Analysis of Seasonal Bearing Capacity Correlated to Pavement Deterioration in Cold Region

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ABSTRACT: The *Laboratoire Central des Ponts et Chaussées* (France) and the *Ministère des Transports du Québec* (Canada) have developed a joint research project on the behaviour of pavements in a cold region. This project aims to increase understanding about fatigue damage of pavements under the combined effect of traffic and a decrease in bearing capacity during the thawing period. An experimental site was constructed in Quebec in 1998 and its behaviour was monitored for six years. Pavements with a cement-treated base and a hot-mix asphalt base were selected. Two test beds of each type were constructed. One of these two test beds was thermally insulated by a layer of extruded polystyrene, while the second was not, so that the researchers could distinguish between traffic and climate effects. This paper presents the analysis of the seasonal variation of bearing capacity related to deflection, subgrade modulus and tensile strain. Also, an analysis of the results describes the difference observed between the quasi-static and dynamic responses and the relationships between traffic loading and pavement performance.

KEY WORDS: thaw, deflection, modulus, strain, pavement.

1 INTRODUCTION

The behaviour of pavements and, in particular, their mechanical behaviour in thaw periods, has a major influence on pavement design (Doré and Savard 1998, Roy et al. 1997, Corté et al. 1995, Janoo and Berg 1990, White and Coree 1990). Given the progress of design methods and the absence of severe winters in France, the *Laboratoire Central des Ponts et Chaussées* (LCPC) and the *Ministère des Transports du Québec* (MTQ) undertook a cooperative project in 1998 with the objective of optimizing their pavement design method under frost-thaw conditions (Corté et al. 1999, Rioux et al. 1999). The two types of pavement most commonly used in France (hot-mix asphalt pavements and cement-treated bases) were selected.

For their pavement design, the LCPC and the MTQ use models to forecast the propagation of frost-thaw phenomena associated with the thermal characteristics of the paving materials and the soil and the climatic conditions (Boutonnet et al. 2003). The MTQ model also forecasts the swelling of soils. They also have fatigue damage models based on the mechanical properties of pavement layers and the subgrade and the traffic they will carry (Savard et al. 2004a and 2004b).

One of the project's objectives was the calibration of the damage models to the pavement deterioration observed on the experimental site. The pavement structures of the uninsulated test beds were designed for a three-year life cycle so that the calibration of fatigue cracking could be completed in a short time. This paper presents an analysis of the seasonal variation of bearing capacity based on deflections, subgrade moduli, tensile strains and the difference observed between quasi-static and dynamic loading.

2 DESCRIPTION OF THE SITE AND THE TEST BEDS

The experimental site was constructed on highway 155 in St-Célestin, Québec, Canada, located in the St. Lawrence River plain about 100 km northeast of Montréal. Highway 155 was chosen because of the site's homogeneity, the presence of frost-susceptible soils (silty sand resting on clay) and signs of pavement fatigue damage. It is subject to a harsh climate (thirty-year average freezing index around 1130°C days/year) and it supports heavy traffic (750 trucks per day per direction).

The air freezing index measured for the six winters of monitoring ranges from 659 to 1286°C*day (table 1). The frost period extends from 94 to 146 days and the frost depth range from 1050 to 1700 mm. The end of the thawing periods comes between 2 April and 6 May.

Table 1: Climate and frost depths observed at the experimental site

Winter	Beginning of frost period	Number of frost days	Beginning of thawing period	End of thawing period	Freezing index (°C-day)	Frost depth Test bed 1 (mm)	Frost depth Test bed 4 (mm)
1998-1999	8 December	99	17 March	6 April	666	1300	1170
1999-2000	17 December	94	20 March	4 April	796	1450	1350
2000-2001	21 November	129	30 March	26 April	1114	1540	1420
2001-2002	8 December	109	27 March	2 April	659	1120	1050
2002-2003	15 November	146	10 April	6 May	1286	1700	1620
2003-2004	30 November	116	20 mars	26 April	1128	1600	1520

