# Effect of the future increases of precipitation on the long-term performance of roads

P. M. Thiam, G. Dore, J- P. Bilodeau
*Laval University, Department of civil engineering, Quebec, Qc, Canada*

ABSTRACT: The long-term performance of the road network of the province of Quebec (Canada) is strongly influenced by climatic conditions (Dore and Zubeck, 2008). Amongst other factors, high levels of saturation in soils and pavement materials are an important cause of pavement deterioration. According to climate change scenarios established by Ouranos (2012), the South of Quebec will undergo a monthly precipitation increase between -0.1% and 8.45% for a future horizon from 2010 to 2039. The purpose of this project is to quantify the effect of these expected precipitation increases on the mechanical behavior of road structures, materials and soils. Based on data collected on instrumented road sections, a relationship between precipitations increase and saturation level of pavement layers is proposed. In order to determine the existing relationship between mechanical properties and moisture content, the resilient modulus and permanent deformation behaviors for various moisture contents and four different subgrade soils were determined using triaxial tests, the later being validated using a small-scale heavy vehicle simulator. Using the precipitation increase scenario and the relationship developed between precipitation and pavement layers moisture content in Quebec, a damage analysis is performed to quantify the decrease of pavements service life caused by climate change. It is found that climate change, and more precisely the increase of precipitations expected in the Province of Quebec, will have a significant impact on pavement performance and that adapted pavement structures and materials, such as improved drainage, increased structural capacity or materials with reduced sensitivity to water, are possible options to reduce the loss of pavement service life associated with climate change.

KEY WORDS**:** Precipitation, soils, moisture content, pavement damage, climate change.

## 1 INTRODUCTION

Throughout history, climate changes have always manifested themselves in a natural way (GIEC, 2007). However, since the industrial revolution, the increasing human activity has influenced the radiative activity of the atmosphere. This impact is illustrated in many ways and the most imminent remains an increase of precipitations. More specifically, according to climate-change scenarios established by Ouranos (2012), the South of Quebec will undergo an average monthly precipitation increase between -0.1% and 8.45% in a future horizon from 2010 to 2039. These increases of precipitation have a direct impact on pavement performance due to the increase of the moisture content of the pavement layers, more precisely the subgrade soils. Thus, this project aims to quantify this impact and, using widely recognized calculation approaches, to determine the reduction of the service life of pavement structures in the province of Quebec.

## 2 DESCRIPTION AND PURPOSE OF THE PROJECT

The main purpose of this project is to determine the change of mechanical properties of subgrade soils caused by an increase of precipitations between -0.1% and 8.45% expected from 2010 to 2039 in southern Quebec, the latter is divided in three different zones. These increases of precipitation are established by optimistic and pessimistic scenarios representing the 90th and 10th percentiles of the Canadian regional climate model (RCM). To quantify the effect of increased precipitations on the pavement performance, a relationship between the increase of precipitations and the moisture content for subgrade soils is established as part of this project. Then, the relationship between the moisture content and the mechanical properties of the soils is determined. The soil's properties considered are the resilient modulus and the permanent deformation. The objective is to quantify the effect of increasing saturation levels caused by the increase of precipitations on the resilient modulus and permanent deformation behaviors. To do so, three types of tests are performed on four types of soils typical of southern Quebec. The description of the materials and the testing methodology will be discussed in the next section.

Finally, using the different established relationships between precipitations and the moisture content and between the moisture content and mechanical properties, it is possible, with a damage analysis to quantify the reduction of service life caused by different scenarios of increasing precipitations developed by Ouranos (2012) for each of the three studied zones. However, for the purpose of this paper, only the results of one of the zones (zone 1), located in the furthest south of Quebec, will be illustrated for the increasing precipitation scenario of 6 %, which represents the $90^{th}$ percentile.

## 3 TEST METHODOLOY AND RESULTS

This section describes physical properties of the soils, the tests performed and a summary of results obtained. Three mechanical tests are performed on the soils: resilient modulus, permanent deformation tests performed in a triaxial cell, and a permanent deformation test in a small-scale heavy vehicle simulator (for two subgrade soils). The methodology for each of these tests is described below. In this section, the relationship between the moisture content and precipitations is also described.

