Comparison between France and Quebec backanalysis methods of deflection measurements

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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 behavior of roadways during severe frost conditions. This project aims to increase understanding about fatigue damage and their diminished load-bearing capacity under the combined effect of traffic and frost-thaw cycles.

An experimental pavement was built in Quebec in 1998 and its behavior 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 each two test beds was thermally insulated by a layer of extruded polystyrene, to distinguish traffic and climate effects.

This paper compares France and Quebec backanalysis methods of deflection measurements of the two uninsulated test beds. It describes :

- the experimental site (pavement structures, weather conditions and surveys),
- the surface deformability measurements with a Benkelman test truck (inclinometer) for the LCPC and FWD for the MTQ
- the determination of moduli values by backanalysis of deflection measurements on test beds 1 and 4, and the differences and the difficulties met with French and Quebec methods.

KEY WORDS : Thaw, pavement, deflection measurements, back-calculated moduli.

1 INTRODUCTION

The Laboratoire Central des Ponts et Chaussées (LCPC, France) and the Ministère des Transports du Québec (MTQ, Canada) have developed a joint research project on the behavior of roadways during severe freezing conditions. This project aims to increase the understanding of fatigue damage to roadways and their reduced load-bearing capacity under the combined effects of traffic and frost-thaw cycles.

One of the project’s objectives was the calibration of both French and Quebec damage models, with observation of deterioration on two types of pavements most commonly used in France (cement-treated bases and hot mix asphalt pavements). To do so, a backanalysis of deflection measurements has been carried out, for each approach, to evaluate the layers’ moduli during the different periods of the year, and in particular the variation of the bearing capacity of the unbound layers and subgrade during the thaw period

The project was centred on the analysis of four experimental pavement tests sections. The observation of these sections is continuous since their construction in 1998, and includes in particular a large number of deflection measurements, at different periods of the year. After a short description of laboratory tests, measurements and observations done on the site, backanalysis methods of deflection measurements are presented and discussed. Finally, layers' moduli obtained by back-calculations for both approaches are commented on.

2 DESCRIPTION OF THE SITE

The experimental site was constructed on National Route 155 in St-Célestin in the St. Lawrence River plain, about 100 km Northeast of Montreal (Canada). The site was chosen for its 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 supports heavy traffic (750 trucks/day/direction). Preliminary studies were performed to characterize the bearing capacity of the subgrade soil, its frost susceptibility, the drainage conditions and the forecast traffic intensity.

2.1 Test beds and climate

The site included four test beds. The base course is composed of hot mix asphalt (HMA) for two of them and cement-treated base (CTB) for the other two (Figure 1). Two test beds were thermally insulated to avoid penetration of frost into the subgrade and thus dissociate the effects of traffic from those of the loss of bearing capacity during the thaw period. Test bed construction was subjected to rigorous controls of the constituents, manufacturing and application of paving materials. The paving materials and the soils were sampled before and after construction to determine their thermal and mechanical characteristics. Parallel laboratory tests were conducted at the LCPC and the MTQ.

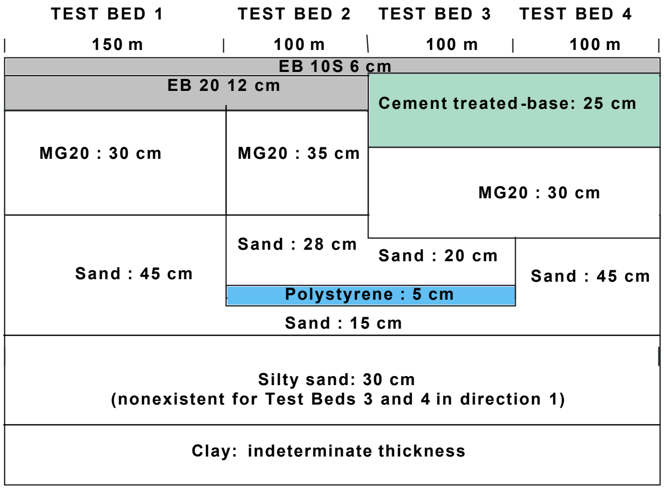

Figure 1 : Composition of the Test Beds

The monthly average air temperatures measured, since the building of the project, ranged between 15 and 20°C in summer, from 7 to 2°C in the pre-winter period, from –2 to -15°C in the winter period, around –3°C during the thaw and from 5 to 15°C during the bearing capacity restoration period. The air frost indexes measured range from 659 and 1286°C.day and the frost depth reached a maximum of 1.7 m.