The site includes four test beds (Figure 1). The base course for two of the test beds is composed of hot-mix asphalt (HMA), while the other two have a cement-treated base course (CTB). The four test beds have a HMA at the surface course. The base course is a fractured granular and the subbase a natural sandy gravel. The subgrade is composed of silty sand resting on natural clay. Two test beds were thermally insulated to dissociate the effects of traffic from those of the loss of bearing capacity during thawing. Test bed construction was subjected to rigorous controls (the constituents, manufacturing and application of paving materials). The paving materials and the soils were sampled before and after construction to determine the thermal and mechanical characteristics. Parallel laboratory tests were conducted at LCPC and MTQ (Savard et al. 2004b).

The four test beds were equipped with measuring instruments (thermistors, frost depth gauges, piezometers, TDR sensors). Multi-level sensors were added on Test Beds 1 and 4 and strain gauges on Test Bed 1. A dynamic weigh-in-motion (WIM) station and a weather station completed the site instrumentation. The measurements taken periodically at the site included manual mapping of distress, ruts and the longitudinal pseudo-profile.

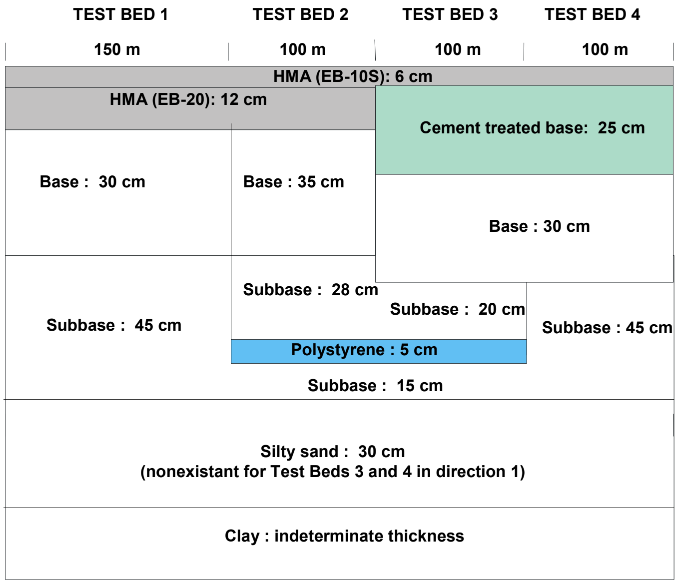


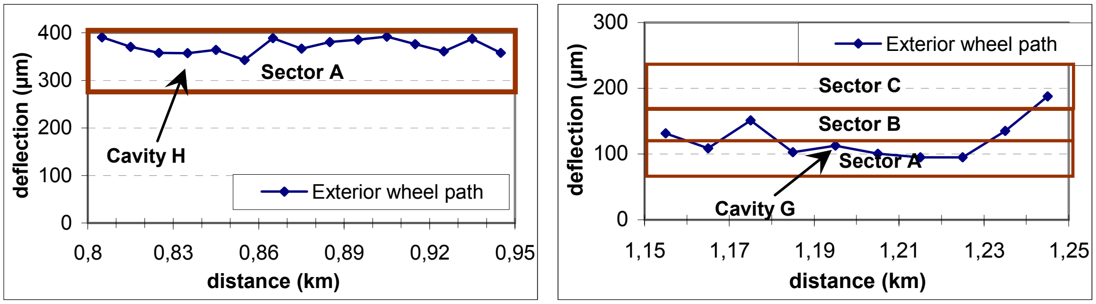
Figure 1: Composition of the test beds

3 SEASONAL VARIATION OF BEARING CAPACITY MEASURED ON TEST BEDS

The mechanical behaviour of test beds was evaluated by means of an inclinometer (LCPC) and a FWD (MTQ) at different times of the year. The inclinometer measures the surface deformation of a pavement under a moving load performed with a truck loaded at 81.6 kN (reference load) on the dual tire rear axle, and traveling at approximately 3 km/h (quasi-static load). This is the Benkelman test, combined with a continuous deformation recording system. The measurements recorded serve to calculate the maximum deflection by integration of the signal (derivation of deflection) and the radius of curvature of the deflection basin. The measurements are taken every 20 meters in the outer wheel paths. During each measurement, the temperatures at the surface and at depths of 5 and 15 cm were recorded.

