depends largely on the quality of the materials used. Low-quality materials combined with poor construction methods can lead to early development of distresses on pavements. The typical distress developed with asphalt pavements during their service life are rutting deformation and fatigue cracking [8,28]. Distresses may also occur due to excessive traffic load and environmental effects [9,28]. A particular challenge associated with pavement distress and deterioration is that deteriorated pavements are very sensitive to continuous freeze–thaw cycle due to water infiltration into the pavement [9]. It is thus important to design and construct the unbounded granular base layer of the pavement with high-quality materials in order promote resistance to shear failure, to avoid excessive deformation, and to boost the resistance to fatigue-induced cracking of the pavement overlay [10]. A common method of pavement failure mitigation is to increase the thickness or material quality of the base course. This approach has some major drawbacks, however, such as adverse environmental effects and increased pavement cost [28]. As such it is critical to find a method that can improve pavement performance while at the same time reducing the cost of construction. Several studies have found that base stabilization may be a promising alternative in this regard [10–12].

Mechanical and chemical stabilization are two notable base course stabilization techniques. Mechanical stabilization is a method of improving soil properties by grading the soil. This includes applying mechanical energy to achieve compaction and densification using rollers, rammers, and vibration techniques [11]. Chemical stabilization, meanwhile, involves the modification of soil properties by mixing or injecting chemically active compounds such as cement, lime, fly ash, or viscoelastic materials [10,12]. Stabilization of the pavement base course with cement, lime, and fly ash has been found to improve pavement performance [28]. Previous studies have also shown that base stabilization using cementitious material can improve the tensile strength and load spreading ability of flexible pavements [9,28]. In addition, it has been found to increase the shear strength, bearing capacity, durability, stiffness, and resistance to moisture damage in pavements [83]. On the other hand, application of these materials results in development of shrinkage cracking and early brittleness in pavement layers, especially in cold-climate regions [22,23].

Mixtures stabilized with asphalt emulsion are more flexible compared to cement-stabilized mixtures, and in cold regions the application of asphalt emulsion-treated aggregates is more cost-effective compared to the application of hot mix asphalt. These benefits have resulted in the emergence of asphalt emulsion stabilization as the preferred method over cement stabilization within the pavement construction industry [13]. Additionally, significant energy consumption savings as well as a reduction in the rate of pollution, are among the factors that have encouraged the use of asphalt emulsion for stabilization within the pavement construction industry [15,16]. Despite these benefits, though, some drawbacks with asphalt emulsion stabilization have also been identified.

Studies have shown that, in order for asphalt emulsion mixtures to have adequate bonding properties (comparable to those of conventional asphalt mixtures), there is a significant curing time requirement [17]. The average time required in order for asphalt emulsion mixtures to achieve adequate strength has been estimated to be as much as three years [18,19]. This longer curing time requirement associated with asphalt emulsion mixtures leads to low mechanical strength and poor performance, especially at the early stages of construction [20]. These shortcomings of asphalt emulsion require additional investigation in order for new methods to be devised to enhance the bonding properties as well as the mechanical strength of asphalt emulsion mixtures.

Cementitious materials, or active fillers, such as cement or hydrated lime, are generally used as additives to asphalt emulsion mixtures; these additives improve the performance properties of stabilized asphalt emulsion mixtures and increase the curing rate of asphalt emulsion stabilized mixtures [17,49,84,85]. The properties improved as a result of adding active fillers include stiffness, strength, resistance to moisture-induced damage, rutting resistance, asphalt aggregate adhesion, and asphalt dispersion in the mixture [16].

An investigation by Terrell & Wang [49] found that, with anionic asphalt emulsion under cold or moist conditions, the introduction of small quantities of cement considerably enhanced the curing time. The ultimate resilient modulus of the modified asphalt emulsion was increased by almost 200% after adding 1% cement. Niazi & Jalili [21], meanwhile, reported that the optimum cement content to achieve adequate performance improvement is between 1% and 2%. Similarly, an investigation by Romeo et al. [86] found that 1% cement can achieve adequate resistance against cracking of asphalt stabilized mixtures in terms of increased tensile limits to failure. A study conducted by Schmidt et al. [87] found that adding 1.3% cement to asphalt emulsion mixture is sufficient for significant improvement in stiffness. This quantity of cement was observed to result in a five-fold increase in stiffness modulus within a curing duration of 24 hr. More recently, in consideration of cost effectiveness and environmental effects, several studies have investigated the application of waste materials as suitable alternatives to active fillers in the stabilization of asphalt emulsion mixtures [88].

Asphalt, being a viscoelastic material, comprises both polar and non-polar components. The elastic behavior of asphalt material is controlled by the polar components, while the viscous behavior of is governed by non-polar components [44]. The primary constituent materials in asphalt are saturates, aromatics, resins, and asphaltenes, referred to collectively as “SARA”. Asphaltenes is the most polar component in asphalt material [89]. In the refining of oil sands bitumen, a large quantity of asphaltenes is removed through a process called deasphaltation. This material from oil sands bitumen has historically been regarded as a waste material with no significant economic value or industrial application.

Previous studies have shown that an increase in stiffness of asphalt mixtures can be obtained as a result of increasing the content of polar components [44,50]. This stiffening effect underscores that the application of asphaltenes in base course stabilization can improve the mechanical strength of the stabilized mixture, reduce the cost of pavement construction, and mitigate adverse environmental effects. However, further scientific study is needed in order to more fully characterize the effects of asphaltenes application in asphalt emulsion-stabilized mixtures and how it influences their performance properties.

4.3 Objectives and scope

The main objective of the study described in this paper was to compare the impact of cement and asphaltenes derived from Alberta oil sands bitumen for stabilization of a well-graded granular base course material using a cationic slow-setting asphalt emulsion (CSS-1H). Marshall stability and indirect tensile strength (ITS) tests were used to compare the compressive and tensile strength of the mixtures, respectively. To investigate the moisture sensitivity of the mixtures, the tensile strength ratio (TSR) after saturating the mixtures with water and subjecting them to freeze–thaw conditions was evaluated. To compare the cracking resistance of the mixtures, IDEAL-CT tests were conducted. In order to evaluate the low-temperature and high-temperature mechanical properties, creep compliance, strength, and Hamburg wheel tracking (HWT) tests were carried out.

4.4 Materials

4.4.1 Aggregates

Various physical tests revealed a specific gravity of 2.601, optimum moisture content (OMC) of 6.3%, maximum dry density (MDD) of 15.4 kN/m^3, and Los Angeles abrasion of 23%. The gradation (see Table 4-1) was determined based on the specifications given by the City of Edmonton [73], Alberta Transportation [74], and the Wirtgen Cold Recycling Manual [9]. The gradation consisted of 57.27% coarse aggregates, 36.73% fine aggregates, and 6% filler.

Table 4-1 Selected aggregate gradation.

Sieve size (mm)	% Passing	% Retain	% Coarse/Fine/Filler
20.00	100.00	0.00	57.27
12.50	75.17	24.83	
10.00	61.23	13.94	
8.00	55.00	6.23	
6.30	48.00	7.00	
5.00	42.73	5.27	
2.50	32.08	10.65	42.73
1.25	25.61	6.47	
0.63	18.93	6.68	
0.315	13.00	5.93	
0.16	9.00	4.00	
0.08	6.00	3.00	
Filler (Pan)	0.00	6.00	6.00

4.4.2 Asphalt Emulsion

A typical asphalt emulsion was used for the stabilization following the specifications suggested in the Wirtgen Cold Recycling Manual [9]: a cationic slow setting (CSS) emulsion with a hard base binder consisting of 61% residual asphalt binder and 39% water. The physical properties of the asphalt used to produce the emulsion were a penetration value of 95 at 25 °C, a ductility value of at least 40 cm, and solubility in Trichloroethylene of the asphalt residue in excess of 97.5% [90], as outlined in Table 4-2.

