Analysis of Alberta's pavement capacity to support winter weight premiums

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ABSTRACT

FPInnovations, in cooperation with Alberta Transportation and the Laval University i3C Chair, undertook a review of the starting threshold for initiating winter weight hauling in Alberta. The objective of this project was to conduct an engineering analysis of freezing pavements to determine the minimum frost depth at which log hauling at winter weight premiums (WWP) in Alberta could start without compromising pavement service life. The report describes literature on freezing pavement engineering, Canadian winter weight policies, a controlled trafficking simulation of an instrumented pavement as it was frozen, and subsequent modeling to valiidate results and extrapolate results ot a wider range of pavement structures. It was recommended that the current 1.0 m starting frost depth threshold be reduced to a depth of 700 mm.

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1. EXECUTIVE SUMMARY

FPInnovations, in cooperation with Alberta Transportation and the Laval University i3C Chair, undertook a review of the starting threshold for initiating winter weight hauling. The current threshold is 1 m of frost, which is the most conservative threshold used by any jurisdiction in Canada that allows winter weights. Neither the Alberta threshold, nor any other threshold, is substantiated by an engineering analysis of the structural capacity of freezing pavements. The objective of this project was to conduct an engineering analysis of freezing pavements to determine the minimum frost depth at which log hauling at winter weight premiums (WWP) in Alberta could start without compromising pavement service life. An extensive literature review on freezing pavement engineering and Canadian winter weight policies was conducted, and a summary of research was prepared. Five provinces and two territories have winter weight policies: Alberta, Saskatchewan, Manitoba, Ontario, New Brunswick and the Yukon and Northwest Territories. The report describes a controlled trafficking simulation of a typical Alberta pavement as it freezes. This pavement was constructed in Laval University's environmentally controlled pavement test pit and trafficking was applied at four load levels with an accelerated traffic simulator. Numerous sensors measured instantaneous pavement responses to the traffic loads and to environmental conditions.

Results from two cycles of pavement freezing and accelerated trafficking consistently showed that the hot mix asphalt of the test pavement experienced a rapid reduction in strain as it cooled. Strains in the hot mix asphalt mat further decreased as it cooled past freezing, and as the frost penetrated the granular base below. When the pavement structure and the top of the subgrade were frozen (at a frost depth of 600 mm), the strains in both pavement and at the top of the subgrade, and the surface deflection, were minimal. The pavement structure became insensitive to increasing axle loading (within the scope of loads tested) at frost depths of 600 mm or deeper, reflecting a global increase in bearing capacity. A long-term damage analysis also was performed using the measured strains. The result was that, from a service life perspective, the risk of pavement damage after 600 mm frost penetration appeared to be very minor, even at the heaviest loading tested. The trafficking test results were validated with layered elastic analyses of the same pavement structure. The modeling predicted very similar trends to the lab testing, although strain estimates were higher than measured in the lab. A sensitivity analysis was conducted to assess the risk associated with hauling WWP at a reduced frost depth for a variety of representative, weak, Alberta pavement structures. It is recommended reducing the current 1.0 m starting frost depth threshold to a depth at which the roadbed is well frozen, and resists thawing during brief warming spells in the early winter. This should lead to WWP staying on once they are instated, causing less upset for both forestry and heavy haul trucking operations and for regulators. Given the results of this study and these considerations, FPInnovations recommends that AT start WWP at a frost depth of 700mm.

Benefits to the Province, the forest industry, and the heavy haul industry are expected to accrue from a longer WWP period and (or) a shallower frost depth threshold. The forest industry is predicted to realize $2.44M in haul savings from a 1.5 week-long extension of WWP. The Province could see savings in pavement rehabilitation costs of between $1.4M and $2.5M per year from the changes to forestry hauling. Given a shallower frost depth requirement, there may be more participation in the winter weight program by forestry companies and heavy haulers in the south of the Province and during warmer winters.

2. INTRODUCTION AND PROJECT OBJECTIVES

Winter weight premiums (WWP) allowed in some provinces help the forest sector increase yearly revenues and offset the impacts of spring load restrictions. It is proven that, given an annual volume of product to be transported, a modest increase in payload during winter can dramatically reduce trucking costs, as the number of trips decreases considerably (Yi et al. 2016). An extensive literature review on freezing pavement engineering and North American winter weight policies shows that five provinces and two territories currently have winter weight policies: Alberta, Saskatchewan, Manitoba, Ontario, New Brunswick, and the Yukon and Northwest Territories.

FPInnovations, in cooperation with Alberta Transportation and the Laval University i3C NSERC Chair, undertook a review of the starting threshold for Alberta winter weights. The current policy is based on a 1 m-deep frost depth threshold. FPInnovations and Laval University ran a series of tests to determine the structural capacity of freezing Alberta-style pavements and, ultimately, the optimum frost depth to be used for setting WWP.

The objective of this research project is to make recommendations to Alberta Transportation regarding optimal frost depths in provincial highways prior to starting the annual winter weight log hauling programs. The objective will be achieved with the following subtasks:

- Measure stiffness properties of unbound pavement materials from Alberta as they freeze.
- Develop a layered elastic modeling approach for freezing pavements using the freezing patterns and frozen material properties as inputs. Conduct preliminary modeling on the two cases studied sites to assess impact of freezing depth on key pavement strains (for brievety, the results from the preliminary modeling were not included in this report).
- Validate the measured instantaneous stress and strain responses the instrumented pavement constructed to Alberta Transportation specifications at the University of Laval by using the modeling approach.
- Validate long-term trafficking results of the frozen Alberta-style pavement to failure by using a strain-based service life model for frozen pavements.
- Establish the economic impact of WWP change.
- Recommend new starting frost depth for WWP according to results from this study.

3. SUMMARY OF PROVINCIAL WINTER WEIGHT PREMIUM POLICIES

Alberta

Alberta Transportation operates a network of frost probes that is used to initiate WWP. The Alberta frost depth threshold for initiating winter weight hauling by both heavy haulers and the forest industry is currently 1.0 m. Regulators have advised FPInnovations that this threshold is based on historical practice rather than a rigorous engineering analysis. The starting frost depth threshold was originally set at 4 feet but was reduced to 1.0 m when metric units were adopted by the province.

Alberta Transportation evaluated the structural sufficiency of its highway bridges to support common log hauling truck configurations loaded to legal and three higher weight conditions. For example, when evaluating bridges for some truck configurations the tandem drive axle groups were assessed at 17000 kg, 20000 kg, 24000 kg, and 25000 kg. Starting in 2009, FPInnovations assessed the dynamic performance of Alberta's log truck configurations when loaded to the maximum axle group weights from the bridge evaluations; configuration-specific weight limit adjustments were made, as necessary, to ensure each configuration achieved acceptable dynamic performance with even the heaviest winter weight premium.

The Technical Services Branch of Transport Engineering, Alberta Transportation, develop maps of the Alberta highway network specific to each log hauling truck configuration. These maps graphically delineate the winter weight premium that applies to that configuration when on each highway. The winter weight premium, denoted with a specific color code (green, blue, yellow, or red), corresponds to the maximum loading for that configuration that respects the minimum bridge capacity along the affected highway. Green routes allow the maximum weights per configuration. Gross vehicle weight may not allow the vehicle to maximize the axle weight allowance. Some configurations may be limited by a cap placed by Alberta Transportation of 65,000 kg. This cap is to allow more routes to be used for log haul during the winter weight period. Blue route maximum axle and GCVW are based on the limitations and bridge restrictions along the route. Yellow routes may or may not allow winter weights. This rating is based on the configuration, interaxle spacing and any bridge limitations and restrictions. Red routes are limited to regulated weights as per the Commercial Vehicle Dimension and Weight Regulation, unless there is a road ban or a bridge that has a limitation less than regulated weights.

A highway may be delineated as a blue route for one configuration but be a green route for another. More detail is available in Alberta's *Guide to Log Haul in Alberta*, which can be accessed at http://www.transportation.alberta.ca/content/doctype276/production/guidetologhaul.pdf

Trucks loaded to green route weights enjoy the highest winter weight premiums (up to 41% higher GCVW); trucks loaded to blue route weights have moderate winter weight premiums (up to 27% higher GCVW), and trucks loaded to yellow route weights have even smaller winter weight premiums (up to 14%) (table 1). No winter weight premiums apply to red routes. The average green route WWP is about 16% of the GCVW for the most common log hauling configurations (those having 7 to 9 axles). This WWP represents an increase of 1.6 tonnes per axle, on average. The heaviest axle loading is 12500 kg and is for dual-tired single axles (used on single axle jeeps) on green routes. A table presenting maximum GCVW and average axle weight increases for 11 common log hauling configurations is presented in Appendix A.

Table 1. Alberta winter weight premiums by route class, as percentages of gross vehicle weight

Log hauling truck configuration	Yellow routes	Blue routes	Green routes
5-axle tractor/ tandem pole trailer	14%	26%	40%
5-axle tractor/ tandem semi-trailer	14%	27%	41%
6-axle tractor/ tridem pole trailer	0%	14%	26%
6-axle tridem drive tractor/ tandem pole trailer	0%	10%	25%
6-axle tractor/ tridem semi-trailer	5%	14%	27%
7-axle tridem drive tractor/ tridem pole trailer	0%	5%	13%
7-axle tridem drive tractor/ tridem pole trailer (2.9 m wide)	0%	5%	20%
7-axle tridem drive tractor/ tridem semi-trailer	0%	5%	13%
7-axle tridem drive tractor/ tridem semi-trailer (2.9 m wide)	0%	5%	20%
7-axle tridem drive tractor/ tridem semi-trailer (2.9 m wide, self-loader)	0%	2%	16%
6-axle tractor/ single axle jeep/ logger	13%	23%	23%
7-axle truck/ 4-axle full trailer	7%	8%	8%
8-axle tridem drive truck/ 4-axle full trailer	0%	6%	6%
7-axle tractor/ tandem axle jeep/ logger	6%	15%	15%
7-axle B-train	6%	15%	15%
8-axle tridem drive B-train	2%	12%	20%
8-axle tractor/ tandem jeep/ tridem semi-trailer	2%	9%	17%
8-axle tractor/ tandem jeep/ tridem pole trailer	2%	9%	9%
8-axle B-train	2%	9%	17%
8-axle tridem drive tractor/ self-steer semi-trailer (quad)	0%	3%	7%
9-axle B-train (tandem drive)	11%	16%	22%
9-axle B-train (tridem drive)	12%	19%	25%
10-axle B-train	12%	23%	39%

Alberta Transportation maintains a network of 68 thermistor stations with which they monitor the onset of freezing and thawing at highway locations across the province. At each station, there is a vertical array of 14 thermistors located in the pavement at standard depths that are from 5 to 300 cm; additionally a 15th thermistor is located at roadside to measure ambient air temperature.

Freezing patterns during the winter of 2016/17 were analyzed using the 25 thermistor stations located in mid-to-northern Alberta where the forest industry is active. Table 2 summarizes the average and range of freezing rates observed.

The average freezing rate during this winter was 3.3 cm per day, while the range was from 6.5 to 1.0 cm per day. Faster freezing rates can be expected in locations with warmer ambient temperatures, more south and south-west exposure, less snow cover, drier soils, and thicker asphalt and aggregate layers (Doré and Zubeck, 2009).

Table 2. Frost penetration rates observed in mid-to-north Alberta in winter 2016/17

	Time for frost depth to increase 10 cm (days)				Average freezing rate (cm/ day)
	from 60 to 70 cm	from 70 to 80 cm	from 80 to 90 cm	from 90 to 100 cm	
Average	3.2	3.6	3.4	3.1	3.3
Slowest	5.5	8.0	6.6	6.0	6.5
Fastest	0.9	1.3	0.9	1.1	1.0

Saskatchewan

The Saskatchewan winter weight program starting frost depth threshold is 0.75 cm. This threshold is intended to develop 0.3 m of well-frozen material at the surface (i.e., -5° to -10° C at the surface). Saskatchewan Highways and Infrastructure estimates that this depth of well-frozen material at the surface will protect even its most vulnerable highway structures from heavy winter traffic loadings.

Saskatchewan's WWPs are configuration-specific and apply to primary and secondary provincial highways and to municipal roads (table 3). There are some provincial highways and roads where WWPs do not apply – notably because of bridge limitations or because of Rural Municipality concerns about weak road conditions. The winter weight premiums are minor for primary highway routes, and for some of the larger truck configurations operating on secondary and municipal routes.

Table 3. Saskatchewan maximum winter weight premiums by truck configuration and route class, as percentages of gross vehicle weight

	Primary Highways	Secondary Highways	Municipal Roads
9-axle tridem drive B-train	0%	3%	0%
8-axle C-train	0%	-1%	-1%
8-axle B-train	0%	17%	0%
8-axle A-train	-1%	8%	8%
7-axle tridem drive/ semi-trailer	0%	11%	11%
6-axle tridem drive/ pony trailer	0%	2%	2%
6-axle or more tractor/ semi-trailer	2%	19%	19%
5-axle tractor/semi-trailer	6%	18%	18%
4-axle truck with tandem steer	3%	14%	14%

Transportation Partnership Program
SHI manages a Transportation Partnership Program under which approved trucking companies may operate permitted over-weight and/or over-dimension trucks on provincial highways. It is through this program that larger truck configurations may operate at significantly above legal GCVW limits on primary highways. Under this program, trucks can carry up to the following on approved routes (bridges being the restrictive infrastructure) without paying road damage fees in the winter:

- 62.5 t on 6-axle semi-trailers (33% more than the legal maximum on Primary Highways).
- 75.0 t on 8-axle B-trains (18% more than the legal maximum on Primary Highways).
- 92.5 t on 9-axle B-trains (46% more than the legal maximum on Primary Highways).

Manitoba
In 2013, after an analysis of surface deflection vs. frost depth measurements (Bradley 2013), Manitoba adopted the same 0.75 m winter weight starting frost depth threshold that is used by Saskatchewan. Seasonal winter weights start on fixed dates in each of Manitoba's three climate zones but will start sooner if the 0.75 m frost depth is reached sooner; seasonal winter weights also end on fixed dates in each of Manitoba's three climate zones but may end later depending on weather (thaw) conditions.

Manitoba's WWPs are applied in two ways: (a) the "seasonal route designation", and (b) the 10% increase in maximum axle weight. Under the seasonal route method, a lower basic weight class highway (e.g., B1 or A1) is reclassified for the winter to a higher basic weight class (e.g., "seasonal A1" or "seasonal RTAC"). In so doing, the allowable axle weight limits on these routes increase from their basic limits to the normal limits applicable on A1 or RTAC highways, plus the applicable WWP, for the duration of the winter. Vehicle GCVWs may not exceed, however, the statutory limit for the seasonal route class. The average GCVW increase for RTAC standard 5-, 6-, 7- and 8-axle truck configurations is 11% for B1 routes reclassified to "seasonal A1", 4% for A1 routes reclassified to "seasonal RTAC", and 15% for B1 routes reclassified to "seasonal RTAC".

Under the 10% premium increase method, the statutory axle group weight limits listed in Table 4 are increased by 10% except for steering axles (no increase allowed) and for tandem axle groups (no more than 17.6 tonnes allowed). Very modest GCVW increases result under this method (e.g., 1% for 8-axle units and 3% to 9% for 6- and 7-axle units). Different weight limits apply to non steering axles equipped with wide base single tires and these can be found at https://www.gov.mb.ca/mit/mcd/mce/pdf/mb_vehicle_weights_and_dimensions_guide.pdf .

Table 4. Manitoba statutory weight limits by axle type and route class

	RTAC route (tonnes)	Class A1 Highway (tonnes)	Class B1 Highway (tonnes)
Steering axle, single tire	6.0 *	6.0 *	6.0 *
Single axle, dual tires	9.1	9.1	8.2
Tandem axle, dual tires	17	15.2 (non-RTAC) 16.0 (RTAC)	13.8 (non-RTAC) 14.5 (RTAC)
Tridem drive, dual tires	21 **	20 **	19 **
Tridem axle semi-trailer, dual tires	21 to 24 ***	20 to 22 ***	19
Statutory GCVW limits (winter and summer)	62.5 to 63.5 (RTAC vehicles) *** 56.5 t (non-RTAC vehicles)	56.5 t	47.63 t

Notes: *No WWP is allowed **axle spread 2.4 to 2.8 m ***depending on axle spread

Ontario

The Ontario Ministry of Transportation allows vehicles hauling raw forest products (i.e., logs, chips, biomass created in the forest) to increase axle load limits during the "freeze up" period; the start and end dates, and geographical limits of which are set by MTO regional staff. The placing and lifting of the WWP are largely subjective, with visual observation of pavements and monitoring of weather and pavement and subsurface sensors indicating that the road structure and sub-grade material is well frozen or will soon begin to thaw. Typically the current practice is to initiate winter weight premiums when there has been in excess of 40 cm frost depth for 7 days, but this can vary based on the road condition. If the road is in poor condition, the Maintenance Supervisor may choose to wait for until the frost depth reaches 50 cm before initiating winter weight premiums.

In addition to subjective observation of weather conditions, pavement condition, and roadside drainage, regional managers also have access to temperature data at the pavement surface and a depth of approximately 40 cm at Road Weather Information System (RWIS) stations on higher classification highways across the province, and for the past 1 to 2 years at 7 special Seasonal Load monitoring stations on surface-treated highways. Instrumentation at those stations includes thermistor strings from the surface down to approximately 2.5 metres. Data from those stations are available to regional staff on MTO's ARWIS website. Predictive models applied to the RWIS station data forecast the dates of freezing and thawing up to three days in advance.

Any axle group mass may be increased by no more than 10% provided this does not cause the GCVW to increase by more than 10% of the legal limit. Regional staff has advised that the 10% raw forest products allowance was intended to address payload weight lost to ice and snow accumulation on round wood cut and loaded in the forest. MTO believes that this additional 10% allowance could be carried, with no damage, on frozen pavements.

The history regarding testing or modelling, political influence or other jurisdictional practice behind the selection of the 10% value is not known. MTO has no immediate plans to change the 10% WWP or to apply it to other transport industries. The WWP weight increase applies to King's Highways but not to Class B highways.

New Brunswick

The New Brunswick Department of Transportation and Infrastructure (DTI) implemented a winter weight log hauling program in 2013. DTI adopted a 1.0 m-deep starting frost depth threshold based on that used by Alberta. The province was divided into four winter climatic zones to assist with the estimation of freezing rates and the implementation of winter weights. Thermistor stations have been installed in each zone to monitor freezing and thawing.

In 2016, with road monitoring data from the thermistor stations, FPInnovations conducted a pavement analysis that indicated winter weights could start sooner, and load increases could be greater (provided the heavier loading didn't jeopardize truck safety or bridge life) (Bradley and Thiam 2016). In response, the Department of Transportation recently announced a policy change to a starting frost depth threshold of 0.85 m. In recent years, winter weight hauling has lasted six to eight weeks in the north of the province but only zero to two weeks in the south. The recent policy change is expected to provide up to two extra weeks of winter weight hauling for all parts of New Brunswick.

Under WWP policy log hauling trucks may carry up to 2 tonnes of additional load on their tandem drive group during the winter weight period. Approved log hauling configurations for winter weight hauling include only 6-axle and 7-axle configurations. The 7-axle unit is similar to the 6-axle unit except that it is equipped with a dual-tired, single lift axle mounted forward of the tridem axle group on the trailer.

Northwest Territories

WWPs are applied to paved and gravel road networks, as well as to winter roads. The start and end of WWPs may vary from year to year depending on assessed road conditions. In the last 10 years, WWPs have typically started within a week of Dec. 9.

Winter weight premiums are normally initiated after a degree-day count of 400° C has accumulated. This threshold value is expected to generate a 300-mm frost depth under normal circumstances. The threshold value may be reduced to as low as 250° C degree days in winters with heavy winds and snow cover less than 20 cm (i.e., rapid freezing conditions). Regional staff also consider fall moisture conditions, subgrade types, and winter weather conditions when judging local rates of freezing. The Department of Transportation maintains one thermistor station and supplements it with frost depth data from Alberta and British Columbia. The application of winter weight premiums on all-season highways is typically delayed until the adjacent winter road networks are constructed and opened. The Department of Transportation reduces WWP during midwinter thaws to improve safety and to reduce operating and maintenance costs.