### 3.1 Soil description and physical characterization

The mechanical tests are performed on four different subgrade soils representative of the geological context found in southern Quebec. The geological history of the region shows the massive presence of marine, glacial and fluvio-glacial deposits (Dore and Zubeck, 2008). In this perspective, the soils used for this project are a glacial till from the Experimental Road Site of Laval University (SERUL) and a sand from Sainte-Catherine de la Jacques Cartier (SCJC) (50km west of Quebec city), as well as two different clays respectively from St-Augustin and Saint-Alban. A series of characterization tests was performed on these soils. The objective was to gather the important physical properties in order to help the interpretation of the results of the mechanical tests. The results of a particle size analysis, shown in the figure 1, indicate that the soils selected for this research cover a wide variety of gradations. Table 1 shows the results of the basic properties characterization.

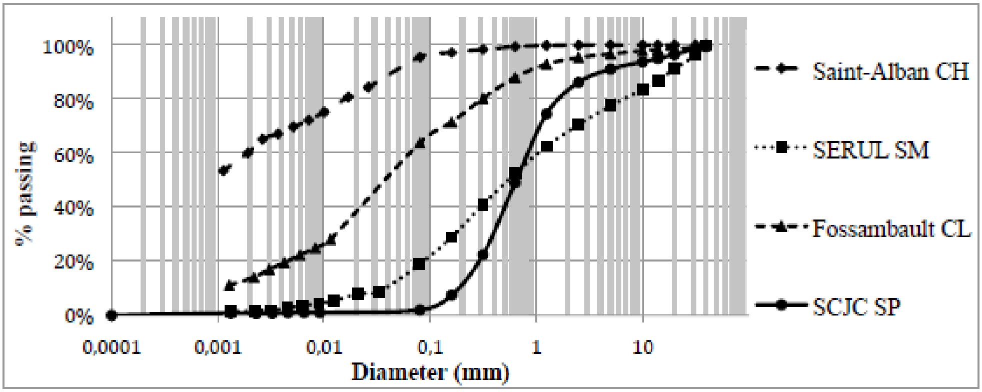


Figure 1: Grain-size distribution for the four soils tested in this project.

Table 1: Materials properties.

| Types of soils | Glacial Till (SM) | Sand (SP) | Clay (CH) | Clay (CL) |
|---|---|---|---|---|
| **Provenance** | SERUL | SCJC | Saint Alban | St-Augustin |
| **Percentage of fine (%)** | 18.90% | 2% | 95.40% | 63.80% |
| **Liquid Limit (%)** | 15.6% | Non-liquid | 46.8% | 46.8% |
| **Plastic Limit (%)** | Non-plastic | Non-plastic | 27.4% | 21.0% |
| **Optimum water content (%)** | 5.9% | 9.9% | 18.0% | 14.2% |
| **Maximum dry density (kg/m$^3$)** | 2220.4 | 1883.3 | 1750.0 | 1860.9 |

### 3.2 Relationship between precipitations and soils volumetric moisture content (*w*)

Data of volumetric moisture contents from highway 520 in Manitoba (data obtained from FPInnovations and Manitoba Infrastructure and transportation) and the SERUL and Saint-Celestin sites were used to assess a general relationship between precipitations and subgrade soils' moisture contents. The soil types at this site are clays and sands. These soil types are fairly representative of a large portion of the territory of southern Quebec. Precipitation data used were obtained from meteorological stations of the respective sites. It is also worth noting that the time periods used to implement the relationship are from March to November. Figure 2 illustrates an example of the existing relationship between precipitations and volumetric moisture contents (*w*) for the highway 520 in Manitoba at different depths of a clayey subgrade. This figure also shows a time delay between an episode of precipitation and the corresponding increase of moisture content in the soils.

