Experimental assessment of flexible pavement behaviour under freezing conditions and winter weight premiums

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Abstract

As it is well documented, structural behaviour of flexibles pavements in cold regions is significantly affected by environmental factors and traffic loads. When it comes to pavement damage, the action of freeze and thaw is one of the most important inputs to consider. During thaw, the loss of bearing capacity is addressed by the seasonal load restriction policies enforced in many countries. On the other hand, during winter, frost action induces an important increase in the bearing capacity of flexible pavements due to the viscoelastic response of asphalt concrete and to the freezing of pore water in granular materials and soils. The pavement strengthening with frost penetration has led some transportation agencies to allow winter weight premiums (WWP). Currently, the main issue related to WWP programs is the variety of legislation for both among and within jurisdictions. This variety is caused, in part, by the lack of a rational decision criterion for the application of an axle load limit increase based on the mechanical behavior of frozen pavements. The objective of this project was to document the mechanical behavior of freezing pavements and to develop a rational criterion for the onset of winter load premiums. An experimental approach with the use of Laval University full-scale heavy vehicle simulator was considered to monitor the response of two different flexible pavements built in a 24 m^3 indoor test pit over a low plasticity clay and a silty sand subgrade soils, respectively. They were instrumented to monitor temperature profiles, surface deflection, as well as stress, strain and moisture content in each layer. The simulator was used to apply the air freezing temperature (-10 °C) and to periodically load the pavement surface using a standard dual-wheel set (half axle) varying in the range of 4500 to 6250 kg. The results collected allowed documenting how the response of different pavement structures changes with respect to frost penetration and temperature, and allowed quantifying the effect of the load magnitude on the change of the pavement response and damage.

Introduction

In regions subject to seasonal freezing, the mechanical response of flexible pavements fluctuates significantly on an annual basis. The stiffness variation is primarily induced by the temperature and moisture content changes in the pavement (Doré & Zubeck, 2009; Huang, 2004; TAC, 1997). The first mechanism affect directly the dynamic modulus of asphalt concrete since this material is a viscous bituminous binder (Carter & Perraton 2002; Doucet & Auger 2012). In fact, it stiffness follows a trend similar to the air temperatures over the yearly cycle (Doré & Zubeck, 2009). In southern Canada, where the temperature can go up higher than 40 °C in summer and lower than -30 °C in winter, the dynamic modulus ranges varies from a couple of hundreds MPa during summer to approximately 20 000 MPa during winter. For the subgrade and unbound materials, the mechanical response is mostly associated to the physical state of pore water pressure that is related to the temperature (Bigl & Berg, 1996). Over 0 °C, the stiffness varies with the degree of saturation (Bilodeau & Doré, 2012; Richter, 2006). Below 0 °C, pore water begins to freeze and stiff bounds are created between the ice, aggregate particles and soils. In the literature, some triaxial tests were conducted on frozen unbound and soils materials (Simonsen et al. 2002; Bigl & Berg, 1996; Li & al. 2010). It was demonstrated that the increase of resilient modulus was mostly related to the residual unfrozen water content under 0 °C. An important stiffness increase, for most soils, occurs when temperatures shift from 0 to -2 °C (Doré and Zubeck 2009; Li et al. 2010).

During thaw, the loss of bearing capacity is addressed by the seasonal load restriction policies enforced in many countries (C-SHRP, 2000). On the other hand, to make, the pavement strengthening with frost penetration has led some transportation agencies to allow winter weight premiums (WWP) (Montufar & Clayton 2002, Bradley 2011, Ovik & Siekmeier 2004). In North America, WWP legislations exist in some states and provinces such as Minnesota, North Dakota, Alberta, Ontario and Manitoba. Currently, the main issue related to WWP programs is the variety of legislation for both among and within jurisdictions. The criterions used to start and stop the WWP period can be based on rule of thumbs, frost depth, weather related data and fixed dates. The axle and maximum allowed gross weight during winter are also different from a region to another. This variety is caused, in part, by the lack of a rational decision criterion for the application of an axle load limit increase based on the mechanical behavior of frozen pavements.

A project was undertaken as part of the NSERC Industrial Research Chair on the interaction between heavy loads – climate – pavements at Laval University (Quebec, Canada). In order to precisely control the experimental conditions, a heavy vehicle simulator and an indoor test pit were used for the study. This project studied the mechanical behavior of pavement layers and structures subjected to real traffic conditions during the freezing process. The results obtained provide engineering tools for road administrations that want to revise their legislation or need to analyze the possibility of implementing winter weight premiums.

Materials, experimental setup and methodology

Characteristics of the experimental site and methodology

The experimental pavement used for the project was built in an indoor test pit at Laval University. The pit dimensions are: 2 m wide, 6 m long, and 2 m deep. Figure 1 presents the tested pavement layered system, typical of an older Alberta pavement design. The structure consists of 180 mm of asphalt concrete EB-10S, 200 mm of MG-20 (granular base) and a low plasticity clay. The pavement structure was initially built in order to aim for an asphalt concrete layer thickness of 170 mm, but it had to be adjusted to 180 mm due to settlements of the clayey subgrade. A geotextile 76-12 was used as a separation layer between the clayey soil and the granular base in order to avoid contamination. In addition, a TEXdrain 80H geotextile from Texel was installed along the edges of the pit to reduce adhesion between the soil and the concrete walls of the pit. Figure 2 presents the grain-size distribution and a summary of the pavement materials characterization tests. 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.

