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.