1 INTRODUCTION

In the Province of Quebec (Canada), environmental factors and traffic loads are the main factors influencing pavement performance (Dore and Zubeck 2009). Amongst other factors, during freeze-thaw, the change of moisture content and temperature play a significant role in pavement behavior variations. During the winter, ice lens growth in frost-sensitive subgrade results in frost heave. During the spring thaw period, the accumulated ice and snow in the pavement structure environment melts and increases the water content of unbound layers and soils. This excess water content causes a reduction of the resilient modulus and increases the accumulation rate of permanent strains and fatigue cracks under traffic loads (Cary and Zapata 2011, Erlingsson 2012, Salour 2015). Therefore, the freeze-thaw cycle influences to a great extent the deterioration rate of pavements in cold regions.

The objective of this project was to better understand the response of pavement structures during thawing and to improve the prediction of the loss and recovery of the bearing capacity as a function of the evolution of the thaw and temperatures in the pavement. Two test sections with the same pavement structure and materials were used for that purpose: an indoor test pavement in the geotechnical laboratory at Laval University and an outdoor experimental pavement at the Laval University Road Experimental Site (SERUL).

2 TEST SITES AND INSTRUMENTATION

The indoor experimental pavement is built inside a 2 x 6 x 2 m^3 test pit in the geotechnical laboratory of Laval University; the outdoor experimental pavement is located at Laval University Road Experimental Site (SERUL). Both pavement structures have a 100 mm asphalt concrete, 200 mm granular base, 450 mm granular subbase and a silty sand subgrade (SM). The detailed information about the sensors used to monitor pavement response at both sites can be found in Figure 1. In the soil and unbound layers,

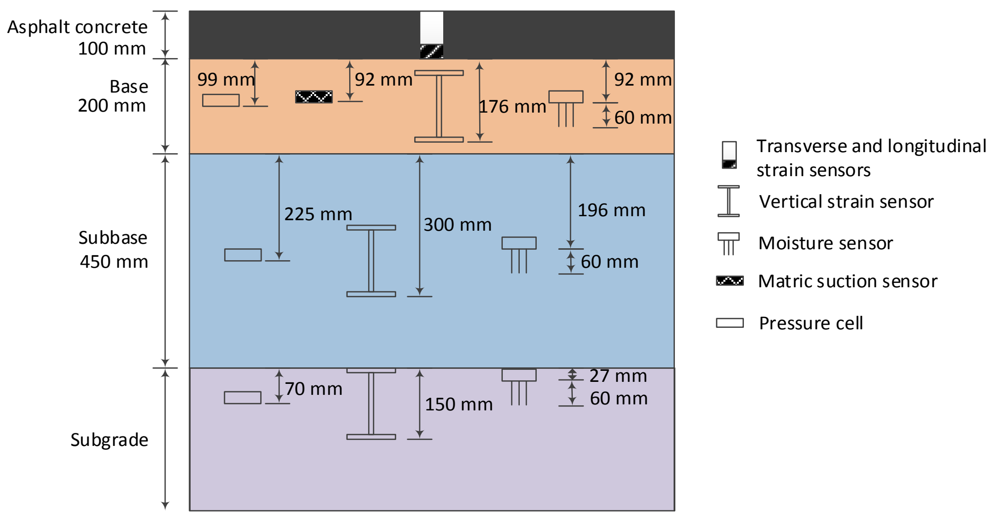

Figure 1. Pavement structure and sensors instrumentation.

data on vertical strain, vertical stress and water content were collected at mid-depth (unbound materials) or at the top of the layer (subgrade), while only strains (longitudinal and transversal) at the bottom of the asphalt concrete layer were collected for the surface layer. In addition, the test sections were also equipped with a 2 m long thermistor string in the laboratory and a road weather station at the SERUL to monitor the temperature profile variations in the pavement structures. Besides all these sensors, a surface deflection sensor was also installed on the surface of the indoor experimental pavement to evaluate the global structural bearing capacity during freeze-thaw. The detailed information about the sensors used to monitor pavement response at both sites can be found in Figure 1.

