CLEAN RESOURCES FINAL PUBLIC REPORT

1. PROJECT INFORMATION:

Project Title:	**Design and Performance Evaluation of Road Base Courses Comprised of Asphaltenes Derived from Alberta Oil-Sands**
Alberta Innovates Project Number:	AI 2518
Submission Date:	January 31, 2021
Total Project Cost:	$340,000
Alberta Innovates Funding:	$240,000
AI Project Advisor:	Dr. Paolo Bomben

2. APPLICANT INFORMATION:

Applicant (Organization):	**University of Alberta**
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3. PROJECT PARTNERS

Please provide an acknowledgement statement for project partners, if appropriate.

- The University of Alberta provided $100,000 in-kind contribution for using asphalt and binder lab facilities.
- Lafarge Canada, Husky Energy, CNOOC energy, VCI, Imperial Oil and other suppliers are also gratefully acknowledged for their supply of materials for this research.

A. EXECUTIVE SUMMARY

Provide a high-level description of the project, including the objective, key results, learnings, outcomes and benefits.

This project is focused on asphalt's base course, which is composed of binders and aggregates. In this study, binders and aggregates are selected and mixed to achieve road performance, particularly for cold-climate applications. In this work, two types of base course mixes are considered, a 'high-modulus base course' and 'asphalt emulsion-stabilized base course.' In both cases, the asphalt is modified using asphaltenes derived from Alberta oilsands bitumen.

With the project goals of gaining comprehensive information and understanding of road base course performance by demonstrating the efficacy and competitiveness of using Alberta oilsands-derived asphalt binders and asphaltenes in the base course, the outcomes demonstrate that the use of these materials can improve the cost-effectiveness and performance of asphalt pavement, while increasing demand for oilsands constituents. The improved performance of the base course can reduce the material requirement (through reduced thickness requirement and longer service life) and thereby reduce GHG emissions compared with current practices.

The key results of this study are as follows: (a) Asphaltenes derived from the deasphalting of Alberta oilsands is a valuable additive to modify asphalt binder properties for use in the high-modulus base course; however, the low-temperature properties of the mix may need enhancement, depending on the binder source used; (b) Asphaltenes is a promising solution for improving the mechanical properties of the stabilized base course using asphalt emulsion; (c) Asphalt binders derived from some Alberta oilsands bitumen sources have the potential to be modified using asphaltenes for use in high-modulus base course applications.

Overall, using a high-strength base course in pavement structures will result in a durable pavement with a longer life cycle and lower thickness compared to traditional pavements (thereby bringing to bear both environmental and economic benefits). Other advantages include decreased construction cycle time, which is particularly beneficial for cold regions with a short construction season.

Both direct and indirect employment opportunities in Alberta can be expected upon the successful implementation of this research. Direct employment opportunities are expected to be generated for the production of the newly developed road construction materials (asphaltene-containing base course, etc.) as demand for these materials increases. Other employment opportunities include the continuation of existing jobs within the Alberta oil-sands industry and jobs related to road networks construction using the new materials, sales and exports of the materials, and investment opportunities.

B. INTRODUCTION

Please provide a narrative introducing the project using the following sub-headings.

- **Sector introduction:** Include a high-level discussion of the sector or area that the project contributes to and provide any relevant background information or context for the project.
- **Knowledge or Technology Gaps:** Explain the knowledge or technology gap that is being addressed along with the context and scope of the technical problem.

B.1 Sector introduction

This research was focused on the use of asphaltenes derived from Alberta oilsands in road construction, specifically in the base course of the pavement. For this purpose, the performance of two different types of road base course asphalt mixes was studied: (1) high-modulus base course with an asphaltenes-enriched binder; and (2) a granular road base material stabilized using asphaltenes and asphalt emulsions.

High-modulus asphalt (also known as EME, from Enrobés à Module Elevé) is an innovation developed three decades ago for high-traffic roads to increase the modulus of the road's base course and reduce pavement thickness while still providing resistance to fatigue and permanent deformation. In the development of this material, resistance to permanent deformation was achieved by using a very stiff asphalt binder. Meanwhile, fatigue life was improved by adding a high binder content (~6% by mass) to the mix[1].

Base course stabilization improves long-term pavement performance indices (shear strength, modulus, moisture resistance, and durability). Granular base soil stabilization can be achieved by adding cementitious materials (e.g., lime, Portland cement, fly ash, or bitumen). The main advantage of an asphalt-stabilized layer over cementitious materials, it should be noted, is its flexibility and resistance to cracking. These properties result in improved performance, especially in cold regions[.5] Asphalt-stabilized layers most commonly involve asphalt emulsion. The addition of active fillers such as cement and lime powder is common in the bitumen emulsion stabilized layer to increase the mix stiffness.

B.2 Knowledge or Technology Gaps

EME materials have not been successfully used in cold regions due to poor performance in low temperatures[2,3]. To apply EME in cold regions, an appropriate asphalt cement is required. It should be noted that asphalt origin and refining process will significantly affect the low-temperature properties of the hard asphalt cement[4].

Considering the high quality and low wax content of asphalt cements produced by oil-sand bitumen[6], it is expected that EME composed of asphaltene-enriched asphalt cement derived from Alberta oil-sand bitumen will outperform air-blown asphalt cements in terms of resistance to cracking.

This research also investigated whether the addition of asphaltene powder to granular aggregate and asphalt emulsion enhances the mechanical properties of the mix.

1 Denneman et al., 2015, High modulus asphalt (EME) technology transfer to South Africa and Australia: shared experiences Conference on Asphalt Pavements for Southern Africa (CAPSA).
2 Perraton et al., 2014, Development of High Performance Mixes for Cold Climate, Proceedings, Annual Conference of the Canadian Technical Asphalt Association, pp. 249–268.
3 Judycki et al., 2015, 1, 362–388, http://dx.doi.org/10.1080/14680629.2015.1029674

4 Ryan Bricker and Simon A.M. Hesp, “Low Temperature P Investigation of low-temperature cracking in newly constructed high-modulus asphalt concrete base course of a motorway pavement, Road Materials and Pavement Design, 2015 Vol. 16, No. S erformance Testing of Asphalt Cement”, Warsaw, Poland, Oct. 18, 2012.
5 Barbod et al., 2014, Laboratory Performance of Asphalt Emulsion Treated Base for Cold Regions Applications, 2014 Conference of the Transportation Association of Canada Montreal, Quebec
6 Axel Meisen, “Bitumen Beyond Combustion (BBC) Project Phase 1 Report”, Prepared for Alberta Innovates, Apr., 2017.

C. PROJECT DESCRIPTION

Please provide a narrative describing the project using the following sub-headings.

- **Knowledge or Technology Description:** Include a discussion of the project objectives.
- **Updates to Project Objectives:** Describe any changes that have occurred compared to the original objectives of the project.
- **Performance Metrics:** Discuss the project specific metrics that will be used to measure the success of the project.

C.1 Knowledge or Technology Description

This project sought to demonstrate novel uses of asphaltenes, which are currently considered a waste byproduct of oilsands processing. Identification of new non-combustion uses for materials from bitumen is important in two respects: (1) by identifying a new application for asphaltenes, previously regarded as a waste material, there is an opportunity for a revenue stream from a material that is presently of little value; and (2) it is expected that using asphaltenes-modified asphalt cement will enhance the performance of the base course.

High-modulus base courses are an innovation in pavement technology that has not been successfully applied in cold regions. The main reason is that the use of very hard bitumen in high-modulus asphalt mixes causes these mixes to be prone to cracking at low temperatures. This may be related to the manufacturing process currently used to produce hard bitumen by air-blowing[7]. To date, several patents have been filed for different asphalt cement-modified materials. Examples include composite polymers, a combination of nanocarbon tubes and styrene-butadiene-styrene (SBS)[8], and a combination of crumb rubber powder, SBS, and direct coal liquefaction residue (DCLR)[9]. DCLR typically consists of 20% to 30% asphaltenes content, and the main rationale for using DCLR as an additive is its low cost compared to polymer additives.

7 Ryan Bricker and Simon A.M. Hesp, “Low Temperature Performance Testing of Asphalt Cement”, Warsaw, Poland – October 18, 2012.
8 Patent No.US9353292B2, “Asphalt modified with an SBS/MMWCNT nanocomposite and production method thereof”, US, 2016.
9 Patent No. CN105884264A, “High-modulus asphalt mixture and preparation method thereof”, China, 2016.

C.2 Updates to Project Objectives

Project objectives did not change in the course of the project.

C.3 Performance Metrics

The table below lists the main objectives, key performance indicators, and completion targets of the project as defined in the proposal.

Key Project Objectives	Key Performance/Success Indicator	Project Completion	Commercialization Target
Using asphaltene to modify asphalt cement for application in high-modulus base course	Rheological properties of hard asphalt cement (Sheer modulus and phase angle, low-temperature properties)	High temp. performance: Min. 82°C Low-temp. Performance: Min. -21°C	High temp. performance: 82°C Low-temp Performance: -22°C
Improving performance of high-modulus base course compared to similar mixes composed of hard asphalt cement from other sources	Mechanical properties of high-modulus base course (modulus, permanent deformation, cold temperature cracking)	Dynamic modulus @ 15 °C >14,000 MPa Permanent Deformation: Max. 4 mm Cold. temp. cracking: higher than the control mix	Dynamic modulus: 14,000 MPa @ 15 °C Permanent deformation: Max. 4 mm Cold temp. cracking: similar to the control mix
Improving performance of stabilized base course using bitumen emulsion and asphaltenes	Mechanical properties of stabilized base course (modulus, permanent deformation, cold temperature cracking)	Indirect Tensile Strength: Min 600 kPa Tensile strength ratio: Min. 50% Permanent deformation improved by more than 200% Cold-temperature cracking potential: Slightly more than the control sample Modulus: 1.5 to 2 times more than the control mix	Indirect Tensile Strength: Min. 600 kPa Tensile strength ratio: Min. 50% Permanent deformation: 50% improvement compared to the unmodified mix Cold temp. cracking: similar to the control mix Dynamic modulus: Higher than the control mix Modulus: greater than the control mix

D. METHODOLOGY

Please provide a narrative describing the methodology and facilities that were used to execute and complete the project. Use subheadings as appropriate.

This research focused on investigating how asphaltenes obtained from oilsands deasphalting can be incorporated in road base courses. The research was conducted at the University of Alberta asphalt binder and asphalt mix testing laboratories.

D.1 Research Focus I: Design and evaluate the performance of high-modulus base courses containing asphaltenes

Task I-1: Implement asphalt cement modification using asphaltenes

Various hard asphalt cements and asphaltenes were acquired from different sources: straight run asphalt PG 70-22 from Husky's Lloydminster refinery, distilled Cold Lake bitumen (penetration grade of 20) and a 10/20 multi-grade from Imperial Oil (this material is used in France for EME courses). Oilsands bitumen were received from four different sources and distilled at InnoTech Alberta to obtain the required grades. Asphaltene samples were supplied by CNOOC Energy and Value Creation Inc. (VCI).

After receiving the hard asphalt cements, rheology testing was performed using a Dynamic Shear Rheometer (DSR), conducting frequency-sweep tests on different samples and calculating the shear modulus (G*) and phase angle. The next step was to blend the prepared asphalt cements with various amounts of asphaltenes and conducting rheology tests on the resulting asphaltene-containing asphalt cement. The final step was to evaluate the low-temperature properties of the asphaltene-modified asphalt cement samples after aging them in a pressure aging vessel (PAV) and comparing their rheological properties with unmodified hard asphalt cements using a bending beam rheometer (BBR).

The output of Task I-1 was the specification and design of asphaltene-modified asphalt cement samples to be used in Task I-3.

Task I-2: Prepare granular base course materials

Granular materials were obtained from Lafarge Canada. Standard laboratory tests, including Los Angeles abrasion value, soundness, sand equivalent, water absorption, density and grain size distribution, were conducted to ascertain the physical properties of the materials in order to evaluate their potential use as a road base course.

Task I-3: Prepare mix design for high modulus base course mixes using unmodified bitumen and asphaltene-modified asphalt cement from Task 1

After designing different asphalt cements from Task I-1 and testing granular aggregates in Task I-2, mix designs were prepared for high modulus base courses composed of unmodified hard asphalt cements and asphalt mixes composed of asphaltene-modified asphalt cements

The output of Task I-3 is determination of the optimum binder content for each type of high modulus base course mix.

Task I-4: Evaluate the performance of high-modulus base courses comprising unmodified and modified asphalt cement

Asphalt mixes were prepared using the above mix designs and were compacted using a gyratory compactor. To evaluate the mix modulus at different temperatures and loading frequencies, dynamic modulus tests (AASHTO T 342) were conducted. Creep compliance tests (AASHTO T 322) were performed to investigate the low-temperature performance of the mixes. A Hamburg wheel tracking test, meanwhile, was conducted to investigate the resistance of the mixes to permanent deformation and moisture sensitivity at high temperatures (AASHTO T324). An indirect tensile test (ITS) (AASHTO T283), finally, was conducted to evaluate the tensile strength and moisture sensitivity of the mixes.

The results of Task I-4 demonstrated the advantages and disadvantages of using asphaltenes as an asphalt cement modifier in high-modulus base courses.

D.2 Research Focus II: Design and performance evaluation of stabilized base courses using asphalt emulsions and asphaltenes

Task II-1: Prepare granular base course material

For this task, base course material was supplied by Lafarge Canada. The grain size distribution of the aggregate was defined for the material using the available standards similar to Task I-1.

Task II-2: Prepare mix design for stabilized base course using asphalt emulsion

Industrial asphalt emulsion type CSS-1H asphalt emulsions were supplied by Husky Energy. To prepare a mix design, mixes with different amounts of asphalt emulsions (a minimum of 3 different values selected to obtain a total asphalt content of 4% to 6% in the mix) and granular aggregates were prepared and compacted using a gyratory compactor. All mixes were oven-cured for 48 hours at 60 °C. After curing, physical properties such as density and air void content were measured. ITS was conducted to evaluate the tensile strength and moisture sensitivity of the mixes.

The output of Task II-2 was the optimum asphalt-emulsion compositions for preparing the mixes.

Task II-3: Prepare mixes containing asphaltenes

Using the optimum asphalt-emulsion compositions (determined in Task II-2) and granular aggregates (characterized in Task II-1), asphalt mixes were prepared, and different concentrations of asphaltenes (ranging from 0.5% to 3% by weight of the mix) were added to the mixes. The mixes were compacted using a gyratory compactor and cured at 60°C for 48 hours. After curing, physical properties such as density and air void content were measured. ITS was conducted to evaluate the tensile strength and moisture sensitivity of the mixes.

The output of Task II-3 was the optimum asphaltene content for the stabilized base course.

Task II-4: Evaluate performance of stabilized base course consisting of granular aggregates and asphalt emulsions with and without asphaltenes

To evaluate the strength of the mixes as well as their resistance to permanent deformation and low-temperature cracking, mechanical tests similar to those in Research Focus I – Task I-4 (with the exception of ITS) were conducted.

The output of Task II-4 was an assessment of the impact of using asphaltenes on the mechanical performance of asphalt emulsion-stabilized mixes.

E. PROJECT RESULTS

Please provide a narrative describing the key results using the project's milestones as sub-headings.

- Describe the importance of the key results.
- Include a discussion of the project specific metrics and variances between expected and actual performance.

A detailed summary report including all the research results is attached at the end of this document. A high level summary of results is below.

E1 Research Focus I: Design and evaluate the performance of high-modulus base courses containing asphaltenes

The results of Research Focus I show that asphaltenes can be used as a modifier to enhance the stiffness of the asphalt binder. However, modified binders could be more prone to low-temperature cracking. Asphalt binders from various sources of Alberta oilsands were shown to possess different properties; however, of the four sources, three were found to be suitable for this application. The mix design for the high-modulus base course, it should be noted, was prepared based on the relevant standards and its performance metrics were found to be similar to the predicted values, with the exception of the low-temperature performance, which was found to be poorer than the predicted performance.

E.2 Research Focus II: Design and performance evaluation of stabilized base courses using asphalt emulsions and asphaltenes

The results of Research Focus II show that stabilized mixes using asphalt emulsion and asphaltenes can be designed to achieve superior properties compared to mixes containing no asphaltenes. All the performance metrics were found to be similar to the predicted ones, with the exception of the low-temperature performance, which was found to be slightly poorer than the predicted performance.

F. KEY LEARNINGS

Please provide a narrative that discusses the key learnings from the project.

- Describe the project learnings and importance of those learnings within the project scope. Use milestones as headings, if appropriate.
- Discuss the broader impacts of the learnings to the industry and beyond; this may include changes to regulations, policies, and approval and permitting processes

F.1 Research Focus I: Design and evaluate the performance of high-modulus base courses containing asphaltenes

Project learnings:

- Both asphalt binder sources (crude oil and Alberta oilsands) can be successfully modified using asphaltenes for use in the high-modulus base course. Depending on the asphalt cement source, an appropriate asphaltenes content was found to be between 6% and 12% by weight of the binder.
- Asphaltenes modification has a negative impact on the low-temperature properties of the asphalt binder. However, its benefits high temperatures outweigh its negative impact at low temperatures.
- A high-modulus base course was designed using asphaltenes-modified binders, and the designed mix was found to satisfy all the design requirements (e.g., dynamic modulus, rutting resistance). However, the low-temperature cracking resistance of the designed mixes was lower compared to the control mix.

Impact on Industry:

- As the findings of this study demonstrate, asphaltenes can be considered an appropriate modifier for asphalt binder stiffening and modification.
- Alberta oilsands binders can be an effective solution in pavement applications, and can be successfully modified using asphaltenes for high-modulus base course applications.
- Innovative asphaltene-modified binders (e.g., binders featuring polymer fibres) could be designed for use in high-modulus base course applications in cold regions as a solution to enhance the cracking resistance of the mix.

F.2 Research Focus II: Design and performance evaluation of stabilized base courses using asphalt emulsions and asphaltenes

Project learnings:

- The mechanical properties of a stabilized base course featuring emulsified asphalt were found to be significantly improved as a result of asphaltenes modification. The optimum asphaltenes content was found to be 1% by weight of the mix.
- Asphaltenes modification was found to have a significant contribution in improving the high and intermediate properties of the stabilized mixes, including the mix modulus, permanent deformation, and shear strength. However, it had a slight negative impact on the low-temperature properties of the mix.

Impact on Industry:

- Asphaltenes could be used as an appropriate modifier to enhance the mechanical properties of the stabilized layer using asphalt emulsion. (This study was limited to the stabilization of granular material using asphaltenes; however, the impact of asphaltenes on the stabilization of reclaimed pavement material (RAP) warrants further investigation.)

G. OUTCOMES AND IMPACTS

Please provide a narrative outlining the project's outcomes. Please use sub-headings as appropriate.

- **Project Outcomes and Impacts:** Describe how the outcomes of the project have impacted the technology or knowledge gap identified.
- **Clean Energy Metrics:** Describe how the project outcomes impact the Clean Energy Metrics as described in the *Work Plan, Budget and Metrics* workbook. Discuss any changes or updates to these metrics and the driving forces behind the change. Include any mitigation strategies that might be needed if the changes result in negative impacts.
- **Program Specific Metrics:** Describe how the project outcomes impact the Program Metrics as described in the *Work Plan, Budget and Metrics* workbook. Discuss any changes or updates to these metrics and the driving forces behind the change. Include any mitigation strategies that might be needed if the changes result in negative impacts.
- **Project Outputs:** List of all obtained patents, published books, journal articles, conference presentations, student theses, etc., based on work conducted during the project. As appropriate, include attachments.

Project Outcomes and Impacts:

- This project demonstrated novel uses of asphaltenes, which is currently considered a waste by-product generated in oilsands processing, as a modifier for asphalt binder modification of high-modulus base course and stabilized soil using asphalt emulsion applications.
- The results of the project demonstrate that asphalt cement derived from different sources of Alberta oilsands could be considered a suitable material for high-modulus base course applications.

Clean Energy Metrics

- The results demonstrate the benefits of innovative use of asphaltenes, which in current practise is considered a waste material resulting from oilsands deasphalting.
- The results show the applicability of Alberta oilsands-derived asphalt cement for the high-modulus base course.
- The results of the project change the range of Technology Readiness Level (TRL) from 1 to 6.

Program Specific Metrics

- As shown in part C3, most of the performance metrics were satisfactory. The only metric that needs further improvement is the low-temperature performance of the mixes.

Project Outputs

The results of this study have been successfully published in highly-ranked conferences and journals as listed below:

Note: An asterisk (*) is used to indicate a student under my supervision

Journal Papers

J.1 Kamran, F.*, Basavarajappa, M.*, Bala, N.*, and Hashemian, L. "Effect of Asphaltenes Derived from Alberta Oil Sands on Stabilized of Base Course using Asphalt Emulsion, Construction and Building Materials", accepted subject to revisions, Oct., 2020.

J.2 Basavarajappa, M*, Kamran, F*., Bala, N*., and Hashemian, L. "Rutting Resistance of Stabilized Mixes Using Asphalt Emulsion and Asphaltenes", International Journal of Pavement Research and Technology, accepted with minor revisions, Jan., 2021.

J.3 Bala, N.*, Ghasemirad, A.*, and Hashemian, L. "Rheological Evaluation of Asphalt Cement Derived from Alberta Oil-sand Bitumen at Different Distillation Temperatures", Canadian Journal of Civil Engineering, accepted Oct., 2020.

J.4 Kamran, F*., Basavarajappa, M*., Bala, N*., and Hashemian, L. "Mechanical Properties of Stabilized Base Course Using Asphalt Emulsion and Asphaltenes Derived from Alberta Oil Sands", Transportation Research Record: Journal of Transportation Research Board, accepted with minor revisions, Oct., 2020.

J.5 Ghasemirad, A.*, Bala, N.*, and Hashemian, L. (2020) "High-Temperature Performance Evaluation of Asphaltenes-Modified Asphalt Binders", Molecules, 25(15), https://doi.org/10.3390/molecules25153326

J.6 Basavarajappa, M.*, Kamran, F*., Bala, N*., and Hashemian, L. (2021) "Investigation the impact of asphaltenes on Rheological Characteristics and Fatigue Performance of asphalt emulsion stabilized mixes", Canadian Journal of Civil Engineering, under review.

J.7 Ghasemirad, A.*, Bala, N.*, and Hashemian, L. (2021), "Application of Asphaltenes in High Modulus Asphalt Concrete", Construction and Building Materials, under review.

Conference Papers

C.1 Uddin, M.*, Kamran, F*., Bala, N*., Corenblum B. and Hashemian, L. (2021), Mechanical Properties of Asphalt Emulsion Stabilized Base Course Modified using Cement or Asphaltenes, Proceedings, International Airfield & Highway Pavements Conference (Pavements 2021)

C.2 Kamran, F*., Basavarajappa, M*., Bala, N*., and Hashemian, L. (2021) "Mechanical Properties of Stabilized Base Course Using Asphalt Emulsion and Asphaltenes Derived from Alberta Oil Sands", Proceedings, 100th Transportation Research Board (TRB) of National Academy of Science Conference, Washington, DC, United States.

C.3 Ghasemirad, A.*, Bala, N.*, Hashemian, L., and Bayat, A. (2021), "Asphaltenes-Modified Binders for High Modulus Asphalt Concrete Applications", Proceedings, 100th Transportation Research Board (TRB) of National Academy of Science Conference, Washington, DC, United States.

C.4 Ghasemirad, A.*, Bala, N.*, and Hashemian, L. (2020), "Investigation of Asphaltenes-Modified Binders for Application in High Modulus Asphalt Concrete Mixtures", Proceedings, Canadian Technical Asphalt Association Annual Conference.

C.5 Kamran, F*., Basavarajappa, M*., Bala, N*., and Hashemian, L. (2020), "Evaluation of Low and High Temperature Performance of Asphaltenes Modified Stabilized Base Course", Proceedings, Canadian Technical Asphalt Association Annual Conference.

Dissertations

MSc

T.1 Basavarajappa, M. (2020) “Rutting and Fatigue Performance Evaluation of Asphalt Emulsion Modified Using Asphaltenes”

T.2 Ghassemirad, A. (2020) “Asphaltenes-Modified Binders for High Modulus Asphalt Concrete Applications”

T.3 Uddin, M.M. (planning to defend in 2021) “Comparison of Mechanical Performance of Cement or Asphaltenes Modified Stabilized Base Courses”

PhD

T.4 Kamran, F. (planning to defend in 2022) “A Mix Design Approach for Modified Asphalt Mixes using Asphaltenes”

H. BENEFITS

Please provide a narrative outline the project's benefits. Please use the subheadings of Economic, Environmental, Social and Building Innovation Capacity.

- **Economic:** Describe the project's economic benefits such as job creation, sales, improved efficiencies, development of new commercial opportunities or economic sectors, attraction of new investment, and increased exports.
- **Environmental:** Describe the project's contribution to reducing GHG emissions (direct or indirect) and improving environmental systems (atmospheric, terrestrial, aquatic, biotic, etc.) compared to the industry benchmark. Discuss benefits, impacts and/or trade-offs.
- **Social:** Describe the project's social benefits such as augmentation of recreational value, safeguarded investments, strengthened stakeholder involvement, and entrepreneurship opportunities of value for the province.
- **Building Innovation Capacity:** Describe the project's contribution to the training of highly qualified and skilled personnel (HQSP) in Alberta, their retention, and the attraction of HQSP from outside the province. Discuss the research infrastructure used or developed to complete the project.

H.1 Economic: Overall, using a high-strength base course in pavement structures will result in a durable pavement with a longer service life and lower thickness requirement compared to traditional pavements, thereby bringing significant economic benefits. Other advantages include decreased construction cycle time, which is particularly beneficial for cold regions with a short construction season.