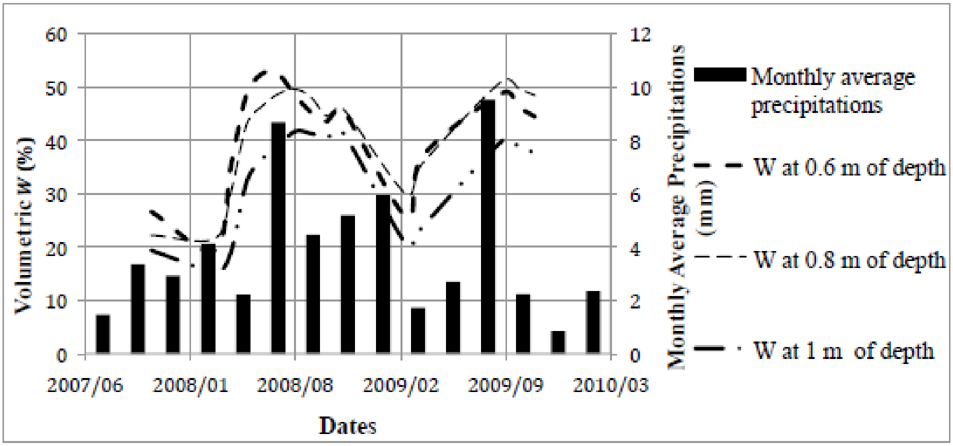


Figure 2: Example of monthly volumetric $w$ and precipitations for highway 520 Manitoba.

Figure 3 shows the pattern of increasing $w$ ($\Delta w$) with precipitations from the data shown in Figure 2. The $\Delta w$ value for a given month between March to November period, which would be associated with precipitations events is given by the $w$ of the following month in which a $k$ value is subtracted. Parameter $k$ is the lowest precipitation over a long period of time. The identified model is given by the following equation, which takes in account the time delay between P and $\Delta w$, as stated earlier, even though, that delay has not been quantified in this study:

$$\Delta w(\%) = 0.9P - 0.1 \tag{1}$$

Where P is the precipitation value in mm. However, this kind of relationship can be extremely difficult to establish due to factors such as soil types and physical properties. Thus, a determination coefficient of 0.22 is considered acceptable according to similar studies from the scientific literature.

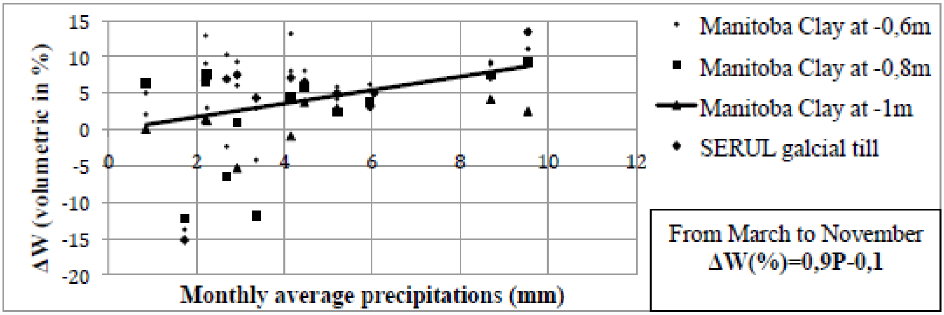


Figure 3: Relationship between the precipitations and $\Delta w$.

## 3.3 Resilient modulus

The resilient modulus tests on the four soils were performed in accordance to the AASTHO T307-99 (2003) standard. The samples were compacted in 6 layers and were 150 mm in diameter and 300 mm in height. Two moisture conditions were considered, which are an optimal condition and a saturated condition. These two conditions allow quantifying the effect of the degree of the saturation of the soils on the resilient modulus. The samples were first prepared at an optimum state, then saturated by gravity. A total of 15 stress states were applied. However, prior to testing, 1000 preconditioning cycles are performed on the sample to reduce the permanent deformation caused by the soil particles restructuration. The modified MEPDG (2000) model was selected for the analysis of the results. This model, given by the equation 2, is a combination of the initial MEPDG model and the Uzan (1985) model. The latter is widely used for subgrade soils.