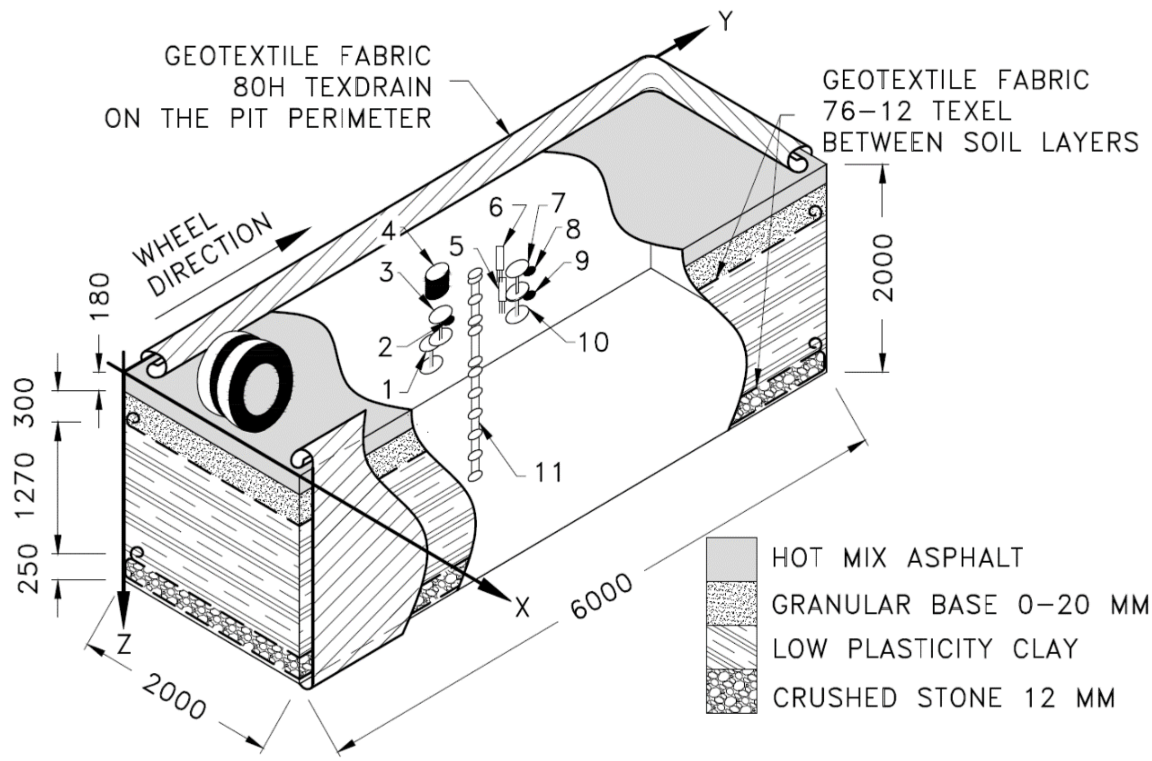
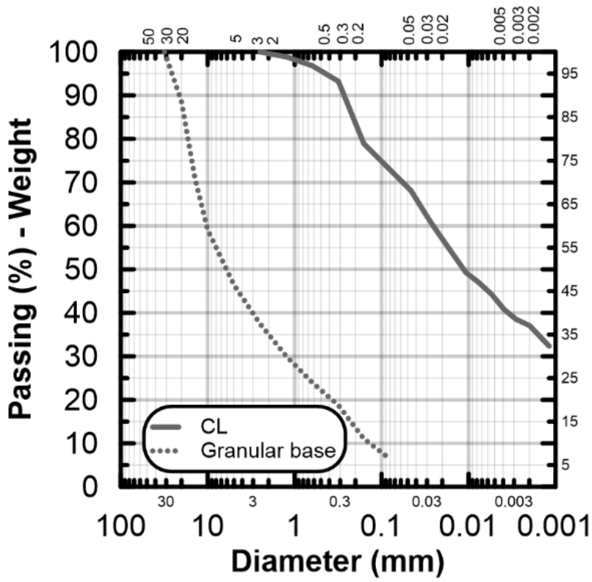


Figure 1 : Tested pavement layers and instrumentations



	Clay Subgrade	Granular Base
ρ_{dmax} (kg/m3)	1700	2249
w_{opt} (%)	21	6.5
w_p (%)	17	-
w_L (%)	28	-
Fines (%)	73	6.4
Clay (%)	37	-
ρ_s (kg/m3)	2765	2.687
CBR (%)	2.5	68.3
USCS classification	CL	GW-GM

Figure 2 : Grain-size distribution and a summary of material characterization test results

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. Some of the simulator's characteristics are:

- Loads on the single half-axle can be varied between 500 and 10 000 kg;
- Travel speed of the half-axle can be varied between 0 and 10 km/h;
- Inflation of the half-axle tire(s) can be adjusted;
- Pavement loading can be in both travel directions (bi-directional mode) or in one travel direction (uni-directional mode);
- Up to 20 000 bi-directional load applications or 10 000 uni-directional load applications can be completed each 24 hours;
- Air temperature below the simulator can be cooled to as low as -12 °C (when the insulation panels are installed).