The Northwest Territories has northern and southern frost zones that are separated by the Mackenzie River and the Great Slave Lake. In addition to the two frost zones, there are four areas where networks of winter roads are commonly constructed to augment the all-season highway system:

1. The Inuvik Region (ice roads built on salt water).
2. The Mackenzie River Valley, north of Wrigley (winter roads on frozen ground).
3. The Community Area north of Behchokǫ̀ (winter roads on frozen ground and lakes).
4. The Slave Geological Province (winter roads on frozen lakes and rivers extending from Detah north and east into Nunavut).

Trucks with winter tolerances are allowed an extra 500 kg on their non-steering axles thus reducing spinouts (Table 5). A, B and C-trains are not allowed any winter load increase.

Table 5. Northwest Territory winter weight premiums

	Winter weight premium (t)	Legal GCVW limit (t)
5-axle tractor/ semi-trailer	41.5	39.5
6-axle tractor/ semi-trailer	49.0	46.5
7-axle tractor/ full trailer	57.0	53.5
8-axle A-Train	53.5	53.5
8-axle B-Train	63.5	63.5
8-axle C-Train	58.5	58.5

Yukon

The Yukon Department of Transportation and Public Works initiates its winter weight program when pavements are stable and well frozen. A 1m frost depth threshold is usually required to enable WWP. It is important to mention that the Yukon Department of Transportation and Public Works does not currently have a particular WWP policy in place. Requests for increased truck GCVW during winter from different industrial sectors are treated on a case to case basis. Therefore, for each request, the short-term and long-term impact of a heavier truck configuration on a frozen pavement structure is estimated. The decision to allow additional loads is then made. Well frozen, stable, winter conditions are judged to exist based on consultation with regional staff, frost depth readings from three thermistor stations, and weather forecasts.

The winter weight premium is governed by assessed capacities of highway bridges and, in no case, exceeds 10% of the allowable GCVW.

4. MEASURING THE MECHANICAL BEHAVIOR OF FREEZING ALBERTA PAVEMENTS USING LAVAL UNIVERSITY PAVEMENT SIMULATOR

Characteristics of the simulator, pit, and temperature control system

The experimental pavement used for the project was built in an indoor test pit at Laval University. The pit dimensions were: 2 m wide, 6 m long, and 2 m deep. Figure 1 illustrates the instrumented, as-built, test pavement, which was typical of an existing Alberta pavement structure. The structure consisted of 180 mm of hot mix asphalt EB-10S, 300 mm of MG-20 (granular base equivalent to the Alberta 2-20 specification) on a low plasticity clay subgrade. The design target was for 170 mm-thick hot mix asphalt layer but this had to be increased to 180 mm to compensate for subgrade settlement. A 76-12 geotextile was used as a separation layer between the clayey subgrade soil and the granular base course in order to prevent their mixing. It is important to mention that the 76-12 geotextile does not increase the structural capacity of the pavement structure. In addition, TEXdrain 80H geotextile was installed down the concrete walls of the pit to reduce adhesion of the soil to the walls. The instrumentation used in the test pavement (number 1 to 11) are described in detail in Table 6 below (page 17). The mix characteristics of the hot mix asphalt, and the complex modulus of the hot mix asphalt, and the resilient modulus of the granular base are included in Appendix B. Figure 2 presents the grain-size distribution and a summary of the pavement materials characterization tests. The sensors are described in Table 6. The pavement materials were comparable to those used in Alberta but were accessed from the Quebec City area because it was not possible to transport the materials from Alberta for economic and logistical reasons.

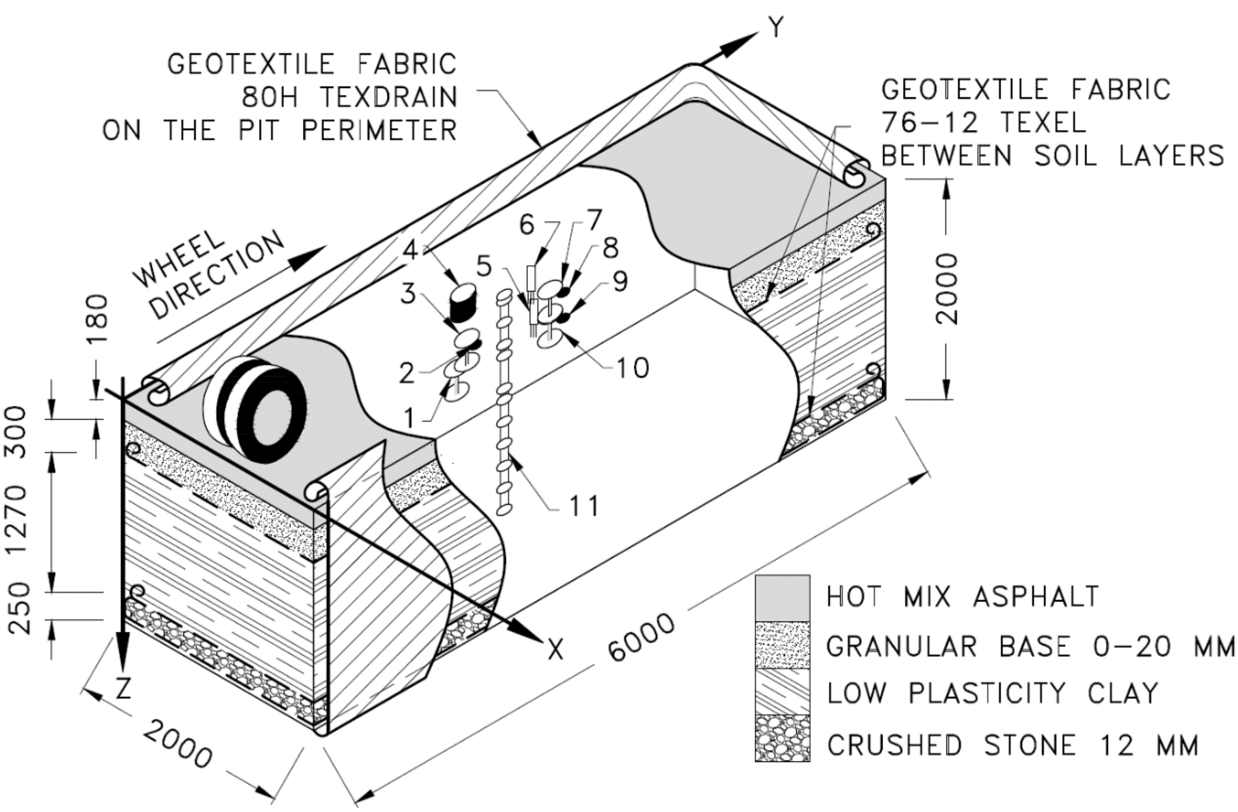
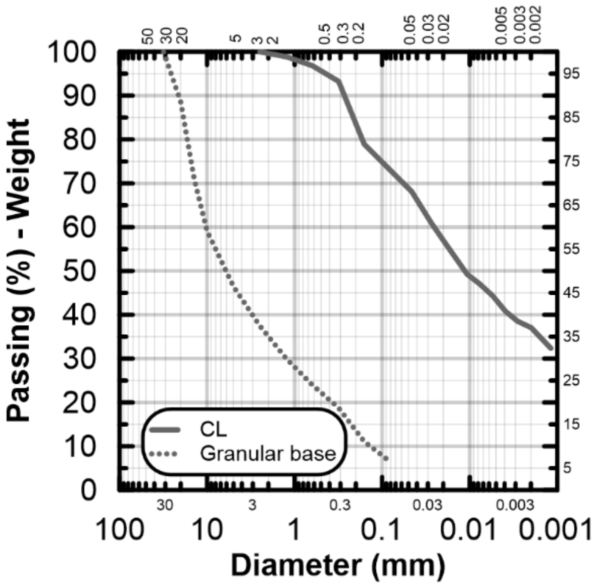


Figure 1. Tested pavement layers and instrumentation.



	Clay Subgrade	Granular Base
ρ_{dmax} (kg/m^3)	1700	2249
w_{opt} (%)	21	6.5
w_p (%)	17	-
w_L (%)	28	-
Fines (%)	73	6.4
Clay (%)	37	-
ρ_s (kg/m^3)	2765	2.687
CBR (%)	2.5	68.3
USCS classification	CL	GW-GM

Figure 2. Gradation and material characteristics of granular base and subgrade materials.

The heavy vehicle simulator of Laval University was used to traffic the test pavement (Figure 3 and Figure 4). The heavy vehicle simulator has the capability to replicate environmental and mechanical conditions experienced on real pavement structures. The simulator is portable and was positioned over the test pit once the test pavement construction was completed.

Figure 3. Heavy vehicle simulator installed above the test pavement.

Figure 4. Heavy vehicle simulator in freezing mode, with insulation panels positioned.

Data acquisition methodology

A ProSens data acquisition system (manufactured by OPSENS Solutions) was used for the fiber optic strain gages, and a CompaqDAQ system (manufactured by National Instruments) was used for the electrical stress and strain gauges. Pavement water content and temperature readings were collected hourly. The pavement's mechanical responses changed rapidly at the beginning of the freezing cycle so measurements were collected three to four times a day.

At deeper frost penetration the pavement mechanical responses changed more slowly, and the frequency of data collection was reduced to one to two times a day. Reference measurements were gathered prior to freezing the pavement, at a surface temperature of 20° C.

Temperature and drainage control

The temperature at the pavement surface was controlled using the heating and cooling system of the simulator. During the initial conditioning load applications the pavement's surface temperature was held at 20° C; and, during the freezing and subsequent load applications, the surface temperature was kept at -10° C. The temperature at the bottom of the pit was maintained at 1° C throughout the test using a temperature-controlled concrete slab. The combination of top and bottom temperature controls resulted in a realistic thermal gradient within the test pavement structure.

The pit was also equipped with a drainage system with which the pavement's water table height was maintained at 1.5 m below the pavement surface during freezing cycle 1, and at 0.8 m below the pavement surface during freezing cycle 2. These water table depths were representative of well drained and wet subgrade conditions, respectively.

Pavement trafficking

The test parameters selected for this study were based on standard practice, machine limitations, and practical considerations, and are summarized in Table 6. The travel speed of the single half-axle carriage was 9 km/h. The half-axle was equipped with 315/80R22.5 dual tires inflated to 710 kPa. Loading was varied between 4550, 5000, 5500, and 6250 kg and this corresponded to Alberta single-axle legal loading of 9000 kg, and three winter weight premium loadings (10 000 kg, 11 000 kg, and 12 500 kg). These winter weight loadings were 10%, 21%, and 37% heavier than the legal loading. Testing with four loadings throughout the freezing process allowed researchers to carefully and precisely document how an Alberta-style pavement responds to loading under winter conditions.

Table 6. Testing parameters and loading characteristics for this project

Testing parameters	Values
Carriage speed	9 km/h
Half-axle loads	4550 kg (reference load), 5000 kg , 5500 kg and 6250 kg
Tire size	315/80R22.5
Tire inflation pressure	710 kPa
Pavement temperature	-10° C (at AC surface), 1° C (bottom of pit)
Depth to water table	1500 mm (freezing cycle 1), 800 mm (freezing cycle 2)

Construction of test section

Prior to pavement construction, TEXdrain geotextile was positioned on the side wall. The open graded layer then was put at the bottom of the pit and covered with the 76-12 geotextile.

Next, the clay and granular base materials were placed and compacted in 300 mm and 150 mm-deep lifts, respectively. After the compaction of each layer of pavement material, the upper surface was carefully leveled. The dry density at the top of the clay and granular base layers, as measured using the sand cone-equivalent method, were 1506 kg/m^3 (with a moisture content of 20.7%) and 2400 kg/m^3 (with a moisture content of 4.7%). The hot mix asphalt was compacted in two layers. Figure 5 and Figure 6 show the clay subgrade under construction and the completed granular base course.

Figure 5. Clay subgrade under construction.

Figure 6. Completed granular base course.

Mechanical response instrumentation

The test pavement was instrumented to monitor temperature and moisture conditions, and mechanical responses to trafficking during freeze-up (Figure 1). Table 7 presents a detailed list of the gauges used in the pavement layers to collect data on strain, deflection, stress, water content, and temperature. The hot mix asphalt tensile and vertical strains, and the surface deflection were measured with fiber-optic-based sensors, while the vertical stress, volumetric water content, and temperature were measured with electrical sensors. The mechanical responses (stress and strain) of the subgrade soil were measured at the top of the subgrade under the center of the dual wheel assembly. The mechanical responses of the granular base course were measured at the mid-depth of the layer under the center of the dual wheel assembly, as well. The hot mix asphalt strain sensor was positioned under one of the tires. Finally, the surface deflection sensor was positioned between the two tires of the carriage.

Some issues and challenges were encountered during experimental pavement construction, among other:

- Clay subgrade: The clay for the subgrade layer was air-dried prior to placement in the pit because it was too wet to compact at its original, in-situ, moisture content. After drying to approximately 40% (the clay's plastic limit), the clay was placed in lifts and compacted with a vibratory plate compactor. Density of the clay subgrade was measured using a sand cone device, and the subgrade's resilient modulus was estimated using a lightweight deflectometer.

- The clay subgrade material was highly sensitive to freezing and thawing. During testing, especially during thawing of the test pavement, settlement occurred in the clay subgrade. The instability of the subgrade soil, and it's very low bearing capacity, resulted in damage to some of the strain sensors in the pavement.
- Water table: The water table was raised gradually to the target depths for testing, and no visible swelling of the clay due to the increase in water content was noted.
- Granular base course: The granular base material was installed in two layers, leveled, and then densified with a vibratory plate compactor. To avoid sensor displacement and damage, compaction around the sensors (and in the corners of the pit) was done with a Hilti AVR-1500 jackhammer.
- Asphaltic concrete (AC) or Hot mix asphalt EB-10S type: Due to the subgrade settlement during construction, the hot mix asphalt mat thickness had to be increased from 170 to 180 mm in order to keep the pavement surface flush with the surrounding lab floor.

The asphaltic concrete (AC) mat was installed in two layers and compacted using a small vibratory roller compactor. The compacted lifts were each approximately 90 mm thick which was too thick because the recommended lift thickness for EB-10S is more typically 50-60 mm. This required more effort during compaction in order to achieve the target AC density.

Table 7. Instrumentation installed in the test pavement

Sensor		Sensor type	Structural layer	Position (x,y,z) (mm)
1	Vertical strain	Optical	Subgrade	(990, 2500, 485)
2	Vertical stress	Electrical	Granular base	(990, 2630, 292)
3	Vertical strain	Optical	Granular base	(990, 2500, 242)
4	Transversal strain	Optical	AC mat	(819, 2750, 180)
5	Water content	Electrical	Subgrade	(980, 3350, 505)
6	Water content	Electrical	Granular base	(930, 3350, 342)
7	Vertical strain	Optical	Granular base	(990, 3480, 245)
8	Vertical stress	Electrical	Granular base	(990, 3590, 317)
9	Vertical stress	Electrical	Subgrade	(990, 3580, 532)
10	Vertical strain	Optical	Subgrade	(990, 3480, 480)
11	Thermistors	Electrical	all	(1000, 3000, z[1])
-	Surface deflection	Optical	AC mat surface	(1000, 3000, 0)

[1] Depth of thermistors (mm): 50, 100 (in AC mat), 300, 500 (in granular base), 600, 900, 1000, 1200, 1400, 1600 (in subgrade), 1800, 2000 (in drain rock).

5. LAB TEST RESULTS AND MODEL VALIDATION FOR THE ALBERTA-STYLE PAVEMENT

Pavement testing was conducted between February and June 2016. To evaluate the impact of WWP, first the pavement baseline response was established by loading it with 4550 kg and 5000 kg loads under summer-like conditions. Summer-like conditions were obtained before freezing the pavement referred as t = 0 hour at room temperature with a stable water table. Stress and strain measurements made with Alberta's 4550 kg single axle legal loading under summer-like conditions are taken to be baseline references (hereafter referred to as measurements at *t* = 0). All results collected as the test pavement froze were normalized relatively to the reference measurements and expressed as relative values (RV):

$$\mathrm{RV}\ (\%) = \frac{\text{Value at t (all loads)}}{\text{Value at t} = 0\ \text{h (4550 kg)}} \qquad (1)$$

Temperature gradients

Figure 7 and Figure 8 show the temperature gradients obtained as a function of various frost depth for both freezing cycles. In cycle 1, frost penetration reached 1150 mm. In cycle 2, with the higher water table and warmer springtime ambient temperatures in the lab, frost penetration only reached 940 mm. At the start of both freezing cycles (at *t* = 0 h), the temperature gradient was generally linear and uniformly varied with depth from 18° C at the hot mix asphalt surface to 1° C at the bottom of the pit. In the early stages of the freezing cycles, there was a rapid shift in temperature to the upper pavement layers, followed by a slower frost penetration as the freezing front got further from the surface and encountered wetter materials.

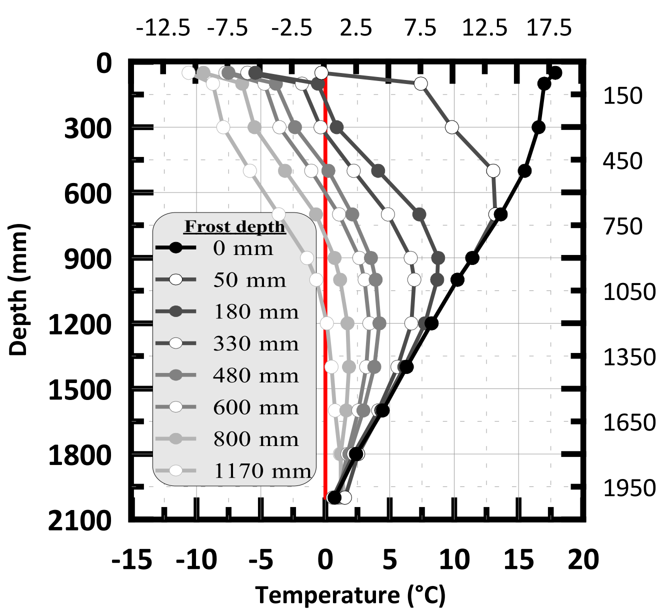


Figure 7. Temperature gradient during freezing cycle 1.

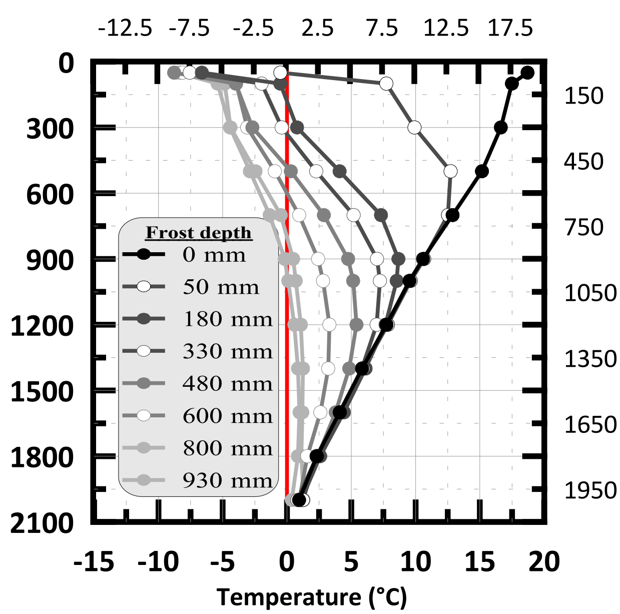


Figure 8. Temperature gradient during freezing cycle 2.

Structural measurements

In order to simplify the results presentation, only strains and surface deflections from freezing cycle 1 are shown in Figure 9. Measured horizontal strains ε_r (m/m) at the bottom of the AC mat and vertical strains ε_z (m/m) at the top of the subgrade for cycle 1 are presented in Appendix C. Freezing cycle 2 presented the opportunity to evaluate pavement response in a freezing pavement that had previously been thawed. The results obtained in freezing cycle 2 were very similar to those from freezing cycle 1. Because the results were similar, freezing cycle 2 results were not reported separate from those of freezing cycle 1 and, instead, are included in Appendix D. As it can be observed, there was a loss of data between 200 and 580 mm of frost penetration for the AC-RV_{strain} sensor (green lines) which was caused by a temporary malfunction of the strain gauge. In addition, a mechanical problem with the heavy vehicle simulator's cooling system caused a brief thaw at a frost depth of 400 mm ($t = 12\ h^{0,5}$), and this generated small increases in surface deflections and strains. To avoid damaging the pavement, no loads were applied until the hot mix asphalt mat was completely refrozen.