$$Mr(MPa) = K_{1opt(uzan)} \left( \frac{\theta_{opt}}{P_a} \right)^{k_{2opt(uzan)}} \left( \frac{\sigma_{dopt}}{P_a} \right)^{k_{3opt(uzan)}} 10^{k_s (w - w_{opt})} \tag{2}$$

where $K_1$, $K_2$, $K_3$ are regression parameters, $\theta$ is the bulk stress in kPa, $\sigma_d$ is the deviatoric stress in kPa and $P_a$ is the atmospheric pressure in kPa. The parameter $k_s$ in this model was found by a target value obtained from the data at the saturated state. The combination of the two models allows obtaining the relationship between the resilient modulus and the moisture content for 15 different stress states. Table 2 summarizes of the resilient modulus models based on equation 2.

Table 2: Parameters for the resilient modulus and VMC models of tested soils.

| Soil type | $K_{1\ opt\ (Uzan)}$ | $K_{2\ Opt\ (Uzan)}$ | $K_{3\ opt\ (Uzan)}$ | $K_s$ | Volumetric $W_{opt}$ (%) |
|---|---|---|---|---|---|
| **SM Till** | 1.36 | 1.17 | -0.64 | -1.20 | 0.11 |
| **SP Sand** | 1.07 | 0.87 | -0.38 | -0.79 | 0.16 |
| **CL Clay** | 2.15 | 0.10 | -0.37 | -10.55 | 0.23 |
| **CH Clay** | 3.81 | 0.07 | -0.41 | -7.92 | 0.28 |

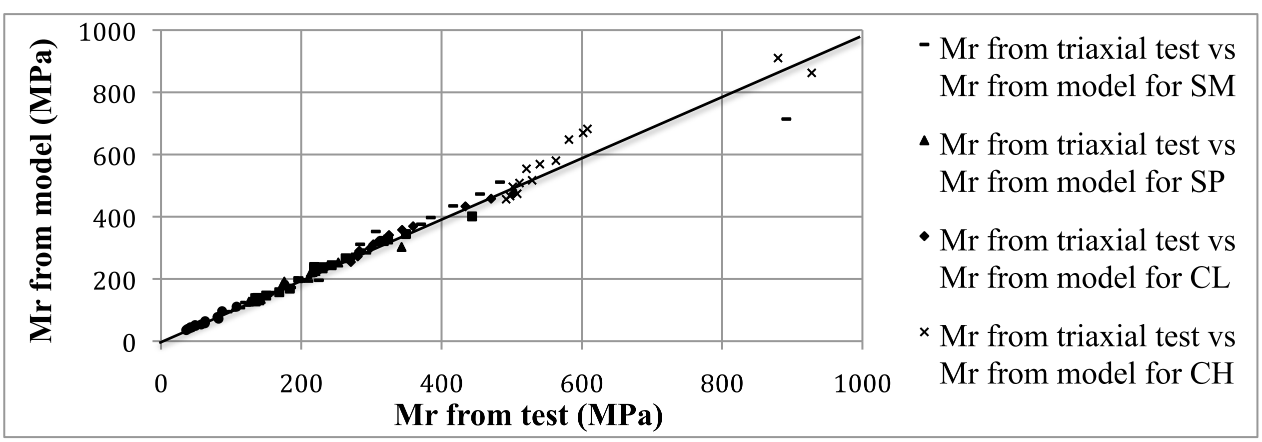


Figure 4: Analysis of the reliability of the MEPDG (2000) model

In order to verify the reliability of the MEPDG (2000) model, shown in the equation 2, the figure 4 illustrates the relationship between the resilient modulus given by the model and the resilient modulus given by the triaxial tests for the different soils. The regression line shows very satisfactory results from the MEPDG (2000) model.