H.2 Environmental: It is expected that the results of this research will increase the application of asphalt cement derived from Alberta oilsands in the asphalt industry, thereby significantly reducing the associated GHG emissions. The use of asphaltenes in the high-modulus base course and bitumen emulsion stabilized base layers can be expected to result in both a reduction in asphalt thickness requirement and extended pavement service life. Both of these developments will be critical factors in reducing the GHG emissions associated with road construction.

H.3 Social: Both direct and indirect employment opportunities can be expected as a result of the successful implementation of this research. Direct employment opportunities related to the production of pavement materials will result from increased demand for asphaltene-modified materials. Other employment opportunities may include the continuation of existing jobs within Alberta oilsands industry and jobs related to the construction of road networks using the new materials, exportation of the materials, and investment opportunities.

H.4 Building Innovation Capacity: Two postdoctoral fellows, one research assistant, one Ph.D. student, three MSc students, and six undergraduate students were recruited to this project and trained at the UofA's asphalt lab. Each of this highly qualified personnel gained hands-on experience with state-of-the-art equipment and techniques and will be well-positioned to contribute further to knowledge creation in this field, either in industry or academia. Finally, after commercialization, additional research opportunities will continue to be generated.

I. RECOMMENDATIONS AND NEXT STEPS

Please provide a narrative outlining the next steps and recommendations for further development of the technology developed or knowledge generated from this project. If appropriate, include a description of potential follow-up projects. Please consider the following in the narrative:

- Describe the long-term plan for commercialization of the technology developed or implementation of the knowledge generated.
- Based on the project learnings, describe the related actions to be undertaken over the next two years to continue advancing the innovation.
- Describe the potential partnerships being developed to advance the development and learnings from this project.

I.1 long-term plan for commercialization

This project was limited to laboratory investigations. It is expected that in the future field trials will be conducted in collaboration with transportation agencies and road authorities. The long-term goal, after proving the potential benefits of using asphaltene and asphalt cement derived from Alberta oilsands bitumen in terms of improved pavement quality and performance in cold regions, is that a portion of this investment will be allocated to deploying the asphalt mixes constructed from these materials in Alberta and other provinces in Canada. The quantification of GHG emissions is another objective that will be pursued in conjunction with the construction of test road sections for field trials.

I.2 Plan for the next two years

Considering the results of this study, the plan for the next two years is a laboratory study to:

- improve the low-temperature properties of the high-modulus base course using fibre modification, and
- investigate the possibility of stabilizing high contents of reclaimed asphalt pavement (RAP) material (more than 50%) in place of virgin aggregates using asphalt emulsion and asphaltenes.

I.3 Potential partnerships

This may include but is not limited to connecting with parties interested in innovative construction materials for roadways, potential industry partners that currently have stockpiles of asphaltenes, RAP, asphalt suppliers, and roadway authorities.

J. KNOWLEDGE DISSEMINATION

Please provide a narrative outlining how the knowledge gained from the project was or will be disseminated and the impact it may have on the industry.

This project has resulted in twelve papers to date (five journal papers accepted/published, two journal papers currently under review, and five conference papers accepted/published). Furthermore, the results have been or will be presented at the following academic conferences: the Canadian Technical Asphalt Association (CTAA) Annual Conference, the Transportation Research Board Annual Meeting, and the International Airfield & Highway Pavements Conference. Each of these conferences is well-recognized in the transportation industry, and the research presented at these conferences has reasonably wide exposure.

K. CONCLUSIONS

Please provide a narrative outlining the project conclusions.

- Ensure this summarizes the project objective, key components, results, learnings, outcomes, benefits and next steps.

The main conclusions and learnings from this study are summarized below.

K.1 Research Focus I: Design and evaluate the performance of high-modulus base courses containing asphaltenes

The main objectives of this study were to investigate the potential application of asphaltenes to modify conventional asphalt binders for high-modulus asphalt course (HMAC) applications, to evaluate binders derived from Alberta oilsands for high-modulus base courses applications, and, finally, to compare the performance of oilsands asphalt binders derived from different sources in Alberta. The main conclusions of this study are as follows:

- According to rheological test results, the addition of asphaltenes increases the stiffness and elasticity of the asphalt binder, resulting in a considerable improvement in resistance against permanent deformation at high temperatures. On average, and regardless of the binder source, a 6% increase in asphaltenes content corresponded to a one-interval increase in the high PG temperature grade of the asphalt binder. However, at low temperatures, every 10% to 20% increase in asphaltenes content (depending on the binder type) corresponded to a low PG grade increase of one interval.

- Regardless of the asphalt binder source, every 2% increase in asphaltenes content was found to increase the binder viscosity at 135 °C by approximately 0.1 Pa·s and to increase the mixing and compaction temperatures by approximately 2.6 °C.

- Binders sourced from Alberta oilsands bitumen were found to have lower colloidal index values (signifying their higher stability, i.e., stability of the asphaltenes phase in the maltenes matrix) compared to crude oil asphalt binder PG 70-22.
- The dynamic modulus test results for the asphaltenes-modified binders showed that these binders, coupled with a well-graded aggregate gradation, satisfies the dynamic modulus requirement (achieving more than 14 GPa at a loading frequency of 10 Hz and a temperature of 15 °C).
- The IDT results indicate that binder modification decreased the fracture energy for all the samples, and that the samples were more brittle at lower temperatures. On the other hand, the tensile strength of the modified samples increased significantly compared to the unmodified sample.
- The Hamburg wheel-tracking test and flow number test results showed a significant increase in rutting resistance in all the modified samples.
- Using the appropriate distillation temperature and source, oilsands bitumens were found to be capable of achieving high PG for high-modulus asphalt applications in moderately cold-climate regions without further modification.
- A method to reduce the cracking potential of HMAC composed of asphaltenes-modified binders, e.g., the addition of polymer fibres such as polyethylene terephthalate (PET), in order to improve its cold-climate performance warrants further investigation as a next step.

K.2 Research Focus II: Design and performance evaluation of stabilized base courses using asphalt emulsions and asphaltenes

The main objective of our study was to evaluate the impact of adding, through asphalt emulsion, asphaltenes derived from Alberta oilsands for the stabilization of granular base course material. After preparing a mix design for a control mix, the same mix design was used for the asphaltenes-modified mixes. The performance properties of the modified base course were evaluated for moisture damage by conducting indirect tensile strength (ITS) tests on dry and conditioned samples and calculating the tensile strength ratio (TSR) and rutting resistance using a Hamburg wheel-tracking test. Indirect tensile tests (IDT) was performed at 0 °C and −10 °C in order to evaluate the low-temperature properties of the mixes. The main conclusions of this study are summarized below:

- The tensile strength at 25 °C was found to increase by 110.5% and 172.7% for the samples with 1% and 2% asphaltenes content by weight of the mix, respectively. However, it should be noted that the samples with 2% asphaltenes content required extra water to increase the viscosity during mixing with aggregates.
- The tensile strength ratio decreased by 10% and 30% for 1% and 2% asphaltenes concentrations, respectively. This shows that the addition of asphaltenes will increase the moisture sensitivity of the mixes. However, it was not significant for modified mixes using 1% of asphaltenes. TSR during the freeze–thaw cycle also decreased by about 30% and 42.5% for 1% and 2% asphaltenes concentrations, respectively. The second asphaltenes source exhibited a similar decreasing pattern to the first source for 1% asphaltenes.

- The IDT results show that modification of the asphalt emulsion-stabilized material with asphaltenes resulted in lower fracture energy values and, consequently, increasing brittleness of the samples at lower temperatures. However, at lower temperatures, the tensile strength was slightly lower for the modified samples compared to the control samples.

- The Hamburg wheel-tracking test results are indicative of a notable improvement in rutting resistance of the modified mixtures compared to the unmodified samples. The RRI index was found to increase by 141.5% and 138.4% for both the 1% and 2% asphaltenes content samples, respectively, compared to the control samples. The flow number test results also confirm the wheel-tracking test results.

- The dynamic modulus values for the modified samples increased compared to the control sample. Comparing the 1% and 2% asphaltenes samples, improvement in dynamic modulus for the samples containing 1% asphaltenes was more significant.

- Asphaltenes as a waste material has a similar—or, in some cases, superior—impact on the asphalt emulsion-stabilized courses in comparison to the various conventional active fillers such as cement. This material could be used as an inexpensive and environmentally friendly alternative to satisfy or improve the properties of the mix.

- This study was limited to the granular layers composed of raw aggregates. However, using the same stabilizing material (asphaltenes and asphalt emulsion) to stabilize reclaimed asphalt pavements (RAP) could be very beneficial for the asphalt industry. Hence, this should be given consideration as the next step in this research.

Final Summary Report

Date: **January 31, 2021**

Project Title:	Design and Performance Evaluation of Road Base Courses Comprised of Asphaltenes Derived from Alberta Oil Sands
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1. Design and evaluation of the performance of high modulus base courses containing asphaltenes

1.1 Introduction

Currently, as highway transportation is the most common mode of transportation, pavements are now an essential asset for each country's development plan (Mallick & El-Korchi, 2013). Pavements can be categorized as asphaltic (or flexible) pavements, concrete (or rigid) pavements, and composite pavements (Mohod & Kadam, 2016; Papagiannakis & Masad, 2008). Flexible pavements generally consist of an asphalt concrete layer placed over a base and/or a subbase layer supported by compacted soil, called subgrade (Papagiannakis & Masad, 2008). Rigid pavements typically consist of a portland cement layer over the subgrade with or without a base layer (Papagiannakis & Masad, 2008). On the other hand, composite pavements usually happen in pavement rehabilitation when a layer of portland concrete is placed over a damaged asphalt concrete layer, or vice versa (Papagiannakis & Masad, 2008). According to a survey in 2016, asphalt paved roads are the most common type of pavements in North America, composing almost 94% of roads in the United States (Buncher, 2018). It's also found that according to Canada's core public infrastructure survey in 2016, almost 50% of all roads in Canada were located in Ontario and Alberta, while Alberta (28.4%) and Saskatchewan (23.9%) accounted for the largest share of highways (Statistics Canada, 2018).

Pavements, especially asphalt pavements rather than concrete ones, are layered structures, with every layer functioning to decrease the stress within the layer's load-bearing capacity underneath with an inferior quality (Huang, 1993). Figure 1 shows the conventional cross-section of a flexible pavement (Huang, 1993). From top to bottom, the layers of a pavement structure are known as surface, binder, base, subbase, and subgrade; however, some of these courses might be discarded (Papagiannakis & Masad, 2008).

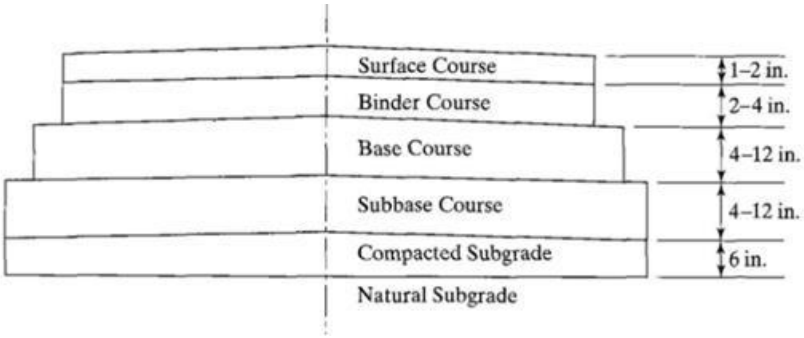

Figure 1. Typical Cross Section of a Conventional Flexible Pavement (Huang, 1993)

As can be seen in Figure 1, the surface course (also known as the wearing course) is the top layer in the pavement structure. The asphalt mixture used in this layer is typically dense-graded hot mix asphalt (HMA) (Huang, 1993). Moreover, this layer must be resistant against the distortion under traffic loading, waterproof to protect the whole system from moisture damage, and for the purpose of safety, it should provide a smooth and skid-resistant riding surface (Huang, 1993).

According to Figure 1, the binder course is the layer placed below the surface course. There are mainly two reasons to use this layer in the pavement structure. First, the wearing course is usually too thick to be compacted in a single layer; second, as this layer is not directly subjected to traffic loading or the destructive effects caused by water and oxidative hardening of asphalt binder, comparing to wearing course, it has less binder content, and larger aggregates of lower quality (Huang, 1993).

Under the surface or binder course, the base course would be placed as shown in Figure 1. This layer is the primary load-carrying layer and hence the most structurally important course in full-depth flexible pavement (Speight, 2015). This layer's main responsibility is to dampen the stress transferring to the subbase and subgrade from traffic loading. This layer should be resistant to permanent deformation, fatigue cracking caused by repeated loading, and thermal cracking when being exposed to low temperatures or intense temperature fluctuations (Huang, 1993). 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 (Lavin, 2003). When the pavement is going to experience heavy traffic loads, the base layer is usually hot mix asphalt (Huang, 1993).

The layer of material under the base course would be called the subbase course. The main reason to have two granular courses under the surface (or binder) course is to have a more economical design; comparing to the base course, the aggregates used in subbase course are usually cheaper and of a lower quality that would be readily found locally (Huang, 1993).

Asphalt mixtures are mainly composed of asphalt binder, aggregates, and filler (Mallick & El-Korchi, 2013). In recent years, with increasing traffic loads and intense climatic conditions, the addition of modifiers to asphalt binders/mixtures has become more conventional in order to prevent premature distresses in asphalt pavements (Daly, 2017; Kocak & Kutay, 2020). Asphalt binder is a hydrocarbon product, which is produced in crude oil or oilsands refineries mainly through fractional distillation (Hunter et al., 2015). After separation of lighter fractions (like liquid petroleum gas, gasoline, aviation fuel, kerosene, etc.), the heaviest fraction taken from crude oil distillation, which is a complex mixture of high molecular weight hydrocarbons, is processed further to obtain bitumen or asphalt binder (Hunter et al., 2015).

Rehabilitation projects with depth constraints in urban areas back in the 1980s made French engineers seek pavement materials with a higher modulus than conventional hot mix asphalt, in order to produce thinner layers but with the same service life (Corté, 2001). These efforts led to the introduction of high modulus asphalt concrete (HMAC), or Enrobé à Module Élevé (EME) in French (Sybilski et al., 2010). Although HMAC has been used in the construction of surface courses (Chen et al., 2020), the main application of this type of mixture remains in base courses, where the tensile stress in pavement structure reaches its maximum state (Haritonovs et al., 2016).

The key elements of HMAC mix to ensure their superior performance are hard grade binders combined with strong continuous dense-graded mineral skeletons (Moghaddam & Baaj, 2018). Using hard grade binder provides the mixture with high resistance to permanent deformations, while large content of asphalt binder and small content of air voids (closed structure) assure workability, fatigue durability, and water resistance (Sybilski et al., 2010; Chen et al., 2020;Yan et al., 2020; Sabita, 2019).

Hard binders used in the production of HMAC mixes, also referred to as high modulus asphalt binders (HMAB), can be categorized into three different classes: hard grade binders, binders modified with natural asphalt, and polymer-modified binders (Chen et al., 2020; Yan et al., 2020; Si et al., 2019; Wang et al., 2017). The main concern about the application of straight run hard grade binders and those modified with natural asphalt is their poor performance at lower temperatures (Judycki et al., 2017; Espersson, 2014). In the case of polymer-modified binders, the final high cost on one hand, and poor storage stability, on the other hand, limit the application of these binders in the base course, as the thickest layer of a pavement structure (Behnood & Gharehveran, 2019; Liang et al., 2019; Ghasemirad et al., 2017).

Unlike conventional mixture design methods which are based on volumetric properties, HMAC mix design is a performance-based design (Delorme et al., 2007). In this regard, HMAC mixtures should be tested to ensure they meet several performance criteria, including dynamic modulus, workability, durability, rutting resistance, and fatigue life (Denneman et al., 2011).

There are several measures for the asphalt mixture stiffness, including dynamic modulus, flexural stiffness, creep compliance, relaxation modulus, and resilient modulus (Ceylan et al., 2008). Among these measures, the dynamic modulus has a vast record of laboratory data for the test's input and output variables by different researchers over a considerable time, which makes the dynamic modulus prediction models more reliable (Ceylan et al., 2009). One of the main requirements for a high modulus asphalt concrete mixture, as the name implies, is for its dynamic modulus to be greater than 14,000 MPa at a loading frequency of 10 Hz, and a temperature of 15℃ (Denneman et al., 2011; Leiva-Villacorta & Willis, 2017). Difficulty obtaining dynamic modulus measurements in the laboratory at extreme temperature and frequency conditions made researchers develop predictive models using the available mixture and binder data (Ceylan et al., 2008). These models proved to be useful in places with limited access to expensive laboratory facilities as well (El-Badawy et al., 2018). These efforts lead to the development of predictive regression models and, more recently, models based on artificial neural networks (Ceylan et al., 2009, Far et al., 2009).

Sustainability and reduction in cost are the two main factors, which lead to the incorporation of waste materials into the modification of asphalt binders (Choudhary et al., 2020; Wang et al., 2020). In the HMAC area, there have been some efforts to use waste polymers to produce high modulus asphalt concrete, which yielded comparable results to those modified with commercial polymer modifiers (Ranieri & Celauro, 2018).

According to polarity, asphalt binder can be divided into two general chemical groups of asphaltenes and maltenes (Sultana & Bhasin, 2014), with asphaltenes being the most polar fraction of asphalt binder with high molecular weight (Behnood & Gharehveran, 2019; Demirbas, 2016). Asphalt binder is a viscoelastic material, and polar fractions has been shown to be associated with the elastic part of binder behaviour. In contrast, non-polar fraction accounts for the viscous part (Sultana & Bhasin, 2014). More asphaltene content in asphalt binder could cause a decrease in penetration and an increase in softening point, reflecting an increase in asphalt stiffness (Mangiafico et al., 2016).

Asphaltenes are considered a waste material with no value and minimal applications in the industry, with a relatively high production rate in oil refineries. In northern Alberta facilities, it is assumed that asphaltenes are produced at a rate of 17.5% of asphalts (Meisen, 2017). Some efforts have been made to make use of asphaltenes (Alipour et al., 2016), but they proved to be neither economical nor environmental-friendly (Ashtari, 2016). A more practical and sustainable solution seems to be necessary to create value out of this material.

1.2 Asphalt cement modification using asphaltenes

1.2.1. Unmodified asphalt cement rheology test

1.2.1.1. Dynamic Shear Rheometer

Eleven types of different hard asphalt cements (binders) were received from various sources, as listed in Table 1. To understand the high-temperature properties of the asphalt binders, rheology tests were conducted on unaged and aged binders based on the Superpave test method (FHWA, Superpave Fundamentals). A dynamic shear rheometer (DSR) was used for rheology tests based on the standard AASHTO T315. According to the standard, a spindle with a diameter of 25 mm and a 1-mm gap was used for conducting rheology tests on unaged samples, with the spindles and moulds for the test shown in Figure 2. For the dynamic shear rheometer (DSR) testing on the asphalt samples aged in the pressure aging vessel (PAV), an 8 mm spindle and 2-mm gap will be used (Figure 2).

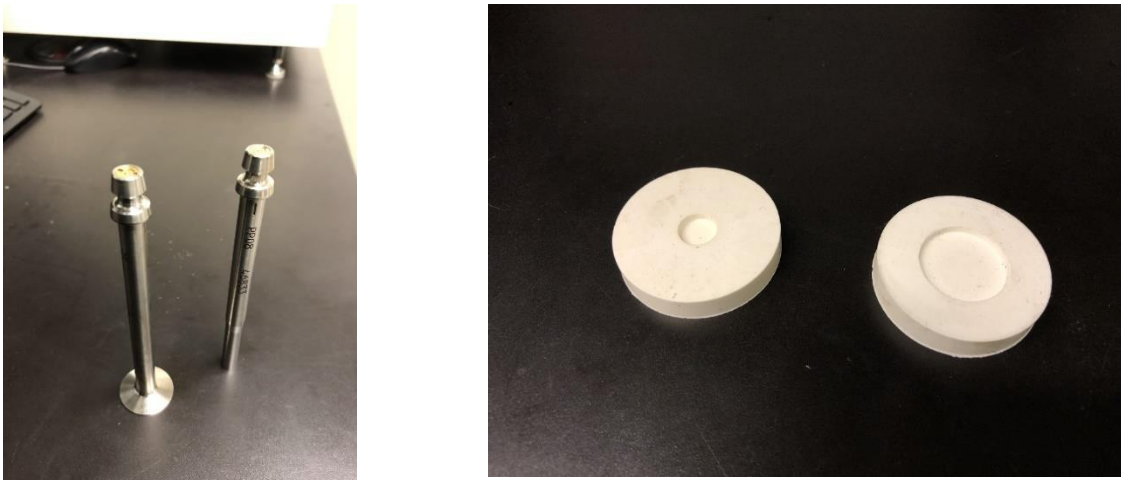

Figure 2. DSR Spindles (on the left) and sample moulds (on the right)

For the next step, to simulate asphalt binder aging in the asphalt plant, the asphalt samples were aged using a rolling thin-film oven (RTFO) based on AASHTO T240. According to this standard, to age an asphalt binder, each of the 8 glass bottles of the RTFO are filled with 35±0.5gr of binder, and the bottles with the binder placed horizontally for at least one hour, but not more than three hours, at room temperature. The RTFO bottles are shown in Figure 3 in their different states. After the horizontal resting period, the filled RTFO glasses are placed in a rotating rack. The binder in the RTFO bottles is then exposed to a temperature of 163 °C, with air blown across the samples at a rate of 4.0 L/min for 85 minutes to simulate short-term aging of the binder. The aged binder samples can then be used for further rheology testing. The RTFO is shown in Figure 4.

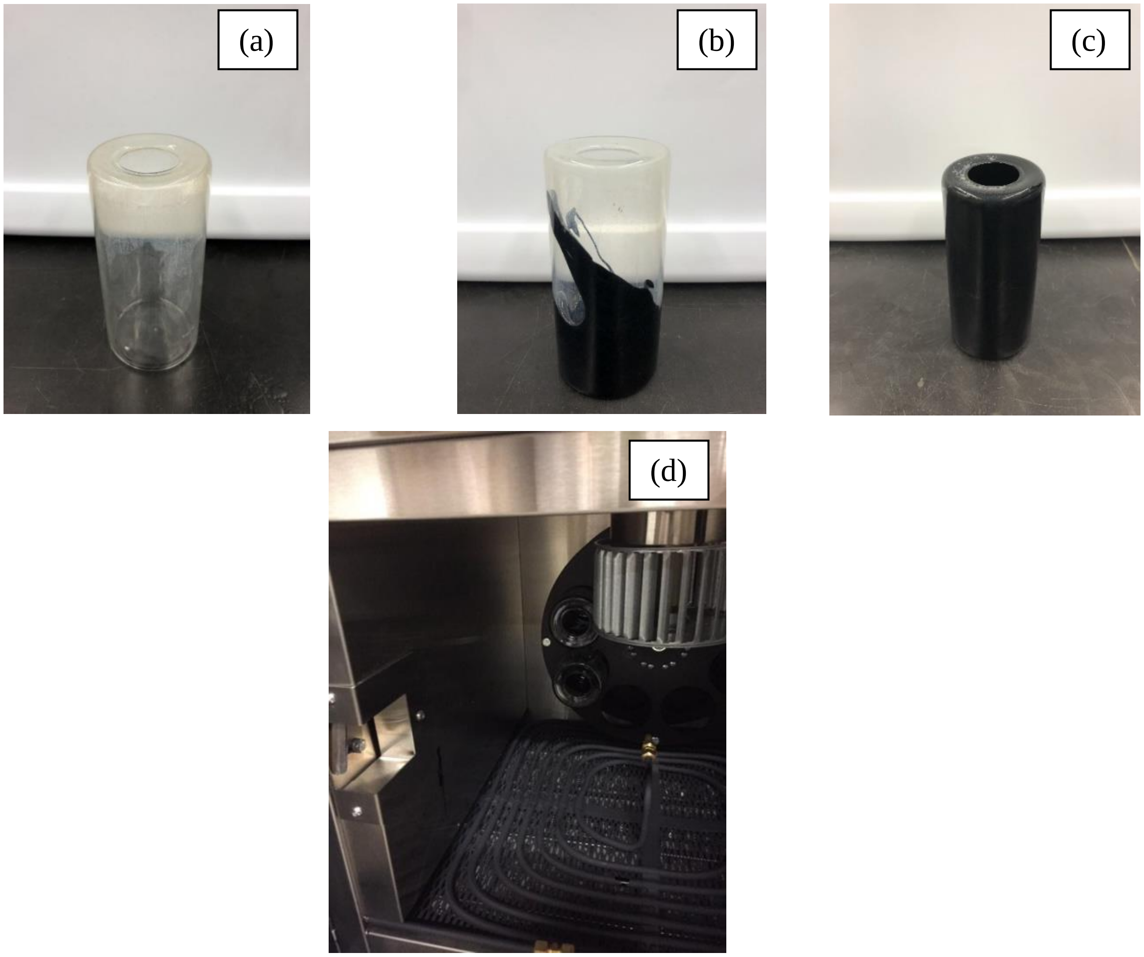

Figure 3 . RTFO bottles in different stages: (a) empty, (b) after conditioning at ambient temperature, (c) after aging, and (d) in RTFO rotating rack

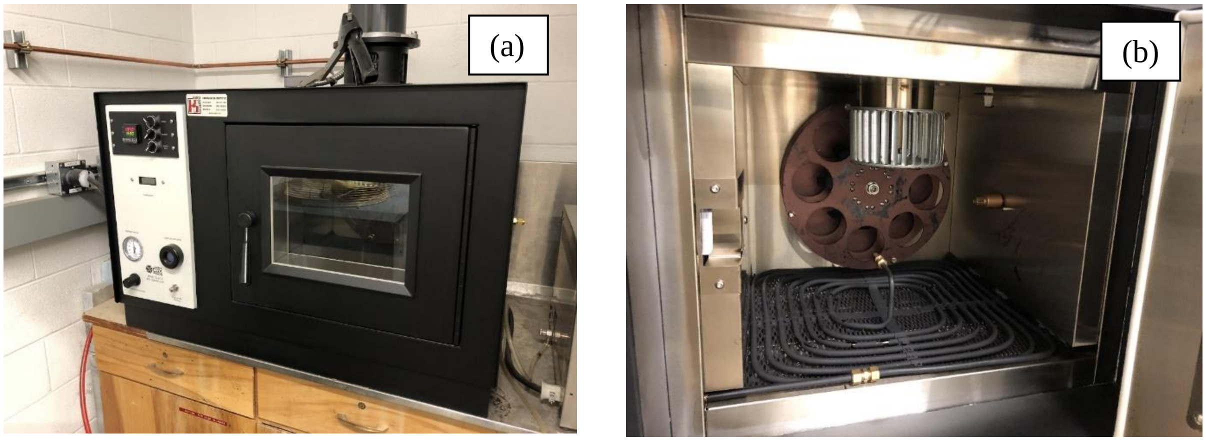

Figure 4 - Rolling Thin Film Oven, (a) overview of the device, (b) rotating rack and air jet inside the RTFO

Table 1 shows the result of the rheology tests performed on all unaged and aged asphalt binders, and the high-temperature grading obtained as a result of this testing. According to AASHTO

M320, when testing (25 mm)-diameter samples at high temperatures, the temperature at which the parameter G*/sin   drops below 1.0 kPa or 2.2 kPa, was recorded as the failure temperature for unaged and RTFO-aged binder, respectively. The minimum temperature among those two was the final continuous high PG grade of the binder. However, the standard high PG grade starts form 46 ˚C and increases with 6 ˚C increments. In order to figure out the standard high PG grade, the continuous grade would be decreased to the nearest standard high PG grade.