Table 4-2 Properties of asphalt emulsion

Property	Unit	Standard (ASTM/AASHTO)	Specification		Results
			Min.	Max.	
Specific gravity at 15.6ºC	Kg/L	D6937[76]/T59[91]	-	-	1.020
Viscosity at 25ºC	S.F.S.	D7496[92], D88[93]/T59[91]	20	100	22
Residue by distillation	%	D6997[79]/T59[91]	57	-	61
Oversized particles (sieve)	%	D6933[94]/T59[91]	-	0.300	0.008
Settlement (24hr)	%	D6930[95]/T59[91]	-	1.0	0.5
Particle charge test		D7402[96]	Positive		Positive

4.4.3 Additives

In this study, two types of additives (cement and asphaltenes) were used separately for the stabilization of asphalt emulsion mixtures. The cement used was commercially available while the asphaltenes was provided by an oil & gas company operating in the Alberta oil sands.

The asphaltenes used was received in solid form from an Alberta oil sands bitumen refinery as shown in Figure 4-1a. This material was crushed into powder form and sieved through a No. 100 sieve as shown in Figure 4-1b. A SARA test showed that the material consisted of 79.62% asphaltenes, 6.85% saturates, 9.68% aromatics, and 3.84% resin.

General use (GU) cement meeting the specifications of ASTM C1157 / CSA A3000 was used in this study. The cement samples were obtained in powder form, as shown in Figure 4-1c. In terms of its basic properties, the cement had an initial setting time of 45 min, a final setting time of 420 min, and a compressive strength of 13 MPa at 3 days, 20 MPa at 7 days, and 28 MPa at 28 days.

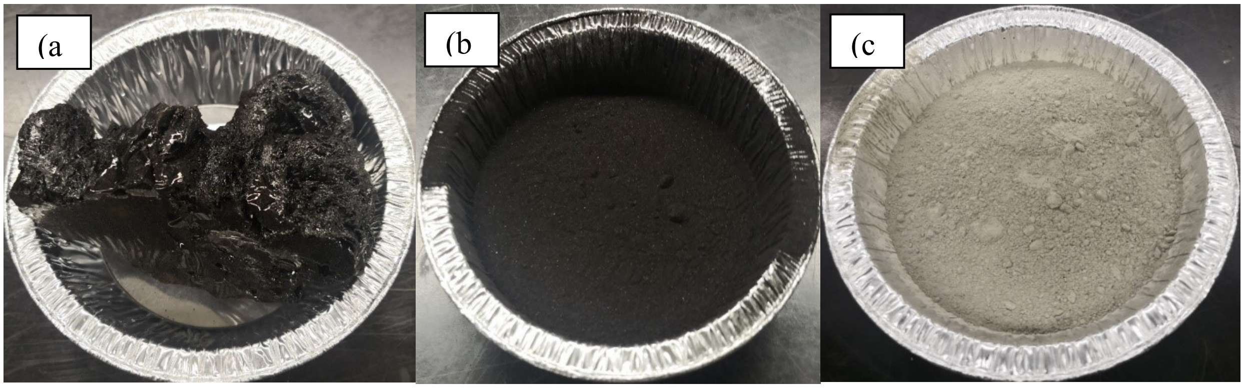


Figure 4-1 Asphaltenes solid form (a), Powder form of asphaltenes for mixing (b), and cement for mixing (c)

4.5 Experimental program

4.5.1 Mix Design and Optimum Emulsion Content (OEC)

Although there is no broadly accepted mix design for asphalt emulsion cold mixtures, guidelines have been developed by several agencies based on empirical formulas, laboratory tests, and field experience [15]. In our study, mixtures were prepared using Asphalt Institute [15] specifications for a well-graded aggregate base. The approximate amount of emulsion was calculated based on Equation [4-1]. The amount of residue in asphalt emulsion remaining after distillation was 61% as determined using ASTM D6997 [79]. For the base mixture, the asphalt emulsion content was determined as follows.

$$\text{percentage of asphalt emulsion} = \frac{(\mathbf{0.06B+0.01C})*\mathbf{100}}{\mathbf{A}} \qquad [4\text{-}1]$$

where

A = Percentage of residue of asphalt emulsion remaining after distillation.

B = Percentage of dry aggregate passing through a No. 4 sieve.

C = Percentage of dry aggregate retained on a No. 4 sieve.

Using Equation [4-1], the approximate asphalt emulsion content was determined to be 5.14% per total aggregate. Using this value, 5 different mixtures with emulsion content increasing at 1% intervals were prepared (3.14%, 4.14%, 5.14%, 6.14%, and 7.14% by total weight of aggregates). After preparation and curing the samples, Marshall stability and ITS tests were carried out in order to determine the OEC as per the design matrix shown in Table 3. The total water content in the mixtures was considered the optimum moisture content (OMC) of the aggregates. The mixing process was initiated by first pouring water into the oven-dried aggregates, which had been cooled to room temperature, and then thoroughly mixing the water with the aggregates until a uniform mixture was achieved. Asphalt emulsion was added gradually into the wet aggregates according to the emulsion contents determined in the design matrix. The specimens prepared were compacted with 50 blows using a Marshall hammer on each of the samples' sides. The compacted samples were left in molds and cured for a period of 48 hr inside the oven at a temperature of 60 °C as specified by the Asphalt Institute (2008). The cured samples were then kept at room temperature for at least 2 hr prior to extraction from the mold. For both tests, three replicates were prepared at each emulsion content, and the averages of the respective results for the three replicates were calculated and used for the analysis.

The Marshall stability tests were performed in accordance with ASTM D6927-15 [57] for the samples of different asphalt emulsion contents as outlined in Table 4-3. The samples were conditioned for 3 hr at 25 °C in an air bath before testing [15].

Table 4-3 Design matrix for determining the OEC

Emulsion Content (% per total aggregates)	3.14	4.14	5.14	6.14	7.14
Emulsion Content (% per total mix)	3.04	3.98	4.89	5.79	6.66
OMC (%)	6.3%				
Additional water (%)	5.1	4.7	4.3	3.9	3.5

The ITS test was performed in accordance with AASHTO T 283-14 [60] for the same asphalt emulsion samples as determined in the design matrix in order to determine the OEC. The ITS tests were conducted by applying loads at a rate of 50 mm/min. The maximum load applied to the sample until failure was recorded in order to calculate the tensile strength of the samples. The ITS of each sample was calculated as per Equation [4-2].

$$\mathbf{S_t} = \frac{\mathbf{2000 * P}}{\boldsymbol{\pi} \mathbf{* t * D}} \qquad [4\text{-}2]$$

where

S_t = indirect tensile strength, kPa

P = maximum applied load, N

t = average height of specimen, mm

D = diameter of specimen, mm

The Marshall stability and ITS test results are shown in Figure 4-2, while densities of the mixtures are shown in Figure 4-3. The test results show that the highest stability was achieved at 3.98% asphalt emulsion per total weight of the mixture. However, in terms of stability, the OEC was achieved at 3.7% asphalt emulsion per total weight of the mixture, and for the samples with 3.7% asphalt emulsion the ITS was calculated to be 298 kPa, meaning that they still satisfied the minimum requirement of 225 kPa in accordance with the Wirtgen Cold Recycling Manual (2012). Therefore, based on the Marshall stability and ITS test results, it was determined that 3.7% asphalt emulsion per total weight of mixture should be used as the OEC for further testing.