The important structural influence of the bound surface layer is demonstrated by the rapid reduction in the surface deflection with decreasing asphalt temperature. When the frost had fully penetrated the asphalt concrete mat (to 180 mm), the relative values of maximum surface deflection were 53%, 58%, 65%, and 75% for loads of 4550, 5000, 5500, and 6250 kg, respectively. The pavement strains showed even greater RV reductions with freezing than did the surface deflections. The granular base course experienced the most substantial strain reduction when the hot mix asphalt mat froze, with a maximum relative value of 29% at the highest load (6250 kg). Following frost penetration of the hot mix asphalt mat, the relative values continued to decrease with freezing of the granular base and the lowering of the temperature of the hot mix asphalt mat. Once the pavement structure and the top of the subgrade were frozen (at a frost penetration of 600 mm), the strain in all layers and the surface deflection were minimal. The surface deflection was the only parameter that continued to decrease as the frost penetrated the subgrade. These observations are similar to Ovik and Siekmeier (2004), who concluded that WWP hauling in Minnesota could start when freezing had penetrated 150 mm into the subgrade layer, without risk of increased pavement damage.

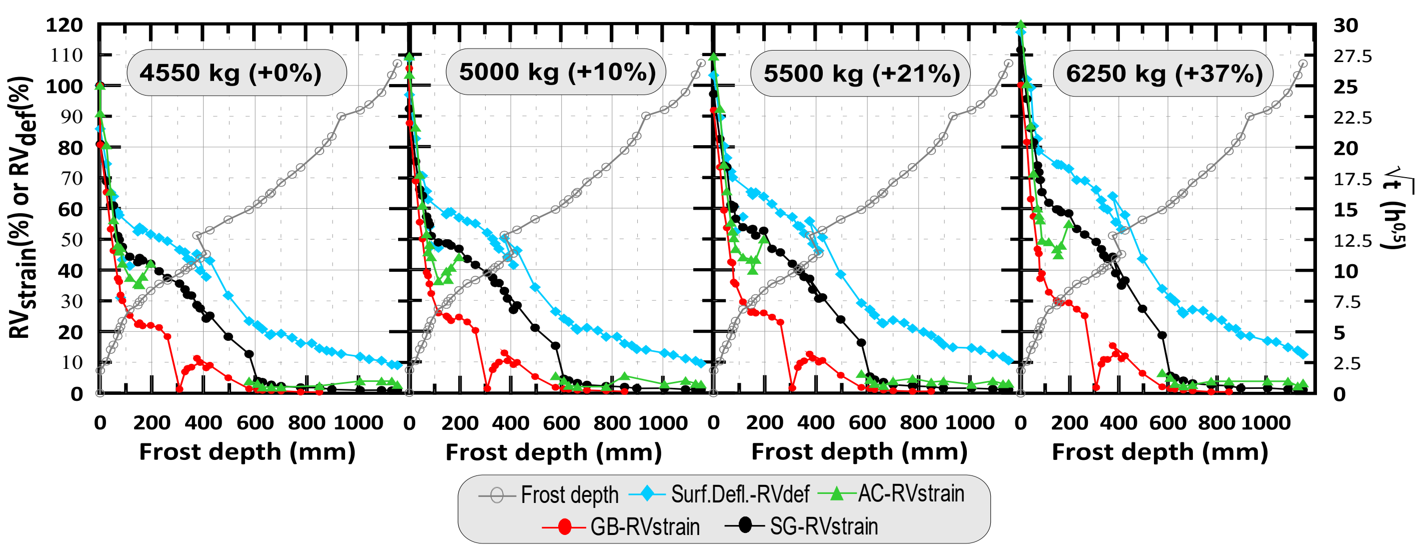


Figure 9. Relative value (RV) of response with respect to frost penetration and axle load.

The effect of loads on the pavement

The effect of axle load on the mechanical responses of the freezing pavement is illustrated in Figure 10. All of the load-response comparisons were made using results from the first freezing cycle except for the AC-RV strain. The chart of load vs AC-RV strain was based on cycle 2 results because there was no loss in hot mix asphalt strain data during that cycle. For all pavement response parameters considered, the slope of the relation between RV and axle load decreases with increasing frost penetration, and this can be associated with the global increase of bearing capacity. At shallow frost depths, the effect of increasing axle load from 4550 to 6250 kg led to an increase of up to 20% in pavement response. When the frost depth reached 600 mm, however, increasing axle load resulted in negligible changes to all response parameters except surface deflection. Surface deflection increased, with respect to the 4550 kg case, by about 3% at the 5000 kg load, 6% at 5500 kg, and 10% at 6250 kg.

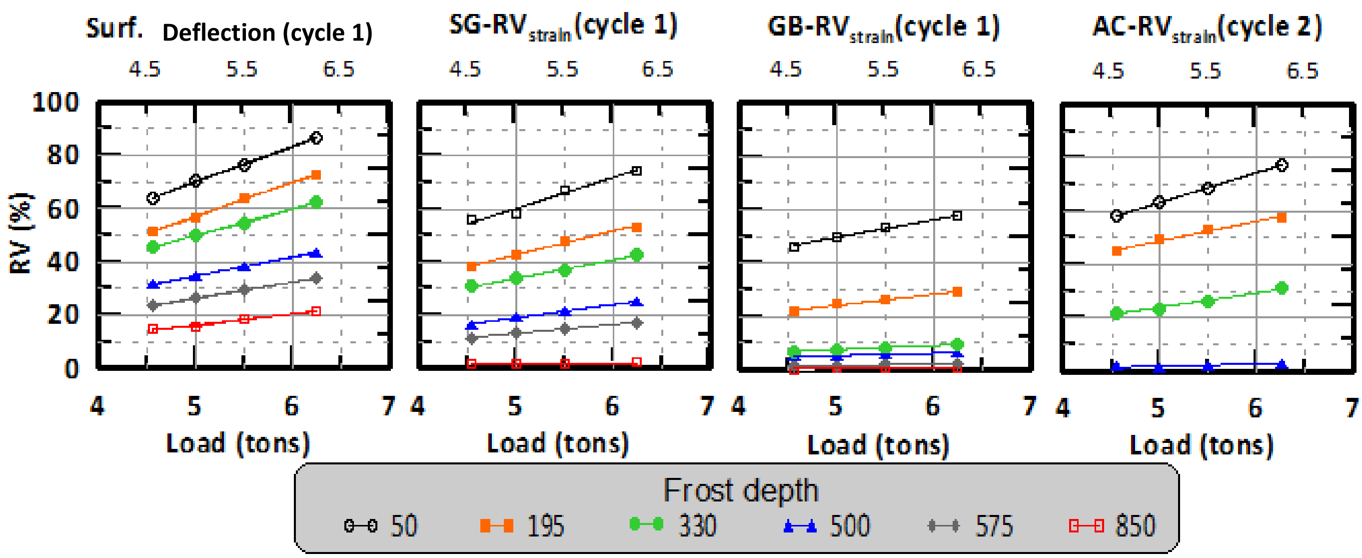


Figure 10. Load effect on relative values of pavement response.

Damage analysis

In order to assess the effect of freezing pavement response and load increase on service life, a damage analysis was performed using the test results. This analysis was focused on two performance parameters:

- Elastic tensile strain at the bottom of hot mix asphalt mat (maximum fatigue cracking criteria);
- Elastic compressive strain at the top of subgrade layer (maximum rutting criteria).

The estimated number of load repetitions to reach a failure condition in the hot mix asphalt mat and in the subgrade soil was calculated using the Asphalt Institute empirical transfer functions (Huang 2004):

$$N_f = C \times KF_1 \times \left(\frac{1}{\varepsilon_t}\right)^{KF_2} \times \left(\frac{1}{|E^*|}\right)^{KF_3} \quad (2)$$

$$N_r = KF_4 \times \varepsilon_c^{KF_5} \quad (3)$$

where, N_f is the estimated number of load repetitions to cause fatigue cracking over 10% of the wheel path, N_r is the estimated number of loads to cause a 12.7 mm-deep rut in the hot mix asphalt mat, ε_t is the horizontal tensile strain at the bottom of hot mix asphalt mat (mm/mm*)*, ε_c is the vertical compressive strain in the top of the subgrade soil (mm/mm), $|E^*|$ *is the dynamic modulus of the AC (MPa)*, C=0.07958, KF_1=1.0, KF_2=3.291, KF_3=0.854, KF_4=1.365x10^{-9} and KF_5=-4.477 (Huang 2004).

For each performance parameter, the theoretical pavement damage *(D)* induced in the pavement per load repetition was calculated as:

$$D = \frac{1}{N} \tag{4}$$

in which N is the estimated number of load repetitions to failure (N_f, N_r). The theoretical pavement damage was also expressed relative to the theoretical pavement damage from Alberta's heaviest legal half-axle load (4550 kg) allowed under summer-like conditions (D_{4550} *(*t = 0*))*. Relative damage*,* calculated for any frost depth (t), was defined as:

$$D(t) / D_{4550}(t = 0) \tag{5}$$

Table 8 presents the predicted repetitions to failure for bottom-up fatigue cracking and rutting at various frost depths using strain measurements from freezing cycle 1. The vertical compressive subgrade strains under unfrozen conditions of cycle 1 were relatively large because of difficulty with compacting the clay during placement; this resulted in unrealistically low predictions of load repetitions to rutting failure. As previously mentioned, subgrade strain measurements under unfrozen conditions of cycle 2 were not measured due to some strain gauge malfunctions. WinJULEA modeling was used, therefore, to predict a strain value for unfrozen conditions upon which to base relative rutting damage rates. (Yi & al. 2016) has shown that WinJULEA analysis results accurately estimated the test results. For frost depths of 600 mm and deeper, fatigue cracking was the governing long-term pavement failure mode because fewer loads were required to reach a fatigue cracked failure condition than to reach rutting failure.

Table 9 presents the predictions of bottom-up fatigue cracking and rutting, expressed as a percentage relative to that predicted for a 4550 half-axle load under summer condition. The results in Table 9 illustrate how freezing (and even cooling) of the hot mix asphalt mat greatly reduced the predicted rutting. Conversely, when freezing reached the bottom of the granular base, the predicted fatigue cracking damage was greatly reduced. At a frost depth of 500 mm, rutting and fatigue cracking from half-axle loads up to 6250 kg were predicted to be no more than 0.3% of that from a 4550 half-axle load under unfrozen conditions. From a service life perspective, at frost depths greater than 500 mm, the risk of pavement damage appears very minor even at the heaviest loading tested because the relative damage values were very small and they rapidly approached zero with increasing frost depth.

Table 8. Predicted repetitions to failure for fatigue cracking and surface rutting at various frost depths based upon strains measured in freezing cycle 1

Frost Depth	Predicted passes to bottom-up fatigue cracking failure by a dual tire half-axle load (kg)				Predicted passes to surface rutting failure by a dual tire half-axle load (kg)			
	4550	5000	5500	6250	4550	5000	5500	6250
0 mm	8.68E+07	7.26E+07	no strains measured		4.43E+06	2.97E+06	no strains measured	
180 mm	2.08E+08	1.54E+08	1.20E+08	9.18E+07	2.23E+08	1.39E+08	8.15E+07	5.07E+07
300 mm	4.16E+08	3.70E+08	3.02E+08	1.48E+08	2.31E+10	3.19E+08	2.23E+08	1.11E+08
500 mm	1.69E+11	2.12E+11	1.36E+11	7.11E+10	2.32E+11	5.12E+09	2.88E+09	1.49E+09
600 mm	1.86E+11	1.18E+11	1.34E+11	9.11E+10	5.10E+11	4.84E+11	3.09E+11	1.92E+11
700 mm	2.47E+11	2.96E+11	1.19E+11	8.90E+10	6.58E+11	5.78E+11	5.48E+11	5.10E+11
800 mm	4.09E+11	2.02E+11	1.44E+11	1.30E+11	1.15E+12	9.32E+11	7.65E+11	6.58E+11
1000 mm	6.33E+11	6.05E+11	2.95E+11	1.78E+11	1.56E+12	1.30E+12	1.15E+12	9.32E+11

Note: Predicted passes to surface rutting failure for unfrozen conditions (0 mm frost depth, yellow highlighted cells) were based upon WinJULEA-predicted vertical compressive strains in the subgrade.

Table 9. Predicted fatigue cracking and surface rutting for various frost depths and winter weight premiums, relative to that from a 4550 kg half-axle load under summer conditions

Frost Depth	Fatigue cracking				Rutting			
	4550 kg	5000 kg	5500 kg	6250 kg	4550 kg	5000 kg	5500 kg	6250 kg
0 mm	100%	119.47%	not predicted		100%	149.08%	not predicted	
180 mm	41.64%	56.44%	72.48%	94.53%	3.20%	3.33%	5.44%	8.74%
300 mm	20.85%	23.48%	28.77%	58.79%	1.39%	1.47%	1.99%	3.99%
500 mm	0.05%	0.04%	0.06%	0.12%	0.09%	0.09%	0.15%	0.30%
600 mm	0.05%	0.07%	0.06%	0.10%	0.00%	0.00%	0.00%	0.00%
700 mm	0.04%	0.03%	0.07%	0.10%	0.00%	0.00%	0.00%	0.00%
800 mm	0.02%	0.04%	0.06%	0.07%	0.00%	0.00%	0.00%	0.00%
1000 mm	0.01%	0.01%	0.03%	0.05%	0.00%	0.00%	0.00%	0.00%

Validation of results with a comparison to QC style pavement test results (Yi et al. 2016)

Yi et al. (2016) performed a study of thawing pavements at Laval University in 2014-2015 for the Ministry of Transportation of Quebec (MTQ). As part of the study, they measured pavement mechanical responses to half-axle loads of 5000 and 5500 kg during pavement freezing (prior to thawing the pavement). 305/70R22.5 size tires and a carriage speed of 5 km/h were used for trafficking.

The test pavement was thicker than the Alberta-style pavement and consisted of 100 mm of hot mix asphalt, 200 mm of granular base, and 450 mm of granular subbase over a silty sand subgrade. The air temperature during freezing was the same (-10° C) for both studies and the water table depth was 1600 mm for the MTQ test.

Figure 11 and Figure 12 compare the results from this study with the MTQ test results. The results are expressed as relative strains at various frost depths with respect to responses to a 5000 kg load before freezing (t=0 mm). Similar trends were observed in both studies. Despite the differences in structure, the two pavements responded similarly to load increases during freezing. In both tests, under both loading conditions, the key pavement strains for fatigue cracking and rutting stabilized at a minimal value when frost depth reached 600 mm, and did not change much - if at all – at deeper frost depths or heavier axle loads. The differences in horizontal tensile hot mix asphalt strain and vertical compressive subgrade strain between the tests mostly can be attributed to the different hot mix asphalt thicknesses, subgrade soils, and water contents. The figures also highlight the effect of a 10% overload (5000 kg versus 5500 kg) which resulted in minor differences in strains for both test pavements.

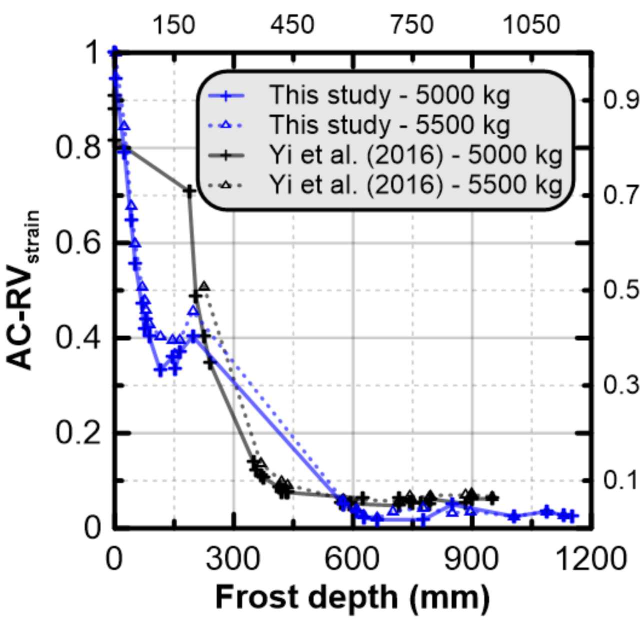


Figure 11. Relative values of AC mat horizontal strain with frost depth for two studies.

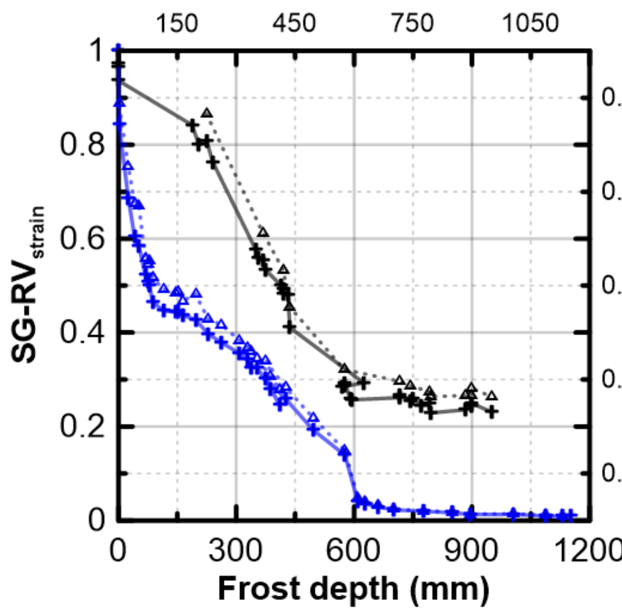


Figure 12. Relative values of subgrade vertical strain with frost depth for two studies.

Trends observed in lab testing of the Alberta-style pavement

A substantial reduction in pavement strains occurred before freezing, when the hot mix asphalt mat cooled and stiffened. By the time the hot mix asphalt mat was frozen, the underlying granular base course and subgrade strain responses to increased axle loadings had reduced by approximately 75% and 55%, relative to the strains caused by a legal load in summer-like conditions. Moreover, at a frost depth of 600 mm (when freezing had penetrated through the granular base and 120 mm into the subgrade soil), the strains were very small throughout the pavement (both relative to the reference condition and absolutely). Stiffening of the hot mix asphalt mat and freezing of the granular base appear to be the main factors associated with such a response. Similar trends were observed in the MTQ test as well;

- Except for surface deflection, pavement response to increasing load was negligible for frost depths of 500 mm or deeper;
- Based on theoretical estimates of fatigue cracking and rutting, predicted damage rates for the tested thin pavement became stable and negligible when the granular base was completely frozen, regardless of axle loading; Pavement responses to changes in freezing and axle loading were very similar in both freezing cycles; and,
- The same trends were observed with a thicker, Quebec-style, pavement tested in the same pit and under similar conditions in 2014/15.

Testing limitations

The experimental approach used in this project was able to measure the pavement mechanical responses to accelerated trafficking during freezing in an indoor pit. Unfortunately, with all the advantages of a lab, it is not able to replicate some real life effects and these should be considered when interpreting test results. The following limitations are likely to induce some slight variations (positive or negative) to the analyses and conclusions:

- The asphalt cracking is another important input to consider on pavement behavior that could not be considered during the tests because of the idealistic indoor conditions. Indeed, cracking lowers the asphalt tensile strength and increases the stresses on the subsurface layers. The lab results showed that a substantial reduction in pavement strains occurred when the hot mix asphalt mat cooled and stiffened. Cracking on an existing road is likely to influence the mechanical response to weight premiums.
- The pavement was not exposed to chemicals like de-icing salts. Vautrin et al. (1996) described that the effect of salt seeping into a pavement increases the number of freeze-thaw cycles of the upper layers of the pavement. The traffic load effect is then higher on the unfrozen granular material that rests over the frozen layers.
- Laboratory pavement was not exposed to weaknesses during winter partial thaws. This study was focused on pavement mechanical response during early winter freezing conditions.
- The water content in the granular layer was near optimum conditions before freezing and did not change throughout the entire testing period. Depending on in situ conditions (e.g., precipitation, drainage, surface cracking), the water content within pavement structures may vary during the freezing process and this may influence the pavement mechanical response during freezing. In fact, resilient modulus testing results from the study conducted by the city of Edmonton as part of this study have shown that when a freezing material moisture content is higher than optimum, the material tends to get stiffer.
- The results collected were for worst case permitted loading conditions - developed by a single axle dual tire arrangement, loaded to the heaviest Alberta WWP for an axle. The maximum axle load for multiple axle groups is less than what was tested, and would generate smaller pavement responses. Also, in real life, over inflated tires would cause greater stresses, while wheel wander causes lower stresses (in a given wheel path).