Table 1. High-Performance Grade of binders, as determined by rheology test results of aged and unaged asphalt binder samples

No.	**Binder**	**High PG grade (Unaged Binder)**	**High PG grade (RTFO-Aged Binder)**	**Continuous high PG Grade**	**Standard high PG Grade**
1	PG 64-22	70.5	71.1	70.5	70
2	PG 70-28 (Air-blown)	78.7	83.0	78.7	76
3	EME Pen 20/30	84.0	83.7	83.7	82
4	Vacuum Tower	88.9	90.2	88.9	88
5	Cold Lake	86.1	85.9	85.9	82
6	Pitch	106.5	104.3	104.3	100
7	Q8 Pen 5/15	96.5	94.3	94.3	94
8	Q8 Pen 15/25	89.1	85.9	85.9	82
9	Q8 Pen 20/30	84.4	82.4	82.4	82
10	Q8 Pen 35/50	77.8	76.0	76.0	76
11	Q8 Pen 50/70	73.4	71.7	71.7	70

According to AASHTO T240, during RTFO aging, volatile components and reaction products (primarily water) evaporate, causing a decrease in mass, while ambient oxygen reacts with the sample, causing an increase in mass. This combined effect determines whether the sample has an overall mass gain or an overall mass loss after the aging process. Samples with a very low percentage of volatile components will usually exhibit a mass gain, whereas samples with a high percentage of volatile components will usually exhibit a mass loss. AASHTO M320 limits this change to less than one percent for either a positive (gain) or a negative (loss) change in mass. According to the Superpave standard, the contents of two bottles must be used to determine the mass loss or gain. The two bottles containing the samples should be cooled and weighed to the nearest 0.001 g. A high mass loss value allows identification of material with excessive volatiles, that is, one that could age excessively. Mass loss is reported as the average of the mass loss for the two samples after RTFO aging and is calculated by Equation (1).

$$Mass\ Loss, \% = \left[\frac{Original\ mass - Agged\ mass}{Original} Mass\right] x100 \tag{1}$$

Mass loss percentages for each of the different binders were measured and the results are compiled in Table 2.

Table 2. Mass loss of different binders (%)

No.	**Binder**	**Mass Loss (%)***	**Mass loss<1%?**
1	PG 64-22	0.08	Yes
2	PG 70-28 (Air-blown)	0.19	Yes
3	EME Pen 20/30	-0.01	Yes
4	Vacuum Tower	0.03	Yes
5	Cold Lake	-0.01	Yes
6	Pitch	0.01	Yes
7	Q8 Pen 5/15	0.02	Yes
8	Q8 Pen 15/25	0.01	Yes
9	Q8 Pen 20/30	-0.07	Yes
10	Q8 Pen 35/50	-0.03	Yes
11	Q8 Pen 50/70	0.04	Yes

* Negative values indicate mass gain

1.2.1.2. **High-Temperature Viscosity**

In order to ensure adequate workability of the asphalt mixture, AASHTO M320 restricts the maximum viscosity of binders at 135°C to 3 Pa·s. In accordance with AASHTO T316, a Brookfield rotational viscometer was used to measure the viscosity of the asphalt binders at elevated temperatures. The rotational viscometer is shown in Figure 5. Table 3 shows the viscosity of the asphalt binders at 135°C.

Figure 5. Rotational Viscometer

Table 3. Rotational viscosity of asphalt binders at 135°C

No.	Binder	Rotational viscosity at 135°C (Pa·s)	Less than 3 Pa·s?
1	PG 64-22	0.42	Yes
2	PG 70-28 (Air-blown)	0.62	Yes
3	EME Pen 20/30	0.79	Yes
4	Vacuum Tower	1.11	Yes
5	Cold Lake	0.97	Yes
6	Pitch	3.21	No
7	Q8 Pen 5/15	2.05	Yes
8	Q8 Pen 15/25	1.26	Yes
9	Q8 Pen 20/30	0.94	Yes
10	Q8 Pen 35/50	0.63	Yes
11	Q8 Pen 50/70	0.48	Yes

As can be seen from Table 3, the only binder which doesn’t pass the workability criterion is the Pitch Binder with a viscosity of 3.21 Pa·s at 135°C.

High temperature viscosity measurements of binders can also be used to calculate the mixing and compaction temperatures for asphalt mixtures made from specific binders. These temperatures are useful for the next steps of the project that is asphalt mixtures preparation. According to the Federal Highway Administration (FHWA, Superpave Fundamentals), compaction asphalt mixtures require mixing and compaction under equiviscous temperature conditions corresponding to 0.170 ± 0.020 Pa·s (for mixing) and 0.280 ± 0.030 Pa·s (for compaction), as determined from the temperature-viscosity plot for the asphalt binder. Figure 6 shows the plot to determine the mixing and compaction temperatures for the PG 64-22 binder as an example. The mixing and compaction temperature ranges for each of the binders are tabulated in Table 4, as determined using the procedure illustrated in Figure 6.

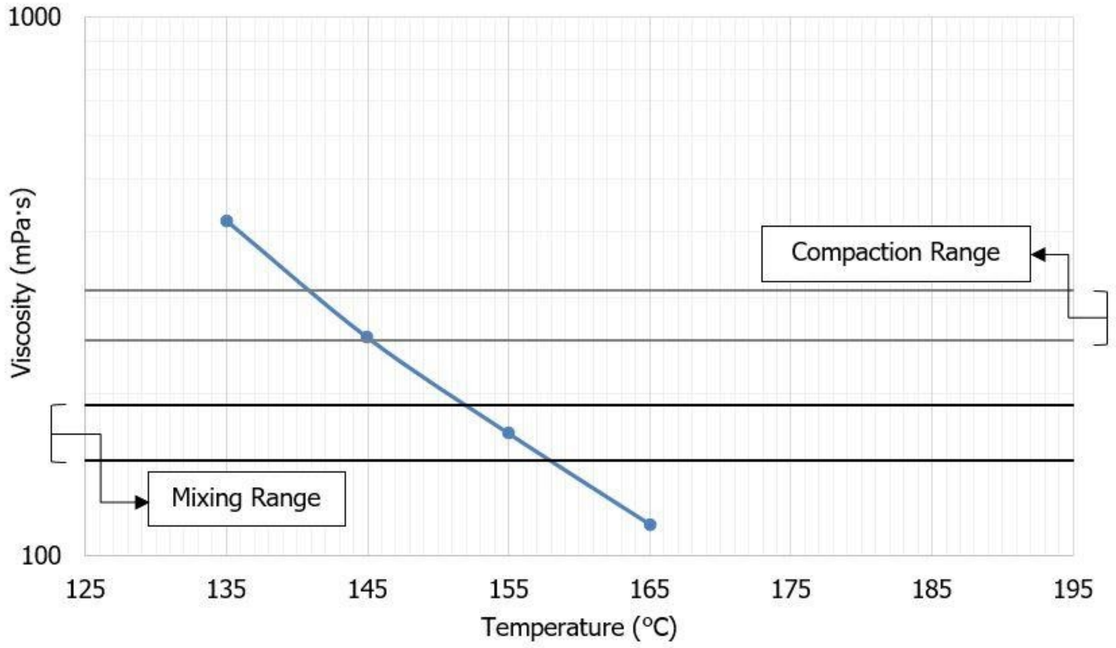

Figure 6. Mixing and compaction viscosity and temperature range for binder PG 64-22

1.2.2. Asphaltenes-modified binders: preparation and rheology test

For this phase of the research project, the binder PG 64-22 from source A was chosen as the base binder to modify by the addition of asphaltenes. The reason for choosing this binder was to have a soft binder as the baseline to be able to observe the impact of asphaltenes on binder properties. The same investigation will be done on asphalt cements derived from Alberta oil sand' bitumen after receiving the material. Asphaltenes material was received from CNOOC in chunks, as is shown in Figure 7. In order to make the asphaltenes easier to mix with an asphalt binder, the chunks were turned into powder and then sieved using a No. 100 sieve, with a mesh of 150 µm. The CNOOC asphaltenes in powder form is shown in Figure 7. The sieved asphaltenes powder was then mixed with the binder at 140 °C using a high shear mixer at a speed of 2000 rpm for 60 min. Higher temperatures were not chosen to avoid asphalt binder ageing at this stage. The high shear mixer used is shown in Figure 8. To modify the base binder 3, 6, 9, 12, 15, 18, and 20% of asphaltenes (by weight) were added to the PG 64-22 binder.

Table 4. Mixing and compaction temperature range of binders

No.	Binder	Mixing Temperature Range (°C)	Compaction Temperature Range (°C)
1	PG 64-22	152-158	141-145
2	PG 70-28 (Air-blown)	160-166	149-154
3	EME Pen 20/30	164-170	153-158
4	Vacuum Tower	172-178	160-165
5	Cold Lake	168-175	157-162
6	Pitch	184-189	174-178
7	Q8 Pen 5/15	184-191	172-177
8	Q8 Pen 15/25	176-182	163-169
9	Q8 Pen 20/30	169-175	157-163
10	Q8 Pen 35/50	160-166	149-154
11	Q8 Pen 50/70	156-163	145-149

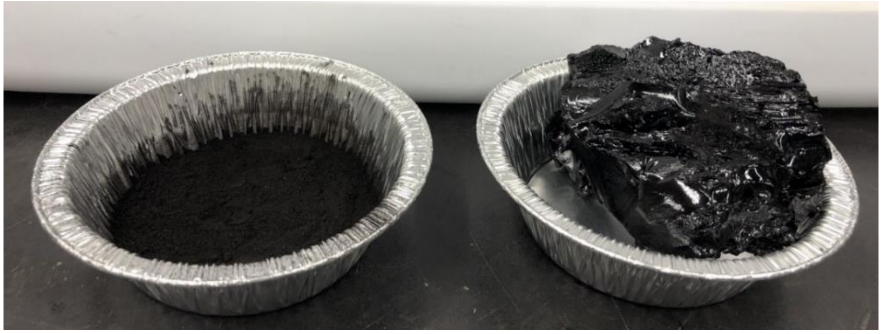

Figure 7. Asphaltenes from CNOOC, chunk form (left), powder form after passing through a No. 100 sieve (right)

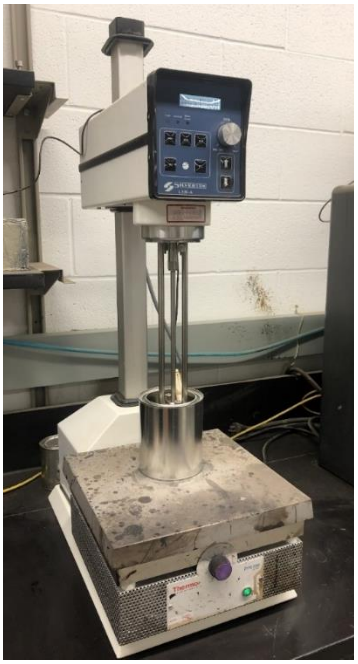

Figure 8. High shear mixer

1.2.2.1. **Dynamic Shear Rheometer**

Using the procedures described in Section 1.2.1.1 and 1.2.1.2, rheology tests were conducted on the PG64-22 binder modified with different amounts of asphaltenes. The results are shown in Table 5.

Table 5. High PG Grade for PG 64-22 modified with different amounts of asphaltenes

Sample No.	Binder	High PG grade (Unaged Binder)	High PG grade (RTFO-Aged Binder)	Continuous high PG Grade	Standard high PG Grade
1	PG 64-22	70.5	71.1	70.5	70
12	PG 64-22 +3% Asph	73.9	75.1	73.9	70
13	PG 64-22 +6% Asph	76.5	78.2	76.5	76
14	PG 64-22 +9% Asph	81.3	81.1	81.1	76
15	PG 64-22 +12% Asph.	82.9	84.6	82.9	82
16	PG 64-22 +15% Asph.	85.9	87.6	85.9	82
17	PG 64-22 +18% Asph.	88.0	90.3	88.0	88
18	PG 64-22 +20% Asph.	89.9	92.6	89.9	88

As can be seen from Table 5, with higher asphaltenes content, the high PG grade of the PG 64-22 binder increases, which is an indicator of increasing binder stiffness. This trend is shown in Figure 9.

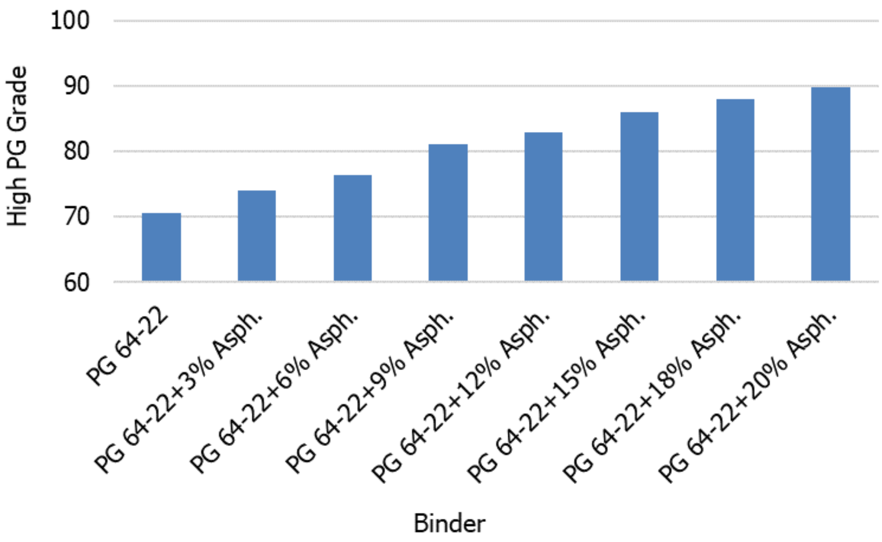

Figure 9. High PG Grade of PG 64-22 binder with different asphaltenes content (% by weight)

According to the results depicted in Table 5, an addition 1% by weight of asphaltenes to the PG 64-22 binder increases the high PG grade by 0.97°C on average, which is comparable with the improvement caused by some other well-known additives used for enhancing high temperature properties of asphalt binder, including crumb rubber (Ghasemirad et al., 2017).

The mass loss during RTFO-aging was also measured for the PG 64-22 binder samples modified with different amounts of asphaltenes. The results of these tests can be found in Table 6.

Table 6. Mass loss percentages for base and asphaltene-modified PG64-22 binder

No.	Binder	Mass Loss (%)	Mass Loss 1%?
1	PG 64-22	0.08	Yes
12	PG 64-22 +3% Asph.	0.10	Yes
13	PG 64-22 +6% Asph.	0.11	Yes
14	PG 64-22 +9% Asph.	0.13	Yes
15	PG 64-22 +12% Asph.	0.15	Yes
16	PG 64-22 +15% Asph.	0.14	Yes
17	PG 64-22 +18% Asph.	0.14	Yes
18	PG 64-22 +20% Asph.	0.13	Yes

1.2.2.2. High-temperature viscosity

To ensure that the binders with varying asphaltenes content meet the Superpave workability criterion, the viscosities of these binders were measured at 135°C. The results of this test can be found in Table 7. To highlight the effect of asphaltenes content on the viscosity of the base binder, the viscosity of the neat PG 64-22 binder is also included in this table. An increase in the viscosity of the PG 64-22 binder due to addition of asphaltenes is apparent from these results. Moreover, even with the addition of 20% asphaltenes (by weight) to the PG 64-22 binder, the workability criterion still remains less than 3 Pa·s, i.e., it still meets the criterion set out in AASHTO M320.

Based on Table 7, it can be seen that, on average, the addition of 1% of asphaltenes to the base binder causes the rotational viscosity at 135°C to increase by approximately 0.05 Pa·s

The viscosity of binders was investigated over a wider range of high temperatures to calculate the mixing and compaction temperatures of asphalt mixtures composed using the different asphaltenes-modified PG 64-22 binder samples. The results are given in Table 8.

Table 7. High-temperature viscosity of base and asphaltenes modified binders

No.	Binder	Rotational viscosity at 135°C (Pa·s)	Less than 3 Pa·s?
1	PG 64-22	0.42	Yes
12	PG 64-22 +3% Asph.	0.57	Yes
13	PG 64-22 +6% Asph.	0.63	Yes
14	PG 64-22 +9% Asph.	0.72	Yes
15	PG 64-22 +12% Asph.	0.84	Yes
16	PG 64-22 +15% Asph.	0.98	Yes
17	PG 64-22 +18% Asph.	1.25	Yes
18	PG 64-22 +20% Asph.	1.38	Yes

Table 8. Mixing and compaction temperature range of base and asphaltenes modified binder

No.	Binder	Mixing Temperature Range (°C)	Compaction Temperature Range (°C)
1	PG 64-22	152-158	141-145
12	PG 64-22 +3% Asph	158-164	147-152
13	PG 64-22 +6% Asph	161-167	149-154
14	PG 64-22 +9% Asph	164-170	152-157
15	PG 64-22 +12% Asph.	167-173	154-160
16	PG 64-22 +15% Asph.	169-175	158-163
17	PG 64-22 +18% Asph.	173-179	161-166
18	PG 64-22 +20% Asph.	177-184	165-170

An increase in the viscosity of a binder containing added asphaltenes results in an increase of the mixing and compaction temperature for the asphalt mixture that it is used in, as can be seen in Table 8. According to this table, an addition of 1% by weight of asphaltenes powder to the base binder (PG 64-22) increases the mixing and compaction temperature by 1.36°C and 1.29°C, respectively (on average)

1.3 Binders Used for Investigation

The binders used for investigation in this part are hard binders, asphaltenes-modified PG 70-22 B and Alberta (AB) oil-sand-based binders. PG 70-22 and PG 76-28 (air-blown) were obtained from source A. EME Pen 20/30 was obtained from Source B. Two binders (Vacuum Tower and Pitch) were obtained from source C. The remaining binder (X) was sourced from source D.

1.3.1. Hard Grade Binders

1.3.1.1. PG Grading

PG grading was conducted to evaluate the performance of binders obtained from various sources at different temperatures. PG grading determination was conducted through three main stages: high temperature, intermediate temperature, and low temperature. To grade a binder at high temperatures, a dynamic shear rheometer (DSR) was used to test unaged and aged binders using a Rotational Thin Film Oven (RTFO). Grading at intermediate temperatures was carried out using a DSR to test aged binders by Pressure Aging Vessel (PAV). Finally, at low temperatures, PG grading was conducted using a bending beam rheometer (BBR) to evaluate a PAV-aged binder.

High PG Grade Temperature: The high PG grade is the highest temperature a binder can resist without pavement experiencing permanent deformation under a standard load. The performance grading of the hard grade binders at high temperatures is presented in Table 9. Based on the test results, all binders have high PG grades greater than 76°C, except for PG 70-22 (A) and Q8 Pen 50/70. To investigate binder modification effects with asphaltenes, PG 70-22 (A) was selected to be used as a base binder for modification with asphaltenes.

Intermediate PG Grade Temperature: This temperature is the temperature that asphalt cracking due to fatigue occurs. The results obtained from this test are presented in Table 10. It was found that pitch binder has the highest intermediate PG grade (67°C), while PG 70-22 has the lowest intermediate PG grade of 22°C, meaning that this binder has the best fatigue resistance.

Low PG Grade Temperature: The low PG grade is a measure of the cracking performance of asphalt binders at low temperatures, as determined by the standard Bending Beam Rheometer (BBR) test. The results of the low-temperature PG grading are presented in Table 11. It was found that PG 70-22 has the best low-temperature performance, with a low PG grade of -22°C. The pitch binder was found to fail low PG grading at all PG test temperature ranges.

Final PG Grade Temperature: The final PG grade is the standard actual PG grade determined for the binders. The final PG grading for the binders is reported in Table 12. Based on the PG criteria tested, the binder PG 70-22 was found to be the softest compared to the others tested.

Table 9. High PG grading results for hard grade binders

No.	**Binder**	**Supplier**	**High PG Grade (Unaged Binder) °C**	**High PG Grade (RTFO-Aged Binder) °C**	**Continuous High PG Grade °C**	**Standard High PG Grade °C**	**Satisfied minimum of 82℃?**
1	PG 70-22	A	70.5	71.1	70.5	70	No
2	PG 76-28[1] (Air-blown)	A	78.7	83.0	78.7	76	No
3	EME Pen 20/30	B	84.0	83.7	83.7	82	Yes
4	Vacuum Tower	C	88.9	90.2	88.9	88	Yes
5	Cold Lake	D	86.1	85.9	85.9	82	Yes
6	Pitch	C	106.5	104.3	104.3	100	Yes
7	Q8 Pen 5/15	E	96.5	94.3	94.3	94	Yes
8	Q8 Pen 15/25	E	89.1	85.9	85.9	82	Yes
9	Q8 Pen 20/30	E	84.4	82.4	82.4	82	Yes
10	Q8 Pen[1] 35/50	E	77.8	76.0	76.0	76	No
11	Q8 Pen[1] 50/70	E	73.4	71.7	71.7	70	No

[1] Binders with high PG grade less than 82 excluded from further testing

Table 10. Intermediate PG grading results for hard grade binders

No.	**Binder**	**Continuous Int. PG Grade (PAV-aged Binder), °C**	**Standard Int. PG Grade, °C**
1	PG 70-22	19.2	22
3	EME Pen 20/30	35.7	37
4	Vacuum Tower	41.1	43
5	Cold Lake	33.5	34
6	Pitch	64.4	67
7	Q8 Pen 5/15	48.2	49
8	Q8 Pen 15/25	39.6	40
9	Q8 Pen 20/30	36.7	37

Table 11. Low PG grading results for hard grade binders

No.	Binder	Low PG grade (m-value), °C	High PG grade (Stiffness), °C	Continuous low PG Grade, ℃	Standard low PG Grade, ℃
1	PG 70-22	-27.2	-27.1	-27.1	-22
3	EME Pen 20/30	-15.5	-19.7	-15.5	-10
4	Vacuum Tower	-9.7	-16.9	-9.7	-4
5	Cold Lake	-18.4	-20.0	-18.4	-16
6	Pitch	N/A			
7	Q8 Pen 5/15	-8.7	-7.9	-7.9	-4
8	Q8 Pen 15/25	-15.0	-15.0	-15.0	-10
9	Q8 Pen 20/30	-16.5	-16.7	-16.5	-16

The final PG grading results for the hard grade binders, as well as the base binder, PG 70-22 from A, are reported in Table 12. It should be noted that in the standard PG grading system, the standard high PG grade usually starts at 46 °C and increases in increments of 6 °C. In order to determine the standard high PG grade, the continuous grade would be decreased to the nearest standard high PG grade. On the other hand, the standard low PG grade generally starts at -10 °C and decreases in 6 °C steps. As it is shown in the table, to figure out the standard low PG grade, the continuous grade would be increased to the nearest standard high PG grade.

Table 12. Final and standard PG grading for hard grade binders

No.	Binder	Continuous High PG Grade, °C	Continuous Int. PG Grade, °C	Continuous Low PG Grade, °C	Standard PG Grade
1	PG 70-22	70.5	19.2	-27.1	70-22
3	EME Pen 20/30	83.7	35.7	-15.5	82-10
4	Vacuum Tower	88.9	41.1	-9.7	88-4
5	Cold Lake	85.9	33.5	-18.4	82-16
6	Pitch	104.3	64.4	N/A	100-N/A
7	Q8 Pen 5/15	94.3	48.2	-7.9	94-4
8	Q8 Pen 15/25	85.9	39.6	-15.0	82-10
9	Q8 Pen 20/30	82.4	36.7	-16.5	82-16

1.3.1.2. Mass Loss, Viscosity and Mixing/Compaction temperatures

By weighing the sample before and after RTFO-aging, the mass loss of each of the binders was calculated as a measure to check for binders with excessive volatiles. The mass loss of the binders was found to be between 0.01% and 0.43%: that is, all binders tested had a mass loss of less than 1%, as required by Superpave.