2.2 Monitoring techniques used

All test beds were instrumented with thermistors, frost depth gauges, piezometers, TDR sensors. Multi-level sensors were added on Test Beds 1 and 4 and deformation gauges on Test Bed 1. A dynamic weighing station and a weather station completed the site instrumentation. Measurements of rut depths, longitudinal profile and manual mapping of distress were performed periodically on the site.

Pavement deflection measurements were performed at different times of the year using two techniques : Falling Weight Deflectometer (FWD) and, inclinometer respectively. The mechanical behaviour of the pavement sections was evaluated both by the MTQ, using the FWD measurements and by LCPC, using the

Distress analyses, performed on the four test beds have led to the following observations :

- the bituminous pavements presented no significant deterioration after 6 years of traffic.
- the cement-treated base test sections presented both transverse cracks, corresponding to thermal shrinkage and longitudinal fatigue cracks. Thermal cracks developed on both cement-treated sections. Fatigue cracks developed essentially on the uninsulated section; they appeared after only one year of traffic in direction 2, which corresponded to the busiest traffic lane, and after two years in direction 1 (Boutonnet et al. 2004)

2.3 Laboratory tests

Table 1 summarizes results of laboratory tests performed at LCPC on samples taken from the site. More details on the laboratory tests can be found in Savard et al., [2004].

Table 1 : Main characteristics of the pavement materials (LCPC tests).

Layers		
Cement treated -base	RT (MPa) 150days1.24	E (MPa)150days 29000
Hot Mix Asphalt	E (MPa)	e$_6$ (µ/m)
	(15 C, 10 Hz)	(10 C, 25 Hz)
EB-10S	4066	-
EB-20 (top)	4890	-
EB-20 (bottom)	4000	135
Granular material MG-20	M$_r$ (MPa) - K- q Model	
	13081 $q^{0.58}$ (w= 5.3%, gd=2215 kg/m^3)	

3 BACKANALYSIS METHODS OF DEFLECTION MEASUREMENTS

3.1 French method

3.1.1 Inclinometer measurements (LCPC)

Measurements of the surface deflections of the pavements were performed with a heavy vehicle, with a dual wheel rear axle loaded at 81,6 kN (reference load) travelling at approximately 3 km/h. The inclinometer measures the derivative of the deflection (the maximum deflection is calculated by integration of the measured signal) and the radius of curvature of the deflection basin. It is similar to a Benkelman test, combined with a continuous deformation recording system. The measurements were 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.

Inclinometer measurements were performed according to the following schedule: once during the frost period, once a week during the thaw period, three times during the recovery period and twice in summer/autumn.

3.1.2 Back-analysis method

The deflections and radii of curvature measured with the inclinometer on each uninsulated test section at two reference test points (point H, direction 2 for section 1 and point G, direction 1 for section 4) were used to backcalculate the moduli of the different pavement layers, using the approach described below :

First, cores made at each reference point were used to determine accurately the thickness of the pavement layers. In addition, observations from frost indicators allowed to determine, at each date of measurement, the thickness of frozen and thawed materials (examples of stratigraphy and freeze/thaw information are presented in Table 2).