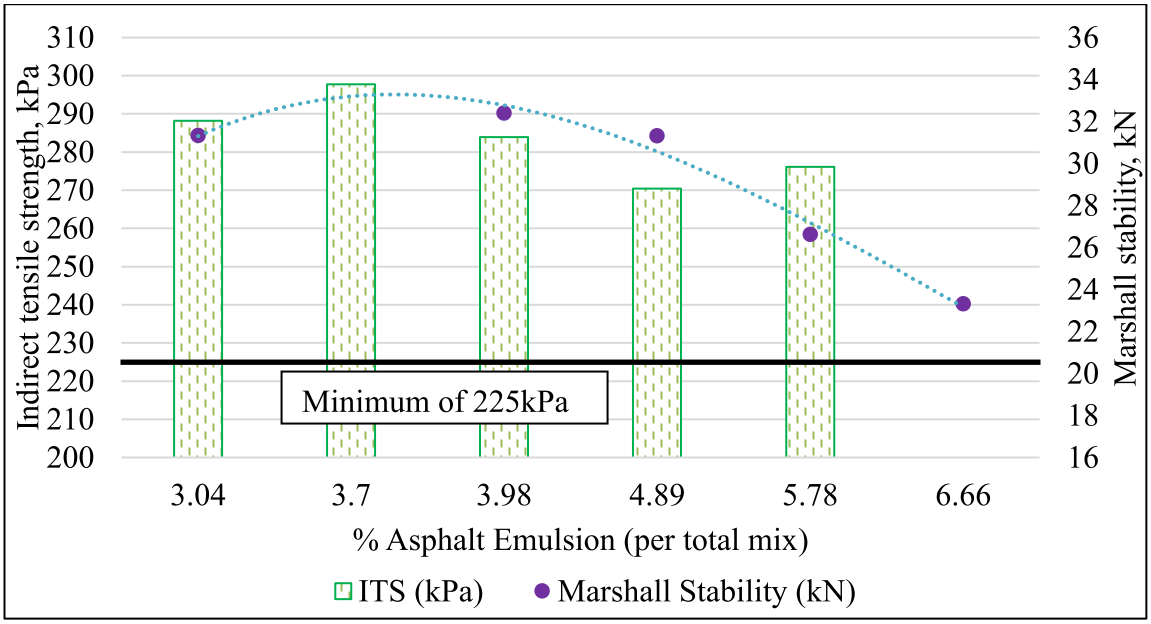


Figure 4-2 Stability and ITS values with respect to asphalt emulsion content

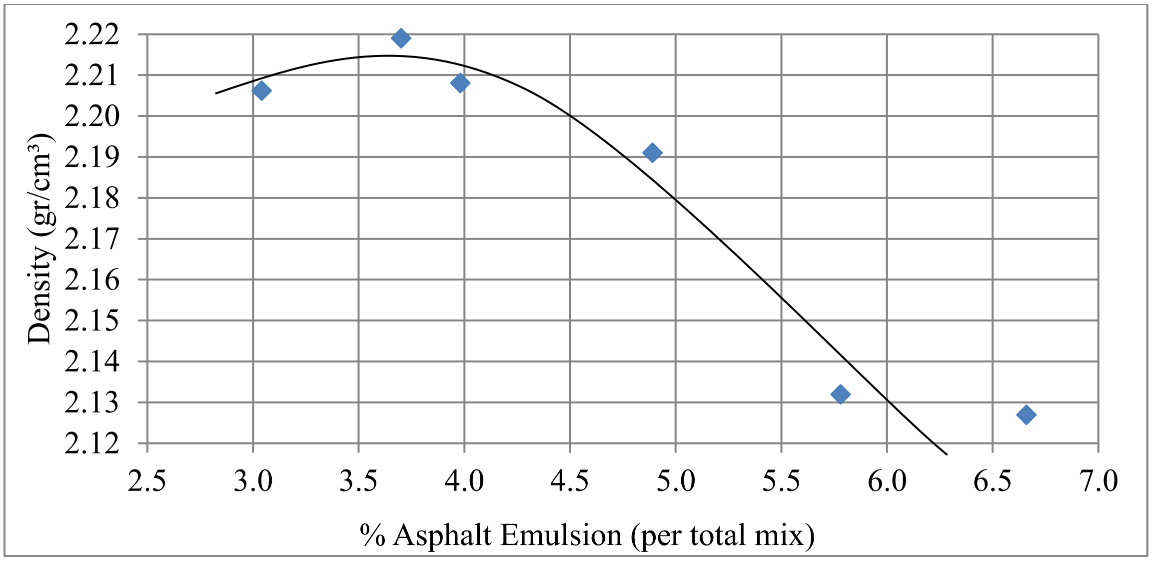


Figure 4-3 Density values with respect to asphalt emulsion content

4.5.2 Preparation of mixtures modified with cement and asphaltenes

In accordance with Kamran et al. [80], samples with 1% and 2% additive by total weight of the mixture were prepared for both the asphaltenes and the cement mixtures in order to compare the impact of cement and asphaltenes on asphalt emulsion stabilized mixtures. It should be noted that these proportions are also in agreement with by Issa et al. [81] with respect to cement content and with the Asphalt Recycling and Reclaiming Association [82] with respect to asphalt emulsion content.

The cement was mixed with oven-dried aggregates after having been cooled to room temperature, and water was then added and mixed until a uniform mixture was achieved. Asphalt emulsion was added afterward, and a similar procedure was followed for compaction and curing for compacted samples.

For asphaltenes, the same procedure was followed, except without adding any cement, and asphaltenes were mixed with the asphalt emulsion manually and subsequently added to the mixture of aggregate and water. As with the cement mixture, this was followed by compaction and curing.

Xu et al. [45] have noted that the ITS values and curing time of asphalt emulsion-stabilized mixtures modified with cement increase linearly. However, in order to maintain similar conditions for the purpose of comparing asphaltenes and cement, the curing conditions were kept uniform. The prepared specimens were tested for Marshall stability, ITS, Hamburg wheel tracking, creep compliance, and strength tests, and the results were compared between the unmodified samples, the cement-modified, and the asphaltenes-modified samples.

4.5.3 IDEAL-CT analysis

The IDEAL-CT test was conducted for both modified and unmodified mixtures as per ASTM D8225-19 [64]. To calculate the cracking tolerance index (CT- Index), the ITS test on dry samples were performed at the same loading rate as described above. Once the load versus displacement curve of each specimen from ITS test had been obtained, the CT Index was calculated using Equation [4-3].

$$\mathbf{CT_{Index}} = \frac{\mathbf{t}}{\mathbf{62}} * \frac{\mathbf{G_f}}{|\mathbf{m_{75}}|} * \frac{\mathbf{l_{75}}}{\mathbf{D}} \qquad [4\text{-}3]$$

where

G_f is the fracture energy (kN/mm) which is determined from the ratio of the area under the load vs. displacement curve divided by the product of the thickness (t) and diameter (D);

l_{75} is the post-peak displacement rate at 75% of the peak load (mm);

$|m_{75}|$ is the slope of the post peak curve at 75% of the peak load (kN/mm);

D is the specimen diameter (mm); and

t is the specimen thickness (mm).