A high-temperature viscosity test was conducted to ensure adequate workability of asphalt mix as well as to estimate the mixing and compaction temperatures of the asphalt binders. The viscosities of the binders were found to be between 0.42 Pa·s and 2.05 Pa·s, with the exception of the pitch binder, which had a viscosity of 3.21 Pa·s. This indicates that it is only the Pitch binder that did not pass the workability criterion (i.e., less than 3.0 Pa·s viscosity at 135°C).

The mixing and compaction temperatures for the binders are found to be in the range of 152 - 189°C and 141 -178°C, respectively. The PG 70-22 binder was found to have the most adequate mixing and compaction temperature ranges as both values are found to be less than 177 °C. Mixing and compaction temperatures greater than 177 °C lead to binder thermal degradation and should not be used.

1.3.2. Asphaltenes Modification

Due to the limited availability of Alberta oil-sand-based binders, it was decided to investigate the effect of the addition of asphaltenes on other similar binders first. Thus, for this objective, the PG 70-22 binder from A was selected as the base binder to be modified with asphaltenes obtained from CNOOC. In addition to considerations of availability, PG 70-22 was selected based on the performance metrics reported earlier in this report.

A series of asphaltenes-modified binders were prepared by adding CNOOC asphaltenes to the PG 70-22 binder in increments of 3% (by the weight of binder), with the exception of the last mix, for which the asphaltenes content was increased from 18% to 20%, giving asphaltene-modified binders ranging from 0% to 20%. The increment of 3% asphaltenes content was selected in order to observe a meaningful improvement in the performances of the modified binders.

1.3.2.1. PG Grading of PG 70-22 Asphaltenes-Modified Binder

High PG Grade Temperature: The results for high PG grading of each asphaltenes-modified binder (3-20% asphaltenes) compared to high PG grading of the base binder (PG 70-22) are presented in Table 13. It was found that the high PG grade increased with increasing asphaltenes content. Since the minimum acceptable high PG grade for high modulus asphalt application is 82°C, the asphaltenes-modified binders containing less than 12% asphaltenes were found unsuitable and were excluded from further testing.

Table 13. High PG grading results of modified PG 70-22

No.	Binder + asphaltenes content (% wt of binder)	High PG grade (Unaged Binder)℃	High PG grade (RTFO-Aged Binder)℃	Continuous high PG Grade℃	Standard high PG Grade℃
1	PG 70-22	70.5	71.1	70.5	70
12	PG 70-22 +3% Asph	73.9	75.1	73.9	70
13	PG 70-22 +6% Asph	76.5	78.2	76.5	76
14	PG 70-22 +9% Asph	81.3	81.1	81.1	76
15	PG 70-22 +12% Asph.	82.9	84.6	82.9	82
16	PG 70-22 +15% Asph.	85.9	87.6	85.9	82
17	PG 70-22 +18% Asph.	88.0	90.3	88.0	88
18	PG 70-22 +20% Asph.	89.9	92.6	89.9	88

Intermediate PG Grade Temperature: The results of the intermediate PG grading for the remaining binders (containing 12, 15, 18, and 20% asphaltenes by weight of binder) are shown in Table 14. It was found that asphaltenes content affects the intermediate temperature for the PG 70-22 binder. The addition of asphaltenes increases the intermediate PG grade temperatures; this improvement may result in lower resistance to fatigue-induced damage during their service life.

Table 14. Intermediate PG grading results for modified PG 70-22 binder

No.	Binder	Continuous Int. PG Grade (PAV-aged Binder), ℃	Standard Int. PG Grade, ℃
1	PG 70-22	19.2	22
15	PG 70-22 +12% Asph.	29.0	31
16	PG 70-22 +15% Asph.	31.5	34
17	PG 70-22 +18% Asph.	34.5	37
18	PG 70-22 +20% Asph.	35.9	37

Low PG Grade Temperature: The results of low PG grade testing are presented in Table 15. It was found that the low-temperature PG grade of PG 70-22 increases with increasing asphaltenes content. The reduction in the low PG grade temperatures of asphaltenes-modified binders might be attributed to an excessive increase in stiffness due to the addition of asphaltenes, resulting in less flexible mixtures at low temperatures. The increase in low PG grade temperatures indicates that the susceptibility of the modified asphalt binders to low-temperature cracking might increase.

Table 15. Low PG grading results for modified PG 70-22 binder

No.	Binder	Low PG grade (m-value), ℃	Low PG grade (Stiffness), ℃	Continuous low PG Grade, ℃	Standard low PG Grade, ℃
1	PG 70-22	-27.2	-27.1	-27.1	-22
15	PG 70-22 +12% Asph.	-21.8	-23.3	-21.8	-16
16	PG 70-22 +15% Asph.	-19.6	-22.1	-19.6	-16
17	PG 70-22 +18% Asph.	-17.4	-21.1	-17.4	-16
18	PG 70-22 +20% Asph.	-16.6	-20.3	-16.6	-16

Final PG Grade Temperature: The PG grading results for PG 70-22 asphaltenes-modified binder are presented in Table 16. It was found that the maximum grade span achieved for PG 70-22 (A) binder modified with asphaltenes was PG 88-16. This result was obtained for asphaltenes at 18% and 20% by weight of the binder.

Table 16. Final PG grading for modified PG 70-22 binder

No.	Binder	Continuous High PG Grade℃	Continuous Low PG Grade℃	Continuous Int. PG Grade℃	Standard PG Grade
1	PG 70-22	70.5	-27.1	19.2	70-22
15	PG 70-22 +12% Asph.	82.9	-21.8	29.0	82-16
16	PG 70-22 +15% Asph.	85.9	-19.6	31.5	82-16
17	PG 70-22 +18% Asph.	88.0	-17.4	34.5	88-16
18	PG 70-22 +20% Asph.	89.9	-16.6	35.9	88-16

1.3.2.2. **Mass loss, Viscosity and Mixing/Compaction Temperatures**

The mass loss results of PG 70-22 asphaltenes-modified binders were determined and found to be in a range of 0.43% to 0.80%. These values satisfy the requirement of less than 1% specified by Superpave.

The viscosity results for PG 70-22 binder modified with asphaltenes were found to be 0.42 Pa·s and 1.38 Pa·s. It was also determined that the viscosity increases with increasing asphaltenes content. However, for all asphaltenes contents studied, the workability criterion for paving applications was satisfied, i.e., the viscosity was less than 3 Pa·s.

The mixing and compaction temperatures for asphaltenes-modified PG 70-22 binders are in the range of 152 to 184°C and 141 to 170°C, respectively. It was found that binders containing asphaltenes have higher mixing and compaction temperatures compared to the base binder. This can be attributed to the increase in viscosity or stiffness of the modified binders, which requires higher temperatures to make the binder fluid enough for mixing and compacting.

1.3.3. **Alberta Oil-sands-Based Binders**

The Alberta oil-sand based binders acquired and used for this aspect of the research were distilled at a temperature of 460 ℃. For the purposes of this report, alphabetic system used to name the binder base on their sources. The performance results for the PG 70-22 binder obtained from A were used for comparison alongside the results presented for the Alberta oil-sand-based binders in this section.

1.3.3.1. **PG Grading**

High PG Grade Temperature: Results of the high-temperature PG grading of the Alberta oil-sand-based binders are presented in Table 17. It was found that the binder D is the stiffest binder, with a high PG grade of 82°C. Considering this high PG grade, binder D is suitable for high modulus asphalt application, even without modification.

Table 17. High PG grading results for AB oil-sand-based binders

No.	Binder	High PG grade (Unaged Binder), °C	High PG grade (RTFO-Aged Binder), °C	Continuous high PG Grade, °C	Standard high PG Grade, °C
1	A (PG 70-22)	70.5	71.1	70.5	70
21	F	77.9	77.2	77.2	76
22	G	70.1	69.0	69.0	64
23	H	83.8	82.6	82.6	82
24	I	75.1	75.2	75.1	70

Intermediate PG Grade Temperature: The intermediate PG grade temperatures obtained for the AB oil-sand-based binders are presented in Table 18. As can be seen from this table, binder G has the best performance for intermediate temperatures, with the lowest intermediate PG grade. Its results are the closest to A. On the other hand, binder H was found to have the highest PG grade for this temperature range.

Table 18. Intermediate PG grading results for Alberta oil-sand-based binders

No.	Binder	Continuous Int. PG Grade (PAV-aged Binder) ℃	Standard Int. PG Grade ℃
1	A	19.2	22
21	F	26.0	28
22	G	17.7	19
23	H	33.5	34
24	I	30.7	31

Low PG Grade Temperature: The results for low PG grading of the binders are presented in Table 19. From these results, it can be seen that F and G binders were determined to have the best low PG grade temperature (-22°C).

Table 19. Low PG grading results for Alberta oil-sand-based binders

No.	Binder	Low PG grade (m-value), °C	Low PG grade (Stiffness), °C	Continuous low PG Grade, °C	Standard low PG Grade, °C
1	A	-27.2	-27.1	-27.1	-22
21	F	-24.1	-23.9	-23.9	-22
22	G	-27.8	-26.6	-26.6	-22
23	H	-19.1	-18.3	-18.3	-16
24	I	-20.7	-18.9	-18.9	-16

Final PG Grade: Final PG grading results for Alberta oil-sand-based binders results are shown in Table 20. It was found that the H and F binders, which exhibit the best performance at low and high temperatures, are the stiffest binders compared to the other Alberta oil-sand-based binders. Binder I seems to be the softest binder and with the low PG grade of -18.9, not a good option for modification and being used in high modulus base course.

Table 20. Final PG grading results for Alberta oil-sand-based binders

No.	Binder	Continuous High PG Grade℃	Continuous Low PG Grade℃	Continuous Int. PG Grade℃	Standard PG Grade℃
1	A	70.5	-27.1	19.2	70-22
21	F	77.2	-23.9	26.0	76-22
22	G	69.0	-26.6	17.7	64-22
23	H	82.6	-18.3	33.5	82-16
24	I	75.1	-18.9	30.7	70-16

1.3.3.2. Mass Loss, Viscosity and Mixing/Compaction Temperatures of Alberta Oil-sand-based Binders

The mass loss results for Alberta oil-sand-based binders were found to be in the range of 0.24% to 0.53%. This indicates that all the binders met the criterion for mass loss of less than 1% specified by Superpave.

The results for the viscosity of Alberta oil-sand-based binders were found to range from 0.42 Pa·s to 0.87 Pa·s. This confirms that all the binders satisfied the minimum viscosity requirement of lower than 3 Pa·s.

The mixing and compaction temperatures for the Alberta oil-sand-based binders were found to be in the range of 161°C to 174°C and 149°C to 161°C, respectively. These temperature ranges are desirable and adequate for mixing and compaction.

1.3.4. Choice of Alberta Oil-sand-based Binders for Asphaltenes Modification

After obtaining all PG grade results for Alberta oil-sand-based binders, the next step was the modification of the most promising Alberta oil-sand-based binders with asphaltenes. This testing is to identify some high-performance binders suitable for use in high modulus asphalt concrete.

Based on the fact that asphaltenes modification was previously observed to cause a slight decrease in the low-temperature performance of the binder, the most promising binders for modification with asphaltenes and further testing was determined to be the binder G and F. This is due to the fact that these two binders showed the best performance at low temperatures, as well as satisfactory high-temperature performance.

1.3.4.1. PG Grading of Alberta Oil-sand-based Binders Modified with Asphaltenes

High PG Grade Temperature: The results for high PG grading of Alberta oil-sand-based binders modified with asphaltenes are presented in Table 21. These results are again compared with the binder A modified with asphaltenes. It was found that the performance of the binder F containing 9% asphaltenes is similar to both the binder G with 12% asphaltenes and binder A with 15% asphaltenes. The noticeable increase in high PG grade with the addition of asphaltenes indicates the effectiveness of asphaltenes in improving the performance of Alberta based binders at high temperatures.

Table 21. High PG grading results of modified Alberta oil-sand-based binders

No.	Binder	High PG grade (Unaged Binder)℃	High PG grade (RTFO-Aged Binder)℃	Continuous high PG Grade℃	Standard high PG Grade℃
1	A +0% Asph	70.5	71.1	70.5	70
14	A +9% Asph	81.3	81.1	81.1	76
15	A +12% Asph.	82.9	84.6	82.9	82
16	A +15% Asph.	85.9	87.6	85.9	82
25	F + 9% Asph.	86.7	87.4	86.7	82
26	G + 12% Asph.	82.6	86.1	82.6	82
27	G + 15% Asph.	84.4	85.6	84.4	82

Intermediate PG Grade Temperature: The PG grade results for the Alberta oil-sand-based binders at intermediate temperatures are presented in Table 22. It was found that asphaltenes-modified Alberta oil-sand-based binders have comparable performance to corresponding asphaltenes-modified A binders at intermediate temperatures.

Table 22. Intermediate PG grading for modified Alberta oil-sand-based binders

No.	Binder	Continuous Int. PG Grade (PAV-aged Binder), °C	Standard Int. PG Grade, °C
1	A	19.2	22
15	A +12% Asph.	29.0	31
16	A +15% Asph.	31.5	34
25	F + 9% Asph.	35.2	37
26	G + 12% Asph.	30.4	31
27	G + 15% Asph.	30.8	31

Low PG Grade Temperature: The results of low-temperature PG grading for Alberta oil-sand-based binders are presented in Table 23. It was found that testing of both the modified Alberta oil-sand-based based binders and A binders at all asphaltenes content resulted in the same standard low-temperature PG grade of -16℃. This indicates that all the asphaltenes-modified binders tested are expected to have similar performance under low-temperature conditions, regardless of the binder source.

Table 23. Low-temperature PG grading results for asphaltenes-modified binders

No.	Binder	Low PG grade (m-value), °C	Low PG grade (Stiffness), °C	Continuous low PG Grade, °C	Standard low PG Grade, °C
1	A	-27.2	-27.1	-27.1	-22
15	A +12% Asph.	-21.8	-23.3	-21.8	-16
16	A +15% Asph.	-19.6	-22.1	-19.6	-16
25	F+ 9% Asph.	-17.8	-20.1	-17.8	-16
26	G+ 12% Asph.	-21.2	-22.1	-21.2	-16
27	G+ 15% Asph.	-21.0	-21.9	-21.9	-16

1.3.4.2. Mass Loss, Viscosity and Mixing/Compaction Temperatures

The mass loss for asphaltenes-modified Alberta oil-sand-based binders was found to be in the range of 0.38% to 0.58%. This shows that all the binders tested satisfied the requirement for mass loss of less than 1%.

The viscosity results for asphaltenes-modified Alberta oil-sand-based binders ranged from 0.84 Pa·s to 1.15 Pa·s. This indicates that all the binders satisfied the minimum viscosity requirement of lower than 3 Pa·s.

The mixing and compaction temperatures for asphaltenes-modified Alberta oil-sand-based binders were found to be in the range of 170°C to 180°C and 158°C to 167°C, respectively.

1.4 SARA Test Results

SARA analysis is used to determine the relative percentages of asphalt constituents: namely, asphaltenes and maltenes. Maltene can be further separated into saturates, aromatics, and resins. These components are often abbreviated using the acronym SARA. The asphaltenes content of asphalt binders is very important, as it determines the overall physical, chemical, and rheological performance of the asphalt binders, as well as their mechanical performance. SARA test results obtained for selected asphaltenes samples (CNOOC and VCTek), as well as A, asphaltenes-modified A and Alberta oil-sand-based binders are presented in Table 24. It was found that, as expected, there was an increase in asphaltenes content for all asphaltenes-modified binders with respect to the unmodified binder. The chemical change (confirmed by a decrease in maltene content with a corresponding increase in asphaltenes content) in the modified binders indicates an improvement in the stiffness of the binders.

Table 24. SARA test results for asphaltenes and selected binders

SARA Content Sample	Saturates	Aromatic	Resin	Asphaltenes
CNOOC Asphaltenes	6.85	9.68	3.84	79.62
VCTek Asphaltenes	2.35	7.30	6.62	83.63
A	25.41	20.36	31.58	22.59
A +12% Asph.	21.63	20.94	24.75	32.17
A+18% Asph.	18.83	20.25	25.23	35.16
A+20% Asph.	17.93	19.74	21.57	39.76
F	11.87	33.6	33.5	21.01
G	26.13	17.76	36.32	19.76
H	19.42	23.65	38.52	18.37
I	22.96	28.33	28.58	19.97

1.5 Mixture Design

For investigating the performance of asphaltenes-modified binders and binders derived from Alberta oil-sands in high modulus asphalt mixtures, the binders with minimum performance grades of 82 at high temperature and -16 at low temperature were selected. The final binders chosen for preparation of high modulus base course mixes were G modified with 15% asphaltenes, F modified using 9% asphaltenes and unmodified H.

1.5.1. Aggregate Gradation

Several aggregate gradations from previous literature and standard specifications were reviewed for the selection of the final gradation envelope. As the main focus of this research is on high modulus base course applications, an appropriate gradation with a nominal maximum aggregate size (NMAS) of 19 mm was selected. The finalized gradation curve is shown in Figure 10.

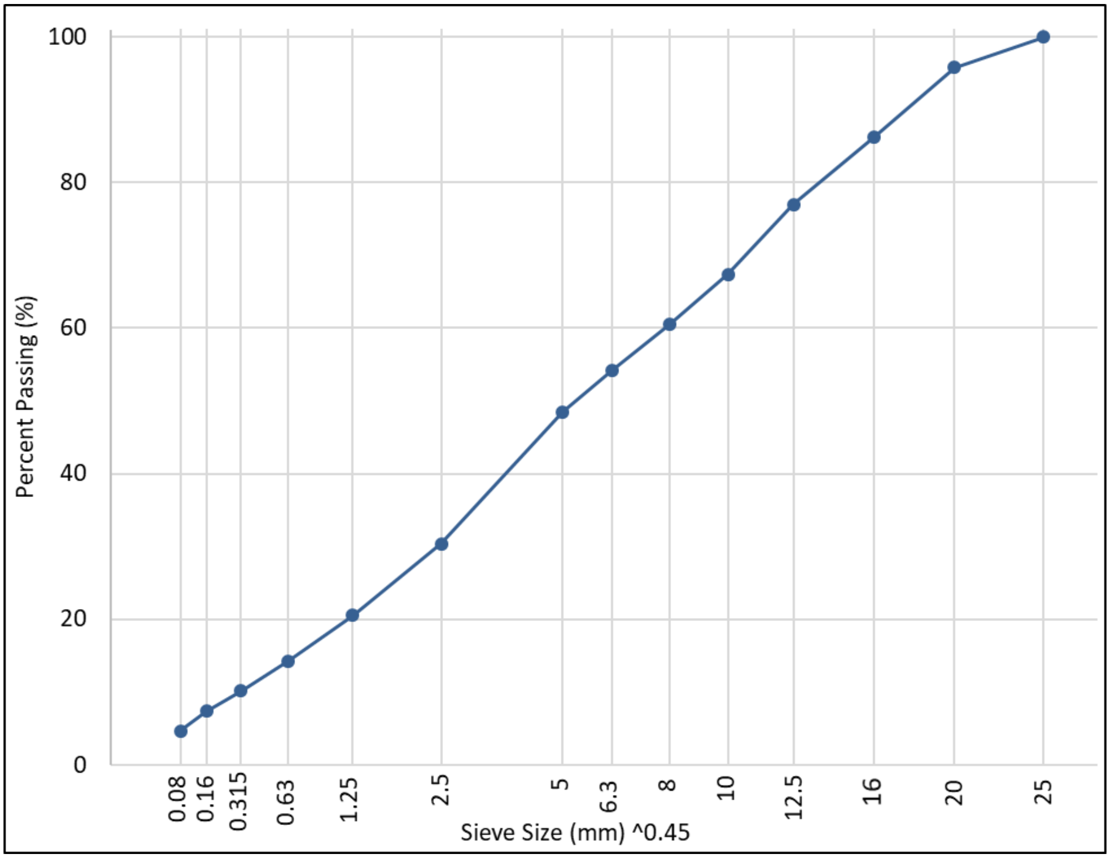

Figure 10. Selected aggregate grain size distribution for high modulus base course

1.5.2. Asphalt Mixture Aggregate Properties

The specific gravity of the coarse and fine aggregates, water absorption and Los Angeles abrasion test results are presented in Table 25. It was found that both the coarse and fine aggregates satisfy the requirements specified for high modulus asphalt preparation (Denneman et al., 2011). Also, the Los Angeles abrasion value for the coarse aggregates was found to be within the specified recommended range.

Table 25. Aggregate properties

1. SPECIFIC GRAVITY RESULTS			
	Bulk Specific Gravity	Bulk Specific Gravity (SSD)	Apparent Specific Gravity
Coarse Aggregate (≥4.75 mm)	2.643	2.652	2.666
Fine Aggregate (<4.75 mm)	2.590	2.600	2.617
2. WATER ABSORPTION RESULTS			
	Water Absorption (%)	Criterion	
Coarse Aggregate (≥4.75 mm)	0.3	≤1.0	
Fine Aggregate (<4.75 mm)	0.4	≤1.5	
3. LOS ANGEL ABRASION TEST RESULTS			
	Value Obtained(%)	Standard Range (%)	
Coarse Aggregate (≥9.5 mm)	23	10 - 45	

SSD: Saturated Surface Dry

1.5.3. **Binder Content**

The calculation of the binder content for the high modulus asphalt concrete preparation was done using the method outlined by Dennemen et al. (2011). The binder content for mixture design was calculated using the richness modulus K and the type of aggregate gradation used. Based on these parameters, the minimum binder content was found to be 5% by weight of the whole mixture of binder and aggregates.

1.6 **Mixture Design**

1.6.1. **Aggregate Gradation**

Several aggregate gradations from previous literature and standard specifications were considered for the selection of the final gradation envelope. For high modulus asphalt concrete mixtures, different countries and regions, including France, South Africa, United Kingdom, and Australia, have developed various gradation envelopes to standardize the mixture design procedure. According to European specification, dynamic modulus of high modulus asphalt (HMA) mixes should meet 14,000 MPa at 15˚C temperature and under 10 Hz loading frequency.

To assess the minimum binder performance grade requirements needed to attain a dynamic modulus of at least 14,000 MPa at a temperature of 15 ℃ and a loading frequency of 10 Hz, aggregate gradation, with a nominal maximum aggregate size (NMAS) of 19 mm was selected. Volumetric parameters were taken from the same references. This aggregate gradation in the company of a hard grade binder has proved to provide superior performance with regards to dynamic modulus values, as compared to others. The target gradation, as well as French envelopes and maximum density curves, are shown in Figure 11. As can be seen, the target gradation almost fits into the French envelopes.

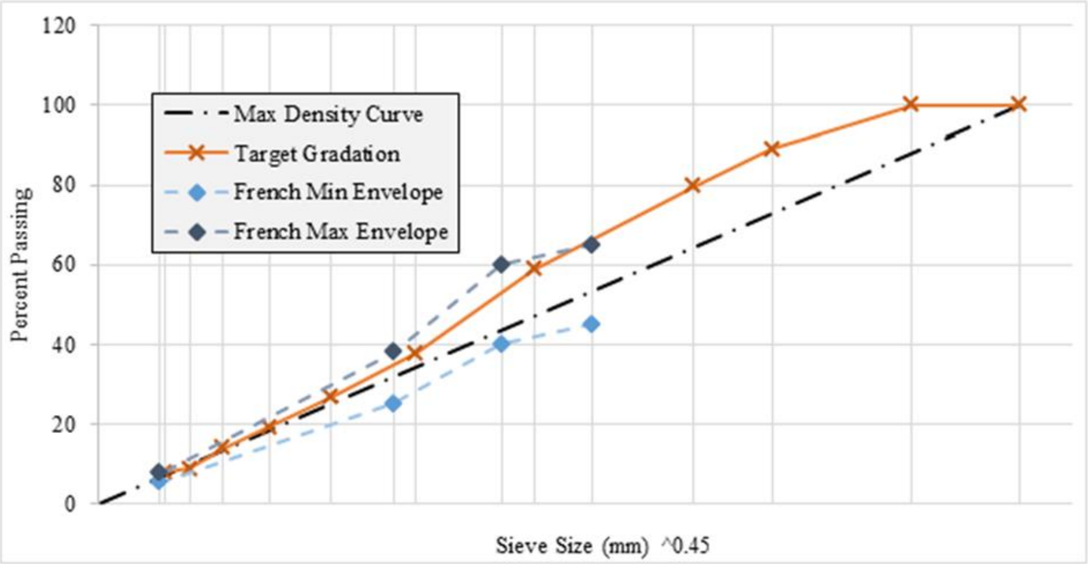

Figure 11. Selected aggregate grain size distribution for high modulus base course

1.6.2. Mixture Volumetric Properties

The volumetric properties required for the high modulus asphalt base course are presented in Table 26. These required parameters were obtained from the mechanistic-empirical pavement design guide (MEPDG), which was developed under the National Cooperative Highway Research Program (NCHRP). MEPDG level 3 was used according to the performance grade of binder based on Superpave.

Table 26. Volumetric properties of HMAC mixes with NMAS=19 mm

Property	Value
Binder grade	PG 88-16
Design air void (%)	1.5
VMA (%)	15.0
VFA (%)	90.0
Effective binder content by volume (%)	13.5

1.6.3. Aggregate Properties

The specific gravity of the coarse and fine aggregates, water absorption and Los Angeles abrasion test results are presented in Table 27. It was found that both the coarse and fine aggregates satisfy the requirements specified for high modulus asphalt preparation. Also, the Los Angeles abrasion value for the coarse aggregates was found to be within the specified recommended ranges.

