Long-term performance of flexible pavement structures in a changing climate

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Abstract: Climate changes may cause an increase of precipitation in the Province of Quebec over the next decades. As the performance of flexible pavement structures is closely related to moisture content of soils and aggregates, these structures can be considered vulnerable to climate changes. In order to quantify the effect of future precipitations increase on the pavement service life, this research project was based on a three steps approach: 1) Establishment of a relationship between precipitations and water content in the subgrade layers; 2) Establishment of the relationship between soils water content and soils mechanical properties, quantified with the resilient modulus and the permanent deformation behaviour; 3) Quantification of the effect of increased precipitations on pavement life, based on modification of their mechanical behaviour due to water content increase. For the example considered in this paper, it was found that the service life of pavement structures submitted to future climate may present a service life reaching 0.72 times the service of actual pavement structures. These results vary depending on the soil and damage types considered.

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1. Introduction

Climatic conditions are, with heavy vehicles loading, among the main factors affecting the long term performance and serviceability of flexible pavement in northern countries like Canada [1, 2]. Among the main climatic factors that have a significant influence on the pavement behaviour, water has received considerable attention through pavement design and past researches. Some authors [3] suggest that up to 80 % of pavement damage may be attributable to the effect of moisture on soils and materials behaviour under wheel loading and under environmental solicitations, such as frost action. In an evolving climate due to climate change, it is expected that an increase of precipitation between -0.1 to 8.45 % is likely to happen in southern Quebec in a future horizon from 2010 to 2039 [4]. These scenarios represent optimistic and pessimistic output of the regional climate model (RCM), corresponding to the 90^{th} and 10^{th} percentiles. As the pavement performance is closely related to subgrade soils, and those are the materials in the flexible pavement layered systems that are the most sensitive to moisture increase, this study aims to quantify the effect of the future increase of precipitation on the flexible pavement structures from a subgrade soils behaviour perspective.

2. Materials and methods

This research project is based on a three steps approach: 1. Establishment of a relationship between precipitations and water content in the subgrade layers; 2. Establishment of the relationship between soils water content and soils mechanical properties, quantified with the resilient modulus and the permanent deformation behaviour; 3. Quantification of the effect of increased precipitations on pavement life, based on modification of their mechanical behaviour due to water content increase. To quantify the resilient modulus, laboratory triaxial tests were performed on compacted soil samples. The permanent deformation behaviour was also quantified with cyclic triaxial tests, but also with the measurement of rutting behaviour of laboratory small-scale pavement structures loaded with a small-scale heavy vehicle simulator. Four subgrade soils representative of Quebec's geological conditions were sampled for this research: SM, SP, CH and CL. The main results of the geotechnical characterization can be found in Table 1 and Figure 1.

Table 1. Subgrade soils geotechnical characterization [5]

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

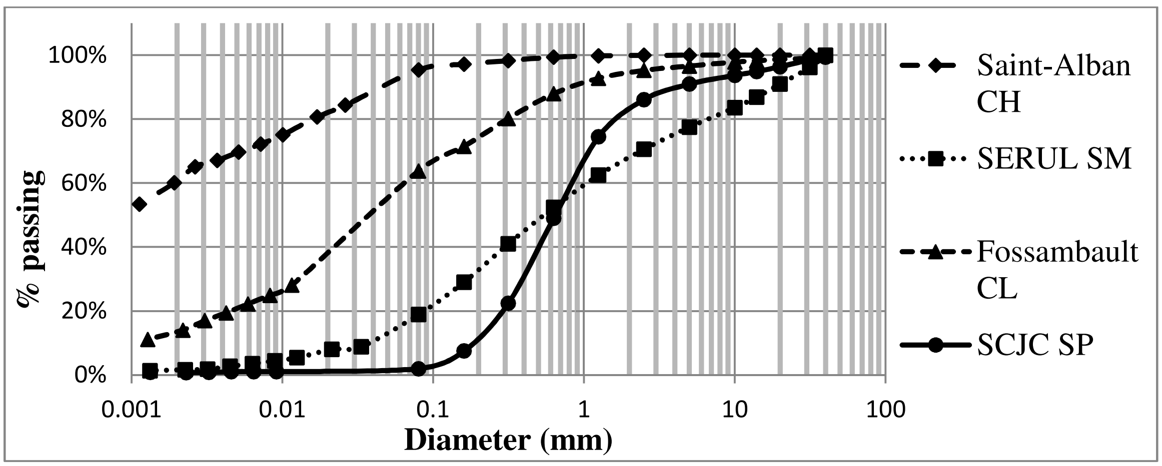

Figure 1. Subgrade soils grain-size distribution [5]