6. VALIDATION OF RESULTS FROM ACCELERATED PAVEMENT TESTING USING LAYERED ELASTIC MODELING

Summary of literature on frozen pavement mechanical behavior

As their bound and unbound pavement materials freeze, asphalt pavement bearing capacity increases substantially. The bearing capacity of a freezing pavement is increased by both deeper frost penetration and by colder material temperatures (Benson et al. 1998; Watson and Rajapakse 2000; Simonsen et al. 2002). The strength of some unbound materials may approach that of the asphalt mat (e.g., 20 000 MPa) at temperatures of -5° to -10° C (Figure 13).

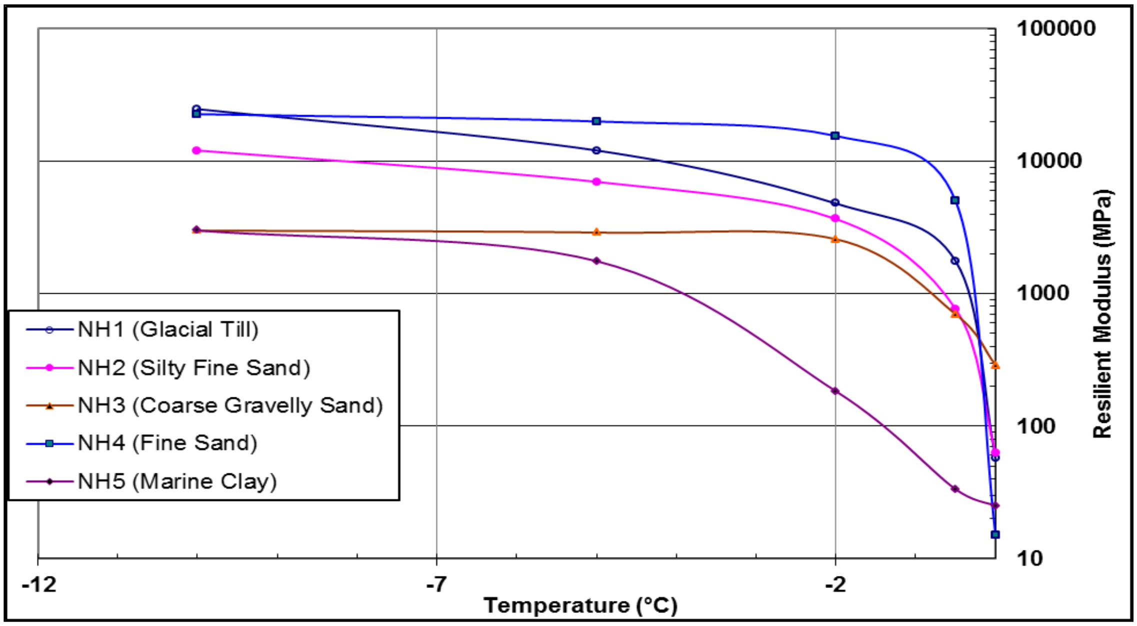


Figure 13. Effect of freezing on the strength of unbound road materials.

Wisconsin DOT supported a study to develop a method to predict the timing of weight limits on the state's secondary highways (Benson et al. 1998). A computer model (UWFrost) was developed to predict seasonal changes in the capacity of the pavements based on user inputs of meteorological data, pavement location, pavement layer geometry, and timing criteria. UWFrost is operated from a Microsoft Excel spreadsheet. A one-dimensional heat transfer module uses the input to define the frost depth and/or thaw depth. Historical meteorological data are used to predict subsurface thermal conditions.

UWFrost predicts subsurface thermal conditions that influence the moduli of the pavement layers for the purpose of layered elastic analysis. The elastic analysis is used iteratively to determine the load that induces no more damage (strain) than a design load applied during late summer. This load is referred to as the equivalent damage load (EDL). EDLs are defined for fatigue and rutting damage. UWFrost computes EDLs for each day during the prediction period selected by the user. For the pavements studied, when the AC and granular base froze, the EDLS were as much as three times higher than the late summer design loads. Wisconsin's WWP policy does not explicitly rely on UWFrost; however, it does incorporate elements of the analysis including frost depth predictions based on meteorological data.

Minnesota has also sponsored research into the structural capacity of its pavements during winter and its current policy incorporates several of the recommendations from its work. As part of these efforts, Minnesota DOT has developed MnPAVE, a computer program to assess pavement and pavement overlay designs within the state. MnPAVE combines known empirical relationships with a representation of the physics and mechanics behind flexible pavement behavior. The mechanistic portions of the program rely on finding the tensile strain at the bottom of the asphalt layer, the compressive strain at the top of the subgrade, and the maximum principal stress in the middle of the aggregate base layer.

Ovik and Siekmeier (2004) used MnPAVE to analyze the impact of carrying heavier wintertime loads on frozen pavements as part of a pilot study in northern Minnesota. Their study predicted that pavement life would not be reduced if 6-axle trucks were allowed 6% higher winter loadings. The predictions were evaluated with a pilot study conducted using sugar beet haulers on three northern MN trunk highway sections in the winter of 1999/ 2000. The three pavement structures were 75 mm AC on 100 mm of GBC, 75 mm of AC on 280 mm of GBC, and 125 mm of AC on 300 mm of GBC; all three sections were on a low plasticity clay subgrade (CL). The haulers were permitted to increase the winter weight of their 6-axle tractor semi-trailer from 40 to 42.5 t (+6%). This load limit was chosen, rather than the MN-legislated 10% WWP, because the destination was in North Dakota where the trucks' load limit was 42.5 t. The modeling indicated that WWP hauling could commence when the frost level had penetrated 150 mm into the subgrade layer, and should end when the granular base course had thawed to 150 mm.

The predictions of the MnPAVE analysis were compared to measurements of frost and thaw depths in the pavement structures using thermistors and moisture content (Watermark) sensors. The measured data had a reasonable accuracy, and were used to develop viable relationships that could predict the subsurface freezing and thawing based on air temperature. However, specific criteria for the placement and removal of WWP were not determined. Field work also included falling weight deflectometer testing that measured decreasing deflections with cooler weather, indicating a significant increase in the structural capacity of the frozen pavements. A similar trend was seen in strain data measured concurrently at the MnROAD site. The condition surveys conducted showed no visible signs of increased surface distress due to the increased loads; however, the results from this study are limited because the transporter was able to participate in the study for only 3 weeks (1350 trips) starting in January when frost depth had reached 0.6 m. This depth is similar to what has since been the practice for starting WWP in Minnesota.

The Minnesota study recommended that it should be determined how much axle weights could be increased during the winter before the pavement structure begins rapid deterioration due to increased brittle fracture or other mechanisms. Other studies' recommendations concern the expansion of the State's road weather information system, and the creation of more applicable frost zones that could be used for both WWP and SLR programs. These latter two recommendations were acted upon and are incorporated in the current Minnesota seasonal load-limit monitoring program.

Estimating the mechanical behavior of a freezing Alberta-style pavement using linear elastic modeling

Description of the analysis

The purpose of this analysis was to develop a linear elastic model of a freezing pavement that was validated with laboratory results from testing an Alberta-style pavement. This validation was accomplished by comparing estimated with measured spontaneous strain and stress responses. To do so, WinJULEA, a layered elastic software based on the Burmister theory, was used. The Burmister theory is extension to multilayer systems of Boussinesq's theory on linearity and elasticity of homogeneous strutures. The Burmister model is mainly characterized by flexible pavements responses to external loadings. The assumptions made for the Burmister model are:

- Each layer is homogeneous, isotropic and linear elastic;
- The material is weightless and extends infinitely in a horizontal direction;
- Each layer has a finite thickness, except the bottom layer which is of infinite thickness;
- The load is distributed uniformly over a circular area;
- A continuity equation is fulfilled at all layer interfaces.

WinJULEA was developped at the Geotechnical and Structural Laboratory of the US Army Corps of Engineers' Engineering Research and Development Center (ERDC) WinJULEA is a widely known and used software in the pavement engineering community. It has been chosen in this study because it is user friendly and it allows modeling multiple layer pavement structures (up to 100 layers) unlike most known softwares (ElSym 5, KenPave, Alizé, MEPads, etc) which have a limited number of layers for the pavement structure. WinJULEA results often compare to all the other softwares that are based on the Burmister theory.

The hypothesis was that the pavement materials would react as if they had linear elastic properties. The input data needed to perform the analysis were:

- pavement materials mechanical properties (resilient modulus and Poisson's ratio);
- pavement material thicknesses; and,
- wheel loads.

Methodology

Pavement layering was defined by both material thicknesses and temperature zones from multi-year average thermal profiles corresponding to various frost depths. Figure 14 illustrates the thermal profiles used to model the Alberta freezing pavement structure used in Figure 1. Figure 14 presents average thermal profiles derived from six years of data from the AT thermistor site at Wandering River in northeastern Alberta.

To the left of the figure is a scale diagram of the pavement structure comprsd of 250 mm asphalt mat and 300 mm of base course over subgrade. Pavement subzero mechanical properties were measured by City of Edmonton testing of unbound pavement materials (granular base and silty clay subgrade)(Kanji 2015). Additional modeling with Laval University's mechanistic-empirical pavement design guide (Doré et al. 2016) was required to resolve resilient modulus to a single value per temperature. The same loads used for the lab testing were used for the WinJULEA modeling.

The frozen asphaltic concrete moduli were taken from the Witczak model in Level 3 of the MEPDG (NCHRP 2011). Subsequent to testing, the asphaltic concrete moduli were evaluated by University of Laval and the values were comparable to the MEPDG values. Resilient moduli for the base granular material and clay subgrade at various subzero temperatures were estimated using the values measured by Kanji (2015), and resolving these with representative pavement confining pressures in University of Laval's mechanistic empirical pavement design model (Doré et al. 2016). Poisson's ratio values used in this analysis, therefore, were based on MEPDG Level 3 ranges. The analysis quantified degrees of load sensitivity with varying frost depth.

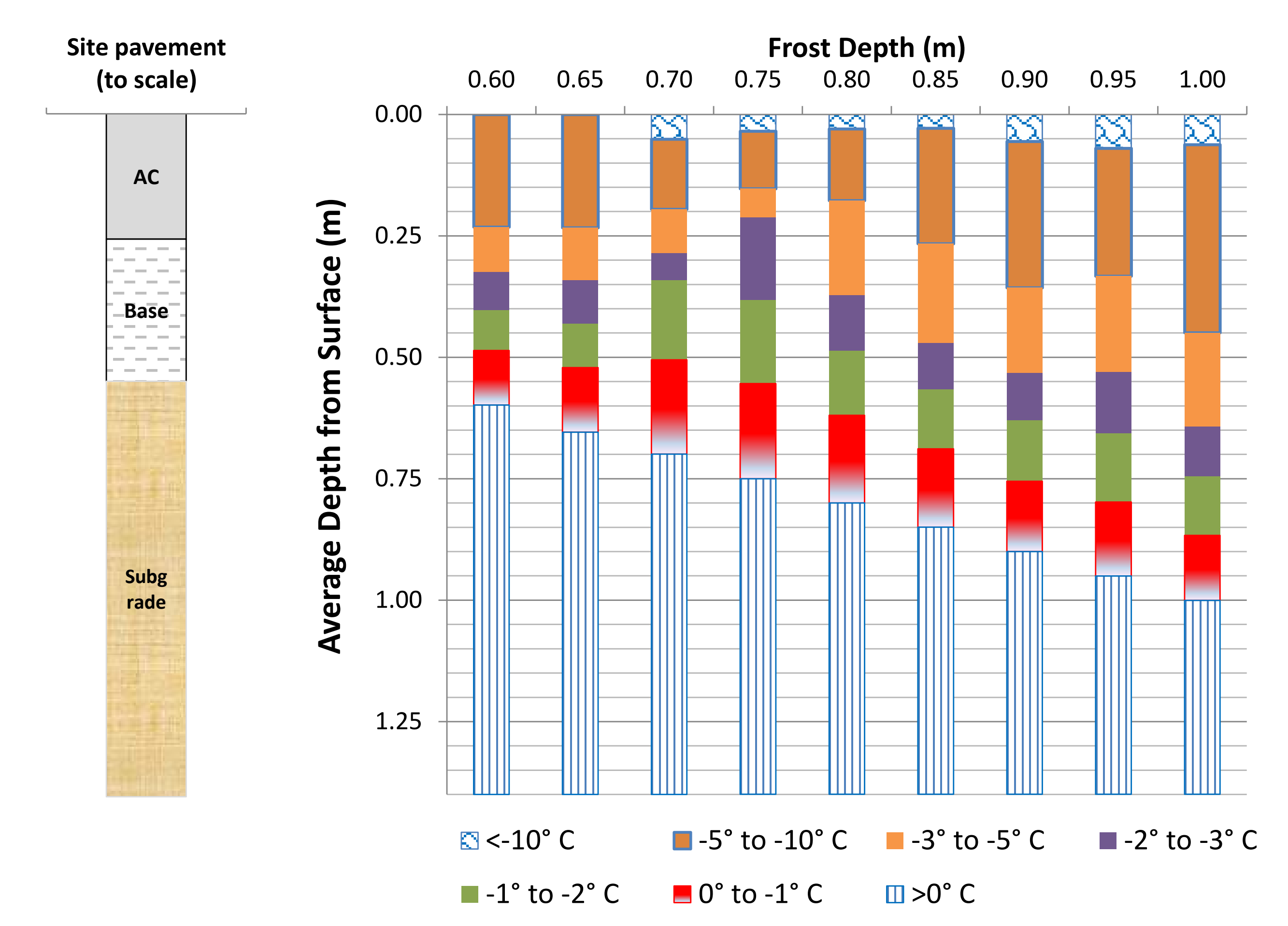


Figure 14. Thermal profiles for various frost depths, six year average. Wandering River, AB.

Results and Analysis

Figure 15 presents results in relative values from WinJULEA analysis. Results were compared with results from laboratory pavement testing, as a function of frost depth. Results were presented for 5000 kg and 6250 kg loads. Figure 15 shows surface deflection as well as permanent strain on top of the subgrade. Results showed great similarity between experimentally and theoretically (WinJULEA) derived relative values. As anticipated, the results showed a decrease in pavement sensitivity to loading with increasing frost depth. Firstly, as soon as the hot mix asphalt is frozen, an important decrease in relative values is noted. Then, as frost depth increases, deflections and strains decrease progressively.

When frost depth reached 600 mm, both experimental and theoretical strain results decreased to very small relative values. Most importantly, the charts slope changes are similar—indicating good agreement between real life and modeling. WinJULEA tends to overestimate pavement strains due to the approximation of materials' mechanical properties and this will result in an underestimate of cycles to failure. The number of load cycles, stress history, confining pressure, stress state, and degree of compaction can influence pavement mechanical response (Poupart, 2013). Some of these variables are not fully represented in WinJULEA and this may cause differences between modeled and measured results.

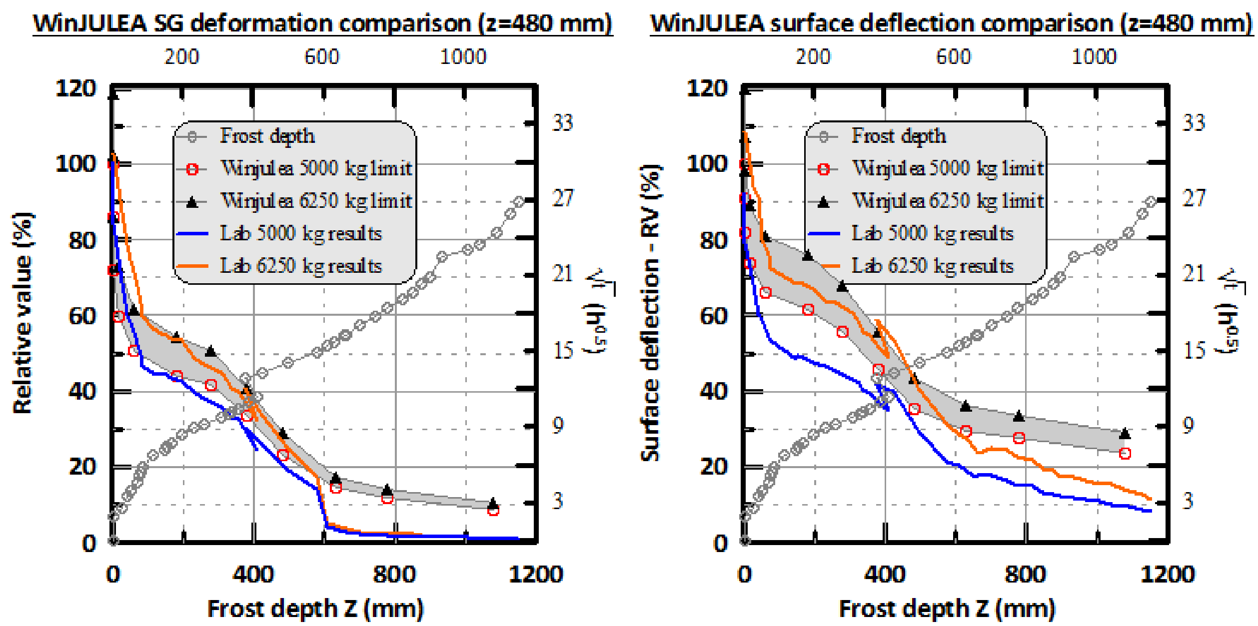


Figure 15. Comparison between WinJULEA analysis results and experimental test results.

7. SENSITIVITY ANALYSIS: IMPACT OF A REDUCED STARTING FROST DEPTH THRESHOLD ON A VARIETY OF AB HIGHWAY STRUCTURES

As discussed in the Section 6, laboratory results showed that when the frost depth reached the granular base course of the test pavement, stress and strain in the pavement and the load sensitivity of the pavement were considerably reduced.

When the freezing had penetrated 120 mm into the granular base course (at a 300 mm frost depth), incremental increases in pavement responses were minimal for additional wheel loading. This testing was conducted with one type of Alberta-style highway pavement. In order to broaden the applicability of conclusions from this project, a sensitivity analysis was conducted using several of the weakest, representative, Alberta pavement structures currently utilized for winter log hauling. The results will support decision-makers with implementing improvements to WWP policy that are applicable throughout the province.

Methodology

The following methodology was used to conduct a sensitivity analysis of the mechanical behavior of a wide range of weak Alberta highway pavement structures.

1. The analysis of the mechanical behavior under frozen conditions of other Alberta pavements was performed using the layered elastic modeling software WinJULEA. As noted in Section 6, this program provided good agreement between modeled and measured test results. Figure 15 provides an example of the good agreement between experimental results from this project and WinJULEA results for the same freezing pavement.

2. Alberta Transportation provided FPInnovations with a complete list of all Alberta provincial road structures. In order to analyze the weakest, representative, pavement structures, pavements not supporting winter weight hauling were excluded, only pavements founded on weak, clayey or silty subgrades were included , and then, of these, the weakest (i.e., with the thinnest granular base equivalency), most common, structures were identified for use in the sensitivity analysis. The subgrade included CH, CH-CI, CI, CL-CI, CL, SM, ML, SC and SC-CL soils. The following provides more specifics:
    a. Three classes of highway structures (public highway (PH), public road (PR) and arterial road (AR)) were considered initially. AR and PR roads, which account for 133 and 135 km of length in Alberta, respectively, were excluded from the analysis because they are a very minor component of the highway inventory and because they are not utilized by forestry vehicles hauling with WWP.
    b. There were 5177 km of provincial highways (PH) identified as routes used for forestry WWP hauling. PH 2, 16, 43, and 63 were excluded from the analysis because they are high standard, thick pavements, and not of much concern for road damage due to WWP hauling.
    c. The subgrade soils of these PH haul routes were considered, and three groupings of the weakest subgrade soils were created (i.e., CH/CH-CI/CI soils, CL-CI/CL soils, and SM/ML/SC/SC-CL soils). The pavement structures founded on these soils were then converted to granular base equivalents so that the thinnest, weakest structures could be identified. Table 10 summarizes the pavement structures that were considered in the sensitivity analysis.
    d. 2485 (48%) of the 5177 km of PH haul routes were built on CH/CH-CI/CI subgrades. Three of the weakest pavement structures founded on CH/CH-CI/CI subgrades were included in the sensitivity analysis. The total length of these types of pavement structure was 422 km (representing 17% of the total length of CH/CH-CI/CI PH haul routes, and 8% of the overall 5177 km of PH haul routes).
    e. 1760 (34%) of the 5177 km of PH haul routes were built on CL-CI/CL subgrades. One of the weakest pavement structures founded on CL-CI/CL subgrades was included in the sensitivity analysis. The total length of this type of pavement structure was 229 km (representing 13% of the total length of CL-CI/CL PH haul routes, and 4% of the overall 5177 km of PH haul roads).

f. Only 103 km (2%) of the 5177 km of PH haul routes were built on SM/ML/SC/SC-CL subgrades. One weak structure founded on these SM/ML/SC/SC-CL subgrades was included in the sensitivity analysis. The total length of this type of pavement structure was 46 km (representing 45% of the total length of SM/ML/SC/SC-CL PH haul routes, and 0.8% of the overall 5177 km of PH haul roads).