## 3.4 Permanent deformation tests

The permanent deformation test is a laboratory method to evaluate the long-term plastic behavior of soils. For the purpose of this project, the permanent deformation tests were also performed at optimum and near saturation conditions using a single stage permanent deformation test approach. As for the resilient modulus, these conditions allow establishing a link between the permanent deformation behavior and the degree of saturation of the soils. Inspired from the European standard and standard from transport Quebec, several tests and simulations using the software Winjulea allowed determining realistic stress conditions for typical flexible pavement structures encountered in Quebec. As a result, 50000 load cycles were applied for each environmental condition at a confining pressure of 15 kPa and a deviatoric stress of 20 kPa on 100mm diameter x 200mm height samples. The loading time and rest period were set to 200 ms and 800 ms respectively. Figure 5 presents the results obtained for the permanent deformation tests. The results from these tests are summarized by an increase of the permanent deformation at the saturated condition when compared to the optimal condition. Table 3 presents the tests' analysis based on the Dresden power model, which uses the regression parameters A and B, the latter being the long-term permanent strain rate.

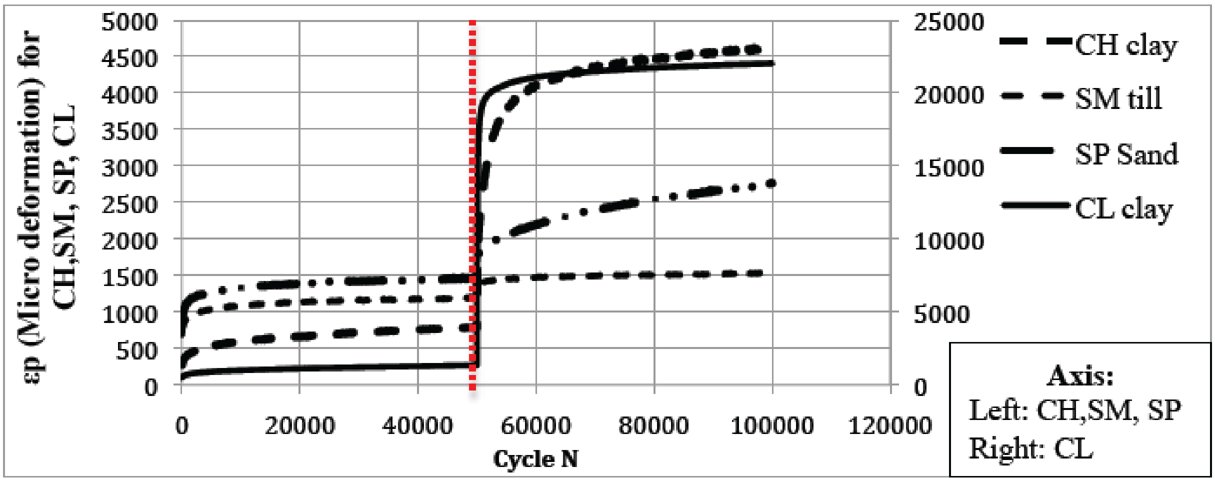


Figure 5: Results of multistage permanent deformation tests.

Table 3: Model parameters obtained for permanent deformation tests.

| Analysis model | Soil | CL Clay | | CH Clay | | SM Till | | SP Sand | |
|---|---|---|---|---|---|---|---|---|---|
| | *W (%)* | **Opt.** 28.8% | **Sat.** 34.4% | **Opt.** 25.1% | **Sat.** 43.3% | **Opt.** 13.3% | **Sat.** 19.8% | **Opt.** 17.2% | **Sat.** 35.1% |
| | $R^2$ | 0.99 | 0.81 | 0.99 | 0.89 | 0.98 | 0.98 | 0.98 | 0.98 |
| $\varepsilon p=A.N^B$ | **A** | 227.2 | 13211 | 129.9 | 699.6 | 582.8 | 100.7 | 721.2 | 47.0 |
| | **B** | 0.16 | 0.04 | 0.17 | 0.16 | 0.07 | 0.11 | 0.07 | 0.30 |