Table 2 : Examples of stratigraphy considered for backanalysis on the 24th of march 1999

Test bed 1, cavity H

Materials		thickness (mm)	
hot mix asphalt materials	EB10	62	thawed
	EB20b	51	thawed
	EB20c	62	thawed
unbound granular material	MG20	300	thawed
subgrade : sand, silty sand and clay	soil	115	thawed
	soil	680	frozen
	soil	30	thawed
	soil	3175	unfrozen
	rigid bedrock		

Test bed 4, cavity G

Materials		thickness (mm)	
hot mix asphalt materials	EB10	68	thawed
cement treated base	GC20	227	thawed
unbound granular material	MG20	260	thawed
	MG20	140	frozen
subgrade : sand, silty sand and clay	soil	435	frozen
	soil	40	thawed
	soil	3525	unfrozen
	rigid bedrock		

Then, the deflections obtained were modelled with the software ALIZE (Multi-layer linear elastic analysis). In these calculations, the moduli of the asphalt layers, unbound granular layers and cement-treated base materials were estimated from laboratory test results (using appropriate models as explained below), and only the modulus of the subgrade was adjusted to fit the experimental measurements. This was done because each inclinometer test gives only two experimental values, the deflection and the radius of curvature, with which it is not possible to backcalculate the moduli of all the pavement layers (as is done with FWD tests).

The elastic moduli of the asphalt materials were estimated from laboratory complex modulus tests. The results of these tests were fitted using the Huet-Sayegh viscoelastic model (Huet,1962, Heck, 1998) and then, the model was used to calculate the values of elastic moduli corresponding to the inclinometer test conditions (frequency of 2 Hz, and temperatures interpolated at the middle of each asphalt layer (EB10, EB20b, EB20c)).

For the unbound granular material (MG20), an iterative procedure was used to take into account its non linear behaviour. The granular layer was subdivided in two sub-layers, and the resilient modulus of each sub-layer was adjusted according to the stress level (at the middle of the layer, under the centre of the load), using the K-Theta model. The elastic modulus of the cement-treated base material was determined from laboratory tensile strength tests.

Finally, the subgrade was divided in two parts : the upper part, subjected to freeze-thaw cycles (consisting of the sand, silty sand and upper part of clay), and the deep clay, not affected by frost. The modulus of the upper part of the subgrade was adjusted to fit the measured deflections. The elastic modulus of the deep clay was assumed constant. For test bed 1, it was taken equal to 30 MPa (value estimated by FWD tests). For test bed 4, this value of 30 MPa did not allow to fit the deflection measurement and it was increased to 65 MPa (this higher value can probably be explained by the non linear behaviour of the clay, since the stresses transmitted by the stiff cement treated layer are lower than on the asphalt pavement). In addition, during the frost period, the elastic modulus of the frozen unbound granular materials was assumed equal to 1000 MPa. Lastly, the depth to the rigid bedrock was assumed equal to 4 m on both sections.

3.1.3 Analysis of the results

- Hot mix- asphalt test beds

To illustrate the back-calculation procedure, examples of results obtained on section 1 (point H) are presented in table 3, for different periods of the year 1998-1999. Pavement temperatures during the tests vary between 0 and 35° C, leading to large variations of moduli of the asphalt layers. The moduli of the granular layers are relatively low, varying between 100 and 240 MPa. They tend to increase when the stiffness of the bituminous materials decreases, due to non linear behaviour (the moduli increase when the stresses transmitted to the granular layers increase). The modulus of the upper part of the subgrade ($E_{subgrade}$ in table 3) presents important seasonal variations : it decreases considerably during the thaw period, and then increases again during the spring (recovery period), and reaches its maximum values during summer (here around 90 MPa).

Table 3 : Example of backalculated moduli for structure 1.

DATE	period	measured deflection	T_{HMA}	E_{EB10s}	$E_{EB20\,b}$	$E_{EB20\,c}$	E_{MG20} upper	E_{MG20} lower	$E_{subgrade}$	$E_{subgrade}$ (frozen)	Eclay	εt
		µm	°C	MPa	MPa	MPa	MPa	MPa	MPa	MPa	MPa	µm/m
29/09/1998	Zero point	505	21	873	1061	987	174	142	84		30	267
25/03/1999	Partial thaw	302	0	10029	11872	11291	102	103	14	1000	30	75
07/04/1999	Complete thaw	490	8	5262	6230	5098	113	106	41		30	135
21/04/1999	recovery	519	18	723	1234	1792	168	138	73		30	229
14/06/1999	Summer/autumn	516	35	135 (1)	143 (1)	175 (1)	238	171	127		30	267
				700 (2)	700 (2)	700 (2)	182	146	88		30	242
04/10/1999	Summer/autumn	374	6	5864	7982	6294	118	113	90		30	109