4.5.4 Moisture susceptibility

The ITS test was conducted in accordance with AASHTO T 283-14 [60] on both the saturated samples and the freeze–thaw-conditioned samples. The conditioning of the saturated samples was done in water at 25 °C for 24 hr, prior to the ITS test. The freeze–thaw conditioning was carried out by storing the samples in a freezer at −18 °C for 16 hr after saturation in water for 24 hr at 25 °C and then conditioning them in a water bath at 60 °C for 24 hr. Prior to ITS testing, all samples were placed in a water bath at 25 °C for 2 hr, after which the TSRs for both the saturated samples and the freeze–thaw-conditioned samples were determined using Equation [4-4].

$$\mathbf{TSR} = \frac{\mathbf{S_2}}{\mathbf{S_1}} \tag{4-4}$$

where

S_1 = Average tensile strength of the dry subset (kPa)

S_2 = Average tensile strength of the conditioned subset (kPa)

4.5.5 Rutting performance

The Hamburg wheel-tracking test was performed in accordance with AASHTO T324-19 [65]. This test, it should be noted, is an indicator of rutting resistance of asphalt mixtures. Slab samples with dimensions of 400 mm length, 300 mm width, and 80 mm height were prepared for the wheel tracking test. In consideration of the binder grade and base layer condition, the test temperature was set to 40 °C. The samples were preconditioned for 45 minutes prior to running the test, and a steel rolling wheel 47 mm wide was used to roll across the submerged samples at a frequency of 52±2 passes per minutes until the samples reaches either 20,000 passes or 12 mm of rutting depth (whichever was attained first). Figure 4-4a shows the compaction of the sample, the sample prior to running the test (Figure 4-4b), and the sample during the test (Figure 4-4c). The rutting depth and the number of passes were used to determine the stripping inflection point (SIP) and rutting resistance index (RRI) and thereby ascertain the rutting potential of the mixtures.

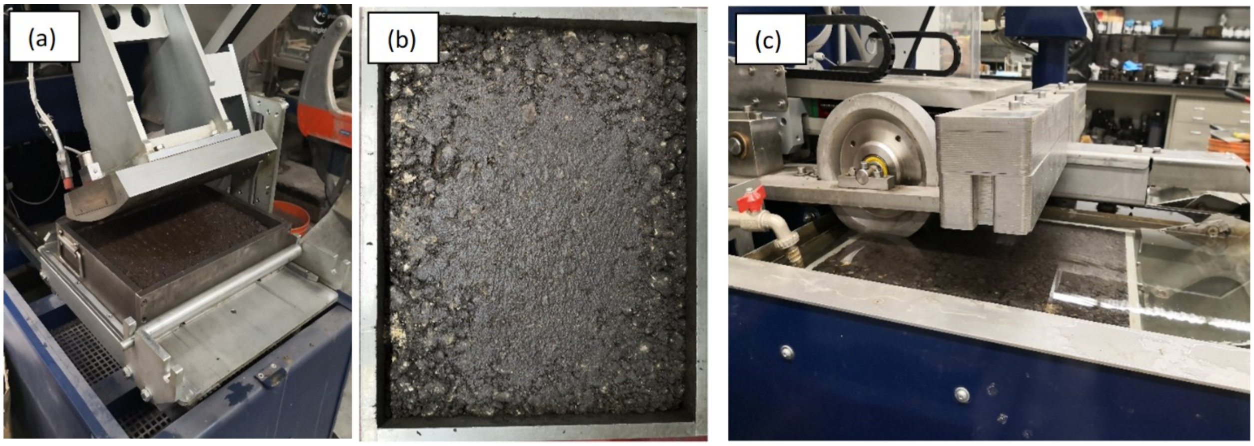


Figure 4-4 Compaction (a), prepared sample for testing (b), and HWT Test performing (c)

4.5.6 Creep Compliance and Strength Tests

The creep compliance and strength tests for the samples were conducted in accordance with AASHTO T322-07 [68] following the ITS setup. These tests are used to estimate the low-temperature performance of mixtures. Marshall samples were prepared for the creep test. However, the surface of the samples were cut to a depth of 38 mm to 50 mm as per the standard. The samples were tested both 0 °C and −10 °C, this having been determined in consideration of the base layer and PG grading of the binder in the asphalt emulsion that was used for the mixtures. Prior to testing, the samples were conditioned in an air chamber for 3±1 hr at the selected test temperatures. For the creep test, a fixed static load was applied on the samples for 100±2 seconds, and linear variable displacement transducers (LVDT) recorded the deformation of the specimens in both the horizontal and vertical axes. After completion of the creep test, the ITS test was applied on the same sample at a rate of 12.5 mm/min until the failure point was reached. Figure 4-5 shows the test setup of a sample prior to testing. The fracture energy of the samples at both temperatures was calculated using the load-deformation values obtained from the test results, while the ITS of the samples was calculated using Equation [2] as stated above.

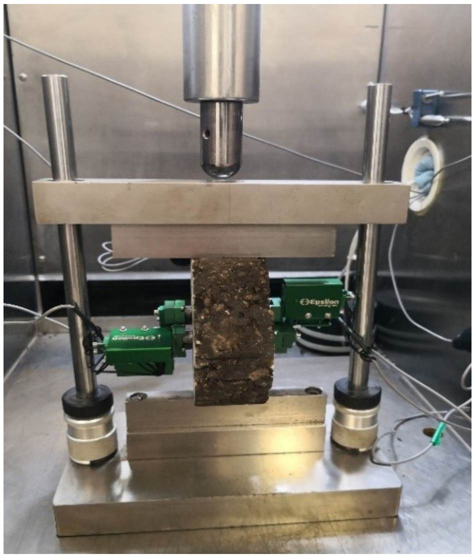


Figure 4-5 Creep compliance and strength test setup

4.6 Results and discussion

4.6.1 Marshall Stability Test

To evaluate the effect of asphaltenes and cement as additives, Marshall stability test [57] results for the control, cement-modified, and asphaltenes-modified mixtures were compared, and the results are presented in Table 4-4. As the results indicate, both the cement- and asphaltenes-modified mixtures exhibited significantly higher values of stability as compared to the control mixture. It can be seen that, in comparison with the control, the 1% and 2% asphaltenes improved the stability by approximately 47.8% and 96.9%, respectively. Similarly, comparing the cement-modified mixtures with the control sample, 46.5% and 89.3% stability improvement was obtained by adding 1% and 2% cement content, respectively. Moreover, the Marshall stability of the samples was found to increase with a corresponding increase in additive content. Looking at the effect of increasing the content of both additives from 1% to 2%, a significant improvement in stability was observed for asphaltenes and cement (about 33.2% and 29.2%, respectively).

Similarly, comparing the Marshall quotient (MQ) results estimated by taking the ratio of Marshall stability to flow value of the mixtures, it can be seen that the samples modified with either cement or asphaltenes had a higher MQ than did the control samples. This higher MQ values for the modified mixtures indicate that the samples have higher stiffness and will have higher resistance to rutting defects. Additionally, comparing the cement-modified samples with the asphaltenes-modified samples at the same additive concentration, it was observed that the cement-modified mixtures had a higher stiffness compared with the mixtures modified with asphaltenes.

Table 4-4 Results of Marshall stability and flow test

Additive types	% of additives	Marshall stability (kN)	Flow (mm)	Marshall quotient (kN/mm)
Control	0%	11.54	5.55	2.08
Asphaltenes	1%	17.06	5.26	3.24
	2%	22.72	7.48	3.04
Cement	1%	16.91	4.50	3.76
	2%	21.85	4.41	4.95

4.6.2 Indirect Tensile Strength Test

The ITS test results for the control, cement-, and asphaltenes-modified samples are presented in Figure 4-6. Comparing the dry ITS results of the control sample with those of the modified samples, it can be seen that the modified samples had a higher tensile strength than the control samples. Moreover, comparing the dry ITS of the modified mixtures, it was observed that samples modified with asphaltenes are more effective as they increase the tensile strength of the mixtures to a greater extent than do the samples modified with cement. Comparing the asphaltenes and cement mixtures at equal concentrations it can observed that 1% asphaltenes increased the tensile strength by about 105.9% compared to the control, whereas 1% cement resulted in a 51.0% improvement. A similar trend was observed with respect to the 2% asphaltenes and 2% cement samples, with 193.1% and 88.4% improvement in tensile strength, respectively, compared to the control.