Figure 3: Heavy vehicle simulator above the test pavement

Figure 4: Heavy vehicle simulator with insulation panels positioned over the test pavement

Data acquisition methodology

A ProSens data acquisition system (manufactured by OPSENS Solutions) was used for the fibre optic strain gauges, 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 penetrations 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 also was equipped with a drainage system with which the pavement's water table height was maintained at 1.5 and 0.8 m below the pavement surface during the first and second freezing cycles, respectively. These water table depths were representative of well drained and wet subgrade conditions, respectively.

Trafficking loads

The test parameters selected for this study were based on standard practice, machine limitations, and practical considerations, and are summarized in Table 1. 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 the Alberta single-axle legal loading of 9000 kg, and three winter weight loadings (10 000, 11 000 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 becomes load insensitive under winter conditions.

Table 1: Testing parameters and loading characteristics for this project

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 pavement

For pavement construction, the geotextile used on the side wall was first positioned. The open graded layer was then put at the bottom of the pit with an overlaying geotextile. The clay and granular base were then compacted in 300 mm and 150 mm lifts, respectively. Between each layer, care was taken to level the compacted layer. After construction of the experimental pavement, the dry density achieved at the top of the clay and base layers, as measured using the sand cone equivalent method, were 1506 kg/m^3 (w=20.7 %) and 2400 kg/m^3 (w=4.7 %). The AC layer was compacted in two layers. Figure 5 and Figure 6 show the clay layer under construction and the granular based once the construction was complete.

Figure 5: Clay subgrade layer under construction

Figure 6: Granular base course under construction

Mechanical response Instrumentation

With respect to Figure 1, the pavement was instrumented to monitor temperature and moisture conditions, and mechanical responses to trafficking during freeze-up. Table 2 presents a detailed list of the gauges used in the pavement layers to collect data on strain, deflection, stress, water content and temperature. The asphalt concrete tensile strain, the vertical strain and the surface deflection sensors are based on fiber-optic technology which was used and adapted for pavement engineering purposes at Laval University over the last decade through the cooperation of OpSens Solutions. The vertical stress, volumetric water content and temperature (thermistor) are electrical sensors. The mechanical response (stress and strain) of the subgrade soil was measured at the top of the layer under the center of the dual wheel assembly. As for the granular layer, the mechanical response was measured at the middle of the layer under the center of the dual wheel assembly as well. For the soil and unbound layer, it should be noted that the volumetric water content sensor was positioned close to the vertical stress and strain sensors. The asphalt concrete strain sensor was positioned so it was centered with the left tire (with respect to the front of the simulator). Finally, the surface deflection sensor was positioned between the two tires of the carriage.

Table 2: Instrumentation installed in the test pavement

Sensor		Sensor type	Structural layer	Position (x,y,z) (mm)
1	Vertical strain	Optical	Subgrade	(990, 2500, 465)
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, 460)
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).

Pavement Testing Results and Model Validation

Pavement testing was conducted between February and June 2016. To evaluate the impact of WWP, the pavement baseline response was first 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 h at room temperature (18 °C) 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 h). All results collected as the test pavement froze were normalized relative to the reference measurements and expressed as relative values (RV):

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

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 mostly linear and uniformly varied with depth from 18 °C at the AC 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.