Table 27. Aggregate properties

<table>
<tr><th colspan="5">1. SPECIFIC GRAVITY RESULTS</th></tr>
<tr><td>Aggregate Type</td><td>Aggregate Portion (%)</td><td>Bulk Specific Gravity</td><td>Bulk Specific Gravity (SSD)</td><td>Apparent Specific Gravity</td></tr>
<tr><td>Coarse Aggregate (≥4.75 mm)</td><td>39.7</td><td>2.618</td><td>2.652</td><td>2.666</td></tr>
<tr><td>Fine Aggregate (<4.75 mm)</td><td>60.3</td><td>2.502</td><td>2.600</td><td>2.617</td></tr>
<tr><th colspan="5">2. WATER ABSORPTION RESULTS</th></tr>
<tr><td colspan="2"></td><td colspan="2">Water Absorption (%)</td><td>Criterion</td></tr>
<tr><td colspan="2">Coarse Aggregate (≥4.75 mm)</td><td colspan="2">0.3</td><td>≤1.0</td></tr>
<tr><td colspan="2">Fine Aggregate (<4.75 mm)</td><td colspan="2">0.4</td><td>≤1.5</td></tr>
<tr><th colspan="5">3. LOS ANGEL ABRASION TEST RESULTS</th></tr>
<tr><td colspan="2"></td><td colspan="2">Value Obtained (%)</td><td>Standard Range (%)</td></tr>
<tr><td colspan="2">Coarse Aggregate (≥9.5 mm)</td><td colspan="2">23</td><td>10 - 45</td></tr>
</table>

SSD: Saturated Surface Dry

1.6.4. Binder Content

The binder content for mixture design was calculated using the richness modulus K and the type of aggregate gradation used. Based on these parameters, the minimum binder content was found to be 5.7% by weight of the total mixture of binder and aggregates.

1.7 High Modulus Base Course Performance Test

Dynamic modulus E* shows asphalt mixture stiffness. Dynamic modulus is a function of temperature, rate of loading, aging and mixture properties such as binder stiffness, aggregate gradation, binder content, and air voids. The asphalt modulus or stiffness is an important parameter for mix design of flexible pavements. Asphalt mixture being a viscoelastic material, the value of its modulus is affected by temperature and loading frequency or time of loading. For conducting dynamic modulus tests, three binders were selected due to their outstanding performance in the previous performance analysis. The selection of the binders was made based on the binder's PG grading (above 82 and having the largest temperature span), and also binder source (two binders with different PG gradings from Alberta's bitumen). The selected binders are presented in Table 28. Considering the lowest high-temperature performance of modified binder A + 12% Asph, this binder was first selected for the dynamic modulus test. It can be concluded if the high modulus base mix containing this binder satisfies the minimum required dynamic modulus, the other two binders that are stiffer, will pass the minimum criteria as well. Test was ran for all three binders in the temperatures and frequencies recommended in AASHTO T378 standard.

Table 28. Binders for dynamic modulus test

No	Binder	Continuous High PG Grade (℃)	Intermediate PG Grade(℃)	Continuous Low PG Grade(℃)	Standard PG Grade
1	A + 12% Asph	82.9	29.0	-21.8	82-16
2	G +12% Asph	84.2	30.3	-19.62	82-16
3	H+6% Asph	88.2	37.1	-16.6	88-16

1.7.1. G_{mb} and Volumetric Properties for Dynamic Modulus Test

The tests has been conducted to determine the density of the loose samples as well as their volumetric properties. Samples were tested according to AASHTO T209-12 for the density of hot mix asphalt. The result obtained for G_{mb} and volumetric properties from Superpave gyratory compacted sample for the first binder (A + 12% Asph.) are presented in Table 29. The results of this test were also used for calculating the air void contents of the samples. Following the NCAT'S gradation, the target air void was 1.5%. It can be seen that the air void calculated for the sample is 1.3, which is almost close to the target air void. Also, the G_{mb} values for the sample are found to very close to the target G_{mb} for the NCAT'S gradation.

Table 29. G_{mb} and volumetric properties

Sample No.	Gmb (gr/cm^3)	Air Void (%)	VMA	VFA (%)
A + 12% Asph (Sample 1)	2.405	1.3	11.0	88.0
A + 12% Asph (Sample 2)	2.404	1.3	10.9	89.4
G+12% Asph (Sample 1)	2.404	1.3	11.0	88.1
G+12% Asph (Sample 2)	2.410	1.1	10.8	90.3
H+6% Asph (Sample 1)	2.412	1.0	10.8	90.7
H+6% Asph (Sample 2)	2.410	1.1	10.8	90.2
NCAT's Results	2.441	1.5	15.0	90

1.7.2. Dynamic Modulus and Flow Number Test

1.7.2.1. Dynamic Modulus Test

Dynamic modulus |E*| test is conducted to determine stress and strain responses in asphalt mix and correlates the time-temperature defendant properties of the mix to field performance. The dynamic modulus test was conducted at different loading frequencies and temperatures as per AASHTO T378 guideline and using a universal testing machine (UTM). Figure 12 shows the UTM set for the dynamic modulus test with linear variable differential transformers (LVDTs) inside the temperature control chamber. Samples were prepared and compacted using Superpave gyratory compactor. Before testing, the samples were cored and cut into standard cylindrical sizes of

100mm diameter and 150 mm height specimens. During dynamic modulus testing, a sinusoidal axial compressive stress with different loading frequencies of 0.01 Hz, 0.1 Hz, 1 Hz, and 10 Hz was applied to the specimen at a specific temperature of 4˚C, 10 ˚C, 20 ˚C and 45 ˚C respectively. The applied stress and the corresponding strain response of the specimen were measured continuously during the test using a data acquisition system, as shown in Figure 12, and the dynamic modulus values were calculated by dividing stress magnitudes by average strain magnitudes. Two replicate samples were prepared and tested for each mixture.

Figure 12. Dynamic modulus test set up with LVDTs

Table 30 shows the dynamic modulus test results for asphaltenes-modified A using the NCAT's aggregate gradation with NMAS of 19 mm. It can be seen that for both samples, the mixes showed higher modulus under higher loading frequencies; that is, as the frequency increases, the dynamic modulus becomes larger, which reflects the viscoelasticity of asphalt mixtures. Furthermore, the dynamic modulus values were observed to reduce significantly by increasing temperature. However, it was found that the obtained stiffness of asphaltenes modified A at 15˚C temperature and 10 Hz loading rate is almost 14,000 MPa. Therefore, it is worth mentioning that the samples achieved the minimum requirement for high modulus asphalt application of 14,000 MPa at 15˚C temperature and 10 Hz loading frequency set out in European standard. Similarly, all other binder also passed the 14,000 MPa limit. binder G with 12% asphaltenes had almost similar result as binder A with 12% asphaltenes with an insignificant improvement. However, binder H with 6% asphaltenes improved the dynamic modulus of the mixture significantly. This value for 15˚C at 10Hz frequency was 33% improvement.

Figure 13 presents the dynamic modulus master curves for the mixtures with different binders. Higher frequencies have higher dynamic modulus as it is shown in the graph. Also, higher binders has higher dynamic modulus values along different frequency ranges.

Table 30. Dynamic Modulus Result

Sample ID	Frequency (Hz)	Dynamic modulus (MPa)				Phase angle (Degrees)			
		Temperature (˚C)				Temperature (˚C)			
		4 ˚C	15 ˚C	20 ˚C	45 ˚C	4 ˚C	15 ˚C	20 ˚C	45 ˚C
A+12% CNOOC	10Hz	19365.5	14020.5	11459.5	2864.5	10.14	14.25	17.00	31.15
	1Hz	14801.5	9533.0	7254.0	221.1	13.02	18.48	21.67	26.58
	0.1Hz	10772.5	5922.0	4133.5	138.8	16.27	22.90	25.95	22.09
	0.01Hz				115.9				17.26
G+12% CNOOC Asph	10Hz	19806.5	14007.5	10863.5	2395.0	10.82	15.78	19.11	34.32
	1Hz	14699.5	9075.0	6488.5	896.2	14.47	20.80	24.68	35.33
	0.1Hz	10315.0	5260.0	3367.5	359.3	18.43	25.90	29.42	31.12
	0.01Hz				168.9				24.20
H+6% CNOOC Asph	10Hz	23590.5	18648.0	15338.0	4283.5	8.76	12.08	14.75	30.17
	1Hz	18612.0	13277.5	10146.5	1807.0	11.55	16.16	19.69	34.10
	0.1Hz	14195.5	8619.5	5959.5	682.9	14.70	21.13	25.10	33.46
	0.01Hz				266.8				28.24

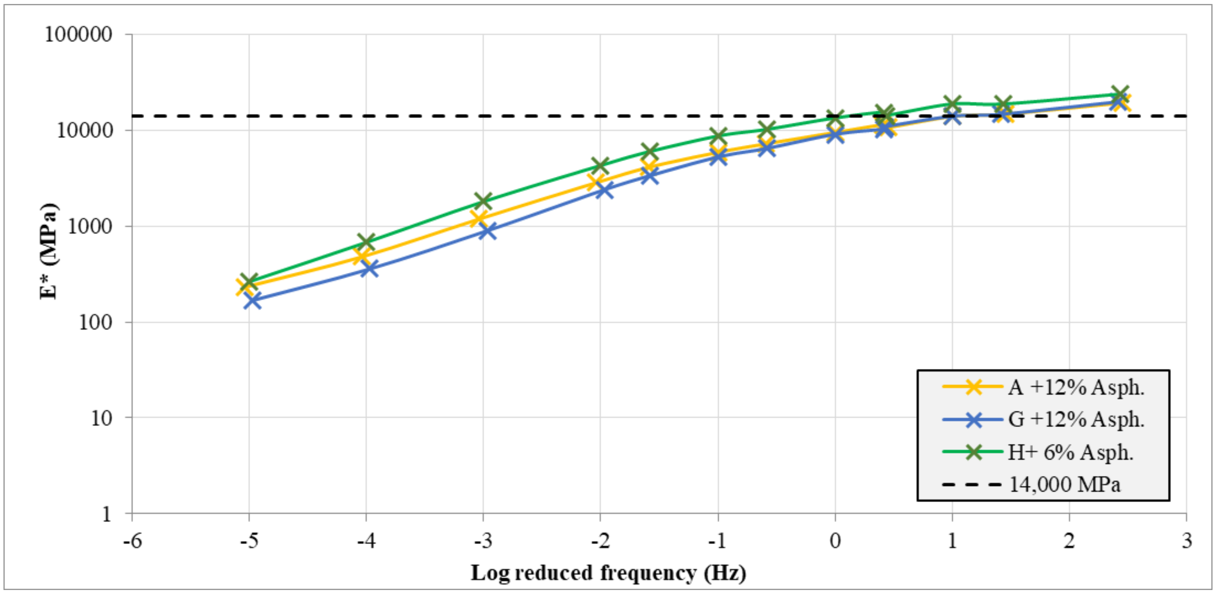

Figure 13. Dynamic Modulus Master Curve for Selected Asphaltenes-Modified Binders at the Reference Temperature of 15℃

1.7.2.2. **Flow Number Test**

A repeated load for testing the permanent deformation of the samples after dynamic modulus test has been applied. This test followed the specifications of AASHTO T378. Test temperature selected to be 60˚C considering the layer information, project location in Edmonton city and climatic data from the nearest weather station using the LTTP Bind 3.1 program estimation for value of High Adjusted PG Temperature. Contact load of 3kPa and 69kPa for deviator stress used with a haversine axial compressive loading pattern and loading and a resting period of 0.1 and 0.9 seconds respectively were adopted. Permanent deformation of the samples measured and divided by the original gauge length at the end of the rest period to calculate the strain value. Test limits set on 20000 cycle numbers or a maximum of 50000 microstrains. Results presented in Figure 14 for all the samples terminated at the maximum number of cycles. Considering the accumulated microstrain value for all three samples, it can be concluded that H + 6% CNOOC asphaltenes has the lowest deformation which means higher resistance for rutting. G + 12% CNOOC asphaltenes has higher deformation value with 81.2% increase in deformation compared to H + 6% CNOOC asph and A + 12% CNOOC asphaltenes is in between these samples with 50.4% increased deformation value compared to H + 6% CNOOC asph.

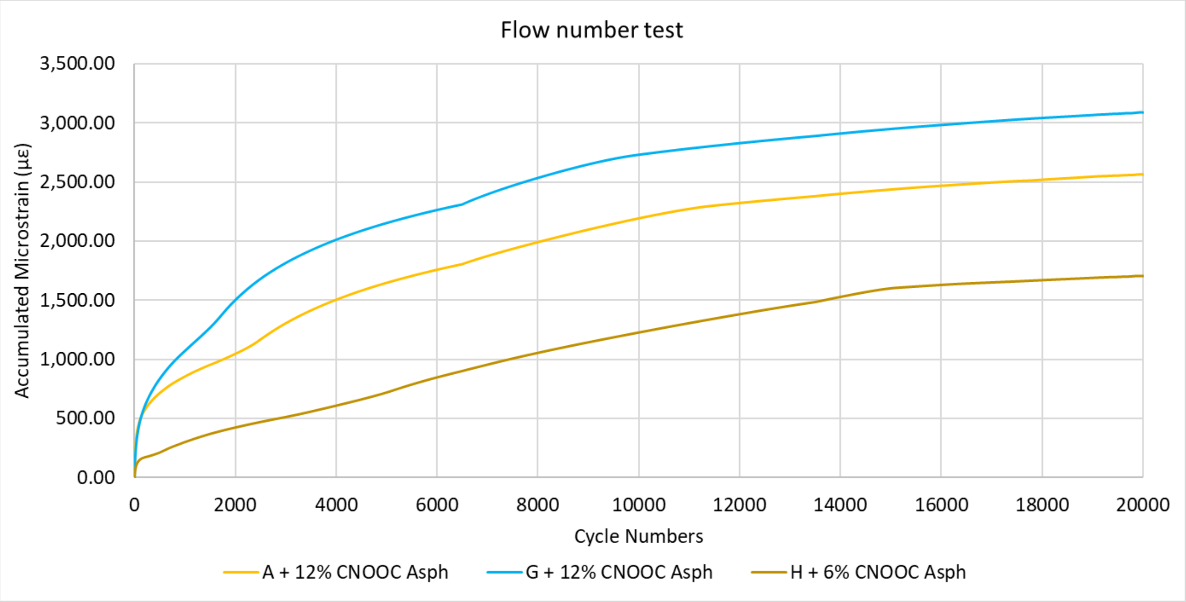

Figure 14. Flow number test results

1.7.3. **Creep Compliance and Strength**

Low temperature properties of the samples has been tested using the creep compliance and strength test (AASHTO T322). Test temperature determined to be -10˚C with three replicates for each sample. Marshall compactor used to prepare the samples using the mixing and compaction temperature determined for each separate binder from the viscosity test (AASHTO T316) results. Three replicates for each one the samples prepared in 100mm diameter and 63.5 mm height and surface cut to the range of 38-50mm according to the standard. Following the specifications, 100±2 second loading with a constant load has been applied for the samples and deformation values from four horizontal and vertical LVDTs attached to both sides of sample has been recorded. Indirect tensile test has been done immediately after the creep test with a loading rate of 12.5mm per minute. Maximum load at failure point of sample is recorded to calculate the tensile strength.

Figure 15(a) presents the picture of samples prepared for the test, Figure 15(b) for before testing and Figure 15(c) for after the test.

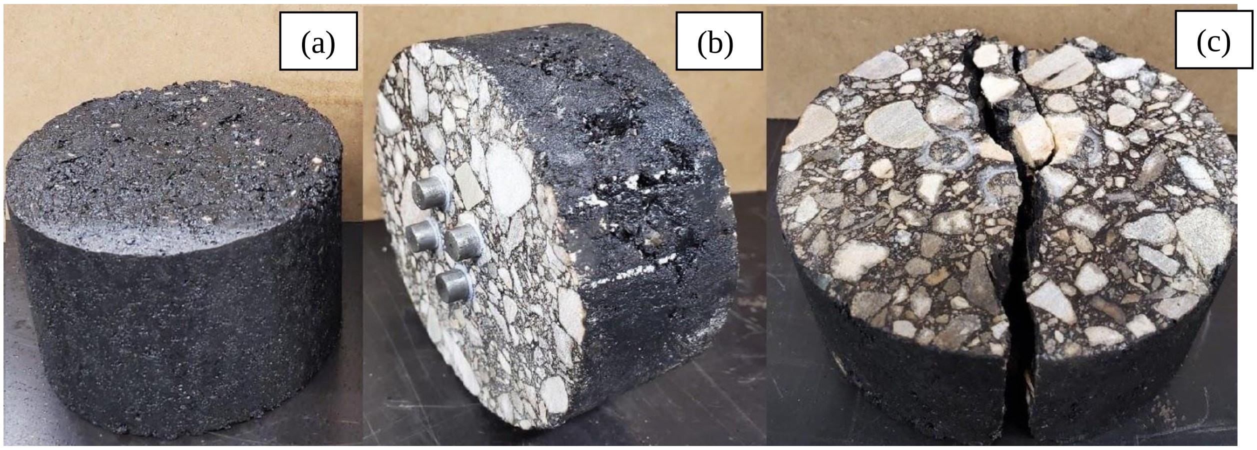

Figure 15. Marshall samples (a), IDT samples before test (b) and after test (c)

Figure 16 provide the results for the load-deformation of the samples at -10˚C for control sample and 3 modified samples. According to the load-deformation graph, tensile strength of samples increased after the modification significantly. Also, samples were stiffer which resulted in sudden drop of the tensile strength after the failure point. binder H with 6% of asphaltenes has higher tensile strength than other samples and 12% asphaltenes A were the second highest tensile strength. G samples with 12% asphaltenes had lower tensile strength than other modified samples, however all of them were more than the control sample that is unmodified PG 64-22 from source A.

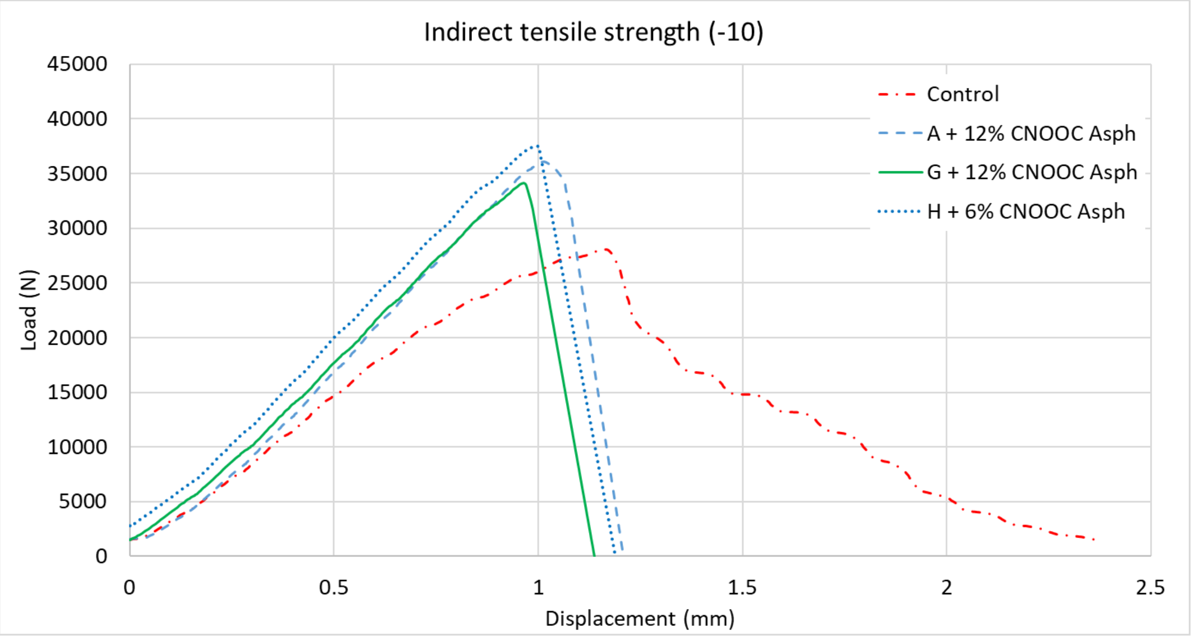

Figure 16. Load-deformation results for -10˚C

Fracture energy is calculated using the data from all the replicates, and tensile strength values are presented in Table 31. Comparing the tensile strength of different binders indicates that A with 12% asphaltenes had 29.9% higher tensile strength than the control sample. Binder G with 12%

asphaltenes also had higher tensile strength compared to the control sample about 25.1% and H with 6% asphaltenes had 26.8% higher tensile strength than the control sample. Considering the fracture energy for the determined binders, A containing 12% asphaltenes decreased the fracture energy by about 32.4% compared to the control sample. Binder G with 12% asphaltenes decreased the fracture energy by 37.2%, and H with 6% asphaltenes had 38.7% lower fracture energy.

Table 31. Creep compliance and indirect tensile test

Sample ID	**Temperature (˚C)**	**Tensile Strength (kPa)**	**Fracture Energy (J/m^2)**
Control	-10	3853.02	8052.17
A + 12% CNOOC		5003.67	5445.90
G + 12% CNOOC Asph		4820.76	5055.25
H + 6% CNOOC Asph		4884.43	4933.47

1.7.4. **Hamburg Wheel-Tracking**

Hamburg wheel tracking test was performed according to the AASHTO T324. Gyratory superpave samples prepared with 150mm diameter and 60mm height. Samples were cut in the edge and placed in the moulds as per the standard sample preparation process, and the test has been run. Test temperature selected to be 55˚C considering the binder grades and binder base layer as the main application of the mixture. Water chamber preconditioning for 45 minutes applied before testing, and a steel wheel with 47mm width and 705±4.5N weight at the frequency of 52±2 passes per minute with a maximum speed of 0.305m/s at midpoint was used for this test. The test's termination point is determined to be 20,000 passes or 12mm rutting depth, whichever comes first. Rutting resistance Index (RRI) is calculated as the ratio of the number of passes over rutting depth at the failure point. Stripping inflection point (SIP) was also determined from the test for the samples. Moisture sensitivity of the samples calculated using the ratio of SIP value over the number of passed. Samples before and after the test are shown in Figure 17.

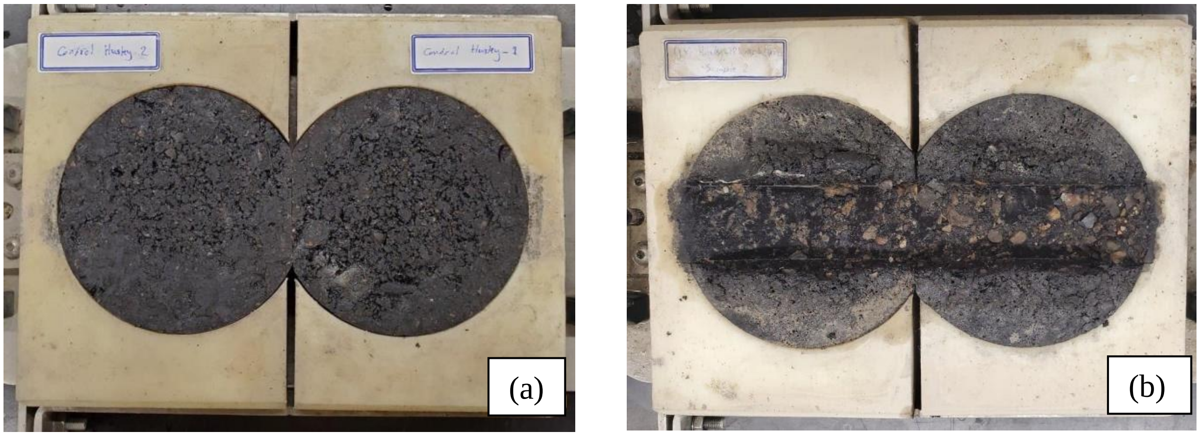

Figure 17. Wheel tracking samples before (a) and after (b) test

Table 32 present the result for the test of the modified and unmodified samples. According to these results, all the modified samples terminated at 20,000 passes. However, the control sample (PG 64-22 from source A) failed at 15,376 passes with a SIP value of 10,692, which moisture sensitivity of 0.7 was the result of it. RRI value for the control sample was determined to be 1281.3 for this test. Binder A with 12% asphaltenes had an RRI value of 10,989 with 757.6% improvement comparing to the control binder. Binder G with 12% asphaltenes with an RRI value of 5,698 improved the rutting resistance by about 344.7% and 3,151.9% improvement in rutting resistance has been seen in binder H with 6% asphaltenes with 41,666.7 RRI value. Figure 18 presents the result of this test as the number of passes versus rutting depth.