3. Relationship between precipitations and soils volumetric moisture content (w)

The establishment of a relationship between soils volumetric moisture content (w) and precipitations is based on experimental data collected at the Laval University Experimental Test Track (SERUL), the Ministry of Transportation of Quebec experimental site of Saint-Célestin, as well as data from highway 520 in Manitoba. The soils at these sites are clays and sands. The precipitation data were obtained from the meteorological stations at the sites. The data from March to November were considered to establish the relationship, which was developed on a monthly basis. The increase in volumetric water content Δw 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 from which a k value is subtracted. Parameter k is the lowest precipitation over a long period of time. The identified relationship, shown in Figure 2, is expressed

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

in which P is the precipitation value in mm. A $R^2=0.22$ is found for this relationship, which is in a similar range than other equations proposed in the literature for this kind of data. The relationship between soil moisture and precipitation is difficult to establish, as it is influenced by numerous parameters such as soil type, soil physical properties, pavement geometry, pavement deterioration, etc.

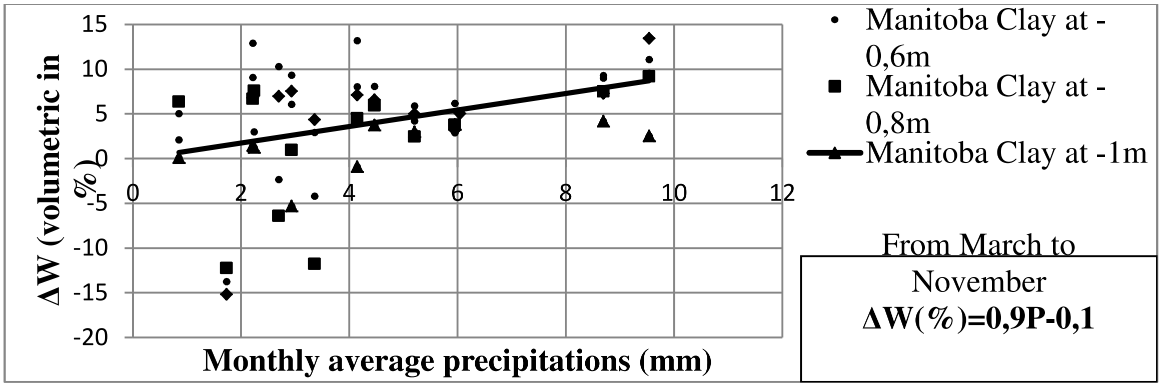

Figure 2. Established relationship between precipitations and Δw [5]

4. Mechanical performance tests

4.1. Triaxial resilient modulus

The resilient modulus tests were performed in accordance with AASHTO T307-99 using a triaxial cell and a hydraulic press. The samples were compacted in 6 layers, and their height and diameter was 300 and 150 mm. The test was performed at two water contents, the optimum and high water contents. For each moisture condition, 15 stress states were applied. The model used for data modelling is a combination of the MEPDG model for taking into account the effect of moisture on the resilient modulus and the Uzan model [6]. It is expressed

(2) $$Mr\left(MPa\right) = K_{1opt}\left(\frac{\theta}{Pa}\right)^{K_2 opt}\left(\frac{\sigma_d}{Pa}\right)^{K_{3opt}} 10^{k_s\left(w-w_{opt}\right)}$$

in which K_1, K_2, K_3 are regression parameters, σ_d is the deviatoric stress (kPa), θ is the total stress (kPa), Pa is the atmospheric pressure (kPa), w is the water content and w_{opt} is the optimal water content. Table 2 and Figure 3 summarize the resilient modulus results obtained during triaxial testing.