The TSR test results for the saturated and freeze–thaw conditioned samples are presented in Figure 4-6. The saturated TSRs were found to be 0.9, 0.8, 1.0, and 1.0 for the 1% asphaltenes, 2% asphaltenes, 1% cement, and 2% cement content, respectively. These results indicate that, in terms of saturated TSR, the samples modified with asphaltenes performed poorly compared to the control sample. However, the samples modified with cement showed higher TSRs, indicating higher resistance to moisture-induced damage. On the other hand, the freeze–thaw TSRs were 0.4 and 0.3 for 1% asphaltenes and 2% asphaltenes, respectively, while the TSR was 1.0 for both the 1% cement and 2% cement samples, meaning that the samples modified with cement showed no sensitivity to moisture after saturation and freeze–thaw conditioning.

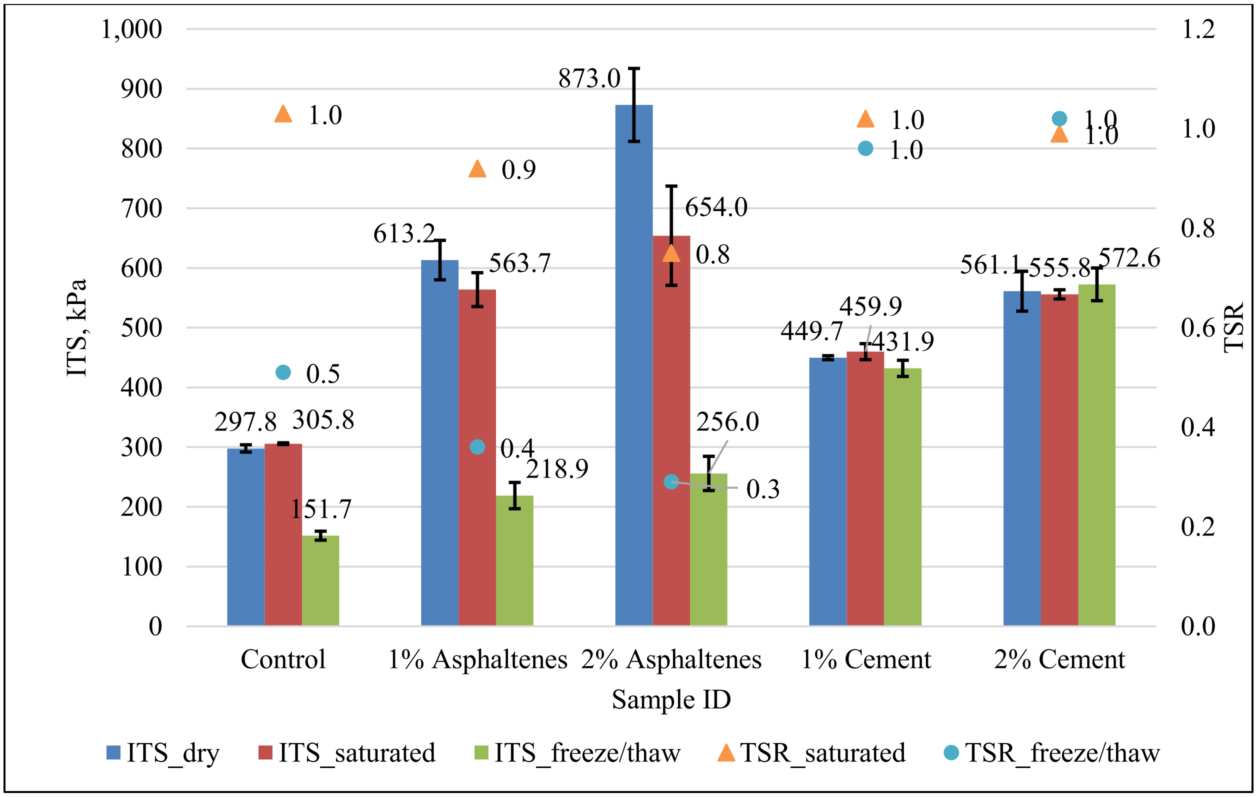


Figure 4-6 Indirect tensile strength (ITS) test results

4.6.3 IDEAL-CT analysis

The load-displacement graphs for the ITS test results are shown in Figure 4-7 were used to estimate the cracking tolerance index of the mixtures. Table 4-5 presents the CT-Index and fracture energy values for the samples, calculated in accordance with ASTM D8225 [64].

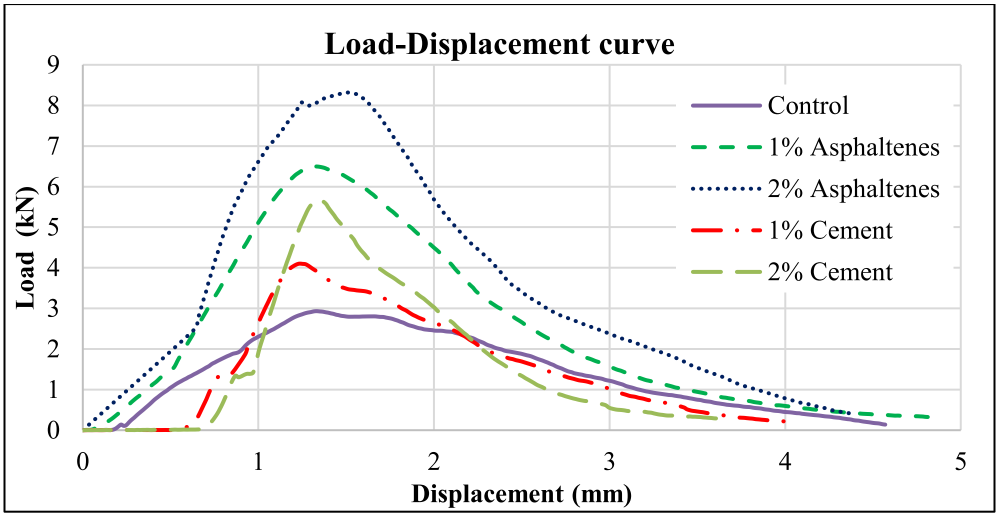


Figure 4-7 Load-displacement curve

Table 4-5 Fracture energy and CT-Index values of test matrix

Additive types	% of additives	Fracture Energy	CT-Index
Control	0%	1.056.4	22.7
Asphaltenes	1%	1,716.8	8.2
	2%	2,176.4	6.8
Cement	1%	944.2	7.6
	2%	961.4	4.4

From the results presented in Table 4-5, it can be seen that the addition of 1% and 2% asphaltenes and cement affected significantly the CT-index values. The CT-index reduction observed relative to the control samples was 63.9% and 70.0% for the 1% and 2% asphaltenes mixtures, respectively, while reductions of 66.5% and 80.6% were observed for the 1% and 2% cement mixtures, respectively. Comparing the fracture energy results of the modified mixtures, the increase in fracture energy was higher in the asphaltenes-modified mixtures than in the cement-modified mixtures. This result indicates that cement has a more significant adverse effect on the cracking resistance of modified asphalt emulsion-stabilized mixtures compared to asphaltenes.

Figure 4-7 presents the load-displacement graphs of the samples, where the slope of the plot or displacement rate after the pick load is indicative of how rapidly a crack, once initiated, will propagate in each the mixtures. As can be seen, the slope after the peak point is steeper in the modified samples than in the control samples, indicating more rapid crack propagation. It can also be observed that the graph of the cement-modified sample is flatter than that of the asphaltenes-modified sample.