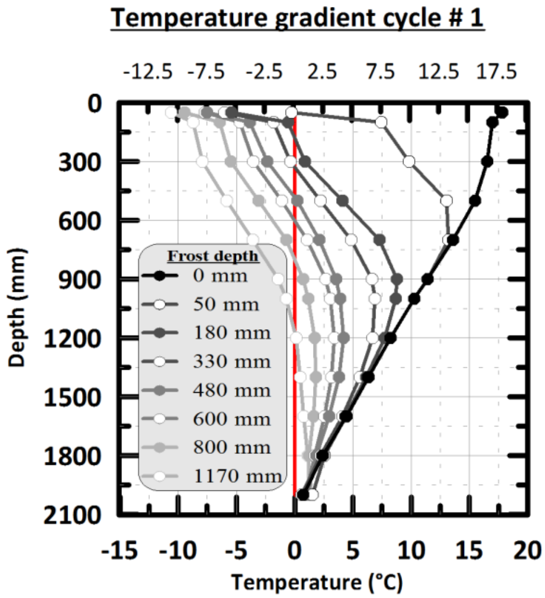


Figure 7: Temperature gradient during freezing cycle 1

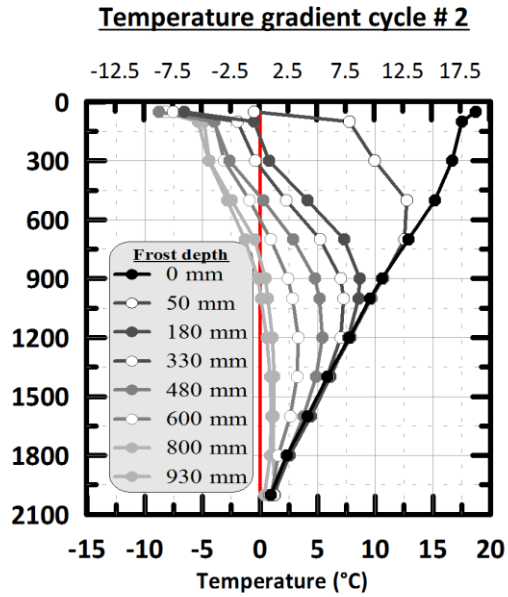


Figure 8: Temperature gradient during freezing cycle 2

Structural measurements

In order to simplify the results presentation, only strains and surface deflections from the first freezing cycle are shown in Figure 9. The results obtained in the second freezing cycle were very similar to those from the first freezing cycle, and for this reason are included in Appendix A. During the second cycle, some issues with vertical strain gauges were encountered. Unfortunately, the vertical strain measurements on top of the subgrade soil were inconsistent. For this reason, the vertical strains on top of the subgrade are not presented in Appendix A. In Figure 9, as it can be observed, there was a loss of data between 200 and 580 mm of frost penetration for the AC-RV$_{strain}$ (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 during thaw until complete freezing in the AC mat.

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 AC mat froze, with a maximum relative value of 29 % at the highest load (6250 kg). Following frost penetration of the AC mat, the relative values continued to decrease with freezing of the granular base and the lowering of the temperature of the AC 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 & 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.

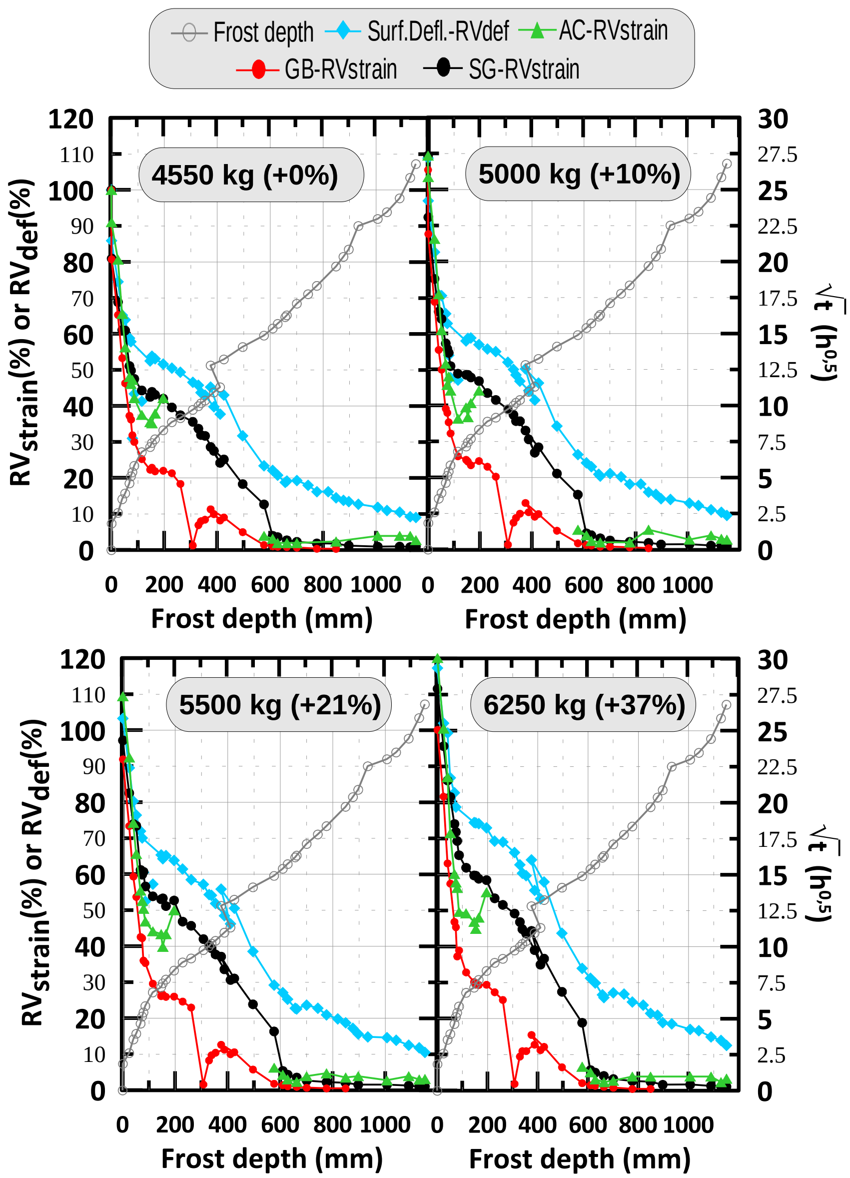


Figure 9 : Relative value (RV) of response with respect to frost penetration and axle load

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. 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 was substantial and 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. The slope (m) of the relationship between RV and axle load can be obtained for each frost depth and response parameter as:

$$RV = m * Load + y$$

where y is the intercept. Once m (% / ton) is known for each response parameters, m can be express with respect to the frost depth on Figure 11. This is another representation that allows appreciating the decrease of the effect of load during freezing.