3.5 Small-scale heavy vehicle simulator

The last part of this project is the assessment of the permanent deformation behavior using a small-scale heavy vehicle simulator described by Juneau and Pierre (2008). The main objective of this test is to measure the accumulation of permanent deformation in the subgrade soil under moving wheel and to validate the results obtained using the triaxial test. Only two simulations were performed using the small-scale heavy vehicle simulator (SM Till and CL clay). One of the biggest advantages of using the simulator is that it can reproduce in the laboratory the rotational movements of a moving wheel on a road sample. The tank in which the sample is compacted is 1.8 m long, 0.6 m high and 0.6 m wide. The wheel has a diameter of 460 mm and a width of 150 mm. Tire prints and Winjulea analysis indicated that a 8.27 kN load on the tire allowed obtaining a surface stress of 593.15 kPa and therefore, a vertical stress at the top of the subgrade layer similar to what was applied during triaxial permanent deformation tests. This was calculated for a pavement structure of 185 mm of subgrade soil, 185 mm of subbase, 140mm of base and 50 mm of asphalt concrete. A total 50000 cycles were performed for each environmental condition (optimum and saturated), which led to 100000 cycles applied to the small-scale pavement sample. The sample was saturated using gravitational energy. The water level was kept slightly above the subgrade soil to simulate elevated groundwater table conditions. The deformations in soils were collected manually at load cycles 0, 50, 100, 200, 350, 500, 1000, 2000, 3500, 5000, 10 000, 20 000, 30 000, 40 000 and 50 000 and for each of the environmental conditions. The layers' displacements were measured using an adapted multidepth deflectometer positioned at the center of the pavement sample. The results from these tests are summarized by an increase of permanent deformation for the saturated condition compared to the optimal. Figure 6 is an example of the results obtained for these tests on the SM Till and the CL clay. Table 4 shows the model analysis and the parameters used for the permanent deformation test. The same analysis method as the permanent deformation test was used.

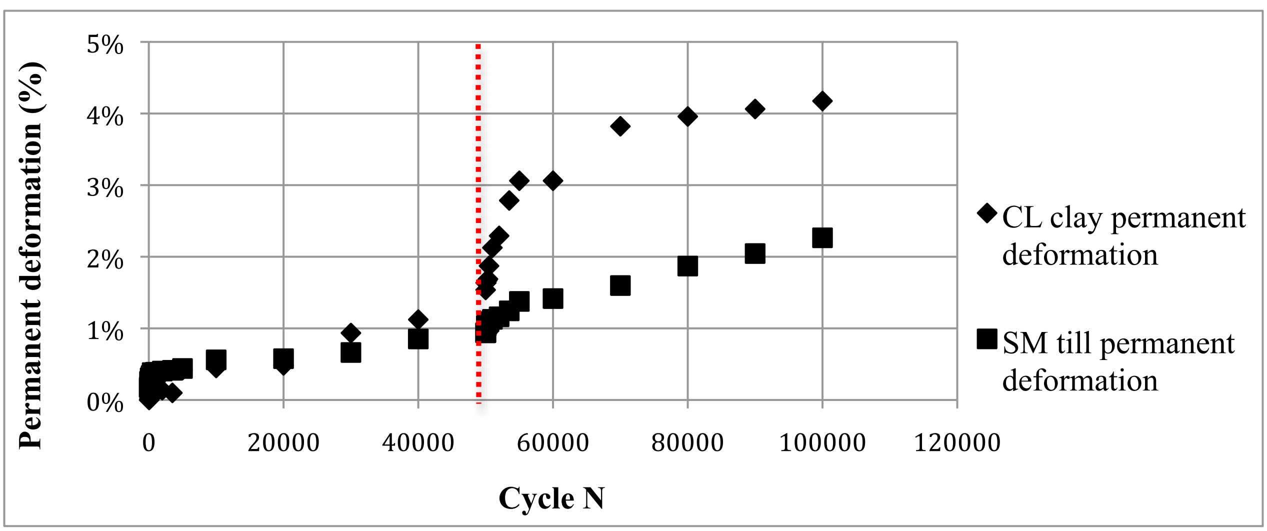


Figure 6: Results of the Small-scale heavy vehicle simulator tests.