T_{HMA} : interpolated temperature in the hot mix asphalt materials, at a depth of 12 cm

(1) elastic moduli of hot mix asphalt materials determined from laboratory tests

(2) elastic moduli of hot mix asphalt materials leading to the best fit of the radius of curvature

Some difficulties were encountered with this backcalculation procedure for the inclinometer measurements made at high temperatures (above 30°C). For such temperatures, the Huet Sayegh model gave very low values of elastic modulus for the bituminous materials (less than 300 MPa), and it was not possible to match the measured values of radius of curvature. Therefore, for these high temperatures, the moduli of the hot mix asphalt layers were increased, in order to improve the fit. In table 3, the two solutions are presented (see results obtained on 14/06/1999) ; the second solution, matching better the experimental results, was finally retained.

As can be seen in table 3, the backcalculation procedure allows to evaluate the seasonal variations of the bearing capacity of the upper part of the subgrade, subjected to freeze-thaw cycles. These seasonal variations are analysed in detail in Savard et al. (2005).

- Cement-treated base test beds

Results of back-analysis obtained on section 4 (point G) until June 2000 are presented in Table 4. The pavement temperatures vary (for the same dates as in section 1) between 8 and 20°C, which leads to smaller variations of moduli of the asphalt layer in relation to section 1. The moduli of the granular layers are somewhat lower than on section 1 (between 80 and 110

MPa), probably due to non linear behaviour. The subgrade moduli presents similar variations as at point H, with an important decrease during the thaw periods (down to 5-10 MPa) and a progressive recovery during the spring and summer (up to about 60 MPa).

For the first partial thaw period (25/03/99), were both part of the MG20 and of the subgrade are frozen, the backanalysis method does not allow to fit a realistic subgrade modulus, probably because the assumed modulus of the frozen materials (1000 MPa) is not correct.

During the spring and summer 2000, it became impossible to fit the measurements with a cement-treated layer modulus of 24980 MPa (corresponding to a sound, undamaged material). So the modulus of the cement-treated layer was decreased. A reasonable fit was obtained with a modulus of 11500 MPa on the 23/03/2000 and 5800 MPa on the 7/06/2000 (see table 4), indicating that the cement treated layer was largely damaged after these two years. This agreed well with the fatigue cracking observed on the pavement surface in the summer 2000

Table 4 : Example of backalculated moduli for structure 4.

DATE	period	measured deflection	T_{HMA}	E_{EB10s}	E_{GC}	E_{MG20} upper	E_{MG20} lower	$E_{subgrade}$	$E_{subgrade}$ (frozen)	Eclay	εt
		µm	°C	MPa	MPa	MPa	MPa	MPa	MPa	MPa	µm/m
29/09/1998	Zero point	154	20	1082	24980	83	98	67		65	25
25/03/1999	Partial thaw	207	10	4112	24980	105	1000	0,2(1)	1000	65	21
07/04/1999	Complete thaw	222	8	4852	24980	82	97	8		65	26
21/04/1999	recovery	202	20	1094	24980	84	99	15		65	28
14/06/1999	Summer/autumn	156	19	1125	24980	88	101	63		65	25
04/10/1999	Summer/autumn	159	16	1717	24980	88	101	53		65	25
23/03/2000	Partial thaw	208	12	3117	11500	95	105	5	1000	65	42
07/06/2000	Summer/autumn	235	17	1633	5800	106	111	63		65	69

T_{HMA} : interpolated temperature in the middle of hot mix asphalt materials (3 cm)
(1) Unrealistic modulus, due to the presence of frozen materials

3.2 Quebec method

3.2.1 FWD measurements (MTQ)

The analyses performed by the MTQ were based on FWD measurements. The principle of the test consists in applying a load similar to the passing of a heavy vehicle, and measuring the corresponding deflection of the pavement using nine geophones. The first geophone is located in a hole in the middle of the loading plate, and the others under the trailer, at different distances from the load (up to 2.25 m). The dynamic loading, measured using a load cell, can be varied between 7 and 125 kN. The standard load generally used for pavement analysis is 40 kN (9000 lbs), which corresponds to one half of the reference axle load, and this was the load value applied in this study. With this load, the duration of the load signal is typically 25 to 30 milliseconds, which simulates a vehicle speed of about 65 to 80 km/h.