4.6.4 Rutting performance

A Hamburg wheel-tracking test was used to evaluate the rutting resistance test matrix in accordance with AASHTO T 324-19 [65]. Table 4-6 presents the SIPs and RRIs of the samples. SIP, it should be noted, is used to measure resistance to moisture damage. From Figure 4-8 and it can be seen that the SIP for the control sample was approximately 3,800 passes, while adding the asphaltenes and cement additives increased the SIP at both additive concentrations (1% and 2%) which are 8,200, 7,400, 5,400 and 10,900 passes. Using the rutting depth and the number of passes for each specimen, the RRI was calculated as per Equation [4-5]. It was found that the rutting resistance increased in asphaltenes- and cement-modified mixtures compared to the unmodified mixture, with the cement-modified samples showing better performance than the asphaltenes-modified samples. The RRI values for the 1% and 2% asphaltenes-modified samples were found to be almost the same, meaning that increased asphaltenes content did not affect the rutting resistance. On the other hand, a comparison of the RRIs for the 1% and 2% cement mixtures indicates that increasing the cement content did improve the rutting resistance.

$$\text{RRI} = \text{No. of passes @ end of test } x\ (1'' - \text{rut depth}) \qquad [4\text{-}5]$$

Table 4-6 Rutting resistance results

Sample ID	No. of passes	SIP	Rutting resistance index (RRI)
Control	3,940	3,800	2,219.74
1% Asphaltenes	8,712	8,200	5,360.97
2% Asphaltenes	8,604	7,400	5,291.12
1% Cement	11,220	5,400	5,698.40
2% Cement	14,068	10,900	9,260.50

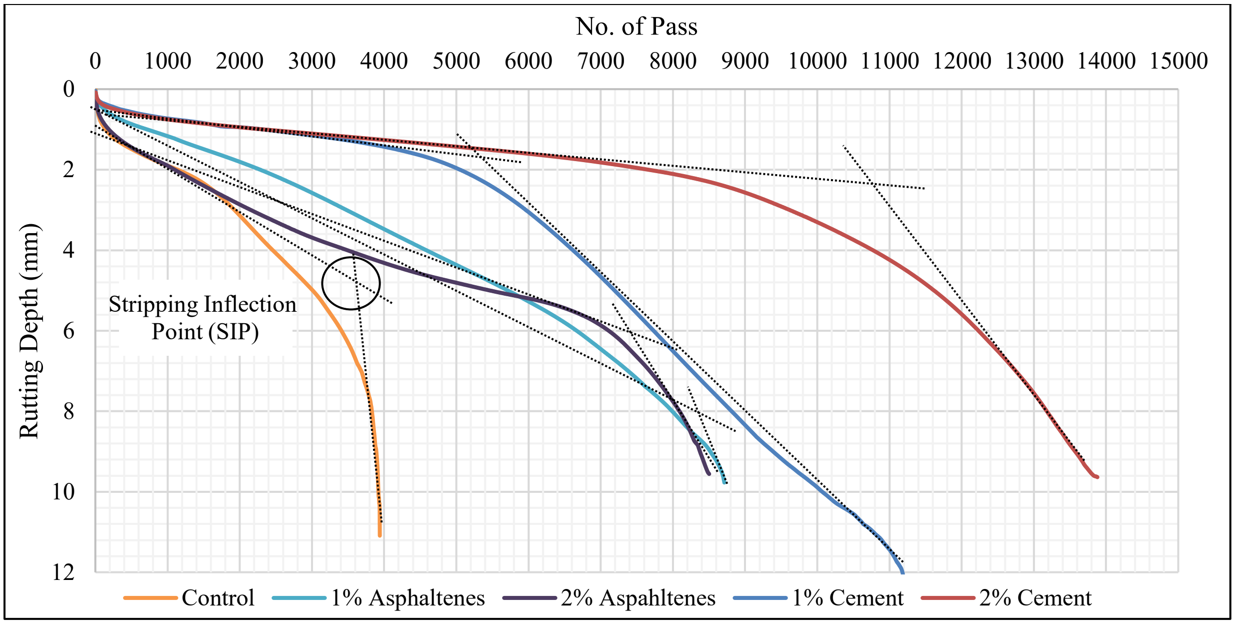


Figure 4-8 Hamburg wheel tracking test results

4.6.5 Creep Compliance and Strength Test

Creep compliance tests were conducted at temperatures of 0 °C and −10 °C in accordance with AASHTO T 322-07 [68] for both the modified and unmodified samples. Figure 4-9 presents the ITS for the samples at both temperatures. Th results at 0 °C reveal that the tensile strength of the modified samples increased by 8.0%, 7.5%, and 5.7% for the 1% asphaltenes, 2% asphaltenes, and 2% cement mixtures, respectively, compared to the control samples, while almost no change was observed in the 1% cement-modified samples. On the other hand, the ITS results at −10 °C show that the tensile strength of the modified samples decreased by 7.5%, 23.9%, 14.6%, and 7.3% for the 1% asphaltenes, 2% asphaltenes, 1% cement, and 2% cement mixtures, respectively, compared to the control samples.

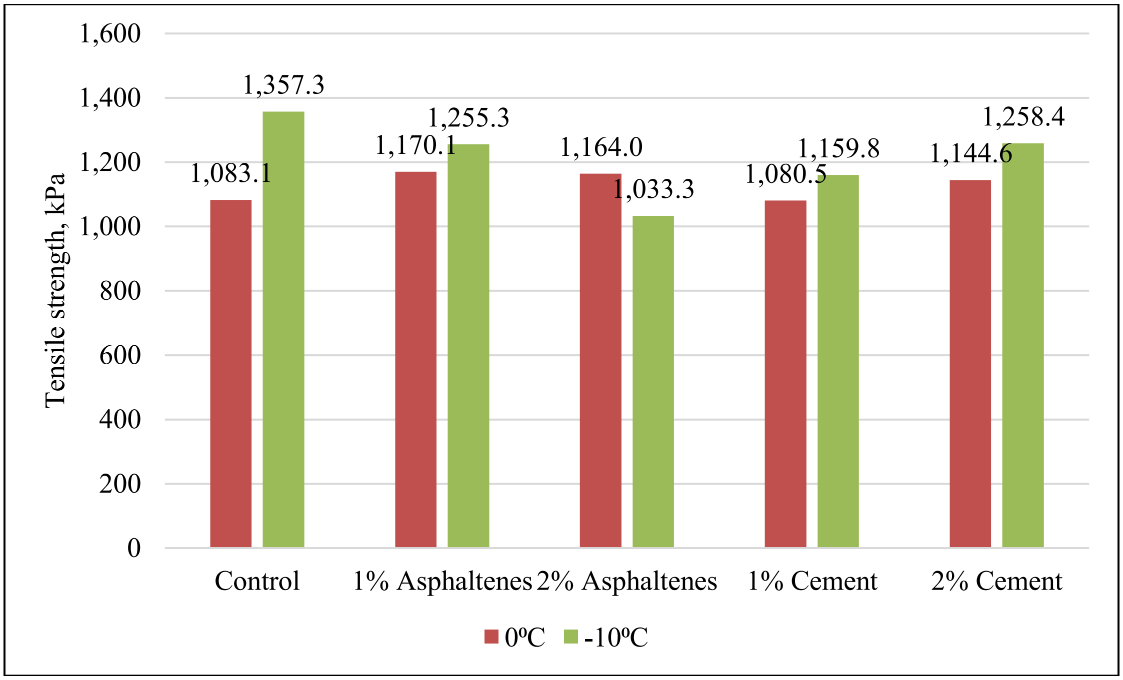


Figure 4-9 Tensile strength for low-temperature creep test

Figure 4-10 presents the fracture energy results. As shown in the figure, the fracture energy at 0 °C decreased by 24.0%, 17.7%, 36.9%, and 41.4% for 1% asphaltenes, 2% asphaltenes, 1% cement, and 2% cement, respectively, while the fracture energy at −10 °C decreased by 25.1%, 21.9%, 44.3%, and 30.7% for 1% asphaltenes, 2% asphaltenes, 1% cement, and 2% cement, respectively, compared to the control mixtures. These results shows that the modified samples had lower fracture energy compared to the unmodified samples, with the asphaltenes-modified samples exhibiting a less significant decrease compared to the cement-modified samples. Both the asphaltenes and cement mixtures were found to be weaker than the control mixture; however, the cement-modified samples were found to be weaker than the asphaltenes-modified samples and, thus, more prone to cracking at low temperatures.