The FWD test reproduces the dynamic stress due to the passage of a heavy vehicle. The pavement reaction is determined by measuring the deflection basin with nine geophones. The standard load used for pavement structural analysis corresponds to one half-axle of the reference load (40 kN) applied to a circular plate 300 mm in diameter. The FWD results presented in this article were obtained at 10 m intervals on the outer wheel paths. The temperature was recorded at the surface and at depth of 12 cm for test section 1 (2/3 of the thickness of HMA) and 5 cm for test section 4.

The test beds were divided into homogeneous sectors according to deflection level and appearance of surface fatigue cracking (Savard et al. 2004b). This article presents the results for Test Bed 1 (HMA) in direction 2 and for Test Bed 4 (CTB) in direction 1 (sector A). The FWD results correspond to the average deflection basin in the homogeneous sector, while the inclinometer results are for a specific point (cavities H and G) in the corresponding homogeneous sectors (Figure 2).



a) Test Bed 1 (HMA), Direction 2 b) Test Bed 4 (CTB), Direction 1

Figure 2: Division of test beds into equivalent mechanical behaviour sectors

3.1 Deflections

The deflections measured by FWD testing during the six-year monitoring of the mechanical behaviour of Test Bed 1 (HMA) are given in Figure 3. Seasonal variations were similar from one year to the next, but the amplitude depended on the climatic conditions observed for each year (Table 1). The results for the first year of monitoring have been used to analyze seasonal variations in detail.

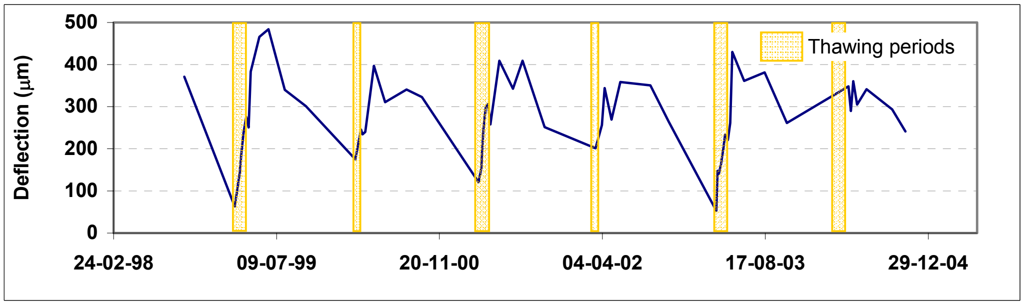
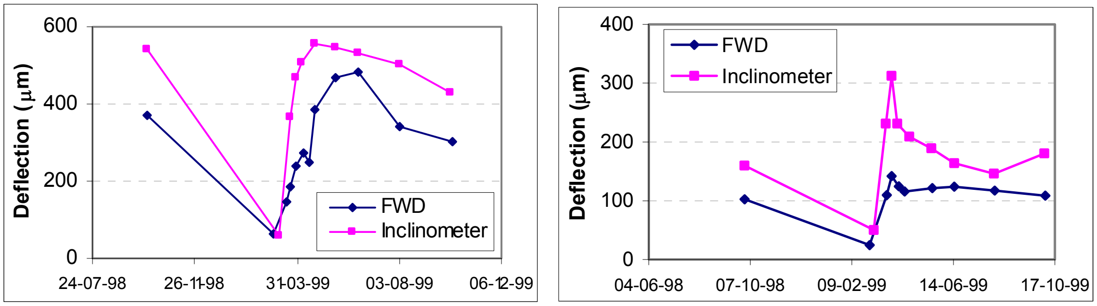


Figure 3: Seasonal deflections measured on test bed 1 (HMA) from 1998 to 2004 (six years).