Table 32. Wheel tracking test results

Sample ID	SIP	Rutting depth (mm)	Number of passes at 12mm rutting	Moisture sensitivity	RRI	RRI improvement
Control	10692	12.0	15376	0.7	1281.3	100.0%
A + 12% CNOOC	19999	1.82	20000	1.0	10989.0	857.6%
G + 12% CNOOC Asph	19999	3.51	20000	1.0	5698.0	444.7%
H + 6% CNOOC Asph	19999	0.48	20000	1.0	41666.7	3251.9%

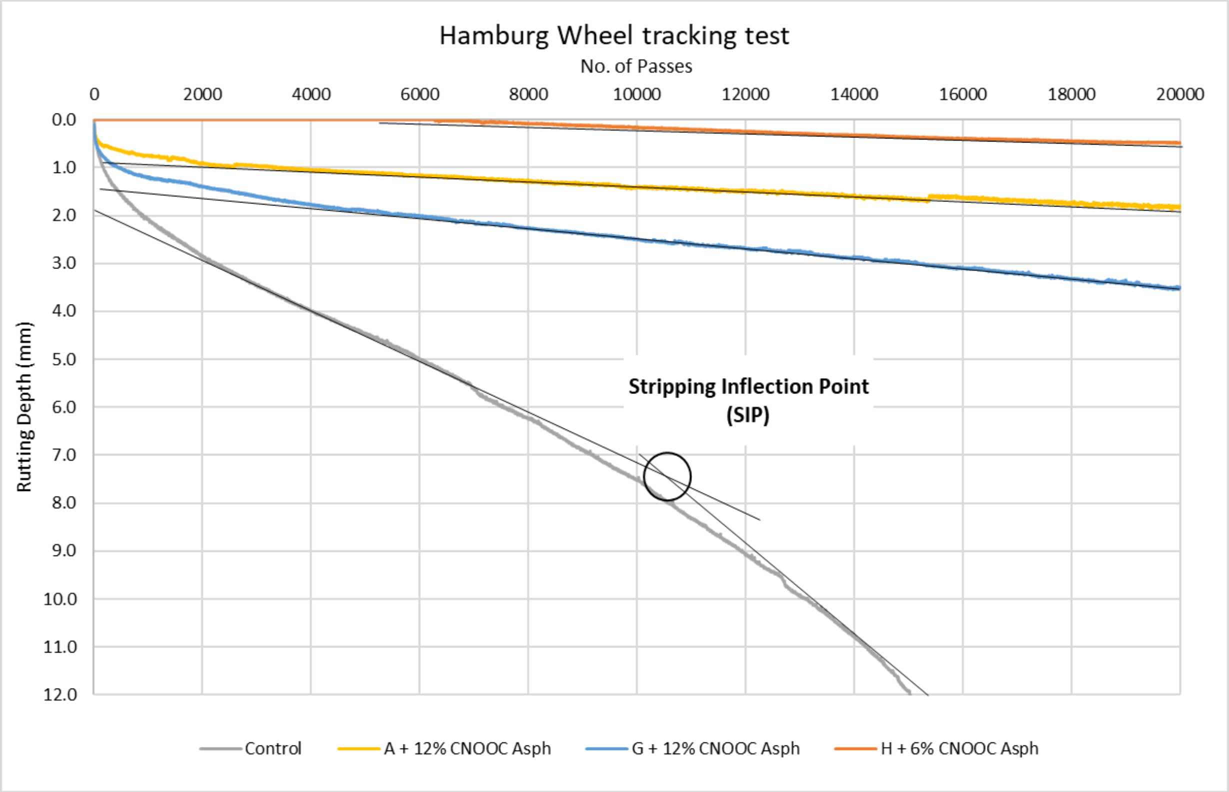

Figure 18. SIP result from Hamburg wheel tracking test

1.8 Conclusions

- According to rheological test results, the addition of asphaltenes increases the stiffness and elasticity of the asphalt binder, resulting in a considerable improvement in resistance against permanent deformation at high temperatures. On average, and regardless of the binder source, a 6% increase in asphaltenes content corresponded to a one-interval increase in the high PG temperature grade of the asphalt binder. However, at low temperatures, every 10% to 20% increase in asphaltenes content (depending on the binder type) corresponded to a low PG grade increase of one interval.

- Regardless of the asphalt binder source, every 2% increase in asphaltenes content was found to increase the binder viscosity at 135 °C by approximately 0.1 Pa·s and to increase the mixing and compaction temperatures by approximately 2.6 °C.

- Binders sourced from Alberta oilsands bitumen were found to have lower colloidal index values (signifying their higher stability, i.e., stability of the asphaltenes phase in the maltenes matrix) compared to crude oil asphalt binder PG 70-22.

- The dynamic modulus test results for the asphaltenes-modified binders showed that these binders, coupled with a well-graded aggregate gradation, satisfies the dynamic modulus requirement (achieving more than 14 GPa at a loading frequency of 10 Hz and a temperature of 15 °C).

- The IDT results indicate that binder modification decreased the fracture energy for all the samples, and that the samples were more brittle at lower temperatures. On the other hand, the tensile strength of the modified samples increased significantly compared to the unmodified sample.

- The Hamburg wheel-tracking test and flow number test results showed a significant increase in rutting resistance in all the modified samples.

- Using the appropriate distillation temperature and source, oilsands bitumens were found to be capable of achieving high PG for high-modulus asphalt applications in moderately cold-climate regions without further modification.

- A method to reduce the cracking potential of HMAC composed of asphaltenes-modified binders, e.g., the addition of polymer fibres such as polyethylene terephthalate (PET), in order to improve its cold-climate performance warrants further investigation as a next step.

2. Design and performance evaluation of stabilized base courses using asphalt emulsions and asphaltenes

2.1 Introduction

One strategy to enhance load distribution within the pavement to increase its bearing capacity and fatigue resistance is to strengthen the base course by increasing its thickness (Christopher et al., 2006). However, increasing the thickness has some drawbacks, such as increased cost, time, and environmental impact due to the additional materials used. Using higher quality material in the base course will result in higher resistance and increase the cost of construction of the layer. On the other hand, base stabilization is a promising solution that can overcome these problems (Little & Nair, 2009; Wegman et al., 2017; Patel, 2019). A well-designed base layer with sufficient thickness can reduce distress on the pavement layers (Wirtgen Cold Recycling Manual, 2012), while the tensile strength of the base layer can be improved through stabilization using an asphaltic or cementitious material (Christopher et al., 2006; Wirtgen Cold Recycling Manual, 2012).

Unbounded base courses generally consist of crushed stones and gravels that transfer the load to lower layers and resist it within the particles (Wirtgen Cold Recycling Manual, 2012; Yideti et al., 2014). However, these layers have a low resistance to the tensile load (Brown, 1996). In this regard, studies have shown that stabilization of aggregate layers will result in higher shear strength, stiffness, durability, and resistance to moisture in asphalt pavements (Branch, 2005). Asphalt emulsion could be used for stabilization of these layers due to its advantages such as low-temperature application, less energy usage, lower emissions, and the fact that it is less hazardous than hot mix asphalt and more environmentally friendly than cutback asphalts (Delmar, 2006). However, disadvantages such as low rutting resistance, higher cracking, longer curing time for asphalt emulsion (to increase the bond between particles), and comparably poor early performance properties have limited its application (Du, 2018; Khweir et al., 2004; Du, 2016). Indeed, some studies have indicated that it may take up to three years for an asphalt emulsion-stabilized layer to reach maximum strength (Marais & Tait, 1989; Quick & Guthrie, 2011; Doyle et al., 2013).

The selection of the proper additive and the adequate amount to be added for stabilization has an important role in the stabilized layers' performance properties (Wegman et al., 2017; Patel, 2019; Betti et al., 2016). Active fillers provide higher mechanical properties, stiffness modulus, permanent deformation resistance, moisture resistance, and fatigue strength when used for asphalt emulsion stabilizations (Brown & Needham, 2000; Giuliani, 2001; Hodgkinson & Visser, 2004). Another significant impact of active fillers on asphalt emulsions is that they reduce the breaking and curing time for asphalt emulsions (Terrell & Wang, 1971). Cement and lime as active fillers result in relatively slow strength gain and longer curing time. Environmental hazards of some active fillers due to their production's nature is another drawback (Fang et al., 2016; Modarres & Ayar, 2016; Paoli et al., 2014; Gutiérrez et al., 2012). In addition, using cement and lime in stabilization for low-temperature conditions will not be as effective as conventional asphalt layers, as the low temperatures have adverse impacts on the strength gain of the stabilized layers (Soliman et al., 2014). However, the mixtures' high-temperature properties with active fillers such as cement, hydrated lime, and slag could be enhanced with specific contents of additives (Modarres & Ayar, 2016; Du, 2015). The rigidity of the mixture after stabilization, adverse effects on the environment, shrinkage cracking, as well as several other drawbacks in cement stabilization make it unsuitable for application in cold climate regions (Perraton et al., 2011; Shafii et al., 2011).

Asphaltenes are waste material produced through the deasphalting process of some bitumen with no significant application in the road construction industry. In addition, asphaltenes are a component of asphalt binders alongside saturates, resins, and aromatics (collectively referred to as "SARA") (Sultana & Bhasin, 2014). Asphalt as a viscoelastic material is made of polar and non-polar components. The polar components are responsible for the elastic behaviour, while the non-polar components govern the viscous behaviour (Sultana & Bhasin, 2014; Ramirez-Corredores, 2017; Behnood & Gharehveran, 2019; Xu et al., 2019). Adding asphaltenes to asphalt materials will result in a stiffening of the mixture, thereby enhancing its mechanical properties (Sultana & Bhasin, 2014). The use of asphaltenes as an additive in asphalt emulsion-stabilized mixtures has not yet been studied, and, considering the effects of this material on the asphalt binder properties, similar enhancements to other additives are expected in stabilized mixtures. The presence of asphaltenes in the asphalt binder also raises the matter of the compatibility between the two materials, which could be a key factor in the final mixture's flexibility.

2.2 Prepare granular base course material

Using the aggregate gradation envelopes indicated in the Wirtgen Cold Recycling Manual, City of Edmonton and Alberta Transportation (Soliman, et al., 2014; UNWTO, 2015; Wirtgen Cold Recycling Manual, 2012; City of Edmonton, 2012), a grain size distribution was selected for the aggregate as shown in Figure 19 and Table 33. This gradation was kept constant for all subsequent experiments.

As Table 33 shows, the cumulative aggregates retained on a 4.75-mm sieve were considered to be coarse, and the remainder were considered fine aggregates.

Lafarge Canada provided the granular aggregate used for the project. As shown in Figure 20. Figure 19, several bags of aggregate from different sources with different aggregate sizes were prepared and delivered to the Asphalt Laboratory of the University of Alberta. In order to separate the aggregate batches delivered from the borrow pit, a sieving machine (Figure 21) was used with different sieve sizes for the gradation. The aggregates remaining on each sieve were collected in different buckets, as shown in Figure 22. To prepare the target gradation, the aggregates were combined based on the values shown in Table 33.

The physical properties of the aggregates were calculated based on ASTM standard tests, with the results shown in Table 34.

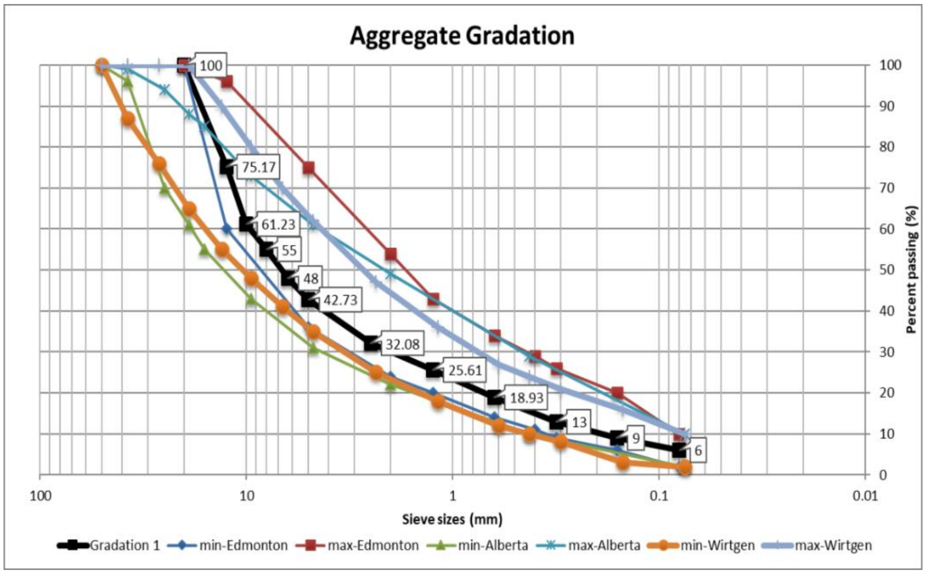

Figure 19. Target aggregate gradation and limitations

Table 33. Aggregate gradation percentage

Sieve size (mm)	**% Passing**	**% Retained**	**Coarse-Fine**	
20	100.0	0.0	57.3%	Coarse
12.5	75.2	24.8		
10.0	61.2	13.9		
8.0	55.0	6.2		
6.3	48.0	7.0		
5.0	42.7	5.3		
2.5	32.1	10.7	42.7%	Fine
1.25	25.6	6.5		
0.63	18.9	6.7		
0.315	13.0	5.9		
0.16	9.0	4.0		
0.08	6.0	3.0		
Filler (Pan)	0.0	6.0		

Figure 20. Unsieved material from the aggregate plant

Figure 21. Sieving device with different sieve sizes

Figure 22. Sieved material

Table 34. Physical properties of the aggregate

Characteristics	Test Method		Result	Limitations
	ASTM	AASHTO		
Amount of material finer than 75-μm (No. 200) sieve in aggregate	C117	T11	6%	2-9%
Specific gravity and water absorption of fine aggregates	C128	T-84	2.604 0.624%	-
Specific gravity and absorption of coarse aggregates	C127	T-85	2.598 0.870%	-
Abrasion of coarse aggregates (Los Angeles Machine)	C131	T96	23%	Max 40%
Proctor test	D698 (Modified D1557)	T99 (Modified T180)	6.3% water	-
			15.4 max. dry density	-

To calculate the aggregate optimum moisture content, a Proctor test based on ASTM D698 (modified D1557) was used. According to the test method, different water contents were added to a specific amount of oven-dried aggregate. After mixing the water and aggregate, the mix was compacted using a standard hammer in a 3-layer mould using 56 blows. Method C was selected for conducting this test, considering the gradation of the aggregate used. The final results of the test are provided in Figure 23. The optimum water content was determined to be 6.3% to provide the maximum compaction and density for the targeted gradation. The result of the compaction test for this moisture content is shown in Figure 23. Please note adding more water made the sample too wet and compaction was not possible.

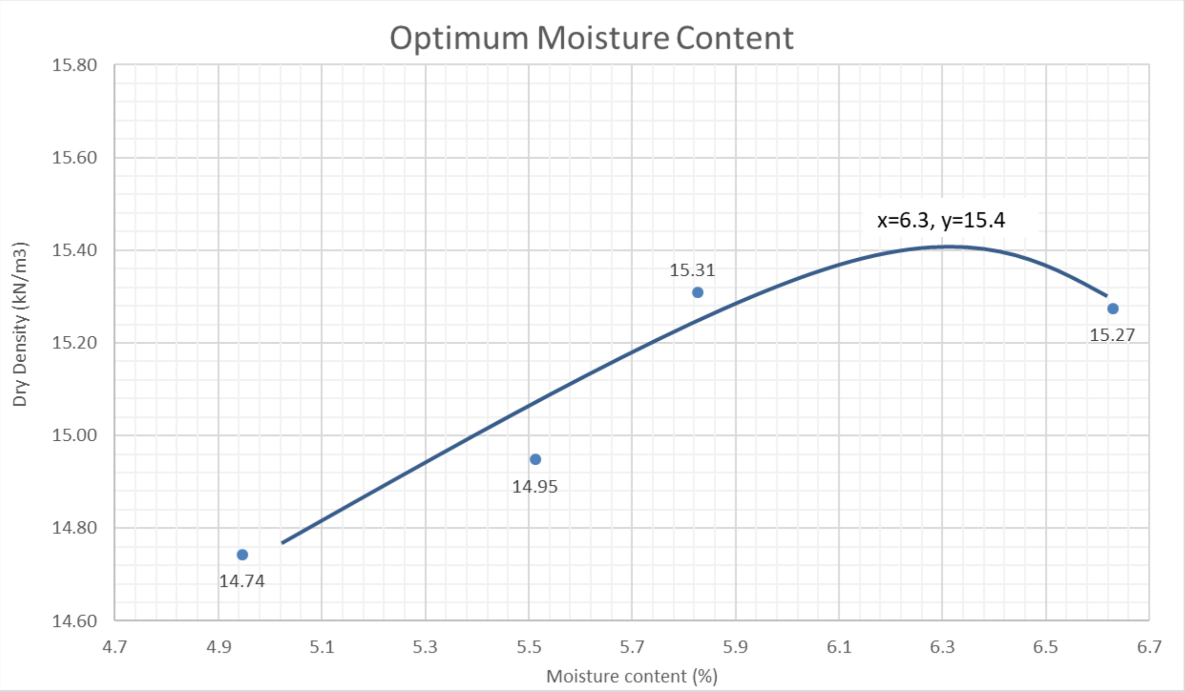

Figure 23. Proctor test results

2.3 Prepare mix design for stabilized base course using asphalt emulsion

2.3.1. Asphalt Emulsion

The asphalt emulsion for this project was typically used for soil stabilization provided by Husky Energy and contained 61% asphalt cement and 39% water. The material used is a cationic, slow-setting emulsion with a hard base binder (CSS-1H). The material specifications included with the product are summarized in Table 35.

Table 35. Asphalt emulsion (Husky Energy, 2019) properties

Property	Standard ASTM/AASHTO	Specification Min.	Specification Max.	Typical Analyses
Tests on Emulsion				
Specific gravity (Density) at 15.6˚C, kg/L	D6937/T59	-	-	1.020
Residue by distillation, % by mass	D6997/T59	57	-	61
Viscosity at 25˚C, S.F.S	D7496-D88/T59	20	100	22
Oversized particles (sieve), % by mass	D6933/T59	-	0.3	0.008
Settlement (24 hours), % by mass	D6930/T59	-	1.0	0.5
Particle charge test	D7402	Positive		Positive
Tests on Asphalt Residue				
Penetration at 25˚C (100 g, 5 s), dmm	D5/T49	40	125	95
Ductility at 25˚C (5 cm/min), cm	D113/T51	40	-	>40
Solubility in Trichloroethylene, % by mass	D2042/T44	97.5	-	>97.5

2.3.2. Asphalt Emulsion-Mix design

The design method used for base course stabilization in this research followed Asphalt Institute (2008), considering granular aggregates with dense gradation. According to this method, the amount of asphalt emulsion used in the mixture should be calculated using a specific formula, which requires the result of a test described in ASTM D6997.

$$Base\ mixture: emulsion\ \% = \frac{(0.06B + 0.01C)100}{A} \tag{2}$$

where A is the percentage of residue of asphalt emulsion remaining after distillation (as determined using ASTM D6997), B is the percentage of dry aggregate passing through a No. 4 sieve, and C is the percentage of dry aggregate retained on a No. 4 sieve.

From this, the following result is obtained (% by weight of aggregates):

$$Base\ mixture: Asphalt\ emulsion\ \% = \frac{(0.06x42.73 + 0.01x57.27) * 100}{61} = 5.14\% \tag{3}$$

The approximate asphalt emulsion content was determined using this method, and four different asphalt emulsion contents. The latter were set at 1% intervals above and below the calculated values.

During the mixing process, water was added to the aggregate to reach the optimum water content, and the samples were mixed until the water was uniformly distributed throughout the aggregate. After mixing, three samples for each asphalt emulsion content were prepared using a Marshall hammer with 50 blows per each side of the sample. The samples prepared in this way were then tested using the Marshall stability and flow device. Marshall stability measures the maximum load sustained by the bituminous material at a loading rate of 50.8 mm/minute. The density of the samples was determined prior to conducting the Marshall stability test. The compacted samples were cured for 48 hours with Marshall compaction moulds before being tested in the oven at 60°C and then cooled for two hours before extraction from the mould.

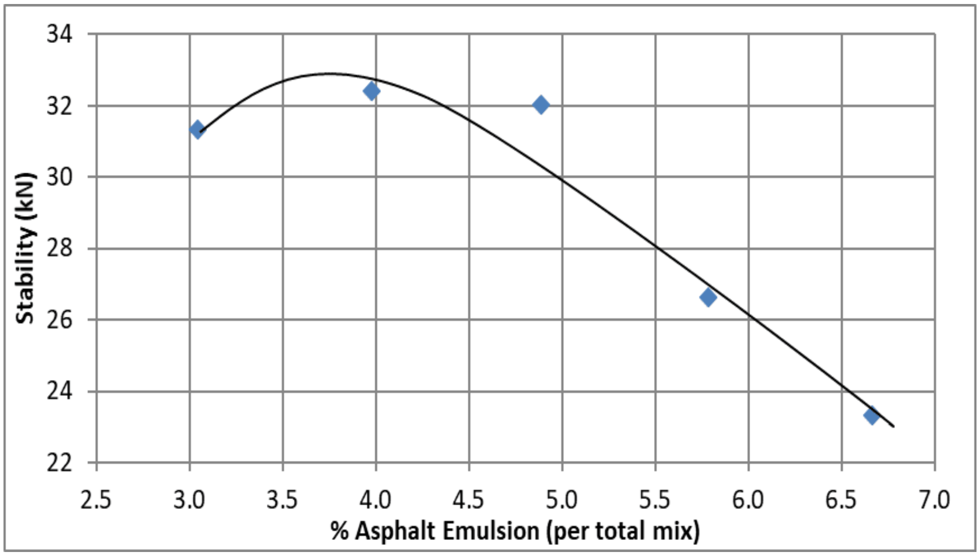

Figure 24. Stability vs. asphalt emulsion content

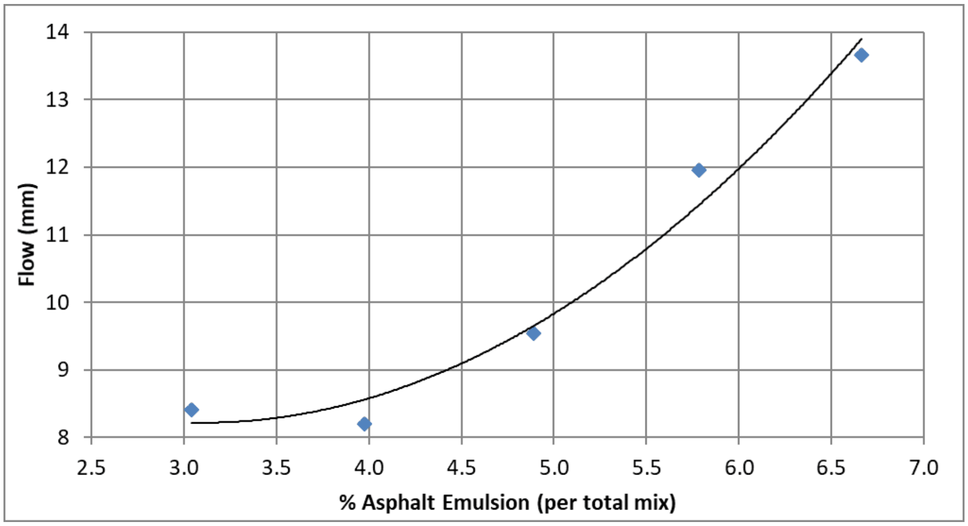

Figure 25. Flow vs. asphalt emulsion content

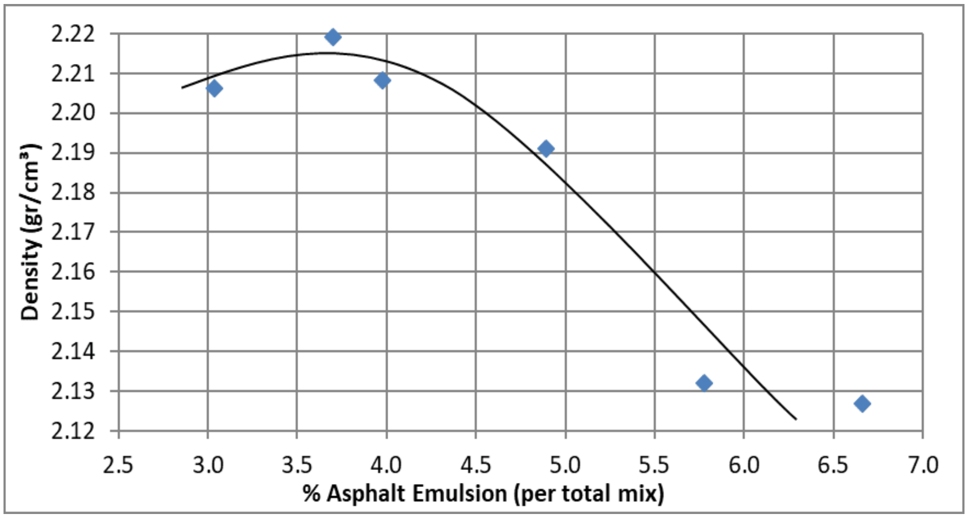

Figure 26. Density vs. asphalt emulsion content

The minimum acceptable Marshall Stability for stabilized base courses is 2.2 kN for low volume roads. However, it has been recommended to adjust the minimum value base on the mix type and its application (Asphalt Institute, 2008). The obtained values for Marshall Stability and flow number are comparable to hot mix asphalt. According to the stability test results, 3.98% asphalt emulsion content per total weight of the mix provided the highest stability for the mixtures; however, the trends for density and stability show that maximum values were attained at about 3.7% asphalt emulsion. This proportion of asphalt emulsion per total mix was thus chosen as the OEC for the performance tests.