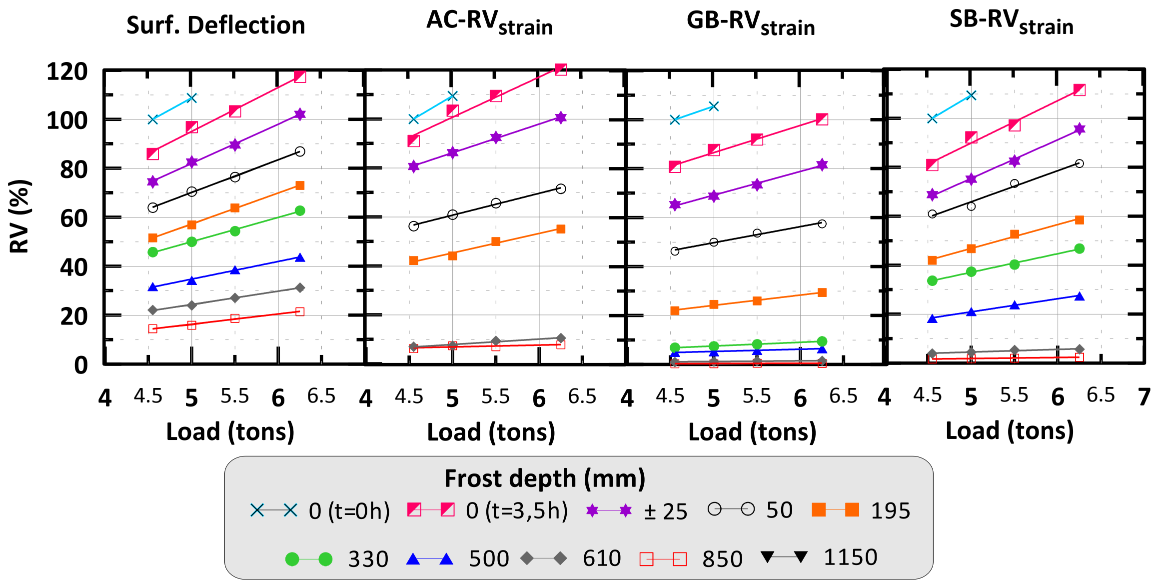


Figure 10: Load effect on relative values of pavement response

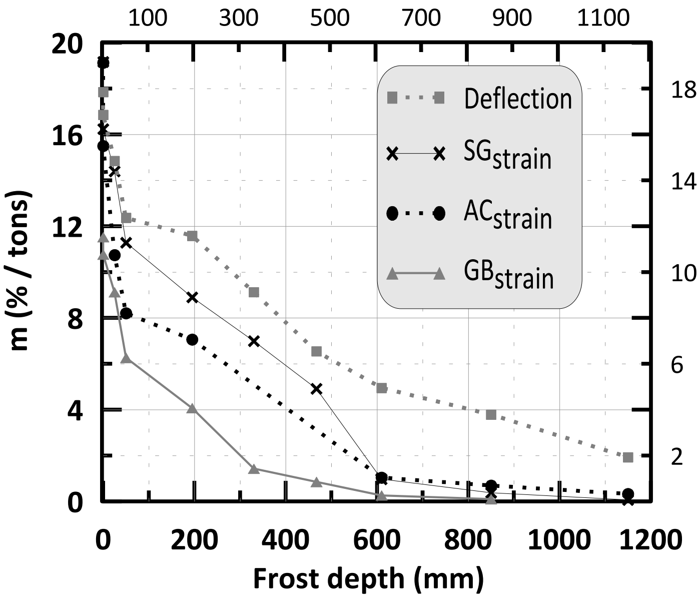


Figure 11 : Relationship between m and frost depth

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 three performance parameters:

- Tensile elastic strain at the bottom of AC mat (maximum fatigue cracking criteria);
- Compressive elastic strain at the top of subgrade layer (maximum rutting criteria);
- Surface deflection of the AC mat surface (maximum deflection criteria).

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

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

$$N_r = KF_4 \times \varepsilon_c^{KF_5} \tag{3}$$

where, N_f is the estimated number of load repetitions to cause fatigue cracking over 10 % of the wheel lane, N_r is the estimated number of loads to cause a 12,7 mm-deep rut in the AC mat,ε_t is the tensile strain at the bottom of AC mat (mm/mm), ε_c is the compressive strain at the top of SG *soils (mm/mm), |E*| is the dynamic modulus (MPa), C=0.001135, KF_1=0.174, KF_2=3.291, KF_3=0.854, KF_4=1.365x10^{-9} and KF_5=-4.477 (Carpenter 2007).*

Maximal surface deflection (d_{max}) is a good indicator for assessment of pavement weak zones. Doré and Zubeck (2009) provide a reference for a rapid analysis of d_{max} given the total number of load repetitions that pavement should withstand. Due to the lack of instrumentations beneath 530 mm, the maximal surface deflection allows to quantify the effect of the unfrozen subgrade under the frozen layers during frost. It also allows indicate the global structural response of a frozen pavement resting over an unfrozen subgrade.

$$N_d = 0.2694383\sqrt{\frac{537.08}{d_{max}}} \tag{4}$$

where, N_d is the *estimated number of load repetitions to cause deflection failure* and d_{max} is the maximum allowable surface deflection (µm).