3. Properties of the modeled pavement materials under various states of freezing were taken from City of Edmonton resilient modulus test results and, where necessary, estimated from published sources (e.g., Poisson ratio values). For reason of brevity, these values are not included in the report but are available from the authors upon request.

4. Typical thermal profiles, corresponding to a range of frost penetration depths (100, 90, 80, 70, and 60 cm), were estimated based on temperature data from Alberta Transportation's frost monitoring network (Figure 14). These thermal profiles were used to create a series of models for each pavement structure, comprised of its constituent pavement material layers in various states of freezing.

5. The impact of starting winter weight hauling at different frost depths was evaluated for each structure. Key pavement responses were predicted for each pavement using the same wheel loads as employed for the lab testing. Results were compared with those obtained from modeling the lab-tested typical Alberta highway structure.

Table 10. Comparison of five representative, weak, Alberta provincial highway structures with the Alberta pavement structure evaluated in the Laval University lab test

	Reference pavement	Subgrade Group A			Subgrade Group B	Subgrade Group C
	Lab-tested structure	Structure 1	Structure 2	Structure 3	Structure 4	Structure 5
AC thickness (mm)	180	110	150	235	110	150
Granular base thickness (mm)	300	250	175	0	230	100
Subgrade soil type	CL	CH/ CH-CI/ CI			CL-CI/ CL	SM/ ML/ SC/ SC-CL
Total thickness (mm)	480	360	325	235	340	250

Results and analysis

Figure 16 presents results from the sensitivity analysis using WinJULEA. Predicted instantaneous pavement responses to a 5000 kg load, as a function of frost depth, were compared for the lab-tested pavement versus five, weak but representative, Alberta pavement structures (defined in table 10).

The same analysis was also conducted for a 6500 kg load; however, due to the trends being similar to those of a 5000kg load, the results were not presented in this study. For each load, hot mix asphalt mat horizontal strain, and subgrade vertical strain are presented. All results were normalized relative to the reference pavement's WinJULEA-predicted responses under unfrozen conditions, and expressed as relative values (RV).

The results of the sensitivity analysis were conclusive. For all six pavement structures, a drastic drop in the relative values of subgrade vertical strain and hot mix asphalt horizontal strain occured when frost depth reached 600 mm frost depth (120 – 365 mm into the structures' subgrades). At this frost depth, subgrade strains were reduced by 85% - 96% and asphalt mat strains were reduced by 93% - 99%.

From this analysis, it is apparent that pavement load sensitivity, for the range of single axle loads considered, decreased with frost depth also, and became very small for all pavement structures by a 600 mm frost penetration.

It can be concluded, therefore, that when frost depth reached 600 mm the strain levels became very small in all of the weak Alberta pavements studied in this project. Given that the analysed structures represented a majority of weaker Alberta provincial highway pavements, it is anticipated that a single WWP starting frost depth could be adopted with confidence for the Province. It should be noted that the sensitivity analysis was conservative in two ways:

- Comparison of WinJULEA analysis results with measured responses from lab testing in this study found that WinJULEA overestimated strain responses by approximately 10%.
- A representative selection of the weakest Alberta pavements was considered in this analysis.

Implementation recommendation. Winter weights should be initiated, therefore, at a frost depth that typically corresponds to a time in winter when freezing proceeds steadily, and the pavement is well frozen and able to resist brief warming spells during the freezing process. This should lead to WWP staying on once they are instated causing less upset for both the forestry and heavy haul trucking, and regulators. Freezing pattern tests and data provided by AT indicate that initiating winter weights at a frost depth of 70 cm, as opposed to 60 cm, is more likely to result in colder roadbed temperatures and consistent freezing. This recommendation concurs with Ovik & Siekmeier (2004), who concluded that WWP hauling in Minnesota could start when freezing had penetrated 150 mm into the subgrade layer, without risk of increased pavement damage.

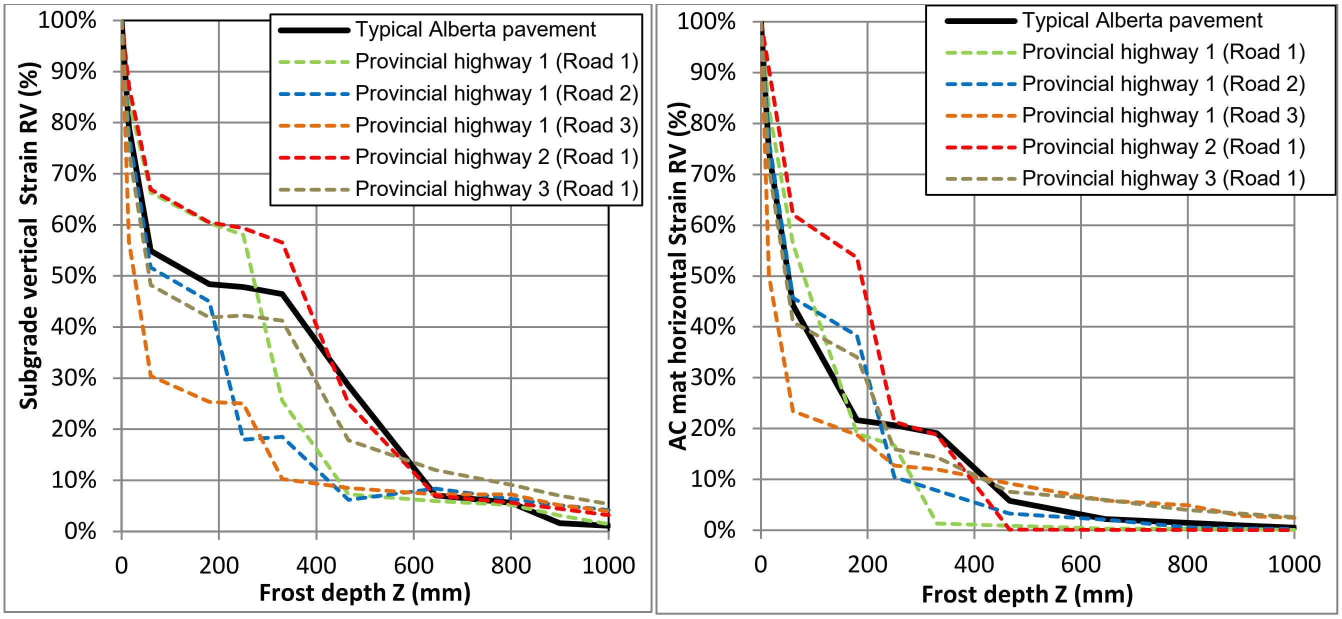


Figure 16. WinJULEA-predicted strain comparison for six, weak, freezing Alberta pavement structures. Subgrade vertical strains (left) and AC mat horizontal strains (right) from a 5000 kg wheel load are expressed relative to the corresponding strains under unfrozen conditions and a 4550 kg wheel load.

8. ECONOMIC IMPACTS OF A LONGER WWP PERIOD

General Benefits. An important economic impact of a longer winter weight haul program is that it may prolong pavement life by encouraging more wintertime transport when road wear rates are a small fraction of summer levels. One estimate from a Saskatchewan Highways and Infrastructure executive was that Saskatchewan achieved 67% longer pavement life on its low volume pavements because of traffic impacts during the winter (e.g., 25 years of life with 15-year designs)[1]. Results presented in Section 7 of this report substantiate this claim—frozen strain levels were a very small fraction of unfrozen pavement strains, regardless of the additional wheel loads in winter.

Winter weights generate substantial economic benefits that increase the competitiveness of local truck-based industries, and help compensate industry for losses incurred from spring load restrictions. Policy changes to increase the length of the WWP period will further promote these benefits.

Policies to encourage fewer, more heavily, loaded trucks increase the efficiency of hauling, thereby reducing GHG production, and reducing overall traffic levels.

The Transport Engineering Branch of Alberta Transportation manages the winter weight haul program in Alberta. They do not anticipate increased operating costs or other barriers to implementing a policy change to a shallower starting frost depth threshold for WWP.[2]

[1] George Stamatinos, P.Eng. former Assistant Deputy Minister, Saskatchewan Department of Highways and Infrastructure. Personal communication. June 2001.

[2] Kim Durdle, P.Eng. Director, Transport Engineering, Alberta Transportation. Personal communication. May 2017.

Forestry industry benefits. Winter weight programs result in operational shifts from summer to winter harvesting and hauling. In the forest industry, where fixed volumes are hauled annually, starting WWP at a shallower frost depth allows companies to haul higher volumes per truck, and in total, under frozen road conditions. Higher winter payloads make for more efficient transport and reduce the cost of wood transport. FPInnovations surveyed its members to quantify the benefits of winter hauling, and a longer winter weight haul period. Haul savings at the current winter weight premiums were estimated by configuration, and extended from FPInnovations' member companies to the entire industry on the basis of processed mill volumes. If winter weight hauling were to start sooner, approximately $1.63 M per week in forest industry hauling savings is anticipated.

This earlier onset of winter weight hauling could occur with a policy change to a shallower starting frost depth. An analysis of frost penetration rates recorded at 25 AT thermistor stations during winter 2015/16 found that it took ten days, on average, for frost to penetrate from 700 to 1000 mm. Starting Alberta's winter weights at a frost depth of 700 mm, therefore, may result in 1.5 additional weeks of winter hauling, and incremental hauling savings to the forest industry of $2.44 M. In areas with wetter soils, or during years with wetter and warmer falls, freezing will be slower. Under these conditions, the time lag between 700 mm and 1000 mm frost depth will be longer than if conditions were dryer; therefore, the WWP period extension and predicted savings would be even greater. Additional, uncalculated benefits could accrue from a shallower starting frost depth because forest operations in the south of the province may now participate in the winter weight program—both in warmer years and in those areas that do not traditionally freeze to 1 m.

Increased opportunity to conduct winter weight hauling reduces the vulnerability of forest operations to climate change-induced interruptions due to wet weather, flooding, or wildfire in the summer. Transporting more wood in the winter with fewer trucks allows mills to reduce mill yard inventory volumes and costs, helps address driver shortages, and reduces summer traffic congestion on public highways used as haul routes.

Heavy haul industry benefits. The heavy haul industry is for the movement of non-divisible loads and is unlike the forest industry where higher weight translates into increased payload. However, heavy haulers do experience a benefit if they can transport loads with fewer axles (i.e., transport configurations are less costly and easier to manoeuver).

Unlike the forest industry, heavy haulers have the advantage of a seasonal (fall) weight program so the increase to allowable winter weights is incrementally less. An early start to winter weights could mean an extra one to two weeks of hauling for some carriers, if the loads can't be hauled with enough wheels at fall weights. Like the southern forest industry, a big benefit could be to carriers in the south who were not able to participate in the winter weight program in the past because frost depths in the area did not reach 1 m.

Crane carriers also would see an advantage as they are able to drop the boom dolly during winter moves, if there are no bridge capacity issues.

Economic impact to Alberta. In order to quantify the change in pavement costs arising from starting WWP at a shallower frost depth, the impact of moving a limited number of log hauling truck trips from summer to winter conditions was assessed. The analysis started with the normalized percent fatigue cracking and rutting rates that are presented in Table 9. Changes in fatigue cracking damage Equivalent Single Axle Loads (ESALs) due to frost depth and axle load are given in Table 11.

These were estimated by multiplying a baseline ESAL count (for a dual-tired 4550 kg half-axle) by the relative percentages given in Table 11. The ESAL concept (one ESAL is defined as an 80 kN load) is universally known and used as a reference to normalize different axle loads and different axle configurations, which helps simplify truck impact calculation for pavements. The ESAL count of the 4550 kg dual-tired half-axle was calculated using Alberta Transportation's equation for a dual wheel, single axle load under unfrozen pavement conditions (equation 6). Equations 7 – 9 list the other Alberta Transportation ESAL formulae used for this analysis.

$$\textit{Single axle with dual wheels ESAL} = [(\text{axle load (lbs)} + (1))^{4.79}] / (1334000 \times (1)^{4.33}) \quad (6)$$

$$\textit{Single axle with single wheels ESAL} = [\text{axle load (lbs)}/ 11.5]^{3.3} \quad (7)$$

$$\textit{Tandem axle with dual wheels ESAL} = [(\text{axle load (lbs)} + (2))^{4.79}] / (1334000 \times (2)^{4.33}) \quad (8)$$

$$\textit{Tridem axle with dual wheels ESAL} = [\text{axle load (lbs)}/ 47]^{4.49} \quad (9)$$

Importantly, the ESAL results in Table 11 indicate that, after the frost depth reached 500 mm, the ESALs relative to fatigue cracking and rutting became negligible.

Table 11. Estimated ESALs for a range of frost depths and half-axle loads

Frost Depth	ESALs for fatigue cracking				ESALs for surface rutting			
	half-axle load				half-axle load			
	4550 kg	5000 kg	5500 kg	6250 kg	4550 kg	5000 kg	5500 kg	6250 kg
0 mm	1.6228	1.9388			1.6228	2.4193		
180 mm	0.6757	0.9158	1.1762	1.5341	0.0323	0.0519	0.0883	0.1418
300 mm	0.3384	0.3810	0.4669	0.9541	0.0003	0.0226	0.0323	0.0647
500 mm	0.0008	0.0007	0.0010	0.0020	0.0000	0.0014	0.0025	0.0048
600 mm	0.0008	0.0012	0.0010	0.0015	0.0000	0.0000	0.0000	0.0000
700 mm	0.0006	0.0005	0.0012	0.0016	0.0000	0.0000	0.0000	0.0000
800 mm	0.0003	0.0007	0.0010	0.0011	0.0000	0.0000	0.0000	0.0000
1000 mm	0.0002	0.0002	0.0005	0.0008	0.0000	0.0000	0.0000	0.0000

From the results presented in Table 11, the average ESALs per truck pass for four of the most prevalent AB log truck configurations under unfrozen conditions, and for frost depths of 0, 500, 600, 700, 800, and 1000 mm were estimated - by summing the ESALs from all axle groups of each truck configuration at each frost depth (Table 12). Vehicle impacts to frozen AC pavements are more pronounced for fatigue cracking than for rutting; therefore, the following pavement impact estimates are based upon fatigue cracking ESALs estimates. ESALs for frozen pavement conditions were conservatively estimated by:

1) specifying green route axle loads (although not all routes are operated at these loadings); and,
2) ESALs for multiple axle groups were estimated by multiplying the number of axles in the group by the ESALs from a single axle, for that axle load (in Table 11). The average ESALs per log truck load, based on the four common Albertan log trucks, are presented also.

Table 12. Comparison of ESALs per truck for four prevalent Alberta log hauling truck configurations, loaded to green route WWP, for unfrozen and at five frost depth conditions

	ESALs at 0 mm frost	ESALs per truck load at green route WWP frost depth (mm) 500	600	700	800	1000
7-axle tridem tractor/ tridem semi-trailer	5.80	0.0064	0.0058	0.0044	0.0026	0.0017
8-axle tridem tractor/ quad semi-trailer	7.43	0.0065	0.0070	0.0049	0.0033	0.0019
8-axle B-train	6.12	0.0065	0.0073	0.0055	0.0046	0.0022
9-axle B-train	5.73	0.0085	0.0079	0.0068	0.0046	0.0027
Average ESALs per log truck load	6.27	0.0070	0.0070	0.0054	0.0038	0.0021

It is important to note that, for the range of frost depths in Table 12, the average log truck ESALs at green route WWP ranged from about ***900 to 1650 times smaller than at unfrozen conditions (0 mm frost)***. As a result of this difference, a substantial reduction in pavement impacts is expected to result for every trip that is made under frozen pavement conditions instead of under unfrozen conditions.

Hauling at WWP results in higher payloads and more efficient transport of logs. Table 13 summarizes the increase in payload from WWP for red, blue and green route classifications and for the four prevalent Alberta log hauling truck configurations. Hauling at green route WWP increases the payload for the four truck configurations analyzed by 11% to 40%, and by 24%, on average.

Due to this increase in payload there is a corresponding reduction in trips required to transport a given volume of logs. The average number of trips to transport 10,000 tonnes of logs reduces from 258 trips in the summer to 226 trips on blue routes in the winter (a 12% reduction in trips), and to 207 trips on green routes in the winter (a 20% reduction in trips). It is important to note that the annual harvest is relatively stable from year to year so that greater timber volumes hauled in the winter will result in reductions in hauling during the summer and fall when pavements are unfrozen.

Table 13. Increase in payload with winter weights and corresponding reduction in trips

Log truck configuration	Tare Weight (kg)	Red route (regulated) payload (kg)	Blue route WWP payload (kg)	Payload change from red to blue route	Green route WWP payload (kg)	Payload change from red to green route
7-axle tri-drive/ tridem trailer	22000	32,300	35,000	8%	39,300	22%
8-axle quad trailer	22600	40,800	42,400	4%	45,400	11%
8-axle B-train	21000	42,500	48,000	13%	53,000	25%
9-axle tri-drive B-train	23940	39,560	51,360	30%	55,360	40%
Average of these configurations		38,790	44,190	14%	48,265	24%
Trips to haul 10,000 t of logs		258	226	-12%	207	-20%

It is estimated that between 9,000 and 13,500 trips per week occur at the start of winter log hauling operations in Alberta (assuming 18 medium to large log hauling operations, 5 to 6 work days per week, and 100 to 125 loads per week per operation). If 9000 log loads were hauled at green route WWP, the estimated pavement impact would be from 34 to 63 ESALs (Table 14) based on frost depths of 500 to 800 mm. As discussed, 20% more trips would be required to transport the same volume of logs in the summer or fall and, if unfrozen, the average pavement impact would be 67,714 ESALs.

The net annual impact, therefore, would be the difference between the additional ESALs from extra winter hauling at WWP and a corresponding reduction in ESALs from no longer transporting this volume of timber during the summer or fall. The impact of starting green route winter weights sooner would be a net reduction of about 67,670 ESALs per week, on average (Table 15). Using the same approach but with blue route WWP, a net reduction of 63,150 ESALs per week, on average, is predicted (now only 12% more trips are required to transport a comparable volume under unfrozen conditions). Finally, on red routes where there is no WWP, and the reduction in ESALs results only from the ESAL reduction per truckload. A net reduction of about 56,380 ESALs per week, on average, is predicted on red routes.

The damage estimates presented in Table 14 and Table 15 are proportional to the number of truck loads considered. If the number of truck loads were 33% greater (i.e., 13,500 per week), therefore, the net annual pavement impact would also be 33% greater (101,490 fewer ESALs per week on green routes, 94730 fewer ESALs per week on blue routes, and 84,570 fewer ESALs per week on red routes). For simplicity, it was assumed that logs would be hauled in unfrozen summer and fall conditions. In reality, some of the logs might be hauled in late fall when the frost depth has reached 100 mm to 200 mm; and, the reduction in ESALs per truckload would be less. Mills typically curtail harvest and hauling in late fall if they can, however, because of wet ground conditions and because lower cost winter hauling is soon to start.

Table 14. Comparison of pavement impacts for early winter hauling versus hauling under unfrozen conditions

	Average ESALs per week of log hauling in early winter[1,2]					ESALs to haul same volume of logs at regulation weights in summer
	starting frost depth threshold (mm)					
	500	600	700	800	1000	
At green route WWP	63	63	48	34	19	67714
At blue route WWP	59	62	42	29	17	63200
At red route weights (no WWP)	61	58	43	28	17	56429

Note 1: Assuming 9000 log truck loads are transported in AB per week, at the start-up of winter log hauling.