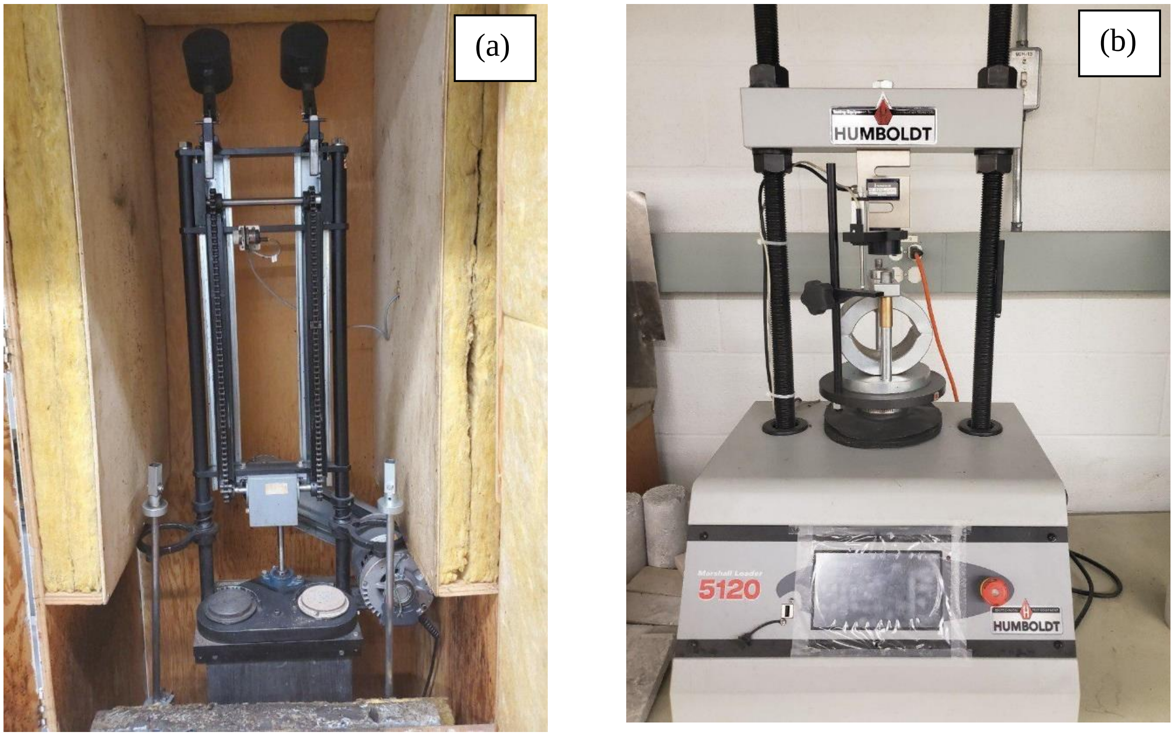

Figure 27. Marshall Hammer (a) and stability and flow device (b)

2.3.3. **Indirect tensile strength test (ITS)**

In addition to the Marshall stability test, another test was used to determine the optimum emulsion content (OEC). It is the indirect tensile strength (ITS) test, as suggested by several researchers (Du, 2015; Wirtgen Cold Recycling Manual, 2012). ITS is an indirect measure of the tensile strength and reflects the stabilized mix's flexibility and flexural characteristics. In this project, the ITS test was used to verify the mix design results.

Samples for the ITS test were prepared using five different asphalt emulsion concentrations (3.04%, 3.70%, 3.98%, 4.89% and 5.78% by weight of aggregate). These concentrations were chosen to ensure consistency with the results of the Marshall stability tests. Three samples were prepared for each asphalt emulsion concentration. The samples were prepared using the Marshall hammer and same compaction procedure as for the Marshall stability tests.

The samples were cured for 48hours in 60˚C oven and then conditioned for three hours in an air chamber at 25˚C after cooling down, according to AASHTO T283. After conditioning the sample, a load was applied on the samples at a rate of 50 mm/min. The maximum load applied to the sample before it failed was recorded (Figure 28) to determine the indirect tensile strength according to the following equation:

$$S_t = \frac{2000P}{\pi t D} \tag{4}$$

where S_t is the indirect tensile strength (kPa), P is the maximum applied load (N), h is the average height of the specimen (cm), and d is the diameter of the specimen (cm).

To calculate the ITS for wet specimens, the samples are conditioned in water at 25˚C for 24 hours and then tested. According to the available specifications, the ITS of the dry samples should be more than 225 kPa and the ITS of the wet samples should be more than 100 kPa (Wirtgen Cold Recycling Manual, 2012).The tensile strength ratio (TSR) of the samples was calculated using the equation below. It has been suggested that the TSR value should be greater than 50% (Wirtgen Cold Recycling Manual, 2012).

$$TSR = \frac{S_2}{S_1} \tag{5}$$

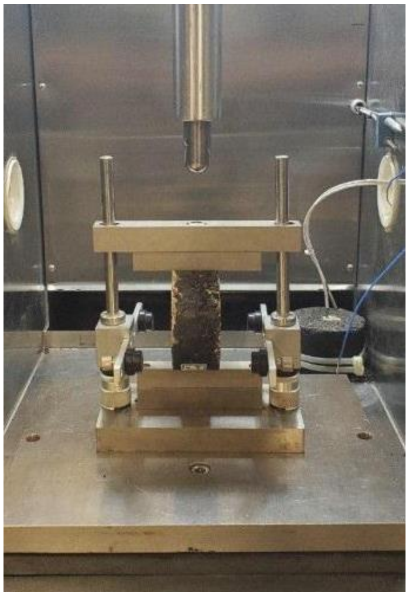

Figure 28. ITS test apparatus

Figure 29 shows the dry ITS test results for different samples. As Figure 29 shows, the maximum ITS was achieved after adding 3.7% asphalt emulsion by weight of total mix to the aggregates, similar to the results of the Marshall stability tests. To ensure that the wet ITS results would fall in the recommended range, the ITS test was also conducted on samples conditioned in water (as described above). As Table 36 shows, there was no strength loss after conditioning the samples. Furthermore, the TSR value was above the recommended 50% value.

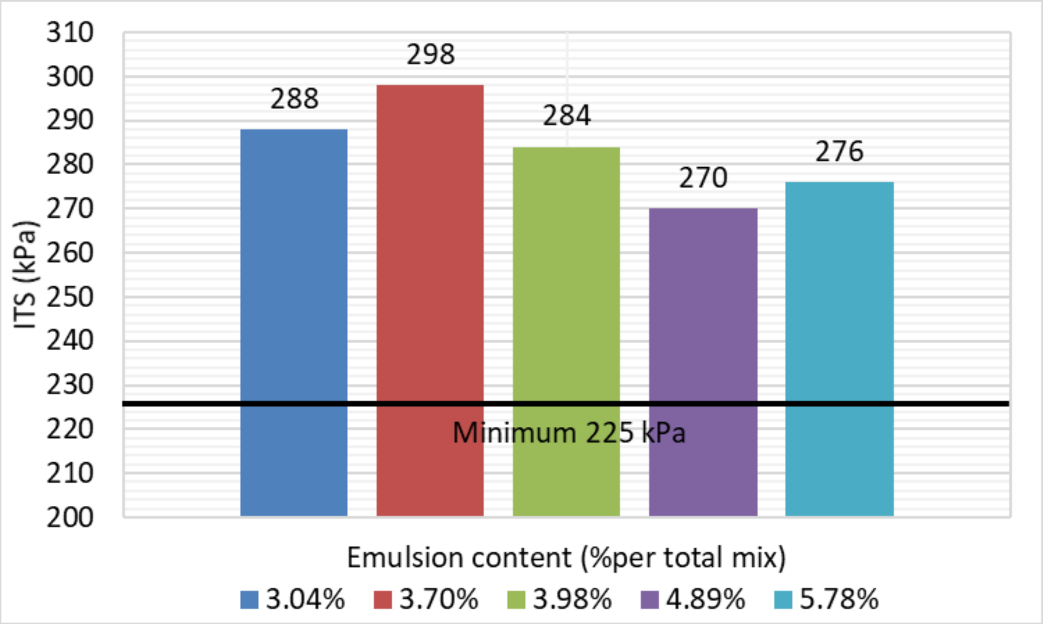

Figure 29. ITS results for samples with various asphalt emulsion contents

Table 36. ITS and TSR test results (Wirtgen Cold Recycling Manual, 2012)

Samples	ITS (kPa)	Tensile Strength Ratio (TSR)	Min. ITS (kPa)	Min. TSR
Optimum Dry$_{ITS}$	298	1.0	225	0.5
Optimum Wet$_{ITS}$	306		100	

2.4 Asphaltene-modified asphalt emulsion (Indirect Tensile Strength test)

To determine the tensile strength of the unmodified and stabilized mixes with asphaltenes-modified emulsion, Indirect Tensile Strength (ITS) test based on AASHTO T283 were conducted. Samples were prepared, by adding 1, 2 and 3% of asphaltenes (by the weight of total mix) to the asphalt emulsion. After that, the asphaltenes modified asphalt emulsions were mixed with aggregates. It was observed that after increasing asphaltenes content to 2% and above, the workability of the asphalt emulsions was significantly reduced. In these cases, to be able to mix the modified asphalt emulsion with the aggregates, some extra water was added to the mixes. Table 37 shows differently prepared samples for the ITS test.

Table 37. Prepared samples for ITS tests

Sample ID	Filler existance (Y or N)	Asphaltenes (% of total mix)	Extra water (% per total emulsion)
Control	Y	0	0
N-6-0	N	6	0
N-2-0	N	2	0
N-2-25	N	2	25
Y-1-0	Y	1	0
Y-2-25	Y	2	25
Y-2-50	Y	2	50
Y-3-50	Y	3	50
VCTek-Y-1-0	Y	1	0

The results obtained from the ITS tests are presented in Figure 30. As the figure shows, the more asphaltenes were added to the mix resulted in higher tensile strengths. However, to be able to add more than 2% asphaltenes to the mix, it was needed to add extra water to the mixes which resulted in some difficulties with sample preparation and compaction. Hence, the addition of more than 2% asphaltenes was not considered for the next steps.

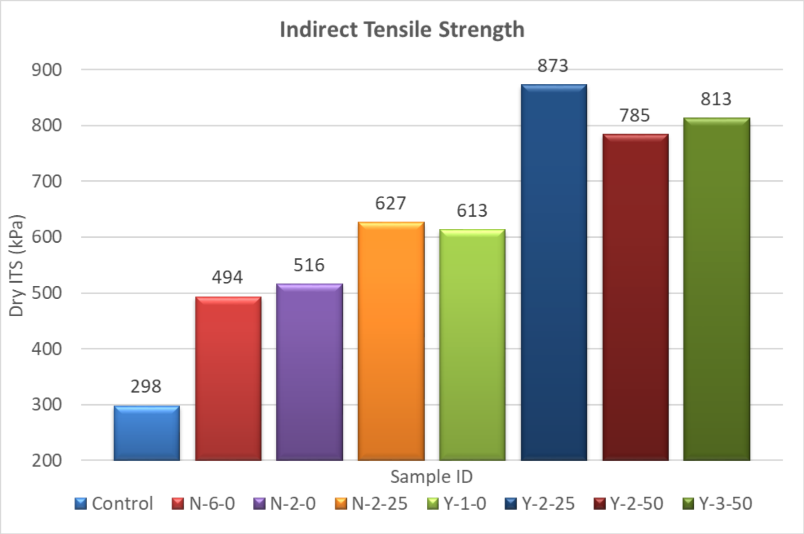

Figure 30. Dry ITS for asphaltenes modified and unmodified samples

2.4.1. Asphaltenes-Modified Asphalt Emulsion (Marshall Stability and Flow Test)

Marshall stability and flow test were conducted to determine the performance of mixes in terms of strength and permanent deformation. Marshall stability is a measure of resistance to rutting damage under the condition of pavement loading. The stability of the base course should be high enough to adequately resist traffic loading. Table 38 presents the average values of Marshall stability, density, flow, Marshall quotient and air voids for the mixtures. It was found that the addition of asphaltenes to the samples increases stability with little increase in the air void content of the mixtures. In terms of density, an insignificant reduction was observed in the density of the mixtures containing asphaltenes. Additionally, the increase in Marshall quotient indicates significant improvement in flexibility of the asphaltenes-modified mixes compared with unmodified mixes. By investigating the properties of both mixtures modified with two different sources of asphaltenes (VCTek and CNOOC), using the same mix design and preparation process, it was found that the two different types of asphaltenes had almost the same impact on the performance parameters that were measured.

Table 38. Marshall test results

Sample ID	Stability (kN)	Density (g/cm^3)	Flow (mm)	Marshall Quotient (kN/mm)	Air voids (% of total mix)
Control	11.536	2.197	5.545	2.08035	11.113
Y-1-0	17.059	2.150	5.263	3.24149	11.395
Y-2-25	22.718	2.143	7.482	3.03659	12.574
VCTek-Y-1-0	16.730	2.094	4.575	3.65706	13.798

2.4.2. Tensile Strength Ratio (TSR)

To determine the susceptibility of the samples to moisture damage, TSR of modified and unmodified mixes were calculated. TSR is the ratio of the ITS of the conditioned samples to the ITS of the dry samples. Samples were conditioned using two methods. With the first method, samples were submerged underwater for 24 hours at 25 ˚C before testing. In the second process, after conditioning the samples underwater for 24 hours, they have been frozen for a minimum of 16 hours and then thawed in a hot water bath at 60±1˚C for 24±1 hours.

TSR results after conditioning in water are presented in Figure 31. The results show that the TSR values for asphaltenes-modified mixes are lower compared to unmodified mixes. Hence, asphaltenes modified mixes were more susceptible to moisture damage. Saturated samples met the specifications of the AASHTO 31-17 for TSR value (0.7).

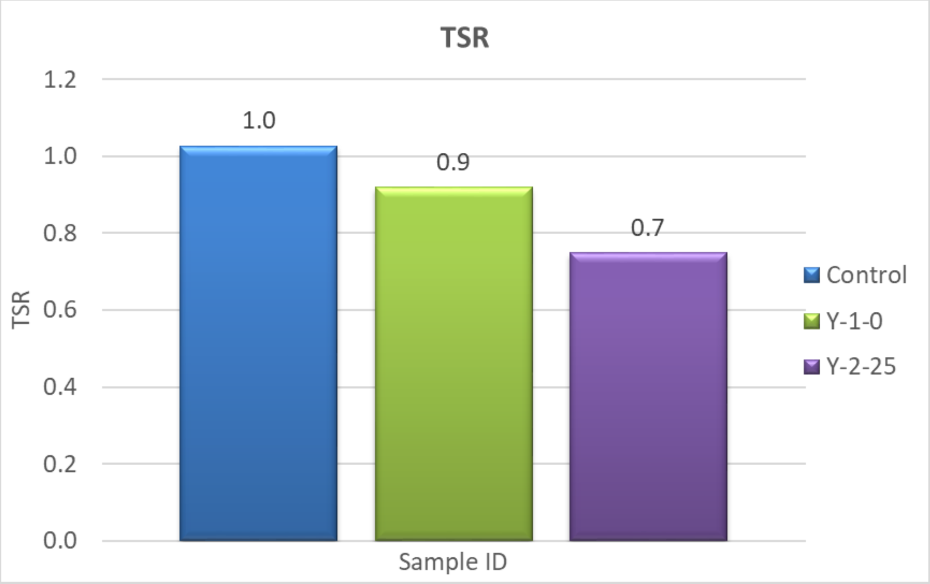

Figure 31. TSR results for conditioned samples in water

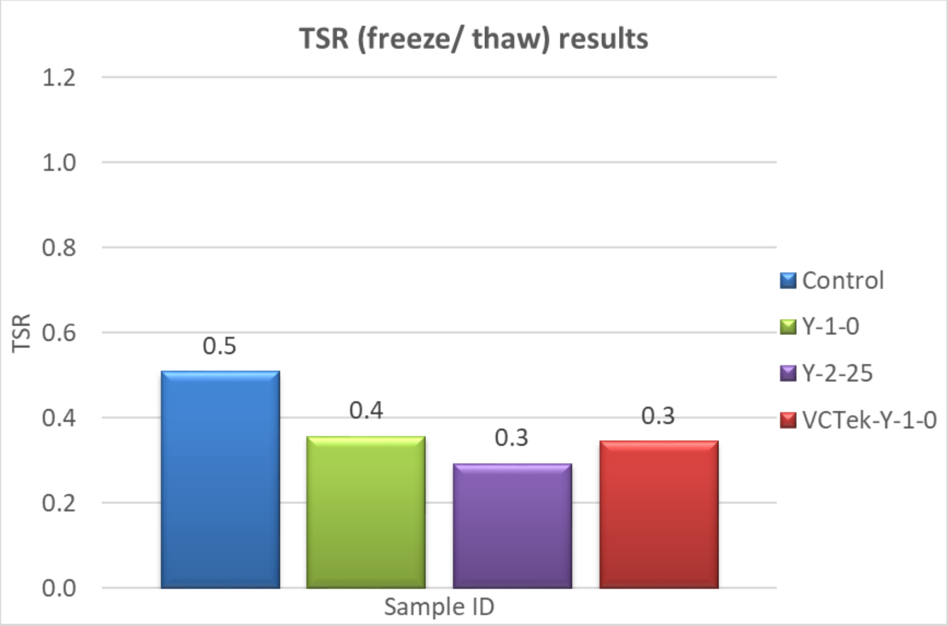

Figure 32. TSR results for conditioned samples with the freeze/thaw conditioning

The TSR results for the samples conditioned with the freeze/thaw cycle are shown in Figure 32. It can be concluded from the figure that the TSR values for all modified and unmodified samples were decreased after subjecting the samples to freeze/thaw conditioning. However, the reduction rate is almost similar for asphaltenes-modified samples and unmodified samples. Hence, modified samples using asphaltenes were not more susceptible to freeze/thaw cycle conditioning compared with the unmodified mixes. Freeze/thaw samples failed to satisfy the TSR value of the 0.7 but this process is not mandatory since the base layer is been studied.

2.5 Stabilized Base Course Performance Tests

2.5.1. Creep Compliance and Strength

Creep compliance test was performed to evaluate the low-temperature performance of asphalt mixtures. In this study, the creep compliance test was conducted at temperatures of 0˚C and -10˚C for both modified and unmodified samples. Marshall samples of dimension 63.5 mm height and 100 mm diameter with three replicates for each of the emulsion contents were prepared. The surface of the samples was cut to the height of 38 to 50mm. Test temperatures of 0˚C and -10˚C were used considering the base layer and PG grading of binder used to prepare the asphalt emulsion. Samples have been conditioned in the air chamber for 3±1 hours before testing. A constant static load was applied to the specimens for 100±2 seconds, and LVDTs recorded samples' deformation in both horizontal and vertical axes. After completing of the creep test, an indirect tensile test with a loading rate of 12.5mm per minute was conducted on the samples until the samples' failure point was reached. Figure 33a presents the setup for performing creep compliance tests, while Figure 33b and Figure 33c show the test samples before and after testing.

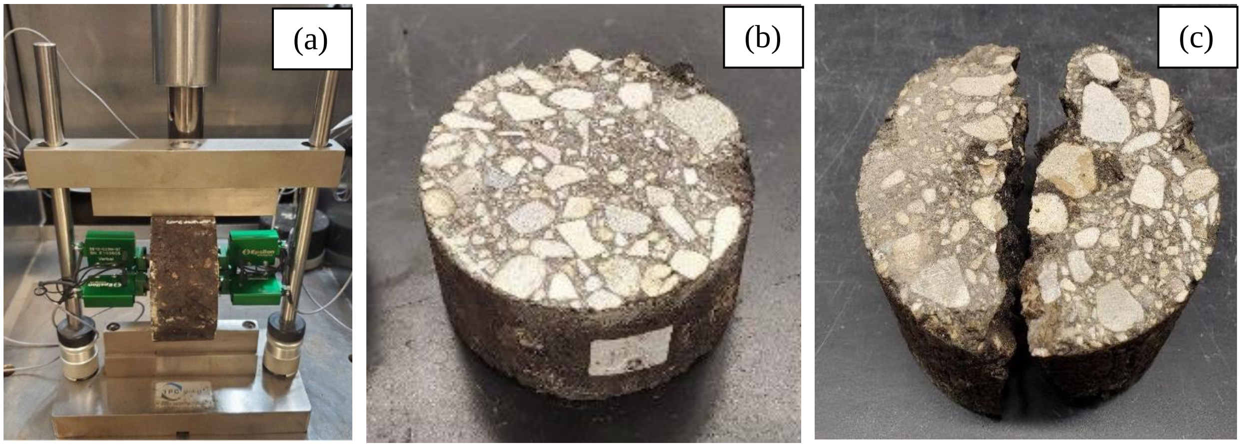

Figure 33. (a) IDT test setup (b) sample before test and (c) sample after test

Figure 34 presents the load-deformation curve results for the samples at 0˚C, while Figure 35 shows results for -10˚C. Table 39 presents the ITS and fracture energy values calculated from load-deformation graphs for samples at both temperatures. Considering ITS results at 0˚C, it shows that maximum failure load increases slightly, but fracture energy for modified samples decreased. After the addition of 1% and 2% asphaltenes, 8% and 7.5% increase in tensile strength and 24% and 17.7% decrease in fracture energy were observed, respectively.

Test results for -10˚C showed higher values for ITS as compared to that of 0˚C, and lower values for fracture energy for both contents of asphaltenes. Reductions for tensile strength were determined to be 7.5% and 23.9% and for fracture energy 25.1% and 21.9% for 1% and 2% asphaltenes, respectively. The results show that the modified samples using 2% asphaltenes were more prone to low-temperature cracking compared to the modified samples using 1% asphaltenes and the control sample.

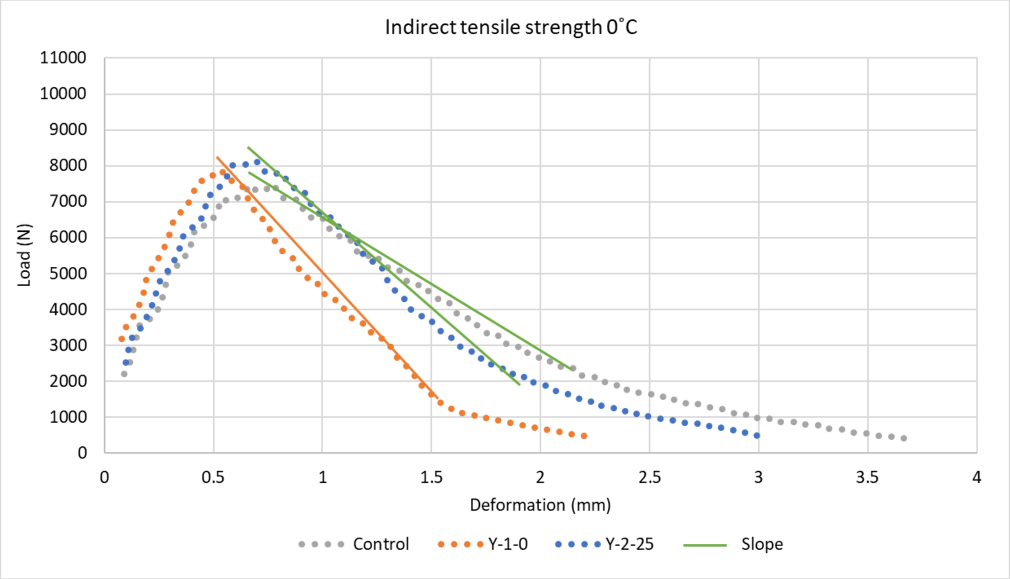

Figure 34. Load-deformation results for 0˚C

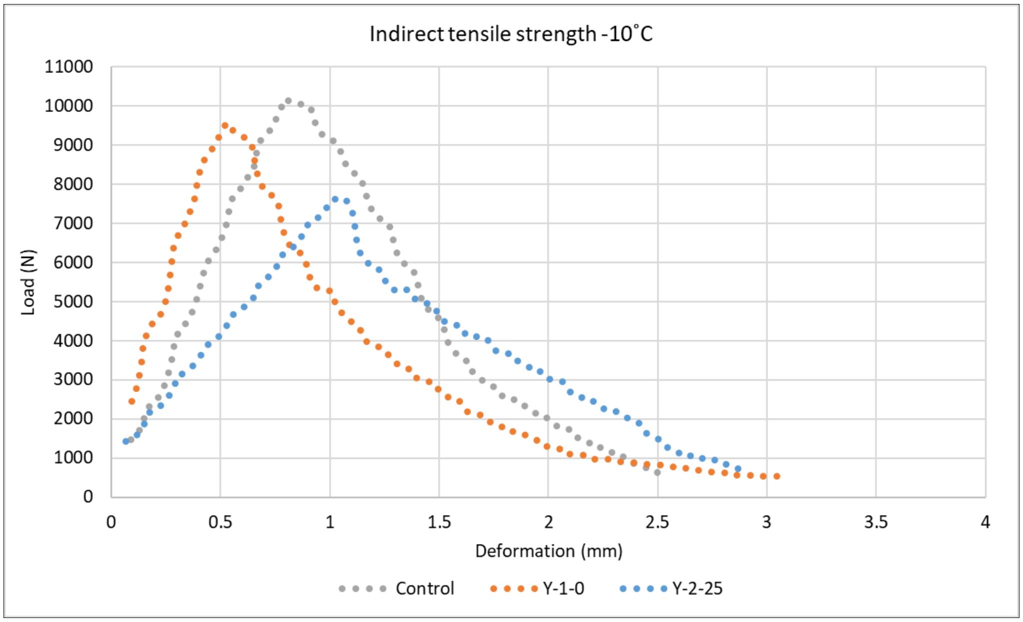

Figure 35. Load-deformation results for -10˚C

Table 39. Tensile strength and fracture energy from creep test

Sample ID	**Temperature (˚C)**	**Tensile Strength (kPa)**	**Fracture Energy (J/m^2)**	**FE Before Peak (J/m^2)**	**FE After Peak (J/m^2)**
Control	0	1083.09	2437.33	637.97	1799.36
Y-1-0		1170.05	1852.65	687.16	1165.50
Y-2-25		1163.99	2006.42	651.29	1355.14
Control	-10	1357.34	2713.02	851.77	1761.25
Y-1-0		1255.27	2032.22	643.58	1388.63
Y-2-25		1033.29	2118.12	926.94	1189.45