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

$$\mathrm{D} = \frac{1}{\mathrm{N}} \tag{5}$$

in which *N* is the estimated number of load repetitions to failure (N_f, N_r or N_d). The theoretical pavement damage also was expressed relative to the theoretical pavement damage from Alberta's 9100 kg legal axle load under summer-like conditions (D_{4550} (t = 0)). Relative damage, calculated for any frost depth (t), is defined as:

$$\mathrm{D(t)} \big/ \mathrm{D}_{4550}(\mathrm{t} = 0) \tag{6}$$

Table 3 presents the results of the relative damage calculations for each of the performance parameters. Measurements from frost cycle #2 were used for the fatigue criteria because some issues with strain gauges were encountered during the first cycle, resulting in a partial loss of data. The analysis indicates that freezing (and even cooling) of the AC 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. At a frost depth of 500 mm, the surface deflection was the only parameter with relative damage values exceeding 1 % (the maximum value was 4.3 % at a 37 % winter weight premium (6250 kg)). Given the low bearing capacity of the subgrade clay and the difficulties with compacting it during construction, the unfrozen subgrade might have emphasized the surface deflection measurements compared to an undisturbed subgrade. 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.

Table 3 : Predicted surface deflection, fatigue and rutting for various frost depths and winter weight premiums, relative to that from a 4550 kg half-axle load under summer-like conditions.

Frost Depth	Surface deflection			Fatigue cracking (cycle #°2)			Rutting		
	5000 kg	5500 kg	6250 kg	5000 kg	5500 kg	6250 kg	5000 kg	5500 kg	6250 kg
180 mm	13.1 %	19.7 %	32.0 %	43.5 %	65.9 %	86.0 %	3.5%	5.3 %	9.2 %
300 mm	8.8 %	12.6 %	21.6 %	24.0 %	40.6 %	54.7 %	1.5%	2.1 %	4.2 %
500 mm	1.8 %	2.9 %	4.3 %	0.05 %	0.07 %	0.12 %	0.09%	0.1 %	0.3 %
600 mm	0.5 %	0.8 %	1.3 %	0.08 %	0.09 %	0.15 %	± 0 %	± 0 %	± 0 %
700 mm	0.3 %	0.5 %	0.8 %	± 0 %	± 0 %	± 0 %	± 0 %	± 0 %	± 0 %

Validation of the results with a comparison to 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. 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 asphaltic concrete, 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 Yi et al. (2016) pavement.

Figure 12 and Figure 13 compare the results from this study and the ones from Yi et al. (2016). 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 AC strain and vertical compressive subgrade strain between the tests mostly can be attributed to the different AC thicknesses, subgrade soils, and water contents. The Figures also highlight the effect of a 10 % overload between 5000 and 5500 kg, which resulted in a non-significant effect for both structures. A damage analysis similar to the one previously presented was conducted for Yi et al. (2016) pavement structure. The same conclusions were observed and the amount of damage induced to the pavement, notwithstanding the load level, is lower then 1.0 % for the fatigue and structural mechanisms when the frost depth reaches about 500 mm. The surface deflection wasn't measured in this project.

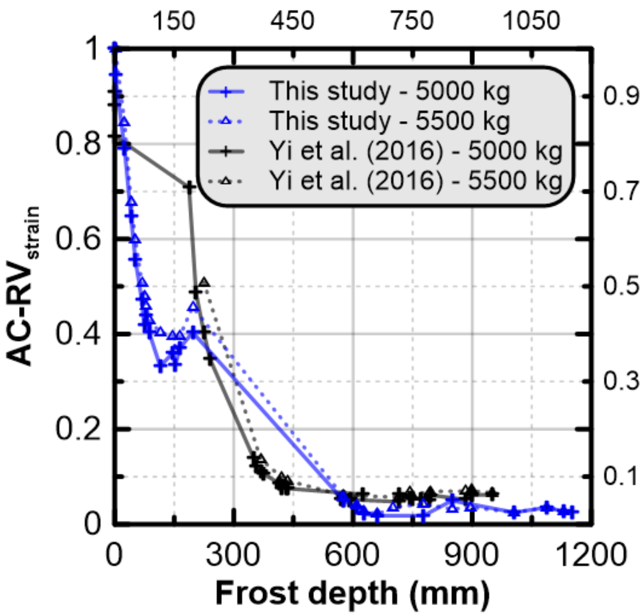


Figure 12: Relative values of AC mat horizontal strain with frost depth for two studies