Figure 4 gives the deflections measured on Test Beds 1 and 4 by inclinometer and FWD testing in the first year of monitoring. Deflection is at its lowest in the winter when the pavement layers and the subgrade are frozen. It increases during the thawing period and summer, and then decreases again as the following winter approaches. Deflection is directly related to the temperature of stabilized materials with hydrocarbon binders and to the condition of unbound granular materials and the subgrade modulus (frozen, non-frozen).

Deflection measured by the inclinometer is about 1.5 times higher than the deflection measured by FWD outside the thawing period and 2.0 times higher than FWD during the thawing period. This indicates greater deformation of granular materials and the subgrade under a quasi-static load during the thawing period. During this period, the water content of the granular materials and the subgrade is greater as a result of surface infiltrations by melting snow and by melting ice lenses in the frost susceptible subgrade. The longer load time in the quasi-static test allows greater dissipation of interstitial pressure compare to the dynamic test. Thus, the deflections measured for a quasi-static load (Benkelman, inclinometer) are more severe than those measured for a dynamic load (FWD, real traffic).

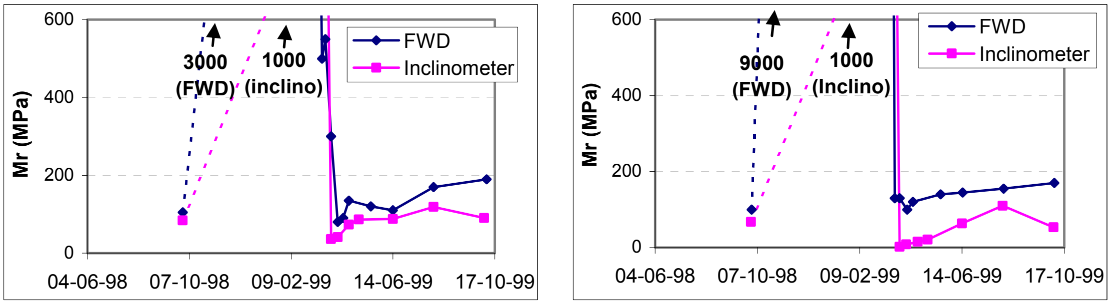


a) Test Bed 1 (HMA), Direction 2 b) Test Bed 4 (CTB), Direction 1, Sector A

Figure 4: Seasonal deflection variations (1998-1999)

3.2 Subgrade Modulus

The methods used by the LCPC and the MTQ to back-calculate the subgrade moduli from deflection testing are described in detail by Mauduit et al. (2005). Figure 5 presents the subgrade moduli variations found by inclinometer and FWD testing. In the case of the inclinometer, the subgrade modulus represents whole layers affected by the freeze-thaw cycle under the granular base (sand, silty sand and clay), whereas for FWD testing, it's only the clay layer affected by the freeze-thaw cycle. Moduli back-calculated using the inclinometer test (quasi-static) were lower than those back-calculated using FWD testing (dynamic). This is true even if the subgrade moduli back-calculated by the inclinometer included, in addition to the clay layer affected by freeze-thaw cycle, the sand layer that is minimally affected by seasonal variations and the silty sand layer that presents a higher modulus than the clay layer. On the other hand, the subgrade moduli back-calculated by FWD show similar values for clay despite the fact that the state of stress is different between the two types of pavement (HMA and CTB). In fact, the subgrade of Test bed 4 is at a lower strength since an excavation was performed deeper during construction following subgrade instability (the FWD measures on the hold pavement before the construction of the tests beds showed very low subgrade moduli in this sector). The high modulus of the CTB from Test Bed 4 creates lower deflections (Figure 4) and thus presents less stresses in the lower layers. This explains that the moduli beneath the CTB layer (Test Bed 4) are the same magnitude than beneath the HMA layer (Test Bed 1) because the state of stress increases the in-situ modulus of this low consistence of clay layer.



a) Test Bed 1 (HMA), Direction 2 b) Test Bed 4 (CTB), Direction 1, Sector A

Figure 5: Seasonal variations of the subgrade modulus (1998-1999)

The subgrade moduli are 10 to 90 times higher in winter than in summer. During the thawing period, they decrease and increase until the next freezing period. We note that the inclinometer shows greater modulus variations in thawing periods than FWD does, for the same reasons previously put forward to explain deflections. The reduction in the modulus during the thawing period is less pronounced under a semi-rigid pavement (Test Bed 4) than under a flexible pavement (Test Bed 1), at least as shown by dynamic testing (FWD).