3 METHODOLOGY

3.1 Test Section in the Laboratory

In the laboratory, a heavy vehicle simulator was installed on top of the indoor test pit. A loading carriage with a dual tire assembly was used to simulate real traffic loading conditions (Figure 2). The simulator has a heating/cooling system, by which the air temperature under the simulator can be controlled and stabilized to a desired value. The insulation side panels were installed around the simulator to help for the temperature conditioning. During the freezing procedure, -10°C was imposed at the surface of the pavement using the cooling system of the simulator. Meanwhile, to represent the real thermal conditions in the field, a temperature of 2°C was maintained at the bottom of the tested pavement structure using a closed circuit cooling glycol system embedded at the bottom of the test pit. In order to obtain moderate frost heaving, the groundwater level was adjusted to -1600 mm from the pavement surface. It was found that this level showed great variations during the freeze-thaw procedure.

In the testing process, the carriage was adjusted to apply 5000, 5500 and 4000 kg dual-wheel weight on the pavement surface to simulate standard, winter premium and spring load restrictions conditions, respectively. The tire pressure was set at 700 kPa and a speed of 5 km/h was used for the carriage through the loading procedure. For each measurement, eight loading passes were applied and all the sensor readings were collected. The average peak values for these eight passes were used to quantify the structural behavior variations for the experimental pavement. At the beginning of the test, the measurement frequency was four times a day, which was gradually reduced to once a day along with the reduction of frost penetration rate. The temperature profile for the pavement structure was collected at each measurement to determine the frost line position using a linear interpolation method based on the two temperatures above and below 0°C. The freezing process stopped when the frost line reached 1.5 m. In the thawing procedure, a constant temperature of 10°C was applied to the surface until the whole pavement structure was thawed and a stabilized mechanical response was obtained.

(a) ATLAS simulator (b) Simulator with environmental panels

(c) Loading carriage for simulator

Figure 2. Environmental chamber and loading carriage for simulator.

3.2 Test Section at the Laval University Road Experimental Site (SERUL)

At the SERUL, experimentations were done during the 2014 thawing period (spring) and recovery period (summer-autumn) of the pavement. A falling weight deflectometer was used to simulate heavy vehicle loading. Three different load levels were used with the FWD: 40, 53, and 71 kN. Table 1 shows the number of tests performed.

Table 1. Number of Tests at the SERUL

Period	Number of experimentations	Season
April to June	9 (once a week)	Spring
August to November	4 (once a month)	Summer-Autumn

4 RESULTS AND DISCUSSION

4.1 Test Section in the Laboratory

To help visualize the variations of the mechanical behavior of the pavement structure, the response values (stress, strain) were normalized using the initial measurement (before freezing). The normalized strain and stress in each layer were calculated by the following equation:

$$Normalized\ (\varepsilon\ or\ \sigma) = \frac{(\varepsilon\ _{or}\ \sigma)_{time\ t}}{(\varepsilon\ _{or}\ \sigma)_{initial(before\ freezing)}} * 100 \qquad [1]$$

where Normalized $\varepsilon\ _{or}\ \sigma\ (\%), \varepsilon = strain\ (\mu\varepsilon), \sigma = stress\ (kPa)$

4.1.1 Strain Variations

Strain variation in the pavement structure during freezing with the 5000 kg load are presented in Figure 3 as a function of the freezing index (FI). At the beginning, the temperature in the asphalt layer decreases gradually until all the asphalt concrete is frozen. The decrease of temperature in asphalt concrete causes an increase in the stiffness of the asphalt layer, which reduces tensile strains (asphalt concrete) and vertical strains (unbound materials). Then, the base layer freezes which allows observing a faster reduction of tensile strains in the asphalt concrete and vertical strains in the base layer. When the frost line reaches the subbase, the strains for all layers keep decreasing and become constant for asphalt concrete and base when the frost front reaches around 0.62 m and a FI of 70°C-days. The strains for subbase and subgrade become constant when the frost font reaches around 0.98 m and a FI of 193°C-days. Table 2 indicates the normalization of tensile and vertical strains at the bottom of asphalt concrete and in the unbound layers, respectively, for the 5000 kg load in comparison to the initial measurement (before freezing) as a function of frost front's depth.