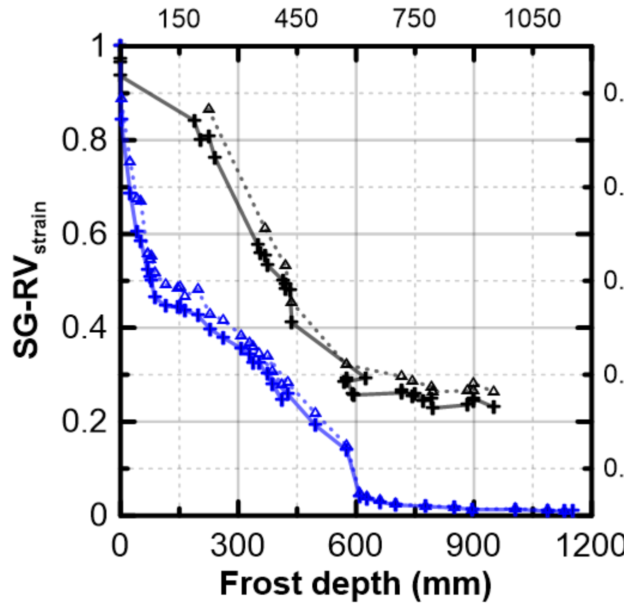


Figure 13: Relative values of subgrade vertical strain with frost depth for two studies

Trends observed and conclusions

The full-scale heavy vehicle simulator of Laval University was used to monitor the response of two different flexible pavements built in the 24 m^3 indoor test pit over a low plasticity clay and a silty sand subgrade soils. The pavement structures were based on typical structures encountered on Transport's Quebec road and Alberta transportation road network. The high quality results obtained with the lab tests have shown very good trends between both structures and the following conclusions can be made:

- For Alberta's typical structure, a substantial reduction in pavement strains occurred before freezing, when the AC mat cooled and stiffened. By the time the AC 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. The decrease was less important for the Quebec typical pavement structure because the AC mat was thinner.
- At a frost depth of 600 mm, the strains were very small for both pavements (both relative to the reference condition and absolutely). Stiffening of the AC mat and freezing of the unbound structural materials appear to be the main factors associated with such a response.
- With the exception of surface deflection, pavement response to increasing load was negligible for frost depths of 500 mm or deeper.
- Similar to the response analysis, damage calculations have shown a very fast damage decrease during freezing. Based on theoretical estimates of fatigue cracking, rutting and

deflection, predicted damage rates became stable and negligible when 500 mm of frost depth was reached.

- For Alberta's structure, the pavement responses to changes in freezing cycle and axle loading were very similar in both freezing cycles.

The experimental approach used in this project allowed measuring precisely the pavement mechanical response during freezing in an indoor pit. Even if lab tests present several advantages, some limitations still have to be considered in the further analysis. First, the pavement was not exposed to chemical solicitations like de-icing salts. Vautrin et al. (1996) described that the effect of salt is likely to cause an increase of the number of freeze-thaw cycles of the water on and inside the AC mat. Second, the asphalt cracking is another important input to consider on pavement behaviour 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 AC mat cooled and stiffened. Without considering cracking on an existing road, it is likely to influence the mechanical response to weight premiums. In addition, salt seepage through AC mat cracks and potholes can thaw the unbound granular foundation (VH, 2005c). Third, the traffic load effect is then higher on the unfrozen soil that rests over a frozen layer. Four, laboratory pavement was not exposed to weaknesses during winter partial thaws. This study is limited to the pavement mechanical response during idealistic freezing conditions. Moreover, the water contents in the granular layer was near optimum conditions before freezing and did not change throughout the entire testing period. Depending on several factors associated with in situ conditions (precipitations, drainage conditions, cracking, etc.), the water content within the pavement structures may vary significantly during the freezing process and this may influence the pavement mechanical response during freezing. Finally, the results were collected for specific loading conditions: one tire type and configuration, tire pressure, no wheel wander conditions and single axle. These simplifications are likely to induce some slight variations (positive or negative) to the analyses and conclusions.

REFERENCES

Bigl, S.R. and Berg, R.L. 1996. *Material Testing and Initial Pavement Design Modeling from Minnesota Road Research Project*. U.S.A Cold Regions Research and Engineering Laboratory, CRREL report 96-14, 56 p.

Bilodeau, J.-P., & Doré, G. (2012). Resilient modulus water sensitivity of compacted unbound granular materials used as pavement base. International Journal of Pavement Engineering, 13(15): 459-471.

Bradley, A. 2011 (2013). Investigation of Pavement Freezing and its Application to Winter Weight Premium Policy in Manitoba. Prepared for Materials Engineering Branch, Manitoba Infrastructure and Transportation (Unpublished). FP Innovations CR-524, Revised July 2013, 68 p.

Canadian Strategic Highway Research Program (C-SHRP). (2000). *Seasonal Load Restrictions in Canada and Around the World.* C-SHRP Technical Brief no°21, Retrevied from http://www.cshrp.org/products/brief-21.pdf

Carpenter, S. H. 2007. *Fatigue performance of IDOT mixtures*. Research report FHWA-ICT-007-2007. Illinois Center of Transportation. University of Illinois, Urbana-Champaign, IL.

Doré, G. and Zubeck, H. 2009. *Cold regions pavement engineering*. McGraw-Hill, NY.

Doucet, F. et Auger, B. 2012. *Complex Modulus Determination of Asphalt Mixes at The Ministère Des Transports Du Québec*. Transports Québec report no. RTQ-10-01, 2010.