Figure 6 presents the annual evolution of the subgrade modulus in Test Bed 1 (HMA) back-calculated by FWD testing. The modulus have presented a diminution since 2002 that it could reflect micro-damage of the HMA layer due to fatigue. The decrease of subgrade modulus can't be linked to an increase of HMA modulus by oxidation because the relation stays linear with the temperature for the six years monitored (figure 7). The monitoring of this test bed will continue in order to verify this hypothesis.

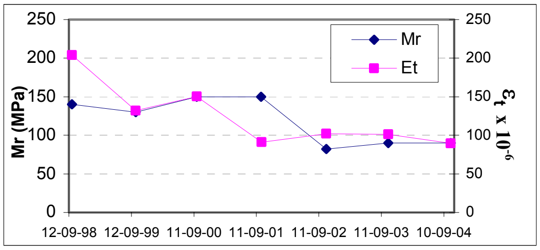


Figure 6: Annual evolution of the subgrade modulus and the tensile strain of test bed 1 (HMA), direction 2

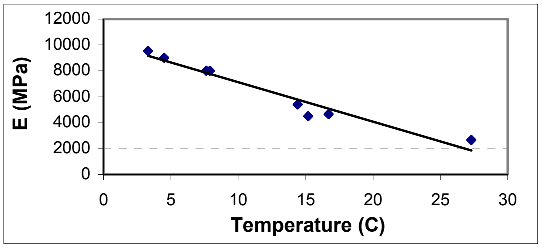


Figure 7: Relation between HMA modulus and temperature (same date that figure 6)

3.3 Tensile Strain

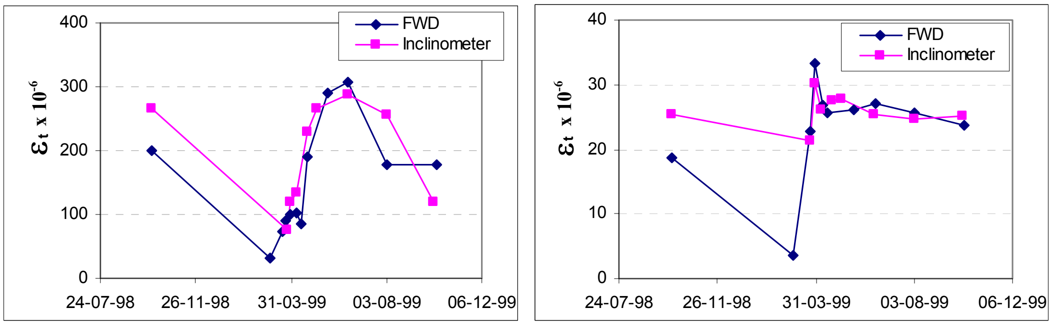
The methods used by the LCPC and the MTQ to calculate horizontal tensile strains (ε_T) at the base of bound layers using deflection testing has been described in detail by Mauduit et al. (2005). Figure 8 presents the seasonal variation in tensile strain at the base of the HMA layer (Figure 8a) and at the base of the CTB layer (Figure 8b), using inclinometer and FWD testing.

The horizontal tensile strains calculated by the inclinometer are about 20% higher than those calculated by FWD. This result is observed despite the fact that the load geometry with the dual tire of the inclinometer test produces lower tensile strains than the circular plate does with FWD at the same load. The longer loading time for inclinometer testing has a compensatory effect which creates greater deflections (Figure 4) corresponding to higher horizontal tensile strains.