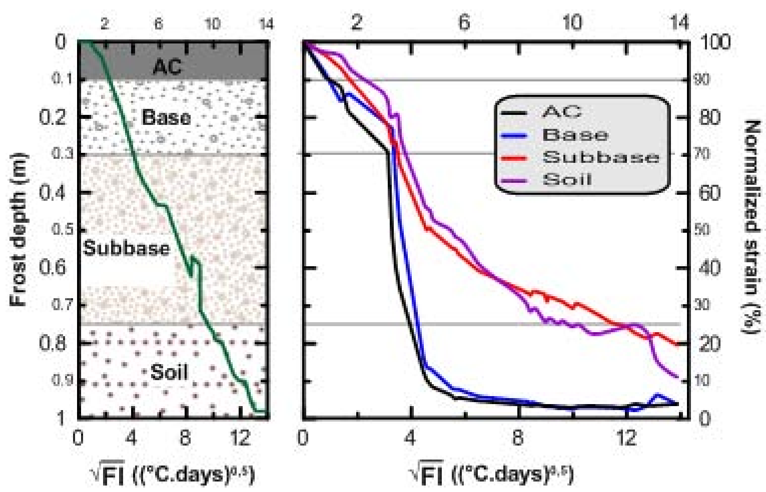

Figure 3. Strain variations at 5000 kg in the pavement structure during freezing.

Table 2. Normalized Strain in Comparison to the Initial Measurement at 5000 kg (Before Freezing) as a Function of Frost Front Progress

	Normalized strain (%)			
Frost depth (m)	Asphalt concrete	Base	Subbase	Subgrade
0.1	77	83	85	90
0.3	23	33	59	66
0.75	3	3	31	26
0.95	4	3	19	6

As shown in Figure 4, during the thawing process of the indoor experimental pavement, the temperature increase and the penetration of the thaw front significantly affect pavement layers behavior. The unfrozen moisture content in the different layers increased. When the thaw front reached a depth of around 0.9 m and a thawing index of 90°C-days, tensile (AC) and vertical (unbound materials and soil) strains increased to their maximal values. Then, the decrease of water content caused a decrease of tensile strain at the bottom of the asphalt concrete and vertical strain in the base and subbase until a complete recovery of the pavement. Some technical issues with the strain sensors in the subgrade caused a signal loss during at the beginning of the thawing procedure. Table 3 summarizes the normalization of strains as a function of thaw front depth in comparison to the initial measurement (before freezing).

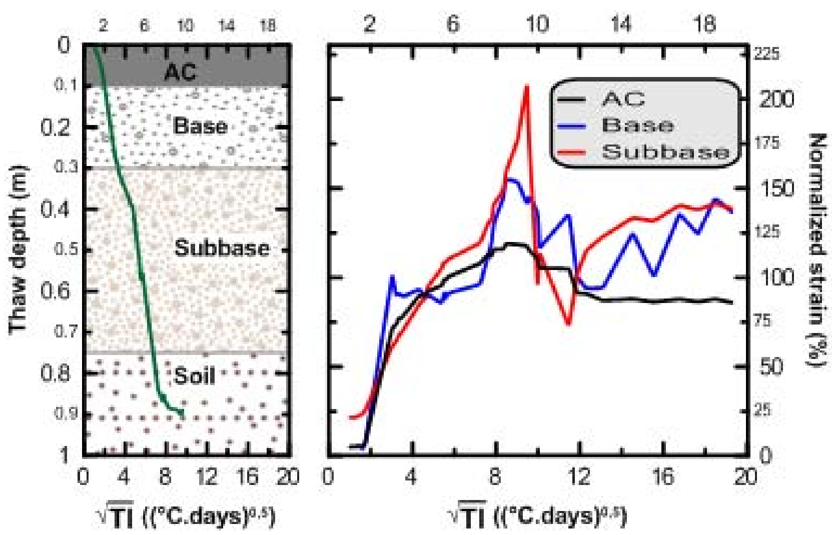

Figure 4. Strain variations at 5000 kg in the pavement structure during thawing.

Table 3. Normalized Strain at 5000 kg in Comparison with the Initial Measurement (Before Freezing) as a Function of Thaw Front Depth

	Normalized strain (%)		
Thaw depth(m)	Asphalt concrete	Base	Subbase
0.1	19	24	32
0.3	76	91	67
0.75	105	95	116
0.9	119	155	208

4.1.2 Stress Variations

The evolution of normalized stress for the 5000 kg load in unbound layers and soil during freezing and thawing as a function of the thawing index is presented in Figure 5 and Figure 6. It is possible to observe that stresses decrease when the frost front progresses in the pavement, as it was observed for strain measurements with a stabilization of the base stress at 0.62 m and for the other layer at 0.9 m. For the thawing, thawing of the base layer leads to the increase of base and subbase stresses. When the subbase begins to thaw, an important stress increase is noticed in the subbase. Through this process, the base stress caused by the moving surface load shows only small variations.