Note 2: The average is the average of the ESALs from tridem/ tridem semi-trailers, 8-axle quad trailers, 8-axle super B-trains, and 9-axle tri-drive B-trains.

Table 15. Net annual pavement impact change for one additional week of log hauling at WWP

	Average net annual ESALs per additional week of log hauling in early winter[1,2]				
	starting frost depth threshold (mm)				
	500	600	700	800	1000
At green route WWP	-67,652	-67,651	-67,666	-67,680	-67,695
At blue route WWP	-63,141	-63,139	-63,158	-63,171	-63,183
At red route weights (no WWP)	-56,368	-56,371	-56,385	-56,401	-56,412

Note 1: Assuming 9000 log truck loads are transported in AB per week, at the start-up of winter log hauling.

Note 2: The average is the average of the ESALs from tridem/ tridem semi-trailers, 8-axle quad trailers, 8-axle super B-trains, and 9-axle tri-drive B-trains.

The theoretical savings in pavement rehabilitation expected from shifting some log hauling to the winter will depend on the amount of the Alberta highway network involved and the length of winter haul season extension arising from a change in starting threshold. Alberta highway networks may be designed to be low volume pavements (1M or 2M ESALs traffic in a 20 year-long service life) or high volume pavements (10M ESALs of traffic in a 20 year-long service life). For the purposes of estimating the theoretical savings in pavement rehabilitation, the rehabilitation to repair structural problems at the end of the pavement's design service life was assumed to cost $265,000 per km.[3] For low volume pavements, designed to carry 1M or 2M ESALs over their service lives, this translates into $0.265 and $0.1325 per km per ESAL, respectively. For a high volume pavement, designed to carry 10M ESALs over its service life (e.g., Highway 2 south of Edmonton, Highway 43, Highway16), this translates into $0.0625 per km per ESAL.

Table 16 summarises the theoretical savings in pavement rehabilitation cost resulting from a winter weight period extension arising from changing the starting threshold frost depth from 1 m to between 600 and 800 mm. The table illustrates a range of results arising from variations in two main variables: the number of additional weeks of log hauling at winter weights and the highway class (design ESALs). The typical loaded, on-highway travel distance was taken to be 125 km, and was derived from the authors' experience and from what might be expected for typical cycle times of 5.0 to 5.5 hours.

[3] Based on discussion with Marta Juhasz, P.Eng., Director, Pavement Engineering, Alberta Transportation. August 2017.

Table 16. Theoretical annual savings in pavement rehabilitation cost as a function of winter weight period extension, pavement class, and typical loaded, on-highway, travel distance

Winter weight period extension	Highway class (design ESALs)	Annual pavement rehabilitation savings
1 week	1M	-$2,067,100
	2M	-$1,033,500
	10M	-$206,700
2 weeks	1M	-$4,134,100
	2M	-$2,067,100
	10M	-$413,400
3 weeks	1M	-$6,201,200
	2M	-$3,100,600
	10M	-$620,100

Note: assumes 9000 trips per week, 125 km travel on highway per trip, and a 1/3 – 1/3 – 1/3 split between timber volume hauled at green WWP, blue WWP, and red route (no WWP) weights. Savings are averaged for starting frost depth thresholds of 600, 700, and 800 mm.

Table 17 presents three costing scenarios to summarize the sensitivity of anticipated rehabilitation savings, given a change in threshold frost depth to 700, 750, or 800 mm. Savings were estimated by interpolating from Table 16.

The scenarios assume that there is a 1/3 – 1/3 – 1/3 split between timber volume hauled at green WWP, blue WWP, and red route (no WWP) weights, and that 40% of the impacted highway was 1M ESAL design, 55% was 2M ESAL design, and only 5% was 10M ESAL design. Analysis of data for the winter of 2015/16 from 25 AT thermistor stations located in active log haul areas (Table 2) revealed that, on average in winter 2015/16, it took about 1.5 weeks for frost to penetrate from 700 mm to 1 m in northern Alberta highways but only 1.0 week to penetrate from 800 mm to 1 m. These frost penetration rates provided the basis for timing in the costing scenarios below.

The theoretical savings in pavement rehabilitation costs were in the order of $1.4M to $2.5M per year, depending on winter weight extension and volume of log hauling trucks. These estimates assume only 9000 truckloads per week and would be proportionately larger for higher traffic levels (e.g., 33% greater for 13,500 truckloads per week).

Table 17. Anticipated rehabilitation savings for threshold frost depths of 700 to 800 mm

		Anticipated annual pavement rehabilitation savings	
Winter weight extension	Frost depth threshold	100 loads per day & 5 haul days per week	125 loads per day & 6 haul days per week
1 week	800 mm	-$1,405,789	-$1,686,946
1.2 week	750 mm	-$1,757,116	-$2,108,539
1.5 weeks	700 mm	-$2,108,443	-$2,530,131

9. CONCLUSION AND RECOMMENDATIONS FOR WWP STARTING FROST DEPTH

FPInnovations, in cooperation with Alberta Transportation and the Laval University i3C Chair, undertook a review of the starting threshold for Alberta winter weights. The current threshold is 1 m of frost and this is the most conservative threshold used by any province that allows winter weight premiums in Canada. Neither the Alberta threshold nor any other provincial threshold is substantiated by an engineering analysis of the structural capacity of freezing pavements. The objective of this project was to conduct an engineering analysis of freezing pavements to determine the minimum frost depth at which log hauling at Alberta winter weight premiums could start. The objective of this research project is to make recommendations to Alberta Transportation regarding optimal frost depths in provincial highways prior to starting the annual winter weight log hauling programs.

The first step of the project was to conduct an extensive literature review of Canadian provincial winter weight policies in Alberta, Saskatchewan, Manitoba, Ontario, New Brunswick, and the Northwest Territories. This provided context for the objectives of the project. Also, two pavements were case-studied to investigate how to model freezing pavements, and to provide a preliminary indication of potential to reduce the starting threshold frost depth for 1 m. The City of Edmonton evaluated the properties of freezing unbound pavement materials, and these properties were used for modeling. Results from the City of Edmonton testing (included in Appendix E) showed that as soils and pavements materials freeze, resilient moduli increase termendously as a comparison to unfrozen conditions.

A layered elastic model was created of each pavement, with layers corresponding to pavement materials at a given temperature. The modeling predicted at shallower frost depths,heavier axle loads created higher values ofstrains and surface deflections. While horizontal strain at the bottom of the asphaltic concrete mat showed smoothly decreasing trends, this was not the case with for vertical subgrade strains. Subgrade vertical strains became very small when frost depths reached 650 mm. These results are shown in this report.

The second step was to measure the mechanical behavior of freezing Alberta pavements using Laval University pavement simulator. A controlled trafficking simulation was conducted on a typical Alberta pavement (a 180 mm-thick asphaltic concrete mat, a 300 mm-thick granular base of well-graded granitic gravel, and a wet plastic clay subgrade). This pavement was constructed in Laval University's environmentally controlled pavement test pit, and trafficking was applied at four load levels with a traffic simulator. Numerous sensors were installed in the pavement to measure instantaneous responses to the traffic loads, and to monitor environmental conditions during testing (water pressure, moisture content, temperature profile). Freezing was initiated from the top down with air temperature maintained at -10° C. A water table was maintained at 1500 mm below the surface of the pavement for the first round of freezing and at 800 mm for the second round of freezing. Two freezing and trafficking cycles were completed with frost reaching a depth of about 1.2 m. The wheel loads were 4550, 5000, 5500 and 6250 kg.

The trafficking test results showed that:

- An increase of load from 4550 to 6250 kg created higher stresses in all layers of the pavement under non frozen conditions.
- As the frost penetrated deeper, the pavement grew increasingly less reactive to mechanical pressure.
- When frost depth reached 600 mm, very minor strain response were observed within the pavement.
- The pavement service life analysis that was conducted following the trafficking indicated that freezing (and even cooling) of the hot mix asphalt mat greatly reduced the predicted surface deflections and rutting. Conversely, when freezing reached the bottom of the granular base, the estimated fatigue cracking damage was greatly reduced. From a service life perspective, the risk of pavement damage after 500 mm frost penetration appears very minor, even at the heaviest loading tested, because the relative damage values are very small, and they rapidly approach zero at higher frost depths.

Results from pavement trafficking were then compared to the study from Yi et al. (2016) and pavement modeling using layered elastic modeling (WinJULEA). Similar trends were observed in both studies. Despite the differences in structure, the two pavements responded similarly to load increases during freezing. In both tests, under both loading conditions, the key pavement strains for fatigue cracking and rutting stabilized at a minimal value when frost depth reached 600 mm, and did not change much - if at all – at deeper frost depths or heavier axle loads.

Since these results were obtained for one Alberta's road type, a sensitivity analysis was performed to corroborate the results from this project with other provincial highways in Alberta. The impact of load increase on the mechanical behavior of pavements under frozen conditions was analyzed on five of the weakest, representative, Alberta pavements and the results were compared with results from modeling of the pavement studied in this project. Results from sensitivity analysis showed great similarity between all pavements behaviors when frost depth reached 600 mm.

To conclude, very minor pavement impacts are predicted for the analyzed log trucks at the recommended WWP under frost depths from 600 to 1000 mm. Winter weights should be initiated, therefore, at a frost depth that typically corresponds to a time in winter when freezing proceeds steadily, and the pavement is well frozen and able to resist brief warming spells during the freezing process. This should lead to WWP staying on once they are instated causing less upset for both the forestry and heavy haul trucking, and regulators. Freezing pattern tests and data provided by AT indicate that initiating winter weights at a frost depth of 700 mm, as opposed to 600 mm, is more likely to result in colder roadbed temperatures and consistent freezing. FPInnovations recommends that AT change the frost depth for starting the winter weight program from 1 m to 700 mm. Although Saskatchewan has a starting threshold of 750 mm (and Manitoba adopted the same threshold in 2011), the scientific underpinning for setting this threshold was not as rigorously developed as was the Alberta effort. Nor is it necessary to harmonize the starting thresholds between Saskatchewan and Alberta because Alberta WWP (and truck GCVW) are different from those allowed in Saskatchewan during the winter.

The economic impact of this change is positive both for AT and the forest industry because it should decrease long-term highway maintenance costs, and it will decrease timber transportation costs. A reduced frost depth threshold may prove to be a big benefit for heavy haul carriers in the south who were not able to participate in the winter weight program in the past because frost depths in the area did not reach 1 m.

The analysis conducted in this project is conservative because it is based on Alberta's most representative and weakest pavements. Predicted pavement wear rates are anticipated to be higher than would be expected for many situations.

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11. APPENDICES

Appendix A: Maximum increase in gross combined vehicle weights and axle weights with Alberta WWP

Log hauling truck configuration	GCVW with green route WWP (t)	GCVW on red routes (no WWP) (t)	Maximum GCVW increase		No. of drive and trailer axles per configuration	Average load increase on drive and trailer axles (t)
			(t)	(%)		
10-axle B-train	88	63.5	24.5	39%	9	2.7
9-axle B-train (tridem drive)	79.3	63.5	15.8	25%	8	2.0
8-axle super B-Train	74.5	63.5	11	17%	7	1.6
8-axle reverse B-train	74.5	63.5	11	17%	7	1.6
Truck/ 4-axle full trailer	60	55.3	4.7	8%	6	0.8
7-axle tridem tractor/ tridem pole trailer	61.3	54.3	7	13%	6	1.2
7-axle tractor/ tandem jeep/ pole trailer	65	56.5	8.5	15%	6	1.4
6-axle tractor/ jeep/ pole trailer	60	48.6	11.4	23%	5	2.3
6-axle tractor/ tridem semi-trailer	57.6	45.6	12	26%	5	2.4
6-axle tridem tractor/ pole trailer	59.3	47.3	12	25%	5	2.4
5-axle tractor/ tandem pole	55.6	39.6	16	40%	4	4.0

Appendix B: Results from pavement materials lab testing

Transports, Mobilité durable et Électrification des transports Québec

RAPPORTS D'ESSAIS - ENROBÉS
ESSAIS EN TRACTION-COMPRESSION DIRECTE

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Service des matériaux d'infrastructures
2700, rue Einstein Québec G1P3W8

ÉCHANTILLON

Mode d'échantillonnage :	Carottier de 150 mm Ø ext.
Type d'échantillon :	Carottes
Type d'enrobé :	EB-10S
Usage :	
Date de réception :	2015-12-08

EXPÉDITEUR ET DISTRIBUTION

Soumis par :	Jean-Pascal Bilodeau, UL
Destinataire :	Jean-Pascal Bilodeau, UL
Numéro de dossier interne :	AM-075-15

PRÉLÈVEMENT

No. de fiche d'échantillonnage :		Entrepreneur :	
Numéro d'échantillon :	1-H - 2-H - 3-H	Route/tronç./sect. :	
Prélevé par :		Chaînage/décalage :	
Date/Heure :		Voie/emplacement dans la voie :	
Lieu :	Fosse d'essais de la Chaire i3C	Municipalité :	
Source de l'enrobé :		Source de granulats :	Carrière LT
Source de bitume :		Classe de bitume :	PG 58–28
Lot :			

Centrale d'enrobage :	Asphalte Lagacé ltée. (024)	Formule d'enrobé :	024-5828-15A
Type d'essai à réaliser :	Module complexe	Teneur en bitume :	5.00%

Remarque : Couche de surface

LC 26-700 Détermination du module complexe des enrobés

Mode de préparation :	Carottage sur la route	
Hauteur des éprouvettes :	129	mm
Diamètre des éprouvettes :	75	mm

Éprouvette :	EB-140-15	EB-142-15	EB-144-15
Dmax :	2.499	2.499	2.499
Dbrute :	2.334	2.327	2.329
% de vides :	6.6%	6.9%	6.8%

MODÈLE HUET-SAYEGH DE MODULE COMPLEXE, E* (MPa)

E_0	E_∞	δ	k	h	τ_0	a_1	a_2
1.8	29 700	2.529	0.201	0.629	0.009	-0.138	9.29E-04

* À la température de référence (Tr) = 10°C

MODÈLE WITCZAK DE MODULE DYNAMIQUE, LOG |E*| (MPa)

δ	α	β	γ	a_1	a_2
-0.414	4.848	-1.313	-0.490	-0.138	8.43E-04

* À la température de référence (Tr) = 10°C

Remarque :

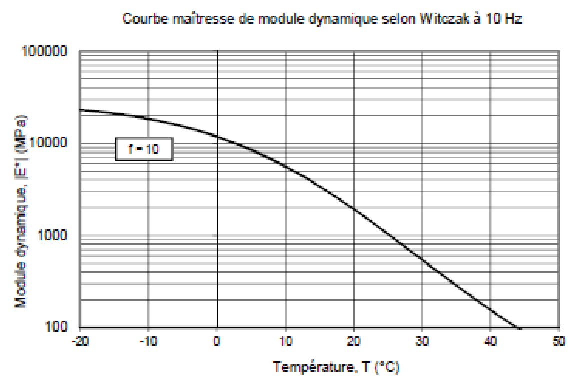

Figure 17. Traction-compression test on hot mix asphalt (1).

Transports, Mobilité durable et Électrification des transports Québec

RAPPORTS D'ESSAIS - ENROBÉS
ESSAIS EN TRACTION-COMPRESSION DIRECTE

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MODÈLE HUET-SAYEGH DE MODULE COMPLEXE, E* (MPa)

$$E^* = E_o + \frac{E_\infty - E_o}{1 + \delta (i\omega\tau)^{-k} + (i\omega\tau)^{-h}}$$

$$\tau = a_T \cdot \tau_o$$

$$\log a_T = a_1 (T - T_r) + a_2 (T - T_r)^2$$

T_r =	10 °C
RMSE log E1 =	0.043
RMSE log E2 =	0.034
R^2 log E1 =	1.00
R^2 log E2 =	1.00
n =	91

E_o	E_∞	δ	k	h	τ_o	a_1	a_2
1.8	29 700	2.529	0.201	0.629	0.009	-0.138	9.29E-04

MODÈLE WITCZAK DE MODULE DYNAMIQUE, LOG |E*| (MPa)

$$\log|E^*| = \delta + \frac{\alpha}{1 + e^{(\beta + \gamma \log f_r)}}$$

$$f_r = a_T \cdot f$$

$$\log a_T = a_1 (T - T_r) + a_2 (T - T_r)^2$$

T_r =	10 °C
RMSE log |E*| =	0.022
R² log |E*| =	1.00
n =	91
E_{min} =	0.4
E_{max} =	27 200

δ	α	β	γ	a_1	a_2
-0.414	4.848	-1.313	-0.490	-0.138	8.43E-04

Éprouvette : EB-140-15 Densité brute : 2.334
Densité max : 2.499 Teneur vides : 6.6%

T (°C)	f (Hz)	σ (kPa)	ε (με)	CV_ε (%)	|E*| (MPa)	ϕ (°)	E1 (MPa)	E2 (MPa)
-19.6	10	712.2	29.8	17	23 892	3.8	23 840	1 564
-19.6	3	665.2	29.5	18	22 538	6.2	22 407	2 431
-19.6	1	616.7	29.1	17	21 180	5.5	21 082	2 035
-19.6	0.3	587.6	30.0	16	19 609	6.7	19 473	2 301
-19.6	0.1	553.8	30.8	15	18 008	7.9	17 838	2 467
-9.7	10	763.7	41.8	4	18 276	7.3	18 129	2 314
-9.7	3	650.3	40.2	3	16 175	8.7	15 988	2 454
-9.7	1	571.4	39.8	2	14 354	10.8	14 100	2 689
-9.7	0.3	499.6	40.6	2	12 312	13.0	11 999	2 759
-9.7	0.1	431.7	41.3	5	10 460	15.3	10 091	2 753
0.3	10	659.5	57.4	6	11 497	14.4	11 136	2 857
0.3	3	480.4	51.9	9	9 255	17.6	8 824	2 793
0.3	1	371.8	50.3	11	7 385	21.2	6 884	2 673
0.3	0.3	283.5	51.6	14	5 499	25.0	4 986	2 321
0.3	0.1	207.5	51.9	18	4 002	29.1	3 498	1 944
10.3	10	328.3	58.6	18	5 604	27.2	4 982	2 565
10.3	3	216.1	57.3	20	3 773	32.9	3 167	2 050
10.3	1	132.2	52.9	20	2 498	38.2	1 964	1 544
10.4	0.3	78.3	52.2	18	1 499	42.4	1 106	1 012
10.4	0.1	46.9	51.7	15	907	45.7	634	649
20.3	10	126.0	63.6	18	1 981	44.8	1 405	1 397
20.3	3	45.7	41.6	13	1 099	49.7	711	838
20.3	1	31.8	53.0	9	600	52.9	362	479
20.3	0.3	15.8	51.9	8	305	54.6	177	249
20.3	0.1	8.7	51.5	9	169	51.2	106	132
30.4	10	27.1	48.8	2	555	54.8	320	454
30.4	3	13.5	50.9	1	265	57.0	145	222
30.4	1	7.3	52.9	1	139	56.3	77	116
30.4	0.3	3.8	52.0	1	73	51.0	46	57
40.1	10.4	10.1	66.0	8	153	56.3	85	128
40.1	3	3.4	50.3	8	67	62.5	31	60

Éprouvette : EB-142-15 Densité brute : 2.327
Densité max : 2.499 Teneur vides : 6.9%