Test Bed 4 showed lower tensile strain than did Test Bed 1 because the CTB modulus is very high. Very low tensile strains in winter correspond to the low deflection level (Figure 4). In the case of Test Bed 1 (HMA), an increase in tensile strain was seen during the thawing periods (Figure 8a), but it remained below the value measured in the fall, whereas higher values were seen at the end of spring and in summer, when temperatures are higher. In the case of Test Bed 4 (CTB), tensile strains were higher during the thawing period (Figure 7b), compared to other times of the year outside the freeze-thaw cycle.

Figure 8 illustrates the different behaviours of Test Bed 1 (HMA) and Test Bed 4 (CTB). Test Bed 1 (HMA) shows lower tensile strains in the thawing period than in warmer periods, despite a reduction in the subgrade modulus. In fact, the lowest temperatures during the thawing period bring higher moduli for the HMA layer and the associated lower tensile strains. On the other hand, even if tensile strains are lower during the thawing period, the HMA layer is more vulnerable to damage because the low-temperature fatigue curve permits less deformation than at a higher temperature (Savard et al., 2006). The CTB modulus in Test

Bed 4 did not vary with the temperature. But its higher value gave it less flexural strength. This is seen in the increased tensile strain in the thawing period, which is the period during which the CTB layer is most susceptible to fatigue damage.



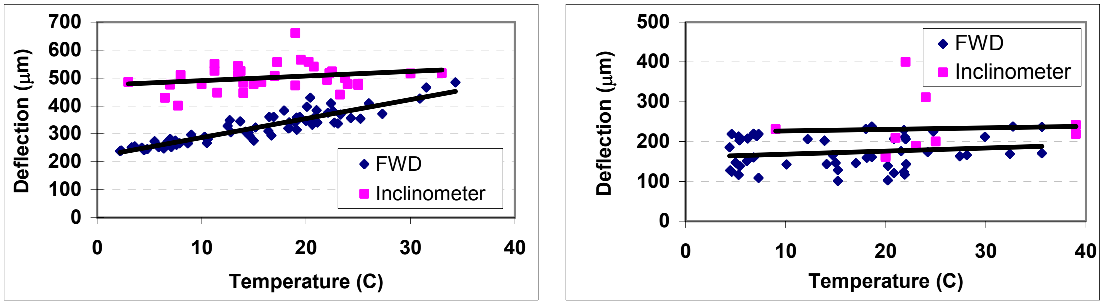
a) Test Bed 1 (HMA), Direction 2 b) Test Bed 4 (CTB), Direction 1, Sector A

Figure 8: Seasonal horizontal tensile strains variations at the base of bound layers (1998-1999)

Figure 6 presents the annual evolution of tensile strain at the base of the bound layer in Test Bed 1 (HMA), back-calculated on the basis of FWD testing. Tensile strain diminished over time to reach a plateau since 2001. For the same reason as for subgrade modulus, this reduction in tensile strain could be due to micro-damage of the HMA layer by fatigue.

4 ANALYSIS OF QUASI-STATIC AND DYNAMIC RESPONSES

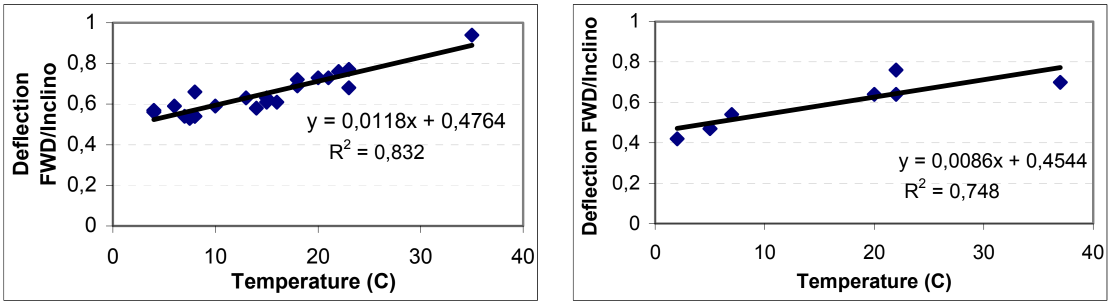
Figure 9 correlates deflection measured by FWD and deflection measured by the inclinometer according to temperature. The deflections measured by the inclinometer are higher than those measured by FWD. The lower loading frequency (2 Hz) for the inclinometer (longer loading time) than for the FWD (25 Hz) is the reason for the different results. The asphalt modulus diminishes with loading frequency, which creates more stresses in the pavement's underlying layers and the subgrade. This then leads to increased pavement deformations. The steeper slope for FWD testing (Figure 9a) is linked to the greater influence of the visco-elastic reaction of the HMA layer to higher load frequency, compared to inclinometer testing. This is confirmed by the almost zero slope obtained for inclinometer testing (Figure 9b), seeing that the effect of the surface HMA layer is reduced by the presence of the CTB, the modulus of which is unaffected by temperature variations.