After the complete thawing, stresses gradually decrease until the complete recovery of the flexible pavement structure.

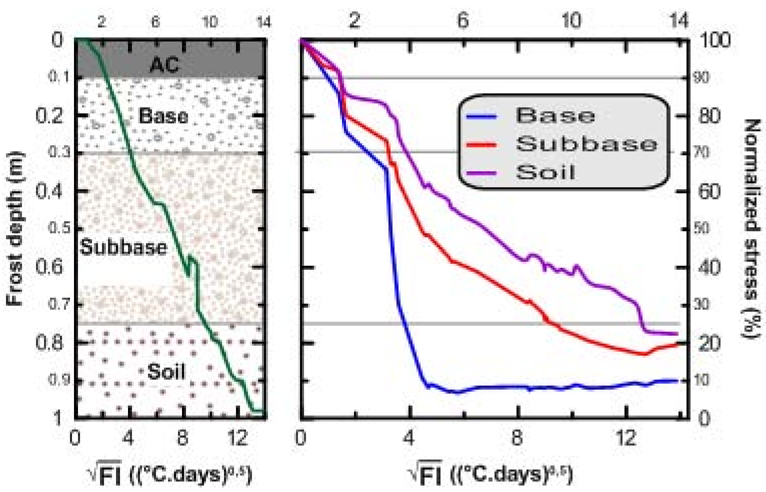

Figure 5. Stress variations at 5000 kg in the pavement structure during freezing.

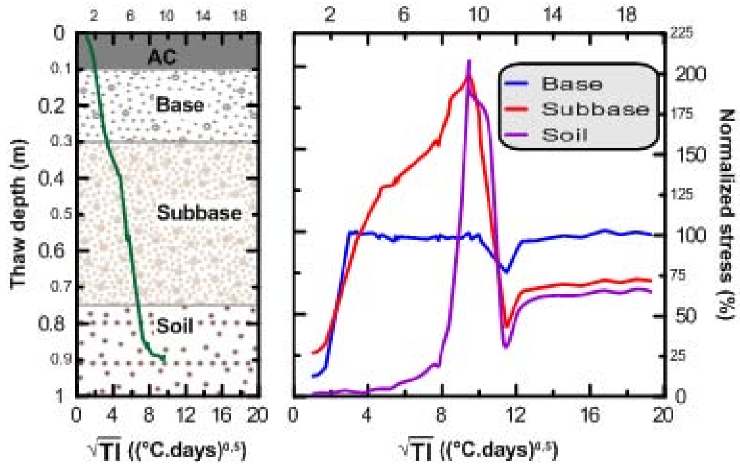

Figure 6. Stress variations at 5000 kg in the pavement structure during thawing.

4.1.3 Effects of Increasing and Reducing Loads

The 5500 kg (10% increase, winter premium conditions) and 4000 kg (20% reduction, spring load restrictions) loads were also applied to the indoor experimental pavement during the freezing and thawing procedures, respectively, to monitor the pavement response during these specific conditions. The variation of mechanical behavior (VMB) was calculated by the following equation:

$$VMB = \frac{(\varepsilon \text{ or } \sigma)_{(5500kg \text{ or } 4000kg)}}{(\varepsilon \text{ or } \sigma)_{(5000kg)}} * 100 \quad [2]$$

Where VMB=Variation of mechanical behavior (%), $\varepsilon = strain\ (\mu\varepsilon)$, $\sigma = stress\ (kPa)$

During freezing, for most of the mechanical response collected (Figure 7), the 10% load increase induces a 10% increase of strain and stress in the pavement structure. During the thawing, as shown in Figure 8, it can be noted that the 20% load reduction could induces approximately a 10-20% decrease of stress and strain in the pavement structure.