Huang, Y.H. 2004. *Pavement analysis and design*. Pearson Prentice Hall, NJ.

Montufar, J. and Clayton, A. 2002. Seasonal weight limits on prairie region highways: opportunities for rationalization and harmonization. Canadian Journal of Civil Engineering, NRC Research Press 29(1): 8-16

Ovik, J.M. and Siekmeier, J.A. 2004. *Investigation of the impact of increased winter load limits*. Minnesota Department of Transportation, Report MN/RC – 2004-25, 72 p.

Richter, C.A. 2006. *Seasonal variations in the moduli of unbound pavement layers*. Federal Highway Administration, report FHWA-HRT-04-079, 283 p.

Simonsen, E., Janoo, V. C. and Isacsson, U. 2002. *Resilient properties of unbound road materials during seasonal frost conditions*. Journal of Cold Regions Engineering, ASCE 16(1): 28-50.

TAC 1997. *Pavement design and management guide*. Dr. Ralph Haas Ed., Waterloo, ON

Yi, J., Doré, G. and Bilodeau, J.-P. 2016. *Monitoring and modeling the variations of structural behaviour of a flexible pavement structure during freezing*. Journal of Cold Regions Engineering, 10.1061/(ASCE) CR.1943-5495.0000107, 04016004.

Vautrin, S. and Livet, J. 1996. *Choc thermique produit par un traitement curatif du verglas ou de la neige - synthèse des connaissances - simulation numérique à l'aide du modèle GEL 1D*. Retrieved from : http://www.viabilite-hivernale.developpement-durable.gouv.fr/IMG/pdf/Physique_de_l_interface_atmo_-_chaussee.pdf

VH. 2005 (modified in 2013). *Action des fondants routiers sur les revêtements.* Retrieved from http://www.viabilite-hivernale.developpement-durable.gouv.fr/action-des-fondants-routiers-sur-a4687.html

Appendix A

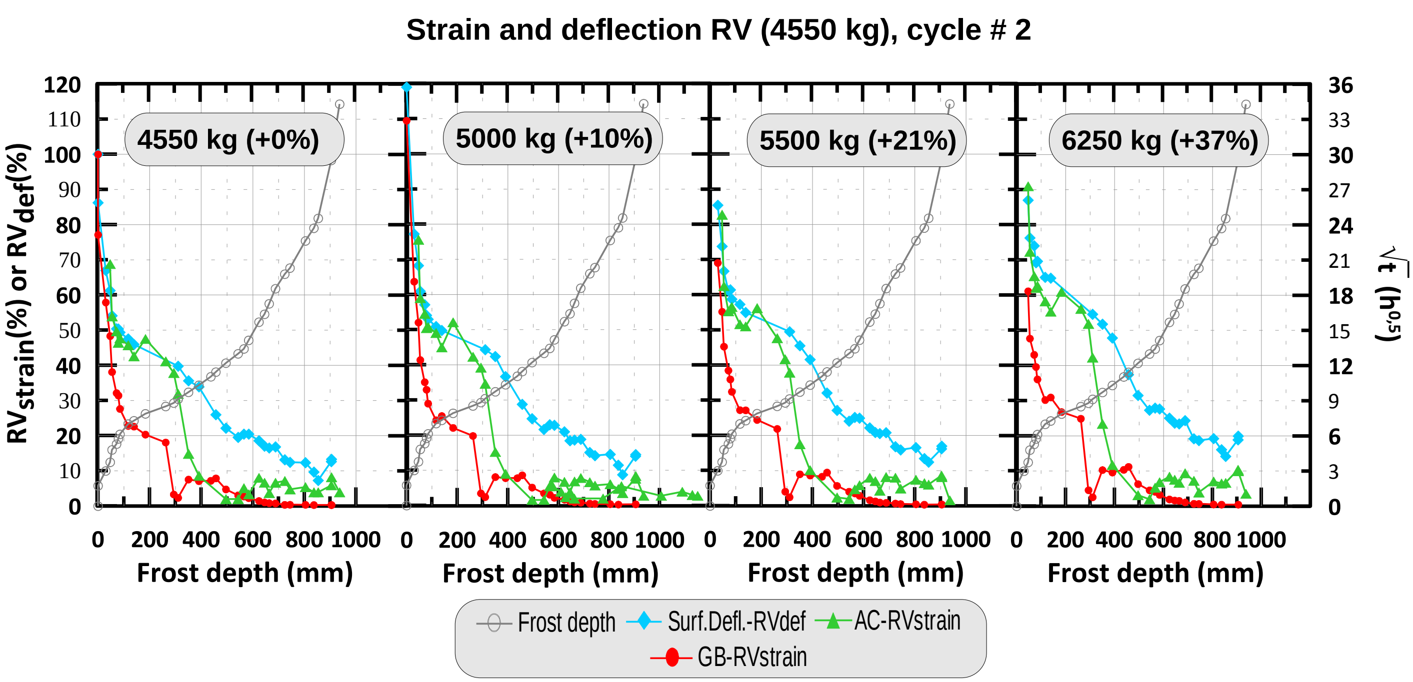


Figure 14 : Relative value (RV) of response with respect to frost penetration and axle load