a) Test Bed 1 (HMA) b) Test Bed 4 (CTB)

Figure 9: Relation between deflection and temperature

Figure 10 presents the ratio between FWD-measured deflection and inclinometer-measured deflection. The values in this correlation are lower than the unit. This is due to the visco-elastic reaction of the pavement under a short-period dynamic load (i.e., FWD test or truck travelling at high speed), compared to the quasi-static load for inclinometer testing (truck travelling at very low speed). Elliot and Thompson (1985) used a deflection ratio of 0.62 to convert deflection measured by the Benkelman test to that of a heavy vehicle travelling at high speed in deflection studies on flexible pavements based on speed at the AASHO Road Test in Illinois (AASHO 1962). The results of the present study show that the deflection ratio varies with temperature. On flexible pavements, the ratio increases from 0.55 to 0.95 for temperatures between 5°C and 35°C, whereas for pavements with a cement-treated bed covered with asphalt, the ratio increases from 0.42 to 0.75 for temperatures between 2°C and 35°C. The deflection ratio approaches the unit at higher temperatures because the influence of the loading frequency diminishes with the decreasing of the HMA modulus in relation with the increase of temperature.



a) Test Bed 1 (HMA)

b) Test Bed 4 (CTB)

Figure 10: Ratio between FWD/Inclinometer deflection

5 CONCLUSIONS

The experimental site at St-Célestin, Québec provides a wealth of information on pavements behaviour in cold climate. This study has dealt with the aspect of seasonal behavioural variations in terms of load responses (deflection, subgrade modulus, and tensile strain) and the type of loading (quasi-static vs. dynamic). Several interesting points have emerged from this study:

- Deflections measured by quasi-static testing (Benkelman, inclinometer) are more severe than under a dynamic load (FWD, real traffic), and more so during the thawing period.
- Quasi-static testing shows lower subgrade moduli than does dynamic testing and more pronounced amplitude of variations during the thawing period.
- The diminution of the subgrade modulus is less pronounced during the thawing period for Test Bed 4 (CTB) than for Test Bed 1 (HMA).
- Tensile strains measured by inclinometer testing at the base of bound layers are approximately 20% higher than measured by FWD testing.
- The HMA layer shows lower tensile strains during the thawing period than in warmer periods despite a diminution in the subgrade modulus.
- The CTB layer shows higher tensile strains during the thawing period.

The inclinometer-testing frequency (2 Hz) corresponding to a longer load time than that of FWD (25 Hz) is the source of the different results observed. The load frequency influences the modulus for the HMA layer (visco-elastic material) and the dissipation of interstitial pressure acts on the granular layers and the subgrade modulus.

Pavements are more susceptible to fatigue damage during the thawing period. The HMA layer in flexible pavements is susceptible to fatigue cracking during the thawing period, despite lower tensile strain at the base of the layer, because it is less able to resist to cyclic deformations before rupturing than it is during higher temperatures (fatigue resistance related to temperature). Tensile strain in semi-rigid pavements is at its highest level during the thawing period, which indicates a greater vulnerability of CTB under flexural loading.

The methods for evaluating the behaviour of pavements under loads (quasi-static vs. dynamic) to predict fatigue damage must take into consideration the load frequency and the load geometry to account for damage under real traffic. The next work in this collaborative MTQ-LCPC project will involve calculating the damage to the test beds.

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