T (°C)	f (Hz)	σ (kPa)	ε (με)	CV_ε (%)	|E*| (MPa)	ϕ (°)	E1 (MPa)	E2 (MPa)
-19.6	10	675.1	30.1	14	22 420	4.2	22 360	1 651
-19.6	3	623.1	29.4	15	21 225	4.0	21 172	1 493
-19.6	1	579.8	29.1	15	19 933	5.2	19 850	1 817
-19.6	0.3	554.4	30.0	16	18 473	6.4	18 356	2 073
-19.6	0.1	520.5	30.7	16	16 964	8.0	16 800	2 354
-9.7	10	709.2	41.6	18	17 048	7.5	16 901	2 234
-9.7	3	603.7	39.9	19	15 143	9.4	14 939	2 481
-9.7	1	532.5	39.7	20	13 398	11.3	13 139	2 620
-9.7	0.3	464.2	40.6	21	11 435	13.3	11 131	2 622
-9.7	0.1	399.7	41.1	23	9 723	15.1	9 386	2 537
0.3	10	616.2	56.9	25	10 828	15.1	10 456	2 813
0.3	3	444.5	51.2	27	8 685	18.3	8 246	2 727
0.3	1	343.9	50.1	28	6 863	22.2	6 353	2 598
0.3	0.3	261.2	51.4	29	5 078	26.1	4 561	2 232
0.3	0.1	188.4	51.6	29	3 654	30.7	3 142	1 865
10.3	10	303.5	55.6	29	5 455	27.2	4 852	2 493
10.3	3	203.7	55.6	29	3 662	33.5	3 054	2 020
10.3	1	127.6	53.1	26	2 404	39.2	1 863	1 519
10.3	0.3	74.3	52.4	21	1 418	44.5	1 012	993
10.3	0.1	42.8	51.6	15	829	47.9	556	614
20.2	10	105.3	53.5	24	1 968	43.7	1 423	1 360
20.2	3	62.3	58.6	18	1 063	49.4	691	807
20.3	1	31.1	52.9	14	587	52.2	360	464
20.2	0.3	15.3	51.8	14	295	54.0	174	239
20.3	0.1	8.2	51.6	16	159	54.1	93	129
30.3	10	22.2	40.2	10	551	55.5	312	454
30.3	3	14.3	55.6	9	256	57.8	137	217
30.3	1	7.0	52.8	9	134	57.4	72	113
30.3	0.3	3.6	52.0	9	69	55.9	38	57
40.2	10	8.8	62.1	11	142	62.2	66	125
40.2	3	3.7	54.9	11	68	55.3	39	56

Éprouvette : EB-144-15 Densité brute : 2.329
Densité max : 2.499 Teneur vides : 6.8%

T (°C)	f (Hz)	σ (kPa)	ε (με)	CV_ε (%)	|E*| (MPa)	ϕ (°)	E1 (MPa)	E2 (MPa)
-19.6	10	724.2	29.9	19	24 208	2.9	24 178	1 205
-19.6	3	669.0	29.4	19	22 759	4.6	22 685	1 832
-19.6	1	623.0	29.0	18	21 448	5.6	21 345	2 098
-19.6	0.3	594.8	30.0	16	19 808	7.0	19 662	2 398
-9.7	10	745.2	41.1	11	18 111	7.4	17 961	2 321
-9.7	3	639.2	39.9	10	16 022	9.8	15 790	2 714
-9.7	1	563.3	39.7	7	14 173	11.2	13 905	2 742
-9.7	0.3	491.0	40.6	4	12 091	13.5	11 755	2 828
-9.7	0.1	421.1	41.2	1	10 213	16.1	9 815	2 824
0.3	3	469.8	51.0	21	9 220	16.5	8 842	2 615
0.3	1	372.8	50.2	19	7 423	22.1	6 877	2 793
0.3	0.3	284.2	51.6	12	5 505	25.6	4 966	2 375
0.3	0.1	205.5	51.5	9	3 989	29.3	3 478	1 953
10.3	10	282.4	53.9	36	5 241	27.3	4 658	2 402
10.3	3	201.6	57.7	36	3 496	33.5	2 917	1 927
10.3	1	122.0	52.8	34	2 309	38.5	1 807	1 437
10.3	0.3	72.1	52.2	28	1 383	43.0	1 011	943
10.3	0.1	43.0	51.7	23	831	45.9	578	597
20.2	10	98.6	51.5	28	1 915	43.9	1 380	1 328
20.2	3	46.6	44.0	20	1 060	48.9	698	799
20.2	1	31.1	52.9	14	587	52.1	361	463
20.2	0.3	15.4	51.8	12	298	54.1	174	241
20.2	0.1	8.5	51.3	13	166	51.8	103	130
30.4	10	30.3	52.5	11	578	54.0	340	467
30.4	3	14.0	50.7	13	276	55.2	157	227
30.4	1	7.7	52.9	15	145	53.8	86	117
30.4	0.3	4.1	52.0	17	78	47.5	53	58
40.4	10	7.8	48.7	11	160	57.0	87	134
40.4	3	4.0	51.9	11	77	51.4	48	60

Figure 18. Traction-compression test on hot mix asphalt (2).

Transports, Mobilité durable et Électrification des transports
Québec

RAPPORTS D'ESSAIS - ENROBÉS
ESSAIS EN TRACTION-COMPRESSION DIRECTE

Service des matériaux d'infrastructures
2700, rue Einstein Québec G1P3W8

ÉCHANTILLON

Mode d'échantillonnage :	Carottier de 150 mm Ø ext.
Type d'échantillon :	Carottes
Type d'enrobé :	EB-10S
Usage :	
Date de réception :	2015-12-08

EXPÉDITEUR ET DISTRIBUTION

Soumis par :	Jean-Pascal Bilodeau, UL
Destinataire :	Jean-Pascal Bilodeau, UL
Numéro de dossier interne :	AM-075-15

PRÉLÈVEMENT

No. de fiche d'échantillonnage :		Entrepreneur :	
Numéro d'échantillon :	1-B - 2-B - 3-B	Route/tronç./sect. :	
Prélevé par :		Chaînage/décalage :	
Date/Heure :		Voie/emplacement dans la voie :	
Lieu :	Fosse d'essais de la Chaire i3C	Municipalité :	
Source de l'enrobé :		Source de granulats :	Carrière LT
Source de bitume :		Classe de bitume :	PG 58–28
Lot :			

Centrale d'enrobage :	Asphalte Lagacé ltée. (024)	Formule d'enrobé :	024-5828-15A
Type d'essai à réaliser :	Module complexe	Teneur en bitume :	5.00%

Remarque : Couche de base

LC 26-700 Détermination du module complexe des enrobés

Mode de préparation :	Carottage sur la route	
Hauteur des éprouvettes :	131	mm
Diamètre des éprouvettes :	75	mm

Éprouvette :	EB-139-15	EB-141-15	EB-143-15
Dmax :	2.499	2.499	2.499
Dbrute :	2.406	2.389	2.414
% de vides :	3.7%	4.4%	3.4%

MODÈLE HUET-SAYEGH DE MODULE COMPLEXE, E* (MPa)

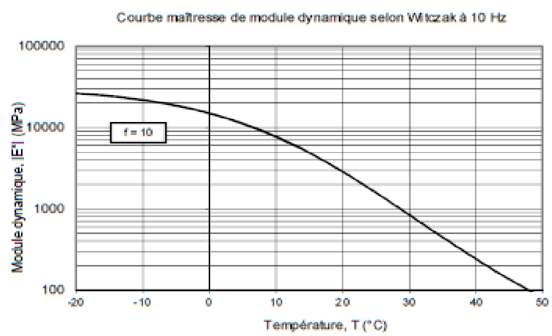
E_0	E_∞	δ	k	h	τ_0	a_1	a_2
2.0	32 500	2.231	0.205	0.604	0.015	-0.141	9.13E-04

*À la température de référence (Tr) = 10°C

MODÈLE WITCZAK DE MODULE DYNAMIQUE, LOG |E*| (MPa)

δ	α	β	γ	a_1	a_2
0.188	4.291	-1.318	-0.515	-0.137	7.20E-04

*À la température de référence (Tr) = 10°C



Remarque :

Essais supervisés par : Christian Larochelle, tech. Date : 2016-02-17

COMMENTAIRES DE L'APPROBATEUR

Original du rapport signé par :

Vérifié par : Maxime Laplante-Boivin, ing. Date : 2016-02-19

Figure 19. Traction-compression test on hot mix asphalt (3).

Transports, Mobilité durable et Électrification des transports
Québec

RAPPORTS D'ESSAIS - ENROBÉS
ESSAIS EN TRACTION-COMPRESSION DIRECTE

MODÈLE HUET-SAYEGH DE MODULE COMPLEXE, E* (MPa)

$$E^* = E_o + \frac{E_\infty - E_o}{1 + \delta (i\omega\tau)^{-k} + (i\omega\tau)^{-h}}$$

$$\tau = a_T \cdot \tau_o$$

$$\log a_T = a_1 (T - T_r) + a_2 (T - T_r)^2$$

T_r =	10 °C
RMSE log E1 =	0.056
RMSE log E2 =	0.040
R^2 log E1 =	1.00
R^2 log E2 =	1.00
n =	97

E_o	E_∞	δ	k	h	τ_o	a_1	a_2
2.0	32 500	2.231	0.205	0.604	0.015	-0.141	9.13E-04

MODÈLE WITCZAK DE MODULE DYNAMIQUE, LOG |E*| (MPa)

$$\log|E^*| = \delta + \frac{\alpha}{1 + e^{(\beta + \gamma \log f_r)}}$$

$$f_r = a_T \cdot f$$

$$\log a_T = a_1 (T - T_r) + a_2 (T - T_r)^2$$

T_r =	10 °C
RMSE log |E*| =	0.031
R^2 log |E*| =	1.00
n =	97
E_{min} =	1.5
E_{max} =	30 100

δ	α	β	γ	a_1	a_2
0.188	4.291	-1.318	-0.515	-0.137	7.20E-04

Éprouvette : EB-139-15 Densité brute : 2.406
Densité max : 2.499 Teneur vides : 3.7%

T (°C)	f (Hz)	σ (kPa)	ε (με)	CV_ε (%)	|E*| (MPa)	φ (°)	E1 (MPa)	E2 (MPa)
-19.6	10	792.9	28.4	15	27 947	2.4	27 922	1 182
-19.6	3	772.0	29.3	15	26 341	4.0	26 278	1 828
-19.6	1	718.6	28.9	16	24 847	5.0	24 754	2 157
-19.6	0.3	688.3	29.8	15	23 130	6.1	22 998	2 461
-19.6	0.1	653.5	30.5	15	21 456	7.1	21 292	2 646
-9.7	10	856.5	39.1	10	21 894	6.6	21 750	2 507
-9.7	3	780.6	39.8	10	19 617	8.2	19 417	2 794
-9.7	1	694.8	39.6	9	17 565	10.0	17 296	3 064
-9.7	0.3	615.9	40.3	8	15 287	11.8	14 962	3 135
-9.7	0.1	540.8	41.1	6	13 149	14.1	12 753	3 201
0.2	10	754.2	51.7	7	14 585	13.4	14 187	3 386
0.2	3	606.7	50.8	6	11 942	16.6	11 442	3 418
0.2	1	480.9	49.5	4	9 719	19.6	9 157	3 257
0.2	0.3	379.6	51.2	2	7 419	23.6	6 799	2 969
0.2	0.1	285.6	51.5	2	5 545	27.7	4 907	2 581
10.4	10	385.5	51.6	10	7 475	25.5	6 746	3 221
10.4	3	292.0	57.3	10	5 099	31.8	4 333	2 689
10.4	1	181.1	52.8	10	3 428	36.9	2 742	2 058
10.4	0.3	107.8	52.1	10	2 069	42.4	1 527	1 396
10.4	0.1	63.9	51.7	11	1 235	46.1	857	889
20.3	10	154.0	52.9	11	2 911	41.2	2 189	1 919
20.3	3	97.3	60.7	10	1 603	47.5	1 084	1 181
20.3	1	47.5	52.9	10	899	51.0	565	699
20.3	0.3	23.9	51.8	10	461	52.3	282	365
20.3	0.1	13.2	51.4	11	258	51.7	159	202
30.3	10	37.6	46.7	8	804	54.7	465	656
30.3	3	18.6	47.8	9	389	56.3	216	324
30.3	1	10.7	53.2	10	202	55.5	114	166
30.3	0.3	5.4	51.9	13	105	53.3	63	84
30.3	0.1	3.2	51.6	14	63	56.2	35	52
40.5	10	8.4	38.6	10	218	55.1	125	179
40.4	3	5.5	49.2	12	112	49.6	72	85
40.4	1	3.8	51.9	14	73	39.5	56	46

Éprouvette : EB-141-15 Densité brute : 2.389
Densité max : 2.499 Teneur vides : 4.4%

T (°C)	f (Hz)	σ (kPa)	ε (με)	CV_ε (%)	|E*| (MPa)	φ (°)	E1 (MPa)	E2 (MPa)
-19.7	10	770.2	29.4	36	26 184	2.3	26 164	1 038
-19.7	3	731.1	29.6	37	24 729	4.2	24 663	1 808
-19.7	1	680.6	29.0	38	23 432	4.8	23 349	1 973
-19.7	0.3	653.6	29.9	38	21 858	5.4	21 762	2 044
-9.7	10	820.3	39.5	28	20 780	6.8	20 634	2 455
-9.7	3	744.3	39.8	30	18 683	8.4	18 481	2 736
-9.7	1	668.1	39.8	30	16 802	9.6	16 568	2 792
-9.7	0.3	594.4	40.6	30	14 627	11.3	14 342	2 871
-9.7	0.1	521.4	41.3	30	12 624	13.7	12 267	2 983
0.3	10	715.3	53.3	29	13 429	14.1	13 025	3 266
0.3	3	556.4	50.9	31	10 926	17.5	10 418	3 292
0.3	1	448.0	49.8	30	8 986	18.7	8 511	2 884
0.3	0.3	355.1	51.5	30	6 896	23.3	6 335	2 725
0.3	0.1	267.5	52.0	27	5 141	24.7	4 670	2 150
10.4	10	364.3	50.0	9	7 286	24.6	6 624	3 036
10.4	3	281.2	56.1	8	5 016	30.5	4 324	2 542
10.4	1	179.9	52.5	7	3 427	35.0	2 806	1 967
10.4	0.3	110.9	52.2	4	2 124	40.0	1 627	1 364
10.4	0.1	68.6	51.6	4	1 328	42.8	975	902
20.2	10	151.9	53.2	12	2 854	40.1	2 183	1 838
20.2	3	67.4	40.6	8	1 659	44.9	1 175	1 172
20.2	1	50.8	53.0	4	958	48.1	639	713
20.2	0.3	27.8	51.9	9	536	48.5	355	401
20.3	0.1	17.8	51.6	18	345	42.5	255	233
30.3	10	44.0	47.2	7	932	50.2	596	717
30.3	3	23.2	49.3	3	471	51.3	294	367
30.3	1	13.9	53.5	10	259	49.6	168	197
30.3	0.3	7.5	52.3	18	143	45.7	100	102
30.3	0.1	4.6	51.9	21	89	44.3	63	62
40.2	10	11.4	49.1	6	231	58.7	120	198
40.2	3	5.8	55.2	3	106	55.8	59	88
40.2	1	3.1	52.1	5	59	50.6	37	46

Éprouvette : EB-143-15 Densité brute : 2.414
Densité max : 2.499 Teneur vides : 3.4%

T (°C)	f (Hz)	σ (kPa)	ε (με)	CV_ε (%)	|E*| (MPa)	φ (°)	E1 (MPa)	E2 (MPa)
-19.6	10	753.5	28.0	17	26 867	3.3	26 822	1 557
-19.6	3	738.9	29.1	17	25 397	3.9	25 340	1 711
-19.6	1	697.3	28.8	18	24 177	4.8	24 093	2 020
-19.6	0.3	679.0	29.9	17	22 681	5.5	22 575	2 189
-19.6	0.1	648.0	30.7	16	21 094	6.6	20 952	2 441
-9.7	10	829.2	39.2	19	21 167	6.5	21 033	2 378
-9.7	3	754.8	39.6	19	19 085	7.9	18 904	2 622
-9.7	1	680.0	39.5	19	17 210	9.8	16 959	2 926
-9.7	0.3	611.5	40.6	18	15 066	11.1	14 784	2 906
-9.7	0.1	538.0	41.2	18	13 065	13.1	12 723	2 972
0.3	10	729.0	50.8	2	14 358	12.5	14 016	3 114
0.3	3	596.4	50.1	2	11 911	15.4	11 482	3 170
0.3	1	480.9	49.2	3	9 768	18.4	9 270	3 080
0.3	0.3	389.5	51.7	3	7 535	22.2	6 975	2 851
0.3	0.1	294.2	51.6	6	5 699	26.7	5 094	2 557
10.4	10	359.1	46.8	12	7 680	23.4	7 045	3 056
10.4	3	294.3	55.0	12	5 348	30.0	4 629	2 678
10.4	1	194.0	52.5	12	3 694	34.8	3 035	2 106
10.4	0.3	120.2	52.3	12	2 297	40.1	1 757	1 479
10.4	0.1	73.6	51.6	11	1 424	43.8	1 029	985
20.2	10	170.4	56.1	9	3 038	39.9	2 331	1 949
20.2	3	82.7	47.4	7	1 743	45.5	1 221	1 244
20.2	1	52.6	53.0	6	992	49.7	641	757
20.2	0.3	26.7	51.9	6	515	53.1	309	412
20.2	0.1	14.6	51.5	7	283	53.3	170	227
30.3	10	34.3	37.8	6	909	53.0	547	726
30.3	3	23.4	54.0	6	433	57.2	235	364
30.3	1	11.8	52.7	8	224	56.0	125	186
30.3	0.3	6.0	51.9	10	116	53.0	70	92
30.3	0.1	3.4	51.8	9	66	51.8	41	52
40.3	10	15.0	57.4	11	262	58.6	136	223
40.3	3	6.7	50.8	14	131	56.9	72	110

Figure 20. Traction-compression test on hot mix asphalt (4).

Ministère des Transports Québec

MÉTHODE LC 22-400
DÉTERMINATION DU MODULE RÉVERSIBLE DES MATÉRIAUX GRANULAIRES

Dossier :	SG-4125-16	Matériau :	MG-20	Source :	Université Laval
Client :	Jean-Pascal Bilodeau	Ajout :		Pétrographie :	

Éprouvette :	MG-001-16	Teneur eau :	2,4 %	Porosité :	16 %	Densité :	2,63	Teneur eau optimale :	6,5 %
		Masse volumique :	2215 kg/m³	Saturation :	21 %	Absorption :	0,9 %	Masse vol. optimale :	2249 kg/m³

Teneur eau intiale : 2,4 % Saturation : 21 %

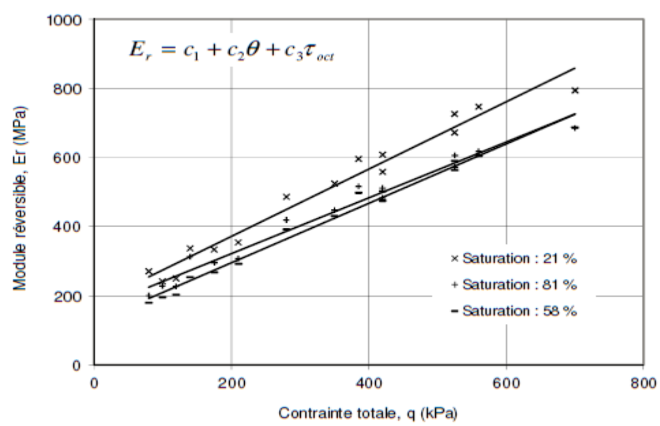
σ_3 (kPa)	σ_{do} (kPa)	$\Delta\sigma_d$ (kPa)	$\varepsilon_{1r\,moy}$ ($\mu\varepsilon$)	ε_{3r} ($\mu\varepsilon$)	CV (%)	θ (kPa)	τ_{oct} (kPa)	E_r (MPa)	ν_r
20	2,0	18	66	-9	14	80	9	271	0,13
20	4,0	36	146	-24	12	100	19	243	0,16
20	6,0	53	213	-40	11	119	28	250	0,19
35	3,5	32	93	-13	18	140	16	338	0,14
35	7,1	63	188	-32	11	175	33	335	0,17
35	10,6	94	266	-52	10	210	49	355	0,19
70	7,1	63	129	-18	17	280	33	487	0,14
70	14,1	126	240	-41	13	350	66	525	0,17
70	21,2	189	338	-69	12	420	99	559	0,20
105	7,1	63	106	-14	25	385	33	597	0,13
105	10,6	95	155	-22	18	420	50	609	0,14
105	21,2	189	281	-50	15	525	99	673	0,18
140	10,6	95	130	-18	24	525	50	726	0,14
140	14,1	126	169	-25	19	560	66	747	0,15
140	28,2	252	317	-57	15	700	132	795	0,18