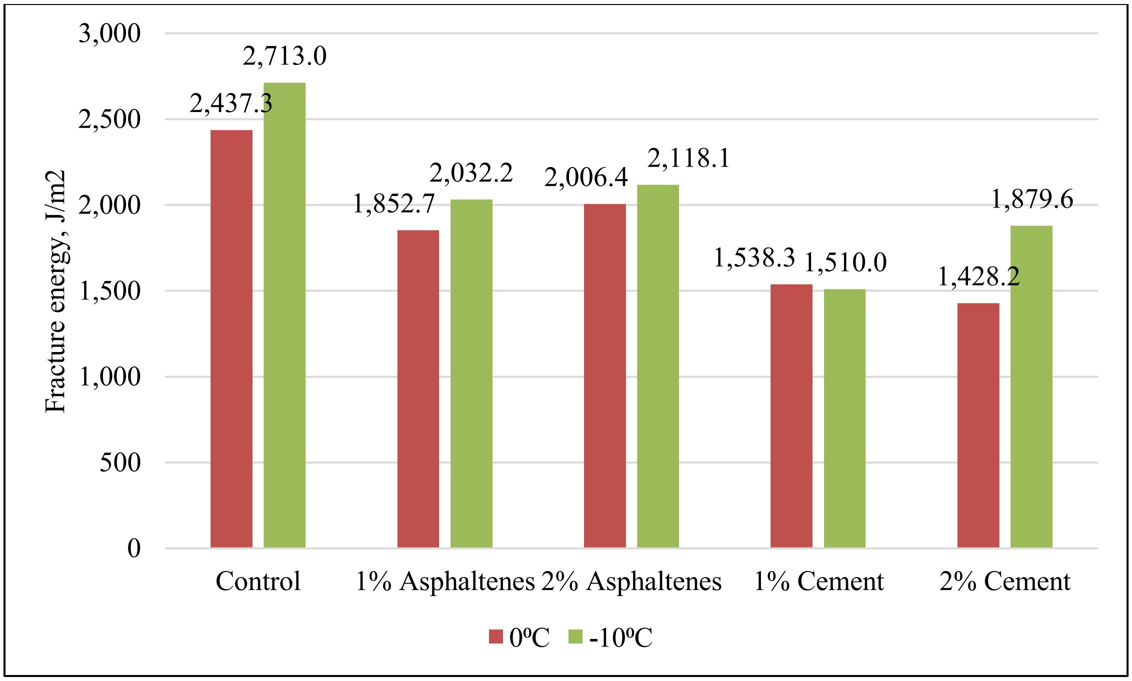


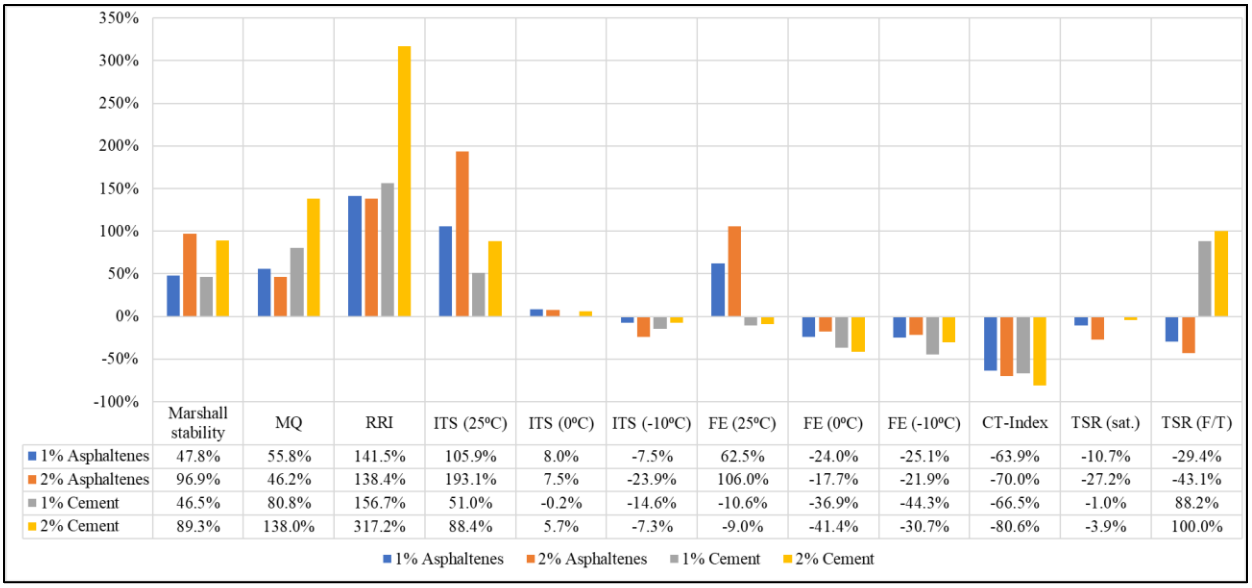
Figure 4-10 Fracture energy for low-temperature creep test

4.7 Discussion

This study focused on comparing the experimental results between asphalt emulsion-stabilized mixtures and modified mixtures with asphaltenes and cement at different concentrations, as shown in Figure 4-11. The Marshall stability of the 1% and 2% asphaltenes mixtures was found to increase by 47.8% and 96.9%, respectively, compared to the control samples, and similar improvements were seen for the cement mixtures (46.5% and 89.3% improvements in Marshall stability for the 1% and 2% cement mixtures, respectively). A comparison of asphaltenes and cement at the same concentration shows that asphaltenes had slightly better stability than cement. Both the MQ and RRI were found to increase significantly following modification of the mixture. Increases in MQ of 55.8%, 46.2%, 80.8%, and 138.0% and increases in RRI of 141.5%, 138.4%, 156.7%, and 317.2% were observed in the 1% asphaltenes, 2% asphaltenes, 1% cement, and 2% cement, respectively. It has been observed 2% asphaltenes has the lowest improvement between all modified mixtures, whereas the highest improvement belongs to the 2% cement-modified mixtures; it can also be concluded this improvement is higher for cement-modified samples in comparison to asphaltenes-modified mixtures.

The tensile strength at 25 °C was found to increase by considerable margins of 105.9%, 193.1%, 51.0%, and 88.4% for the 1% asphaltenes, 2% asphaltenes, 1% cement, and 2% cement mixtures, respectively, compared to the control samples. At 0 °C, in contrast, only a slight increase in tensile strength was observed in most of the modified mixtures in comparison to the control mixtures (8.0%, 7.5%, and 5.7% for the 1% asphaltenes, 2% asphaltenes, and 2% cement mixtures), and in fact the 1% cement mixture saw a decrease in tensile strength of about 0.2% compared to the control mixtures. At −10 °C, meanwhile, the strength of the modified mixtures decreased by a greater margin compared to the control samples (by 7.5%, 23.9%, 14.6%, and 9.0% for the 1% asphaltenes, 2% asphaltenes, 1% cement, and 2% cement mixtures, respectively). The results show that the tensile strength of the modified mixtures performed significantly better than the control mixtures in general, as well as that the asphaltenes-modified mixtures performed better than the cement-modified mixture. However, the tensile strength of the asphaltenes-modified mixtures subject to freeze–thaw conditioning was lower than that of the cement-modified mixtures. Moreover, at low temperatures, the tensile strength of the modified mixtures was lower than that of the control mixtures. The results lead us to infer that, while the asphaltenes-modified samples were superior in terms of tensile strength, the addition of asphaltenes made the asphalt more prone to moisture damage.