On the experimental pavements, FWD tests were performed every 10 m, in the outer wheel paths, and at the same dates as the inclinometer tests.

3.2.2 Back-analysis method

The back-calculations of moduli were performed on average deflection basins obtained for each test section, divided in homogeneous sub-sections when large variations of deflection were observed on one section (Savard et al., 2004). Before starting the effective back-calculations, the apparent depth to the bedrock was estimated using the program MODCOMP based on multi-layer linear elastic theory. For that purpose, a first back-calculation was performed for each test section, to determine approximately the level of modulus of each layer. These values and the thicknesses of the layers were then used as input for the program, to determine the apparent depth to the bedrock. For sections 1 and 2, this depth was estimated at 3.7 and 3.75 m respectively. For test sections 3 and 4, the apparent bedrock depth was estimated at 7.62 m, which is the maximum possible value with this program. In fact the program had difficulties to find the apparent depth of bedrock because the deformations under these sections were too small.

Once the depth to the bedrock known, the program RoadBC was used for the back-calculations. This program is also based on multi-layer linear elastic theory. It allows to determine the moduli of the several pavement layers, knowing the surface deflections, and the layer thicknesses. After entering the deflections, the thicknesses and the Poisson ratios of the layers, the moduli of the layers are adjusted to match the measured deflections. It is assumed a best fit when the root mean square error (RMS) for each geophone is lower than 2%. In this study, the pavement structure and the layer thicknesses were modified depending on the depths of frozen or thawed materials (as in table 2). Thus, during the freeze-thaw period, more pavement layers were considered than during the frost-free conditions.

In the back-calculations, initial values of modulus of the asphalt layers were determined using the modulus versus temperature relationship determined from laboratory tests; however, these values were then adjusted, to match the measured deflection basin.

3.2.3 Analysis of the results

Results of the back-calculations performed by MTQ for sections 1 and 4, for the period 1998 – 2000 are presented in tables 5 and 6.

- Hot mix- asphalt test beds

The back-calculations lead to realistic variations of asphalt modulus with temperature. The unbound materials (MG 20, MG112 et silty sand) present similar moduli (100 to 185 MPa) with only low seasonal variations. Finally, the modulus of the upper part of the clay, subject to freezing and thawing, varies largely, and decreases, in particular, significantly during the thaw period.

Table 5 : Example of backalculated moduli for structure 1 (direction south).

DATE	period	Measured deflection	T_{HMA}	E_{HMA}	E_{MG20}	E_{MG112}	$E_{subgrade}$ (silty sand)	E_{clay} (FROZEN)	E_{clay} (clay touch by frost)	E clay	εt
		µm	°C	MPa	MPa	MPa	MPa	MPa	MPa	MPa	µm/m
29/09/1998	Zero point	372	27	2675	144	140	150	-	105	35	206
23/03/1999	Partial thaw	187	7	8250	115	125/1500*	1000*	550	20	35	91
07/04/1999	Complete thaw	276	8	7800	125	135	155	-	80	35	103
21/04/1999	Recovery	384	18	3300	109	125	160	-	135	32	194
14/06/1999	Summer/autumn	485	34	1210	146	142	147	-	110	30	321
07/10/1999	Summer/autumn	302	14	5800	125	100	185	-	190	35	129

*Frozen layers

- Cement-treated base test beds

The FWD back-calculations lead to a progressive decrease of the modulus of the cement – treated layer, from 27000 MPa at point zero to 17000 MPa after the first thaw period, and 6000 MPa after the second thaw period, confirming the deterioration of this layer.

For the unbound materials (MG 20, MG112 and silty sand), their moduli present again, low seasonal variations, and are slightly higher than on structure 1. The modulus of the subgrade appears affected by the freeze/thaw cycles, but less than on structure 1.