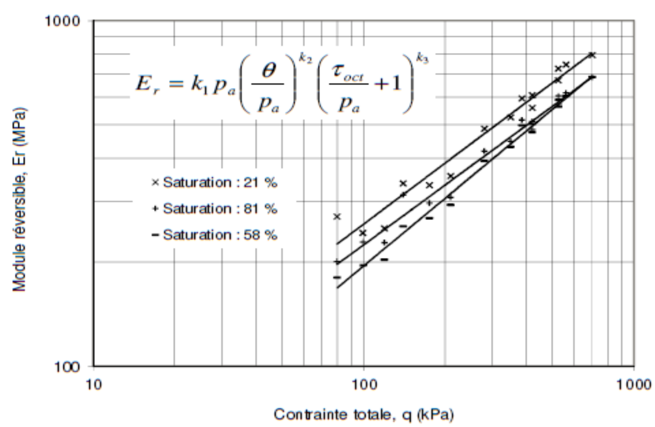
Teneur eau saturée : 6,7 % Saturation : 81 %

σ_3 (kPa)	σ_{do} (kPa)	$\Delta\sigma_d$ (kPa)	$\varepsilon_{1r\,moy}$ ($\mu\varepsilon$)	ε_{3r} ($\mu\varepsilon$)	CV (%)	θ (kPa)	τ_{oct} (kPa)	E_r (MPa)	ν_r
20	2,0	18	89	-14	8	80	9	201	0,15
20	4,0	36	156	-30	8	100	19	229	0,19
20	6,0	53	234	-52	8	119	28	228	0,22
35	3,5	32	101	-16	10	140	17	313	0,16
35	7,1	63	213	-42	8	175	33	296	0,20
35	10,6	95	307	-68	8	210	50	308	0,22
70	7,1	63	150	-24	15	280	33	420	0,16
70	14,2	126	282	-55	10	350	66	448	0,20
70	21,2	189	391	-89	11	420	99	484	0,23
105	7,1	63	122	-18	27	385	33	517	0,14
105	10,6	95	185	-30	17	420	50	512	0,16
105	21,2	189	330	-66	12	525	99	573	0,20
140	10,6	95	156	-24	24	525	50	606	0,15
140	14,1	126	204	-33	19	560	66	618	0,16
140	28,3	252	368	-73	14	700	132	686	0,20

Teneur eau drainée : 5,0 % Saturation : 58 %

σ_3 (kPa)	σ_{do} (kPa)	$\Delta\sigma_d$ (kPa)	$\varepsilon_{1r\,moy}$ ($\mu\varepsilon$)	ε_{3r} ($\mu\varepsilon$)	CV (%)	θ (kPa)	τ_{oct} (kPa)	E_r (MPa)	ν_r
20	2,0	18	99	-16	8	80	9	180	0,16
20	4,0	36	182	-34	5	100	19	196	0,19
20	6,0	54	263	-57	6	120	28	204	0,22
35	3,5	32	124	-19	11	140	17	254	0,16
35	7,1	63	235	-45	7	175	33	268	0,19
35	10,6	95	323	-71	8	210	50	293	0,22
70	7,1	63	161	-26	15	280	33	392	0,16
70	14,2	126	292	-57	10	350	66	432	0,19
70	21,2	189	398	-89	11	420	99	475	0,22
105	7,1	63	127	-18	26	385	33	498	0,14
105	10,6	95	188	-30	17	420	50	503	0,16
105	21,2	189	335	-66	12	525	99	564	0,20
140	10,6	95	160	-24	23	525	50	590	0,15
140	14,2	126	208	-34	18	560	66	606	0,16
140	28,3	252	367	-73	13	701	132	687	0,20





Sat.	c_1	c_2	c_3	R^2	RMSE	n
21%	180	1,193	-1,461	0,99	20	15
81%	163	0,956	-0,984	0,99	19	15
58%	125	0,980	-0,795	0,99	15	15

Sat.	k_1	k_2	k_3	R^2	RMSE	n
21%	2,70	0,675	-0,344	0,97	0,033	15
81%	2,34	0,652	-0,298	0,98	0,023	15
58%	2,01	0,710	-0,233	0,99	0,017	15

Sat.	ν_r	σ	n
21%	0,16	0,02	15
81%	0,18	0,03	15
58%	0,18	0,03	15

Conditionnement 10 000 cycles

No.	ε_p
1	94
2	

Note :

Réalisé par : Stéphane Bouchard
Date : 16 mai 2016

Approuvé par : Félix Doucet, ing. M.Sc.A.
Date : 16 mai 2016

Service des matériaux d'infrastructures, Direction du Laboratoire des Chaussées, Ministère des Transports du Québec
2700, rue Einstein, Québec, G1P 3W8, (418) 644-0181

Figure 21. Resilient modulus test on MG-20 granular material (1).

Ministère des Transports Québec

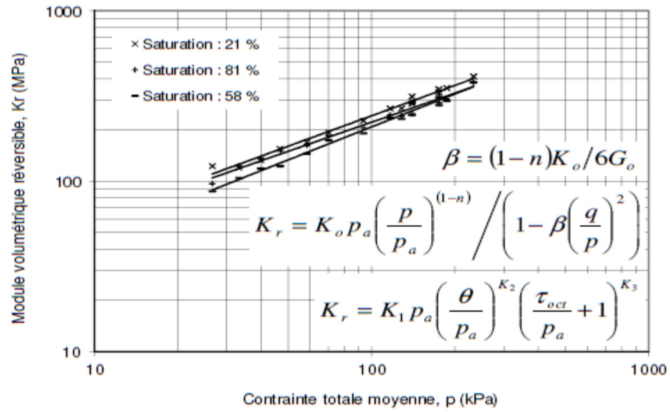
MÉTHODE LC 22-400
DÉTERMINATION DU MODULE RÉVERSIBLE DES MATÉRIAUX GRANULAIRES

Dossier :	SG-4125-16	Matériau :	MG-20	Source :	Université Laval
Client :	Jean-Pascal Bilodeau	Ajout :	0	Pétrographie :	0

Éprouvette :	MG-001-16	Teneur eau :	2,4 %	Porosité :	16 %	Densité :	2,63	Teneur eau optimale :	6,5 %
		Masse volumique :	2215 kg/m³	Saturation :	21 %	Absorption :	0,9 %	Masse vol. optimale :	2249 kg/m³

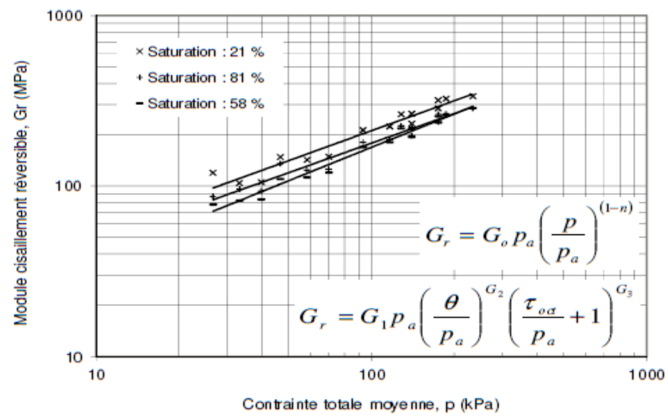
Teneur eau intiale : 2,4 % Saturation : 21 %

p (kPa)	q (kPa)	Δp (kPa)	Δq (kPa)	ε_{vr} (με)	ε_{sr} (με)	K_r (MPa)	G_r (MPa)	q/p	Δq/Δp
27	20	6	18	48	50	123	120	0,7	3,0
33	40	12	36	98	113	121	104	1,2	3,0
40	59	18	53	133	169	133	105	1,5	3,0
47	35	11	32	68	71	155	149	0,8	3,0
58	70	21	63	124	147	170	143	1,2	3,0
70	105	31	94	162	212	194	149	1,5	3,0
93	70	21	63	93	99	227	213	0,8	3,0
117	140	42	126	157	187	267	224	1,2	3,0
140	210	63	189	201	271	314	232	1,5	3,0
128	70	21	63	78	79	268	264	0,5	3,0
140	105	32	95	110	118	285	266	0,8	3,0
175	210	63	189	181	220	348	286	1,2	3,0
175	105	32	95	95	99	333	319	0,6	3,0
187	140	42	126	119	129	353	325	0,8	3,0
233	280	84	252	203	249	413	337	1,2	3,0



Teneur eau intiale : 6,7 % Saturation : 81 %

p (kPa)	q (kPa)	Δp (kPa)	Δq (kPa)	ε_{vr} (με)	ε_{sr} (με)	K_r (MPa)	G_r (MPa)	q/p	Δq/Δp
27	20	6	18	61	68	97	87	0,7	3,0
33	40	12	36	96	123	123	96	1,2	3,0
40	59	18	53	131	191	136	93	1,5	3,0
47	35	11	32	69	78	152	136	0,8	3,0
58	70	21	63	130	170	162	124	1,2	3,0
70	105	32	95	170	250	185	126	1,5	3,0
93	70	21	63	102	116	206	181	0,8	3,0
117	140	42	126	172	224	245	187	1,2	3,0
140	210	63	189	214	319	295	197	1,5	3,0
128	70	21	63	87	93	242	226	0,5	3,0
140	105	32	95	126	143	251	221	0,8	3,0
175	210	63	189	199	264	316	239	1,2	3,0
175	105	32	95	109	120	289	263	0,6	3,0
187	140	42	126	138	158	305	266	0,8	3,0
233	280	84	252	221	294	380	286	1,2	3,0



Teneur eau intiale : 5,0 % Saturation : 58 %

p (kPa)	q (kPa)	Δp (kPa)	Δq (kPa)	ε_{vr} (με)	ε_{sr} (με)	K_r (MPa)	G_r (MPa)	q/p	Δq/Δp
27	20	6	18	68	76	87	78	0,7	3,0
33	40	12	36	113	144	105	82	1,2	3,0
40	60	18	54	150	213	119	84	1,5	3,0
47	35	11	32	86	96	123	110	0,8	3,0
58	70	21	63	145	187	145	112	1,2	3,0
70	105	32	95	181	263	174	120	1,5	3,0
93	70	21	63	110	124	192	169	0,8	3,0
117	140	42	126	179	233	235	181	1,2	3,0
140	210	63	189	220	325	287	194	1,5	3,0
128	70	21	63	90	97	233	218	0,5	3,0
140	105	32	95	128	146	246	217	0,8	3,0
175	210	63	189	204	267	310	236	1,2	3,0
175	105	32	95	113	123	280	257	0,6	3,0
187	140	42	126	141	161	298	261	0,8	3,0
234	281	84	252	221	293	380	287	1,2	3,0

Sat.	K_o	G_o	n	R^2_{Kr}	$RMSE_{Kr}$	R^2_{Gr}	$RMSE_{Gr}$	n
21%	2,13	2,12	0,415	0,95	0,043	0,94	0,045	15
81%	1,94	1,79	0,427	0,98	0,027	0,96	0,037	15
58%	1,79	1,69	0,351	0,99	0,026	0,98	0,030	15

Sat.	K_1	K_2	K_3	R^2	RMSE	n
21%	1,23	0,550	0,166	0,99	0,018	15
81%	1,14	0,481	0,333	0,99	0,016	15
58%	0,98	0,544	0,384	1,00	0,008	15

Sat.	G_1	G_2	G_3	R^2	RMSE	n
21%	1,19	0,712	-0,491	0,96	0,038	15
81%	1,01	0,698	-0,467	0,98	0,028	15
58%	0,87	0,755	-0,399	0,99	0,022	15

Note :

Réalisé par :	Stéphane Bouchard	Approuvé par :	Félix Doucet, ing. M.Sc.A.
Date :	16 mai 2016	Date :	16 mai 2016

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Figure 22. Resilient modulus test on MG-20 granular material (2).

Appendix C: Measured horizontal strains ε_r (m/m) at the bottom of the AC layer and vertical strains ε_z (m/m) at the top of the subgrade for different frost depths for cycle 1

Table 18. Measured horizontal strains εr (m/m) at the bottom of the AC layer and vertical strains εz (m/m) at the top of the subgrade for different frost depths for cycle 1

Frost Depth	E* (MPa)	horizontal strains ε_r at the bottom of the AC mat (m/m)				Vertical strains ε_z at the at the top of the subgrade (m/m)			
		4550	5000	5500	6250	4550	5000	5500	6250
0 mm	1796	2.57E-04	2.71E-04	no strains measured		3.43E-04	3.75E-04	no strains measured	
180 mm	11355	1.22E-04	1.34E-04	1.44E-04	1.56E-04	1.43E-04	1.59E-04	1.79E-04	1.99E-04
300 mm	12166	9.70E-05	1.01E-04	1.07E-04	1.33E-04	5.07E-05	1.32E-04	1.43E-04	1.67E-04
500 mm	14320	1.50E-05	1.40E-05	1.60E-05	1.95E-05	3.03E-05	7.10E-05	8.07E-05	9.35E-05
600 mm	14584	1.45E-05	1.67E-05	1.60E-05	1.80E-05	2.54E-05	2.57E-05	2.84E-05	3.16E-05
700 mm	14997	1.32E-05	1.25E-05	1.65E-05	1.80E-05	2.40E-05	2.47E-05	2.50E-05	2.54E-05
800 mm	15143	1.13E-05	1.40E-05	1.55E-05	1.60E-05	2.12E-05	2.22E-05	2.32E-05	2.40E-05
1000 mm	17563	9.52E-06	9.65E-06	1.20E-05	1.40E-05	1.98E-05	2.06E-05	2.12E-05	2.22E-05

Note: E* is the AC mat dynamic modulus as a function of frost depth.

Appendix D: Result from cycle 2 of accelerated pavement testing

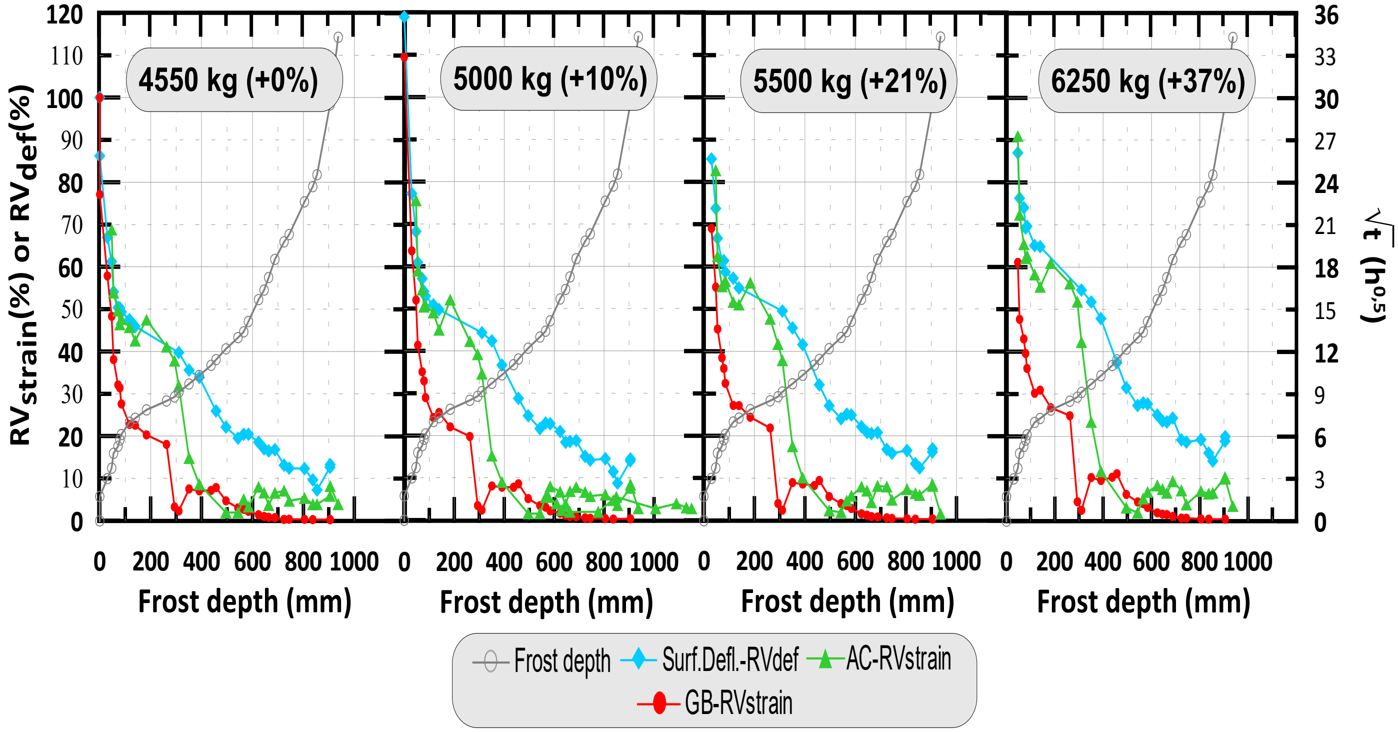

Figure 23. Results from cycle 2 of accelerated pavement testing.

Appendix E: Percent increase of material M_r (%) as a function of unfrozen condition (results from City of Edmonton resilient Modulus testing)

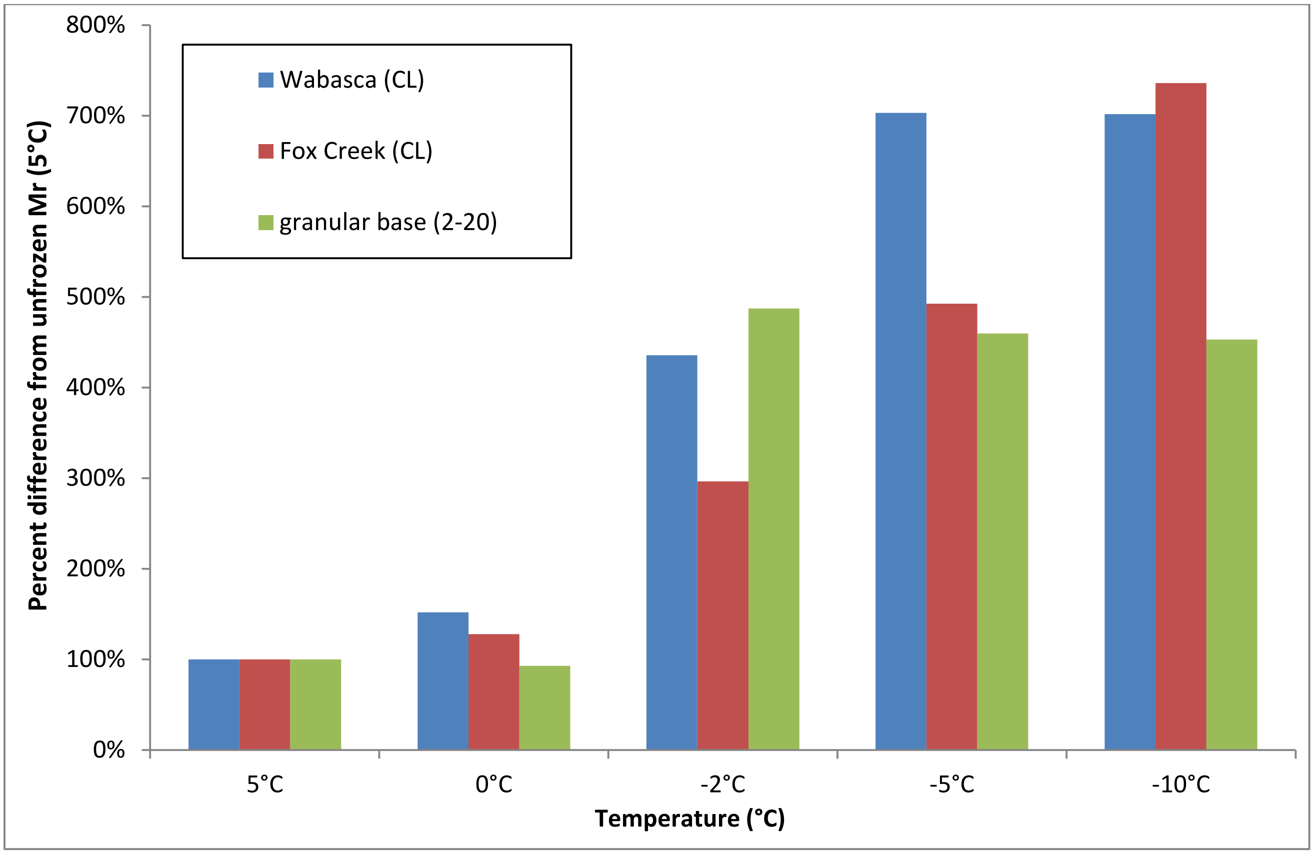

Figure 24. Percent increase of material Mr (%) as a function of unfrozen condition (results from City of Edmonton resilient Modulus testing).

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