Table 4: Model parameters for the simulator test.

| Analysis model | Soil type | CL Clay | | SM Till | |
|---|---|---|---|---|---|
| | Volumetric W (%) | **Opt.** 29.0% | **Sat.** 36.7% | **Opt.** 13.4% | **Sat.** 26.7% |
| $\varepsilon_p = A.N^B$ | **Correlation** | 0.92 | 0.79 | 0.92 | 0.73 |
| | **A parameter** | 0.005 | 0.0014 | 0.1878 | 1.0074 |
| | **B Parameter** | 0.5885 | 0.8352 | 0.1891 | 0.6069 |

## 4 DAMAGE ANALYSIS AND DICUSSION

In this section, the effect on pavement service life of the reduction of the mechanical properties of soils due to increased precipitation is quantified. It has been stated earlier that the scenarios established by Ouranos (2012) for the zone 1 of southern Quebec predicted an increase in monthly precipitation of 6% in the 90$^{th}$ percentile. This value corresponds to a relative increase in average monthly precipitation of 5.5 mm if it is considered that the average monthly precipitation for a reference period from 1971 to 2000 in the zone 1 is 85.5 mm. So for the horizon of 2010 to 2039, the average monthly precipitation expected will be 90.9 mm in the zone 1. As subgrade soils moisture content is directly related to the amount of rainfall, this precipitation increase should be associated with a decrease of the service life. Using equation 1, a moisture content corresponding to precipitation values of 85.5 mm and 90.9 mm can be determined. These precipitation values are associated with an increase of volumetric moisture content of 5%. The following methods assess the quantification of the reduction of the relative service life from a reference period of 1971-2000 to a future reference of 2010-2039,

Firstly, for the resilient behavior, the damage parameter is N which is the number of allowable load repetitions prior rutting failure, or the service life expressed in equivalent of single axle load (ESAL). This value of N is determined using the damage law of the Asphalt Institute according to the following equation:

$$N(ESAL) = 10^6 \left( \frac{\varepsilon_z}{k} \right)^{-a} \tag{3}$$

Where k and a are constant parameters (k=482, a=4.48) and $\varepsilon_z$ is the vertical strain at the top of the subgrade soils. The deformation was calculated using a typical flexible pavement structure of southern Quebec analyzed with the software Winjulea, as shown in table 5.

Table 5: Characteristics of pavement used for damage analysis based on resilient modulus test.

| Material | Thickness | Mr | Poisson ratio | Axial Load | Area |
|---|---|---|---|---|---|
| | mm | MPa | - | kN | mm$^2$ |
| Asphalt concrete | 100 | 2500 | 0.35 | 40 | 70686 |
| Granular base | 200 | 300 | 0.35 | | |
| Granular subbase | 575 | 150 | 0.35 | | |

These characteristics of the pavement structure were established from design standards of the Ministry of Transportation of Quebec. The soils resilient modulus used for this analysis are derived from the equation 2. Thus, N is calculated for each 15 stress states for the reference period as well as for the future period. A summary of the calculated N values for both periods has shown an average decrease of N of 20% from the reference period (1971-2000) to the future period (2010-2039) for the four studied soils in the zone 1.

For the permanent deformation behavior, it is already considered as damage. Thus, unlike the resilient behavior where the service life N was studied, the parameter B (permanent strain rate) given by the considered model (table 3) was studied. In order to determine the value of B for both reference and future periods, a linear interpolation of B between the saturated and optimum state from the laboratory test was used. As a result, an average increase of the B value of 8% from the reference period to the future period, for the triaxial test.

The damage analysis using the small-scale heavy-vehicle simulator results allows making a validation of the findings regarding the damage analysis based of the resilient modulus and the permanent deformation triaxial testing. The approach of damage analysis is the same than for the permanent deformation tests. As a result, an average increase of the B value of 7% from the reference period to the future period.