Table 2. Resilient modulus test results [5]

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

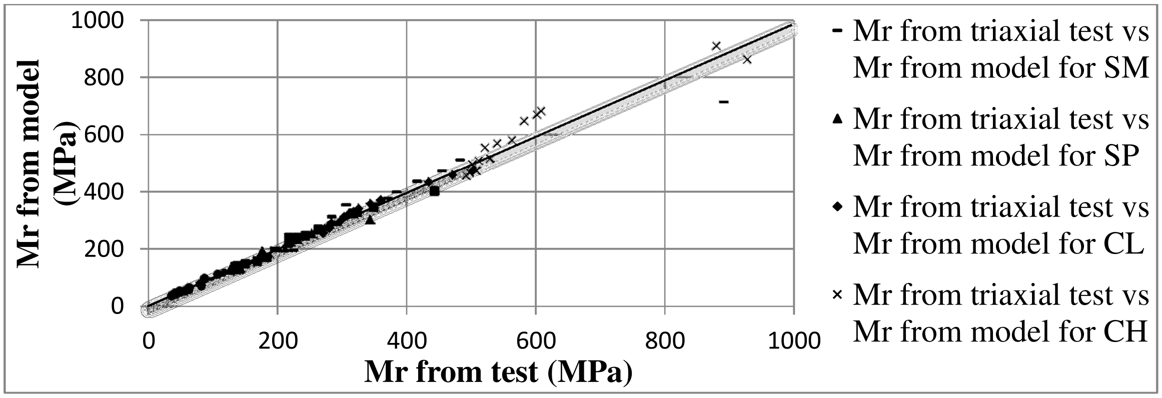

Figure 3. Predicted versus measured resilient modulus for the tested soils [5]

4.2. Triaxial permanent deformation

The permanent deformation tests are used to evaluate the long-term rutting behaviour of the considered subgrade soils. Two water contents were tested, the optimum and high water contents. The samples were compacted at optimum water content in five layers and had dimensions of 100 mm x 200 mm (diameter x height). The tests were performed using a multistage approach using a loading time of 200 ms and a rest period of 800 ms. Therefore the same sample was used for the two water contents. Each stage consisted in 50 000 load cycles at σ_d=20 kPa and σ_3=15 kPa and a given water content. Therefore, a total of 100 000 load cycles was applied to each sample, 50 000 for each water content tested. The stress level was selected using an analysis of typical flexible pavement structures using multilayer elastic software (WinJulea). Prior performing the second loading stage, the water content was increased near the saturated state. The experimental results were modeled using the Sweere [7] model, which is expressed

(3) $$\varepsilon_P = AN^B$$

in which A and B are regression parameters, N is the number of load cycles and ε_P is the permanent strain. According to the model, A represents the modeled permanent strain after one load cycle, and B represents the long term permanent strain rate. Figure 4 and Table 3 summarize the permanent deformation test results.

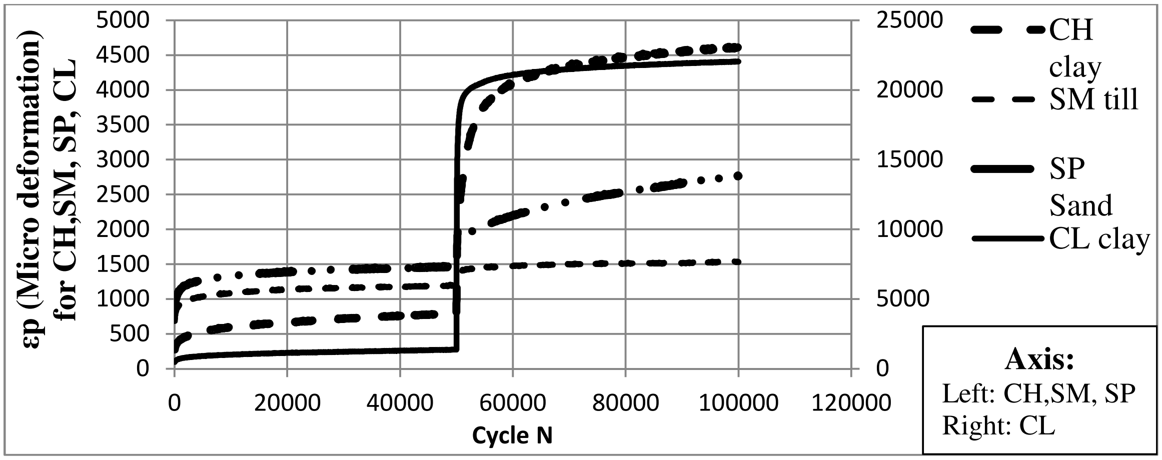

Figure 4. Triaxial permanent deformation test results for the two water contents [5]

Table 3. Model parameters obtained for the permanent deformation test results [5]

	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	99.2%	81.4%	99.6%	88.6%	98.4%	97.8%	97.8%	98.3%
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