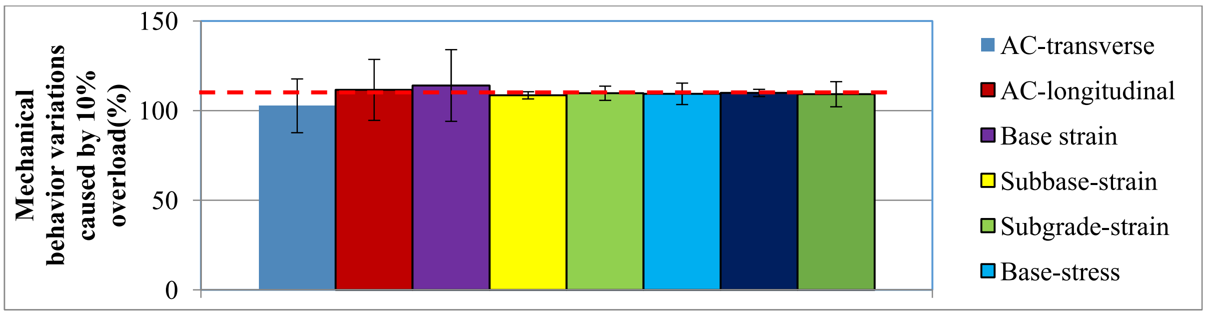

Figure 7. Increased mechanical response caused by 10% overload-5500 kg during freezing conditions.

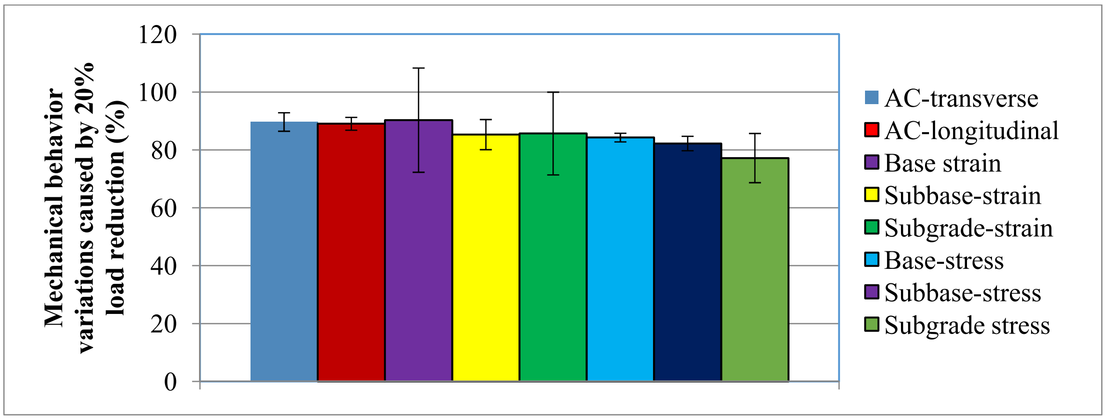

Figure 8. Decreased mechanical response caused by 20% load reduction-4000 kg during thawing conditions.

4.2 Test Section at the Laval University Road Experimental Site (SERUL)

At the SERUL, technical issues were encountered with the pressure cells and it was not possible to collect stresses during the first year of experimentation.

In order to improve the comparison between the indoor and the outdoor experimental pavement, an interpolation method based on the two FWD loads (40 and 53 kN) was used to determine the strains at 50 kN (≈5000 kg). The evolution of strain in the pavement structure during thawing in comparison with the summer values (around July) is presented in Figure 9. At the SERUL, the maximum strain in all unbound layers was recorded when the thaw depth reached 0.9 m and a thawing index of 37.5°C-days (around April 25th), with a normalized strain of 640% and 201% in the base and subbase, respectively. In the subgrade, the normalized strain was 110% when the thaw depth reached 1.19 m (May 5th). On April 25th, the moisture content started to decrease leading to a reduction in measured strains in all layers. At the beginning of the summer (around May 20th), the rise of the temperatures at mid-depth of asphalt concrete, which reduced the layer stiffness, led to increased normalized strains again (510%, 220% and 110% for the base, subbase and subgrade respectively). The complete recovery of the pavement was reached around July.