Finally, the back-calculation results obtained on the 23/03/2000 seem unrealistic, with a very low modulus of the MG20 granular material, and a high modulus of the thawed clay. These unrealistic values may be due to the presence of frozen layers.

Table 6 : Example of backalculated moduli for structure 4 (direction north).

DATE	period	Measured deflection	T_{HMA}	E_{HMA}	E_{GC}	E_{MG20}	$E_{subgrade}$ (MG112)	E_{clay} (FROZEN)	E_{clay} (clay touch by frost)	E clay	εt
		µm	°C	MPa	MPa	MPa	MPa	MPa	MPa	MPa	µm/m
30/09/1998	Zero point	103	20	3500	27000	300	250	-	100	95	19
24/03/1999	Partial thaw	110	3	11000	20000	70/500*	450*	400	130	100	23
08/04/1999	Complete thaw	125	5	9700	17000	120	110	-	100	95	27
15/04/1999	recovery	116	5	9800	17300	155	135	-	120	100	26
15/06/1999	Summer/autumn	124	22	3500	18000	160	155	-	145	106	27
05/10/1999	Summer/autumn	109	7	8000	18900	180	175	-	170	115	24
24/03/2000	Partial thaw	188	4	5000(1)	6000	55	50/450*	350	90	100	62
06/06/2000	Summer/autumn	146	17	4675	9500	160	150	-	130	100	41

*Frozen layers

4 COMPARISON BETWEEN BACK-CALCULATIONS CARRIED OUT WITH THE QUASI - STATIC AND DYNAMIC METHODS

4.1 Comparison between backcalulated moduli

A comparison of the moduli obtained with the LCPC and MTQ back-calculation methods for section 1 , for the MG20 granular subbase material and for the subgrade is presented on figure 2. For the MG20, the two methods lead to remarkably similar results, despite the difference in their principle (estimation of the modulus from laboratory measurements for the LCPC method, fitting of the deflection bowl for the MTQ method).

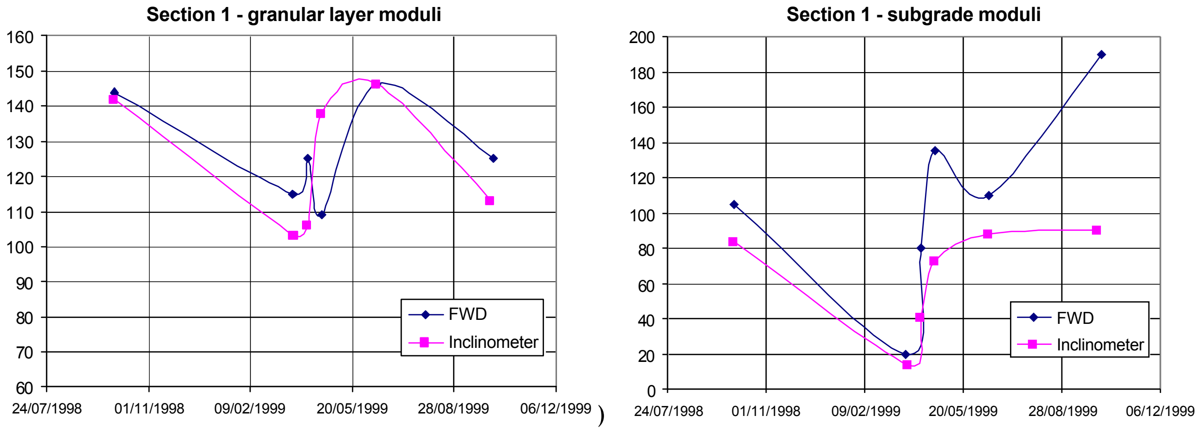

Figure 2 : Section 1 : Comparison of moduli of the MG20 layer and of the subgrade back-calculated using the two approaches.