In terms of fracture energy, at 25 °C the asphaltenes-modified samples showed significantly higher values than the control samples and cement-modified samples, while the cement-modified mixtures in fact saw a decrease compared with the control mixtures. On the other hand, the fracture energy of the modified mixtures at low temperature significantly decreased compared to the unmodified mixtures. Based on the overall results of the low-, intermediate-, and high-temperature tests, the asphaltenes-modified mixtures were found to be more efficient at improving their performance properties than the cement-modified mixtures.



	Marshall stability	MQ	RRI	ITS (25ºC)	ITS (0ºC)	ITS (-10ºC)	FE (25ºC)	FE (0ºC)	FE (-10ºC)	CT-Index	TSR (sat.)	TSR (F/T)
🟦 1% Asphaltenes	47.8%	55.8%	141.5%	105.9%	8.0%	-7.5%	62.5%	-24.0%	-25.1%	-63.9%	-10.7%	-29.4%
🟧 2% Asphaltenes	96.9%	46.2%	138.4%	193.1%	7.5%	-23.9%	106.0%	-17.7%	-21.9%	-70.0%	-27.2%	-43.1%
◼ 1% Cement	46.5%	80.8%	156.7%	51.0%	-0.2%	-14.6%	-10.6%	-36.9%	-44.3%	-66.5%	-1.0%	88.2%
🟨 2% Cement	89.3%	138.0%	317.2%	88.4%	5.7%	-7.3%	-9.0%	-41.4%	-30.7%	-80.6%	-3.9%	100.0%

Figure 4-11 Performance improvement of modified asphalt emulsion stabilized mixtures with asphaltenes and cement in compared to control samples.

4.8 Conclusions

From the test results and analysis conducted in this study for the performance comparison of cement- and asphaltenes-modified mixtures, the following conclusions were drawn:

- Modification with 1% and 2% asphaltenes increased the tensile strength by approximately 106% and 193%, respectively, while modification with cement at the same concentration resulted in an improvement of less than 88%. Comparing the performance of cement- and asphaltenes-modified mixtures, it can be concluded that mixtures modified with asphaltenes are more effective in improving the Marshall stability and tensile strength as compared to those modified with cement.

- From the analysis of the MQ results of the modified mixtures, it was found that both additives (cement and asphaltenes) increase the stiffness and resistance to rutting damage.
- The TSR analysis indicated that modification with asphaltenes decreases moisture resistance compared to control mixtures, whereas modification with cement, in contrast, significantly increases resistance to moisture damage compared to the asphaltenes-modified asphalt emulsion-stabilized mixtures, especially after freeze–thaw conditioning.
- The results of the analysis of the CT-Index values indicate that both cement- and asphaltenes-modified mixtures are more prone to cracking compared to control mixtures; however, the mixtures modified with asphaltenes will have better resistance to low-temperature cracking compared to mixtures modified with cement.
- With regard to the rutting deformation analysis, a significant improvement in rutting resistance was observed for the modified mixtures compared to the control. Furthermore, the sample modified with 1% cement was found to better improve rutting resistance compared to both the asphaltenes mixture and the control mixture.
- Looking at the creep compliance test results, it was found that, with both additives (asphaltenes and cement), modification can adversely affect the low-temperature performance of the mixture due to brittleness and stiffening, as reflected in the fracture energy values obtained. However, the cement-modified mixtures were observed to be more prone to low-temperature cracking compared to the asphaltenes-modified mixtures.
- Comparing all the results, it can be concluded that the addition of either asphaltenes or cement will result in a mixture with higher strength; however, at low temperatures, asphaltenes-modified mixtures have better cracking resistance, while cement-modified mixtures are more moisture-resistant.

Chapter 5 Summary and conclusions

5.1 Summary

Recently, the application of asphalt emulsion mixtures in the base course is popular due to its less energy consumption, fewer emissions, and high effectiveness. Even though the application of asphalt emulsion mixes in the base course has been in use for over a decade, the development of high-performance asphalt emulsion stabilized mixes with different additives is necessary shortcomings associated with asphalt emulsion in order to extend the life span of pavements. This results in an opportunity to explore the advantages of different active fillers and asphaltenes for use in improving the performance of asphalt emulsion mixes.

The main focus of this research study is to investigate and compare the impact of the addition of Portland cement and asphaltenes to asphalt emulsion stabilized mixes for base course applications. Portland cement and asphaltenes are added separately into an asphalt emulsion and samples were subjected to various tests based on Superpave testing protocols as well as AASHTO/ASTM standards. The samples were tested for their rutting resistance, moisture resistance, cracking resistance at both intermediate and low temperatures.

5.2 Conclusions

Different tests of modified asphalt emulsion stabilized mixes using cement and asphaltenes were conducted and compared and the conclusions drawn from the study are summarized as follows:

- The stability of the modified mixes with cement or asphaltenes were found to be improved. In fact, when compared to control mixes, stability increased by 72% for asphaltenes, and 68% for cement, respectively. It was also discovered that asphaltenes modified mixes work better than cement modified mixes.

- Modification with 1% and 2% asphaltenes increases tensile strength by approximately 106% and 193%, while modification with cement at the same quantity resulted mainly in an improvement of less than 90%. Comparing these performances of Portland cement and asphaltenes modified mixes, it can be concluded that mixes modified with asphaltenes are more effective in improving tensile strength of the mixes as compared to Portland cement.

- According to the TSR results for both saturated and F/T samples, asphaltenes modified mixes are significantly more susceptible to moisture damage than control mixes. As compared to control mixes, cement modified samples have a 90% improvement on F/T conditioned. It is concluded that asphaltenes modified mixes more prone moisture damage.

- From IDEAL-CT results analysis, there is a decrease in terms of CT-Index for asphaltenes modified samples compared to the control samples despite improvement in tensile strength and fracture energy. While the cement modified samples have decreased for CT-Index and also decreased for fracture energy. In addition, it was observed that the cement modified samples has decreased than the asphaltenes modified samples. Hence, it is concluded that the addition of cement in the mix more decrease the cracking resistance.

- When rutting resistance was compared to the control mix using wheel tracking test results and MQ values within the mixtures, rutting resistance increased by 142% for 1% asphaltenes modified samples and 157% for 1% cement modified mixtures. On the other hand, the cement modified samples have a higher value than the asphaltenes modified samples.

- From IDT low temperature results analysis, the ITS results at 0ºC revealed that compared to the control samples, the tensile strength of modified samples was not increased significantly after the addition of asphaltenes or cement. However, the fracture energy decreased by about 20% after adding asphaltenes and about 40% after adding cement. In conclusion, cement-modified mixes were more prone to low temperature cracking than asphaltenes-modified mixtures and overall higher tensile strength and fracture energy values were observed for asphaltenes-modified mixtures.
- When all of the findings are considered, it is clear that adding asphaltenes or cement to a mix increases its strength; however, asphaltenes modified mixes have better cracking resistance at both intermediate and low temperatures than cement modified mixes. On the other hand, compared to asphaltenes, cement was more effective in enhancing rutting resistance and moisture sensitivity of the mixes. Furthermore, asphaltenes is a waste and inexpensive and environmentally friendly can be utilized to improve asphalt emulsion stabilized mixes for base course applications.

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