Figure 7 summarizes the results of the damage analysis. It should be noticed that, for the analysis based on the resilient modulus, the N parameters are obtained by averaging the results' analysis for all the 15 stress states.

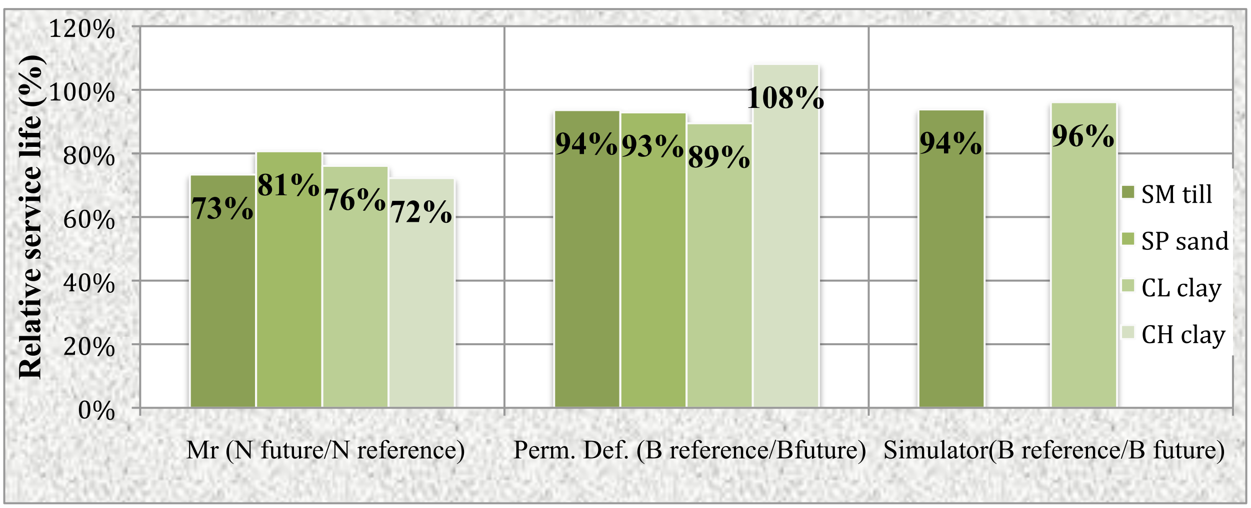


Figure 7: Comparison of the damage ratios for the three mechanical tests in the zone 1.

It is believed that the slight differences in the values obtained could come from several sources. Amongst other things, it appears to be important to improve the modeling of the permanent deformation according to moisture content, as a linear interpolation was used to determine the parameter B from the permanent deformation and heavy vehicle simulator tests in this study. In summary, the long-term performance for the future period (2010-2039) is approximately reduced by 15 % from the reference period (1971-2000) throughout this study and tangible solutions for better adaptation in the future should be considered such as a better materials' choice and improved drainage design.

## 5 CONCLUSION

Climate change for a future horizon from 2010 to 2039 in southern Quebec should be manifested by a precipitation increase of 6% in the zone 1. The objective of this project was to quantify the reduction in pavement service life caused by these increases. In order to meet the objectives, a relationship between moisture content and precipitations was established and the effect of water content on resilient modulus and permanent deformation of typical subgrade soils was quantified. The damage, characterized by the number of axle loads prior failure for the analysis of the effect of the resilient modulus and by the permanent strain rate B for permanent deformation tests, was quantified. In summary, the long-term performance for the future period (2010-2039) was found to be approximately reduced by 15% from the reference period (2010-2039) for typical subgrade soils of southern Quebec. The use of an adapted model remains to address in order to consider more precisely the effect of moisture content on the permanent deformation behavior and would be suitable to improve the analysis performed in this study. The decrease of performance and service life of flexible pavement structures has to be addressed. Solutions such as a better choice of materials, more efficient drainage systems and an adjustment of the geometry of the road structures would be options to consider in order to reduce water sensibility problems and ensure adequate performance of road structures for the next decades.

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