For the subgrade, comparable results are also obtained with the two methods, except for the last date (4/10/1999), despite some differences in the backcalculation methods : in the LCPC method, the subgrade integrates all the layers subjected to frost (sand, silty sand and upper part of clay), while the MTQ method distinguishes all these layers. This could lead to a higher modulus with the LCPC method, because of the contribution of the stiffer, sand layers;

however, this effect may be compensated by the higher frequency of loading of the FWD (around 10 Hz, compared with 2 Hz for the inclinometer). Both methods confirm large seasonal variations of modulus of this subgrade material (reduction of the modulus by a factor of approximately 5 after thawing).

Figure 3 presents the subgrade moduli obtained with the two methods for section 4 (cement-treated base). For this section, the two back-calculation methods lead to very different results, the FWD approach leading to much higher moduli, and lower seasonal variations, than the inclinometer method. Several factors can explain these differences :

- The low values of the deflections (generally between 100 and 200 µm), and the very low strains in the subgrade; this increase the relative errors in the measurements, and makes the back-calculation procedures obviously less accurate.
- The different hypotheses taken for the depth to the bedrock : 4 m in the LCPC method, 7.62 m in the MTQ method (inaccurate value given by the MODCOMP Program).
- The differences in loading frequency between the FWD and inclinometer tests, probably amplified by the presence of the very stiff cement-treated layer.
- The progressive deterioration (thermal and fatigue cracking) of the cement-treated layer; in addition, this deterioration was treated differently in the two methods. In the FWD approach, the modulus of the cement treated layer was found to decrease progressively, whereas in the inclinometer method, it was taken into account only in the two last series of measurements (after march 2000).

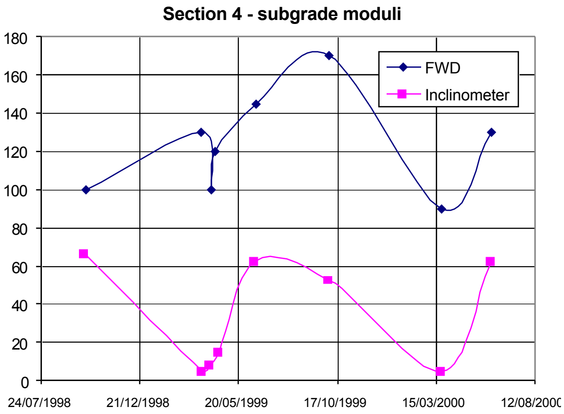

Figure 3 : Section 4 : Comparison of moduli of the subgrade back-calculated using the two approaches.

Thus, the comparison of the two backcalculation studies (carried out independently by each team, without knowing the results obtained by the other team) shows difficulties in the analysis of the response of the stiff, cement treated pavement structure, due largely to the progressive deterioration of the cement treated material. It must be pointed out, however, that this deterioration has been detected with both test methods, before the apparition of surface cracks (and in particular very early with the FWD method).

4.2 Comparison between tensile strain

On the asphalt pavement it is also possible to compare the tensile strains calculated with the two backanalysis methods, at the bottom of the asphalt base layer. These tensile strains are very useful to evaluate the fatigue damage of the structure, under different climatic conditions (for example during the thaw period). As for the unbound layer moduli, the two back-calclation methods lead to similar seasonal variations of the asphalt tensile strains. The values obtained with the FWD method being slightly higher (see tables 3 and 5)

5 CONCLUSION

This paper compared France and Quebec backanalysis methods of deflection measurements for two experimental pavement sections with hot mix asphalt and cement-treated base pavements. The Quebec method, based on FWD measurements, is routinely used for pavement evaluation. The French method, based on inclinometer measurements, is more a research procedure. The FWD test method, giving more experimental values (9 measurement points for each deflection bowl), allows a more complete determination of the moduli of all the pavement layers. Nevertheless, for the asphalt pavement, both approaches (applied independently) indicated very similar trends for the moduli of the main layers (asphalt layers, unbound granular subbbase, upper part of the subgrade touched by frost). For the cement treated pavement, more difficulties were encountered in the analyses, due particularly to the early fatigue damage of the cement-treated base.

The results of the backanalysis work presented here will be used to model the damage of the experimental pavements, and will allow to reach the aim of the project, i.e. increase the understanding about fatigue damage of these pavement, under cold climatic conditions with severe freeze-thaw cycles.

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