4.3. Small-scale heavy vehicle simulator

The mechanical behaviour was also measured using a small-scale heavy vehicle simulator [8]. This test is used for validation of the triaxial permanent deformation tests and to measure the soils behaviour under wheel loading. This test was only performed on the SM and CL subgrade soils. The pavement samples were 1.8 x 0.6 x 0.6 m³ (Length x Width x Depth). The tested layered system consisted of 50 mm of asphalt concrete, 185 mm of subgrade soil, 185 mm of subbase and 140 mm of granular base. The tire pressure and the load applied on the tire were adjusted in order to approximately obtain a vertical stress in the same range than the triaxial tests. Winjulea simulations were used for this purpose, considering the tested layered system. As it was performed for the triaxial permanent deformation experiments, two water contents were tested using a multistage loading procedure with 50 000 for each stage. For the first 50000 load cycles, the samples were tested at the optimum conditions (compaction water content). The samples were then saturated by gravity. The water level was raised slightly over the subgrade top to simulate high water table conditions. Permanent deformation at the top of each layer was measured at cycle 0, 50, 100, 200, 350, 500, 1 000, 2 000, 3 500, 5 000, 10 000, 20 000, 30 000, 40 000 and 50000 for each environmental condition, using a system similar to multidepth deflectometer. The results were modeled using the model introduced in equation 3. Figure 5 and Table 4 summarize the obtained test results.

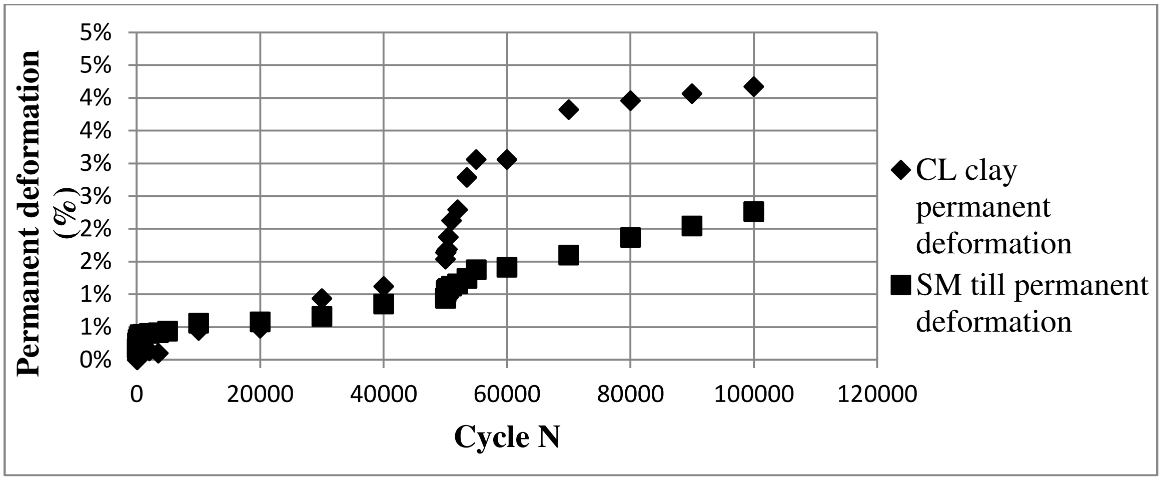

Figure 5. Permanent deformation of the subgrade soils measured with the small-scale heavy vehicle simulator [5]

Table 4. Model parameters obtained for the small-scale heavy vehicle simulator tests [5]

Soil type	CL Clay		SM	
Volumetric W (%)	Opt. 29.0%	Sat. 36.7%	Opt. 13.4%	Sat. 26.7%
R^2	92.0%	79.3%	92.3%	73.2%
A parameter	0.005	0.0014	0.1878	1.0074
B Parameter	0.5885	0.8352	0.1891	0.6069

5. Damage analysis

As an increase in precipitations is predicted for the next decades and as soils mechanical properties decrease with moisture content, a damage analysis was performed to determine the effect of the future increase of precipitations on pavement service life. The southern part of Quebec Province, which includes cities like Montreal and Quebec, might face monthly precipitations increase of 6% (90^{th} percentile) according to the prediction models. As, during the 1971-2000 period, the average monthly precipitation was 85.5 mm, this increase corresponds to 5.5 mm. Therefore, using equation1, the water content was calculated for precipitation values of 85.5 and 90.9 mm, which corresponds to an increase of 5% of the water content.