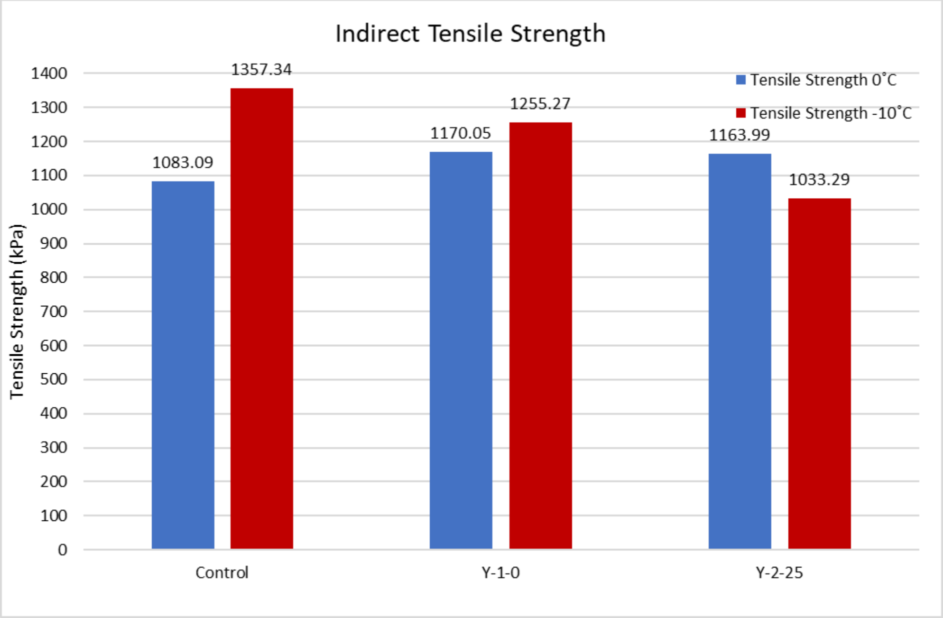

Figure 36. Tensile strength comparison

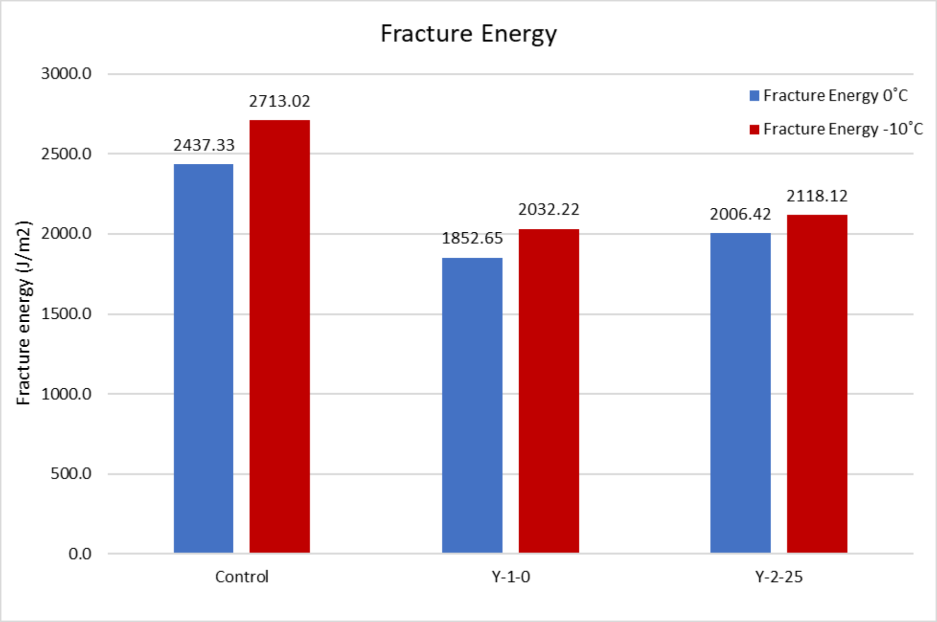

Figure 37. Fracture energy comparison

2.5.2. **Hamburg Wheel-Tracking**

Hamburg wheel tracking test was performed to determine the rutting resistance and moisture susceptibility of the mixes. Hamburg wheel tracking test was conducted as per AASHTO T324-19 using slab samples with dimensions of 400mm length, 300mm width and 80mm height. As shown in Figure 37, a Hamburg wheel tracker was used for testing the samples compacted using a roller compactor device. The test temperature for the wheel-tracking test was determined to be 40˚C based on the binder grade and considering the application of the mix as a base layer. Following the standard procedure, samples were preconditioned inside the water chamber for 45 minutes before testing. Steel wheel with 47mm width and 705±4.5N weight at the frequency of 52±2 passes per minute, and a maximum speed of 0.305m/s at midpoint was used for this test. A maximum of 20,000 passes or 12mm rutting depth, whichever achieved first, was considered as the termination point for the test. The rut depth value and the number of passes were used to determine the rutting resistance index (RRI) and striping inflection point (SIP). The RRI is a ratio of the number of wheel passes and the depth of rutting of the mixes after failure. This parameter is a measure that shows rutting potential of asphalt mixes. SIP is the point at which moisture damage begins to take effect and accelerates the rut depth. A mixture with SIP occurring at a number of load cycles less than 10,000 passes may be susceptible to moisture damage. Figure 39 shows the prepared slab samples before and after conducting the wheel tracking test.

Figure 38. Hamburg wheel tracking device

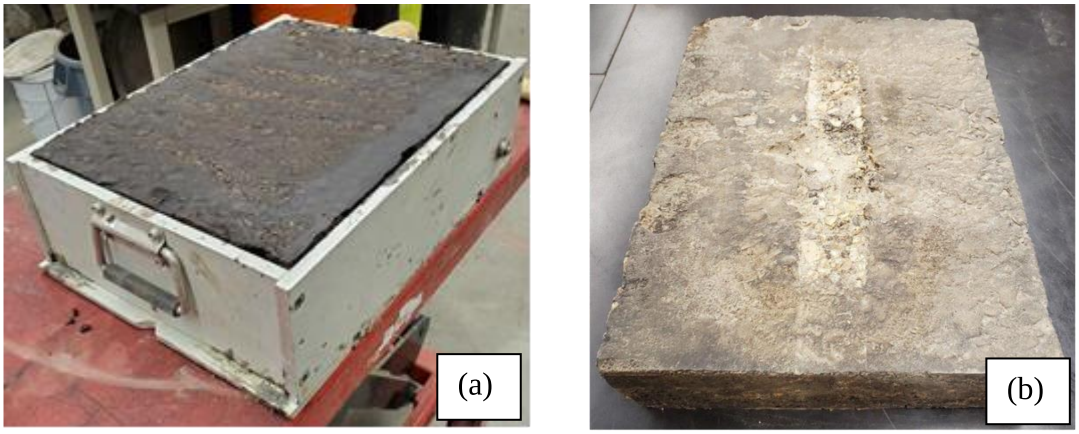

Figure 39. Wheel tracking test (a) compacted slab samples prior to test (b) slab sample after test

Rutting resistance index (RRI) results from the wheel tracking test of the mixes are presented in Table 40. It can be seen that modification with asphaltenes has a positive impact on rutting resistance of the material stabilized by asphalt emulsion. The results show that an increase in RRI values, which indicates an increase in rutting resistance for modified mixtures. A slight decrease in rutting resistance was observed for 2% asphaltenes content modified mixtures as compared to 1%. It could be related to the less compatibility higher air void contents of the mixes with higher asphaltenes content during the sample preparation process. The higher RRI values for the modified samples confirm higher rutting resistance in comparison to the control sample.

Table 40. Rutting resistance

Sample ID	Number of passes at 12mm rutting	RRI	Improvement (%)
Control	3940	2219.74	---
Y-1-0	8712	5360.97	241.5
Y-2-25	8604	5291.12	238.4

A wheel tracking test was also used to determine the mixes' moisture resistance by estimating the stripping inflection point (SIP). The moisture sensitivity of the samples was calculated by dividing the SIP values by the number of passes. This parameter indicates the sensitivity of the mixes to moisture damage. The SIP results for moisture susceptibility of the mixes are presented in Figure 40. It can be seen that the inflection point for the control sample was determined to be about 3800 passes, and the addition of asphaltenes has changed this point to 8200 and 7400 passes for 1% and 2% asphaltenes, respectively. The moisture resistance of the mixes determined using SIP are presented in Table 41. The lower values of moisture resistance for asphaltenes modified mixes indicate that the modified samples could be more susceptible to moisture damage.

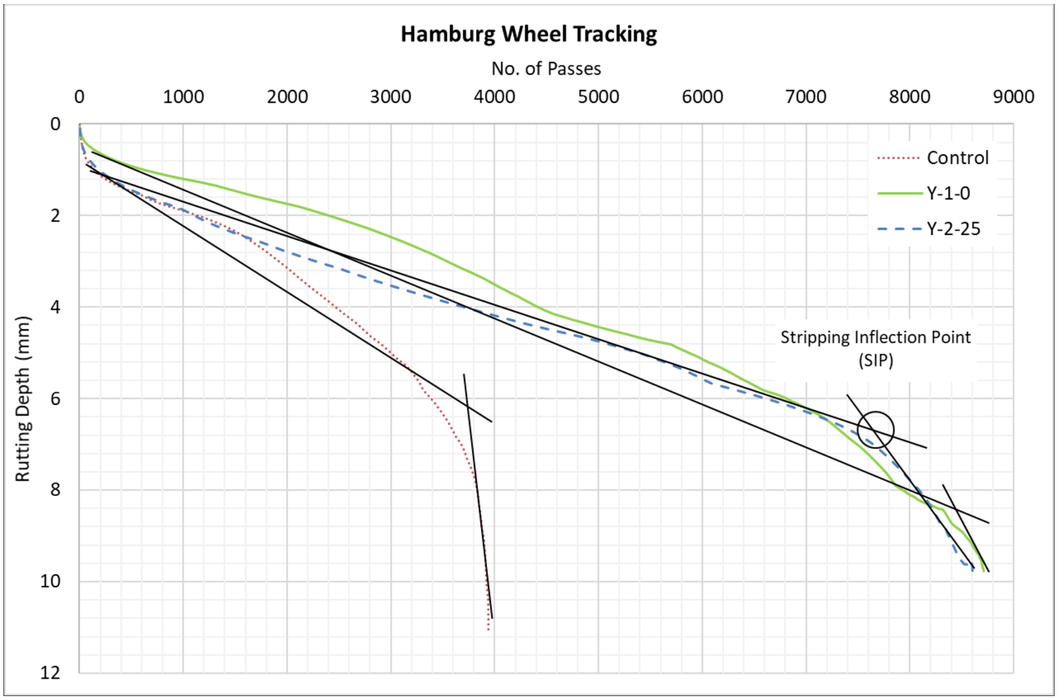

Figure 40. SIP result from Hamburg wheel tracking results

Table 41. Moisture resistance results

Sample ID	SIP	Number of passes at 12mm rutting	Moisture sensitivity
Control	3800	3940	0.96
Y-1-0	8200	8712	0.94
Y-2-25	7400	8604	0.86

2.5.3. Dynamic Modulus and Flow Number Test

2.5.3.1. Dynamic Modulus Test

Dynamic modulus test with a setup similar to section 1-6-2 has been prepared (Figure 1240). Samples prepared with Superpave gyratory compactor with the dimensions of 15cm diameter and 17cm height and cured in the oven for 48hours in mould and 24hours without mould. Using the coring machin, 10cm core has been extracted from the original samples and surface cut with a saw to 15cm height. As it is explained in section I-4-2 a sinusoidal axial compressive stress with loading frequencies of 0.01 Hz, 0.1 Hz, 1 Hz, and 10 Hz was applied to the specimen. The temperature of testing has been determined to be 4˚C, 20 ˚C and 45 ˚C according to the standard. Data from the test has been acquired, and dynamic modulus values were calculated by dividing stress magnitudes by average strain magnitudes. For each sample, two replicates were prepared and tested.

Table 42 provided for properties of the samples prepared. The table shows the average air voids of the samples before and after cut and coring and also the average of G_{mb} values for the test matrix.

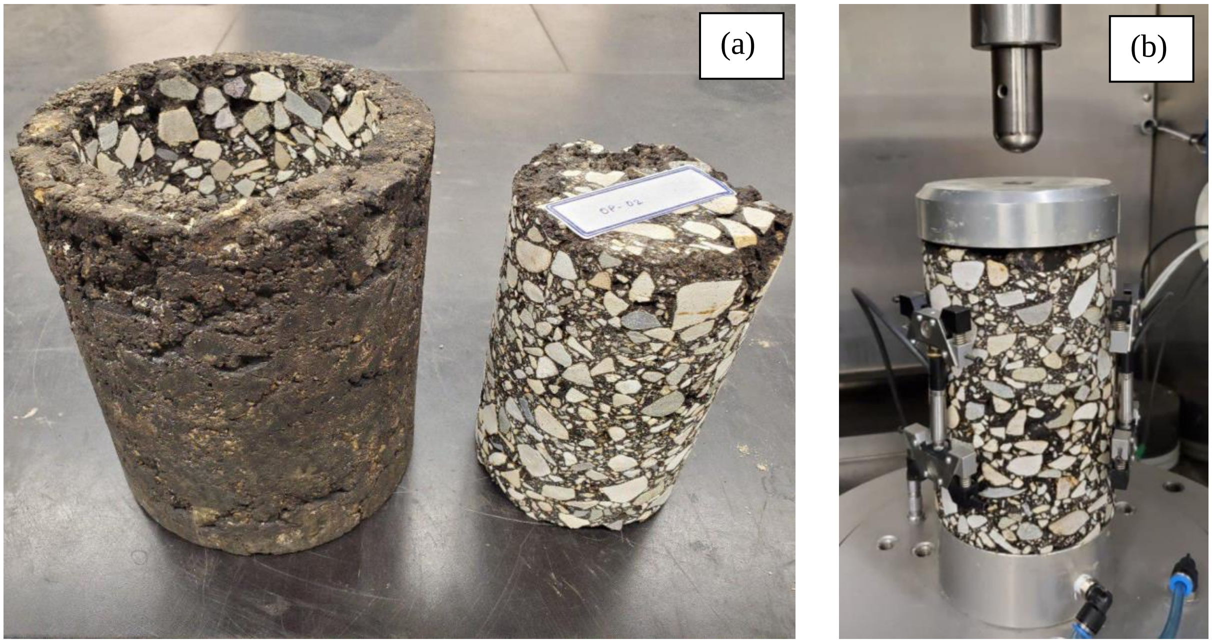

Figure 41. Dynamic modulus test (a) prepared and cored sample (b) test setup

Table 42. Properties of the dynamic modulus samples

Sample ID	Airvoids before cut (%)	Airvoids after cut (%)	G_{mb}
Control	11.937	10.753	2.281
Y-1-0	11.317	10.290	2.272
Y-2-25	11.353	10.202	2.255

Table 43 presents the summary of the results from the test for control, Y-1-0 and Y-2-25 samples for different loading frequencies and temperatures. The average of data for two replicates has been reported in Table 43. Considering the results presented, the samples' dynamic modulus values are decreasing by decreasing the frequency of the load applied as expected. Sample trend is observed by increasing the temperatures of the test. Comparing the result of the modified samples to control, it is indicating that asphaltenes modification is increasing the dynamic modulus of the samples for both concentrations. This enhancement for 1% asphaltenes is more than 2% asphaltenes, which indicates that 1% asphaltenes is more effective. Figure 42 provides the master curve for the samples where the dynamic modulus increases by increasing the frequency. Also, modified samples had a higher dynamic modulus than the control samples as well. The master curves of dynamic modulus are shown in figure 41. This indicates a significant improvement in high-temperature properties at lower speed for modified samples compared to the control sample. However, low-temperature properties at higher speed did not improve adequately in compare to control sample.

Table 43. Dynamic Modulus Results

Sample ID	Frequency (Hz)	Dynamic modulus (MPa)			Phase angle (Degrees)		
		Temperature (˚C)			Temperature (˚C)		
		4 ˚C	20 ˚C	45 ˚C	4 ˚C	20 ˚C	45 ˚C
Control	10Hz	3587.5	1786.5	702.1	20.83	26.31	24.16
	1Hz	2258.5	800.1	221.1	24.64	29.59	26.58
	0.1Hz	1434.5	423.5	138.8	26.81	27.94	22.09
	0.01Hz			115.9			17.26
Y-1-0	10Hz	6383.0	4104.0	1658.5	9.28	15.02	24.58
	1Hz	5236.0	2899.5	906.1	11.21	18.22	27.19
	0.1Hz	4228.5	2023.5	531.4	13.35	20.79	26.86
	0.01Hz			312.4			25.05
Y-2-25	10Hz	5178.5	3211.0	1428.0	10.27	15.96	24.29
	1Hz	4200.0	2240.0	783.4	12.15	19.18	25.98
	0.1Hz	3325.0	1555.5	473.6	13.65	21.61	24.88
	0.01Hz			295.4			22.44

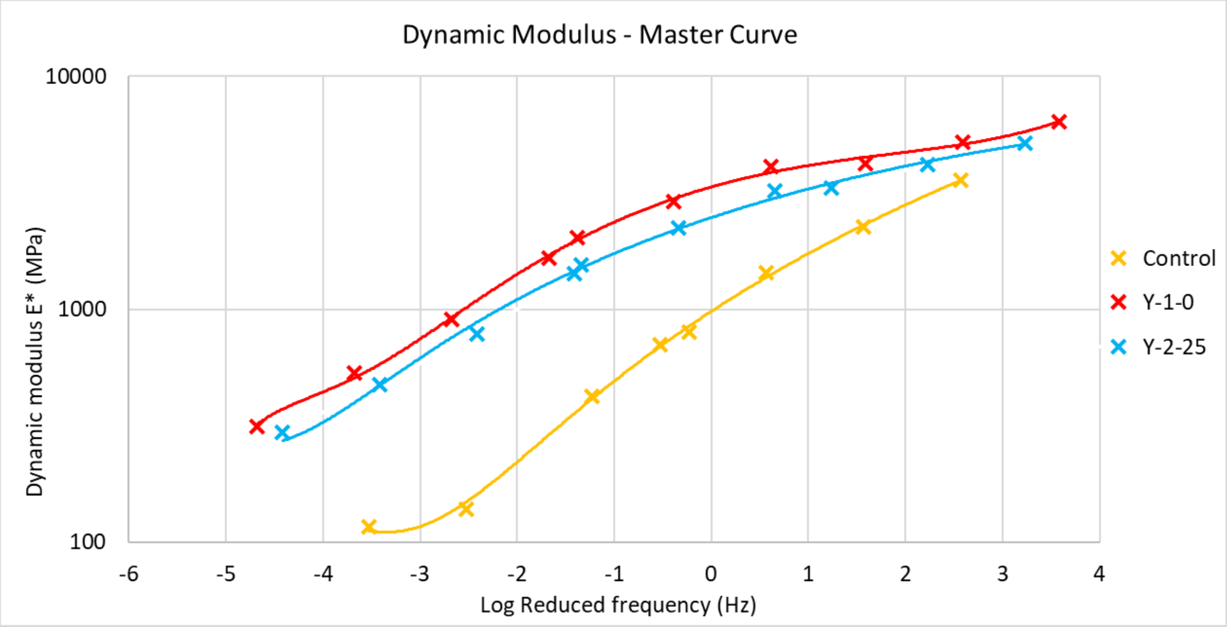

Figure 42. Dynamic modulus master curve for selected asphaltenes-modified binders at the reference temperature of 20℃

2.5.3.2. **Flow Number Test**

Similar to section 1.7.2.2 test procedure has be adopted according to AASHTO T378. Test temperature selected to be 45˚C as estimated High Adjusted PG Temperature determined by LTTP Bind program using the layer information, project location in Edmonton city and climatic data from the nearest weather station. 3kPa and 69kPa for Contact load and deviator stress respectively. Haversine axial compressive loading pattern with loading period of 0.1 second and resting period of 0.9 second were applied. 20000 cycle numbers or maximum of 50000 microstrain which one comes first considered to be the termination limit for the test. Figure 43 shows the results the samples prepared which all terminated at maximum number of cycles. Control sample had the highest deformation and accumulated microstrain value compared to modified samples. This value were almost same for 1% and 2% asphaltenes modified samples and considerably lower than contral sample. Deforamtion and accumulated microstrain value decreased about 81.4% for 1% asphaltenes resulted in better rutting resistance and 84.5% decrease for 2% asphaltenes sample.

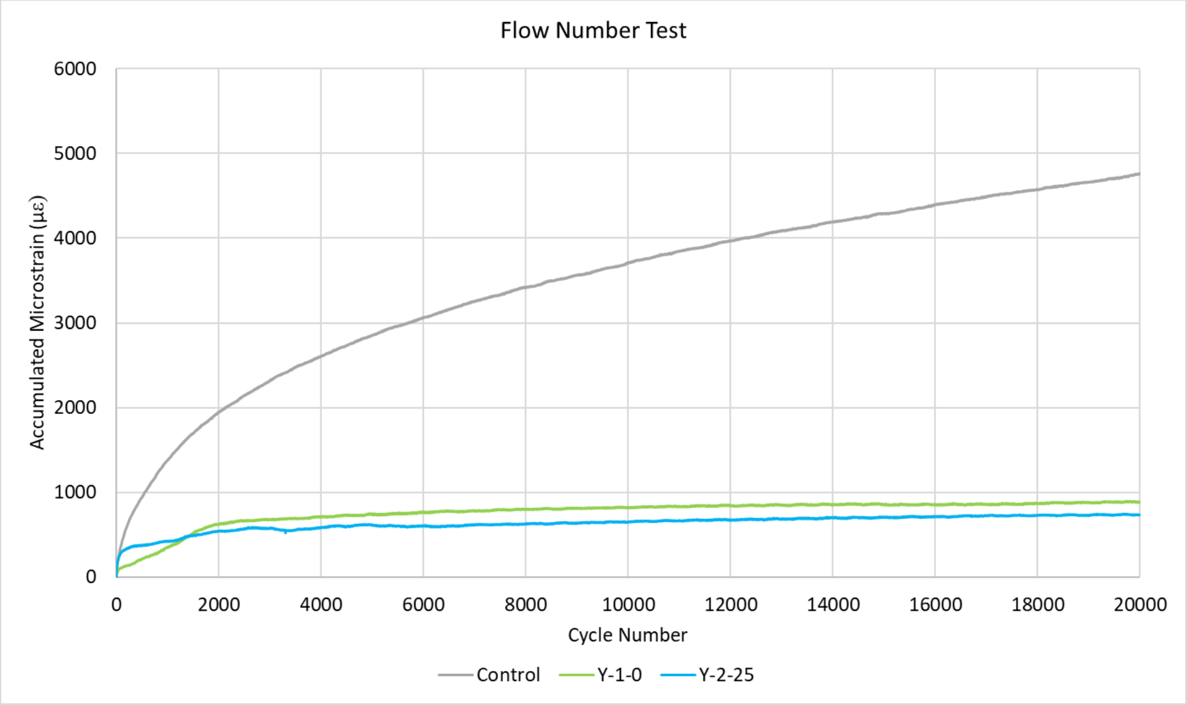

Figure 43 Flow number test results

2.6 Conclusions

- The tensile strength at 25 °C was found to increase by 110.5% and 172.7% for the samples with 1% and 2% asphaltenes content by weight of the mix, respectively. However, it should be noted that the samples with 2% asphaltenes content required extra water to increase the viscosity during mixing with aggregates.
- The tensile strength ratio decreased by 10% and 30% for 1% and 2% asphaltenes concentrations, respectively. This shows that the addition of asphaltenes will increase the moisture sensitivity of the mixes. However, it was not significant for modified mixes using 1% of asphaltenes. TSR during the freeze–thaw cycle also decreased by about 30% and 42.5% for 1% and 2% asphaltenes concentrations, respectively. The second asphaltenes source exhibited a similar decreasing pattern to the first source for 1% asphaltenes.
- The IDT results show that modification of the asphalt emulsion-stabilized material with asphaltenes resulted in lower fracture energy values and, consequently, increasing brittleness of the samples at lower temperatures. However, at lower temperatures, the tensile strength was slightly lower for the modified samples compared to the control samples.
- The Hamburg wheel-tracking test results are indicative of a notable improvement in rutting resistance of the modified mixtures compared to the unmodified samples. The RRI index was found to increase by 141.5% and 138.4% for both the 1% and 2% asphaltenes content samples, respectively, compared to the control samples. The flow number test results also confirm the wheel-tracking test results.

- The dynamic modulus values for the modified samples increased compared to the control sample. Comparing the 1% and 2% asphaltenes samples, improvement in dynamic modulus for the samples containing 1% asphaltenes was more significant.
- Asphaltenes as a waste material has a similar—or, in some cases, superior—impact on the asphalt emulsion-stabilized courses in comparison to the various conventional active fillers such as cement. This material could be used as an inexpensive and environmentally friendly alternative to satisfy or improve the properties of the mix.
- This study was limited to the granular layers composed of raw aggregates. However, using the same stabilizing material (asphaltenes and asphalt emulsion) to stabilize reclaimed asphalt pavements (RAP) could be very beneficial for the asphalt industry. Hence, this should be given consideration as the next step in this research.

3. References

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