Figures 10 and 11 show the normalized strain and the change of water content during the critical period in comparison with the summer value (around July). This period is comprised between April 25th when the thaw depth is around 0.9 m and May 20th at the beginning of the summer. It can be observed that the strain in all layers is mostly function of the moisture content in subbase and subgrade. For example, when the strain in the base increases to 640% and 510% on April 25th and May 20th respectively, the moisture content in the base is low while it is high in the subbase and the subgrade.

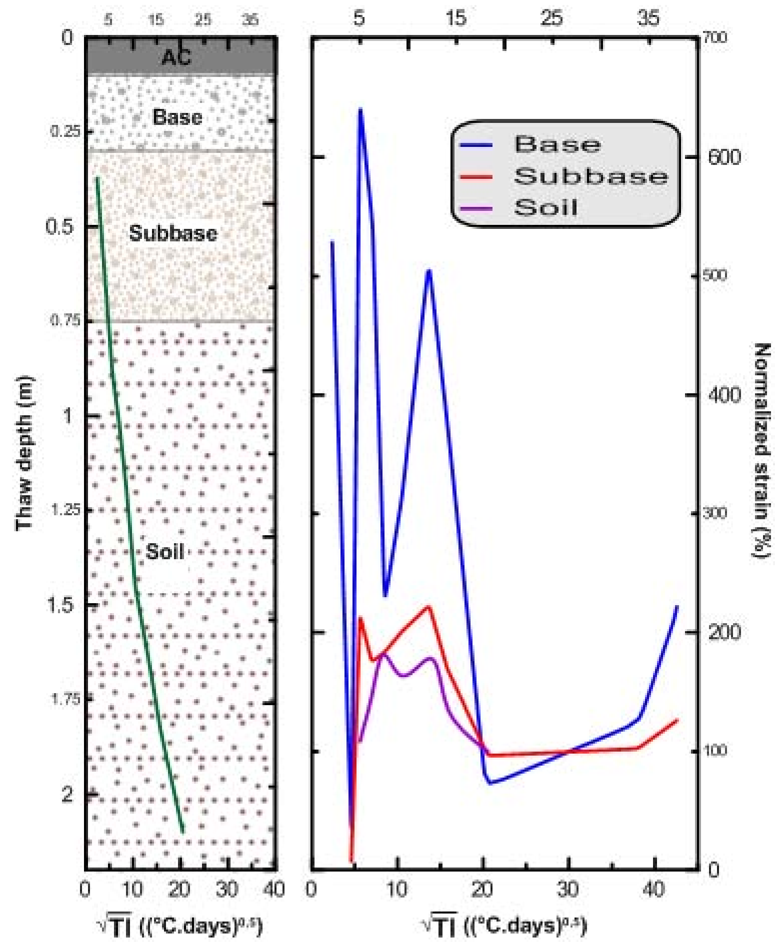

Figure 9. Strain variations in pavement structure during thawing at SERUL.

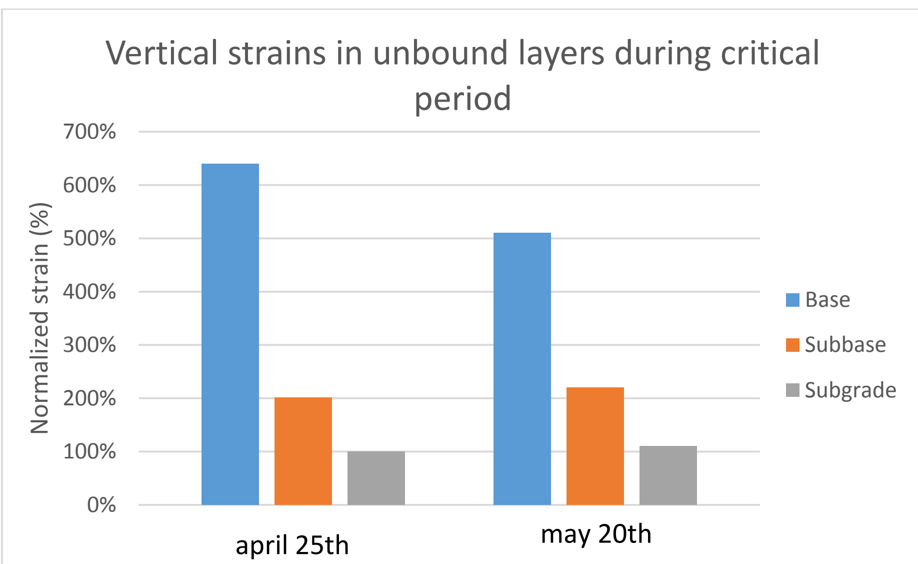

Figure 10. Normalized strain in unbound layers during the critical thawing period.