Using the obtained results from the laboratory tests, a damage analysis was performed with two different methods. The first method is used in combination with the resilient modulus tests, while the second is used in combination with the permanent deformation tests (triaxial and simulator). The damage parameter for the resilient modulus is the number of allowable load repetitions prior rutting failure N, or service life expressed in Equivalent Single Axle Loads (ESAL). The N value is determined with the Asphalt Institute damage law expressed

$$N(ESAL) = 10^6 \left(\frac{\varepsilon_Z}{482} \right)^{-4.48} \quad (4)$$

in which ε_Z is the vertical strain at the top of the subgrade. This strain was calculated for a standard pavement structure as presented in Table 5. This analysis was performed with multilayer elastic software (WinJulea) using typical properties. 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 20% from the reference period (1971-2000) to the future period (2010-2039), for the four studied soils (Figure 6).

Concerning the permanent deformation behaviour measured using the triaxial cell and the small-scale heavy vehicle simulator, it is already considered as a damage. Therefore, the permanent strain rate can be considered as the damage rate and it is treated as the damage parameter for the analysis. 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 from the triaxial test, an average increase of the B value of 8% from the reference period to the future period. For the small-scale heavy vehicle tests, an average increase of the B value of 7% from the reference period to the future period. Figure 6 summarizes the results of the analysis. It is observed that a decrease of the pavement service life is expected due to climate changes. Depending on the damage type considered, there are some variations, whether the resilient modulus or the permanent deformation tests are considered. The analysis based on N shows a decrease to 0.72 to 0.81 the actual N. Lower decreases of pavement service life are found when the permanent deformation is considered as the damage parameter. It is believed that the slight differences in the values obtained could come from several sources. Among 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.

Table 5. Typical pavement structure used for damage analysis [5]

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

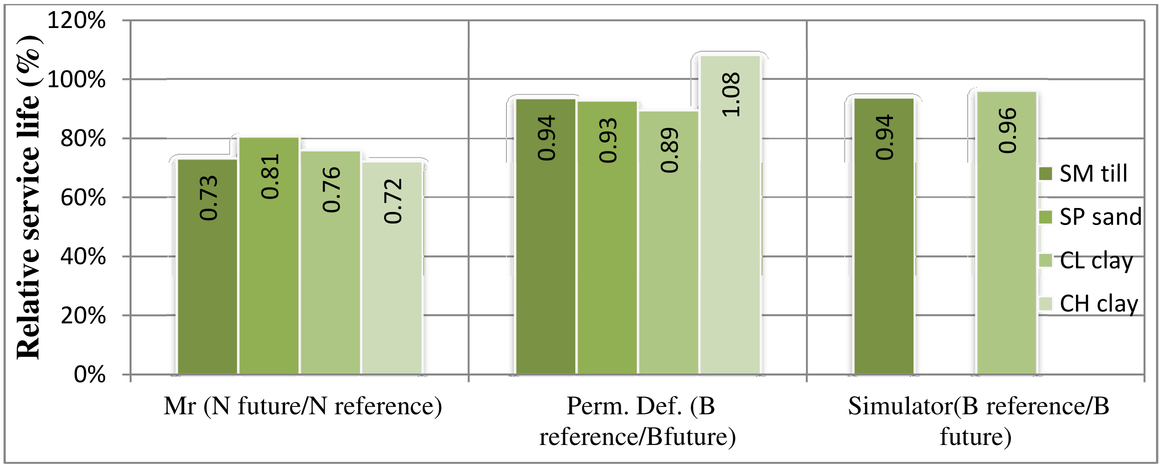

Figure 6. Comparison of the damage ratios for the three mechanical tests [5]

6. Conclusion

Climate changes may cause an increase of precipitation in the Province of Quebec over the next decades. As the performance of flexible pavement structures is closely related to moisture content of soils and aggregates, these structures can be considered vulnerable to climate changes. In order to quantify the effect of future precipitations increase on the pavement service life, this research project was based on a three steps approach: 1. Establishment of a relationship between precipitations and water content in the subgrade layers; 2. Establishment of the relationship between soils water content and soils mechanical properties, quantified with the resilient modulus and the permanent deformation behaviour; 3. Quantification of the effect of increased precipitations on pavement life, based on modification of their mechanical behaviour due to water content increase. For the example considered in this paper, it was found that the service life of pavement structures submitted to future climate may present a service life reaching 0.72 times the service of actual pavement structures. These results vary depending on the soil and damage types considered.

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