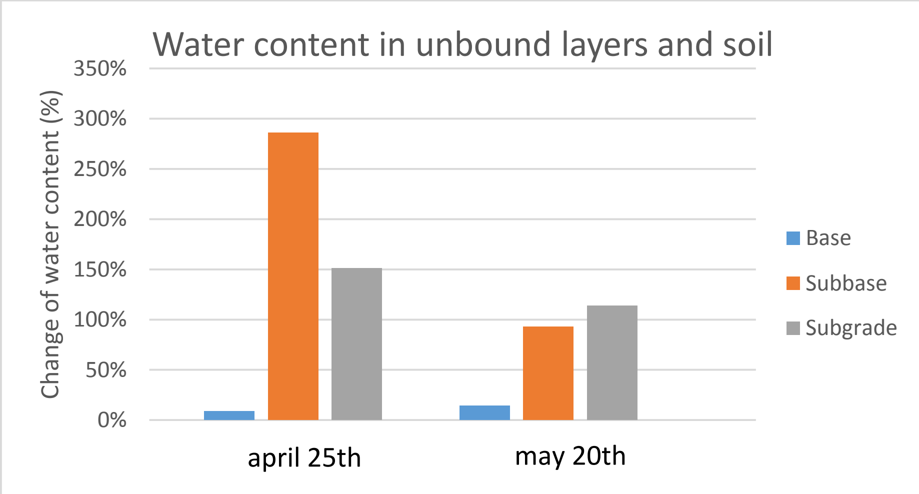

Figure11. Normalized water content compared to the summer value layers during the critical thawing period.

Strains under a 4000 kg load (20% load reduction) was compared to those measured under a 5000 kg load using a polynomial interpolation (50 kN). The data collected at the SERUL are in good agreement with the indoor test pit data, as the 20% load reduction introduced approximately a 13% decrease of strains in the pavement structure at the SERUL (Figure 12). This value appears to be consistent for all the unbound layers and soil, as it was also observed for the indoor test pit.

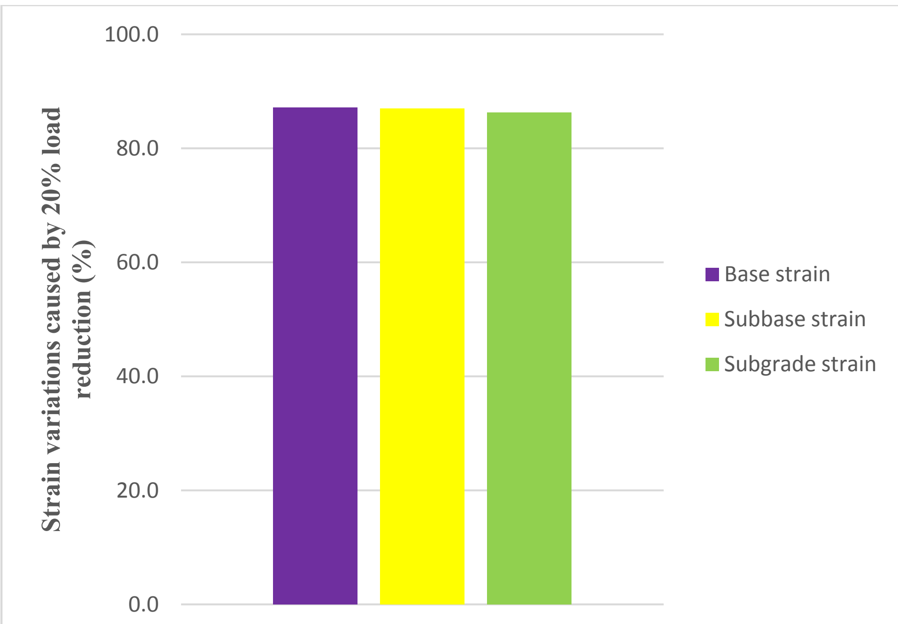

Figure 12. Strain variations caused by 20% load restriction-40 kN.