Monitoring pavement response during spring thaw and validation of the thaw weakening index

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ABSTRACT:

Seasonal variation in pavement response is considered to be a major factor affecting pavement performance. Several studies have concluded that in cold climates, most of the pavement damage by fatigue and permanent deformation can be associated with the loss of bearing capacity during spring thaw. The understanding of the bearing capacity loss phenomena needs to be improved and pavement design methodologies dealing specifically with the problem need to be developed. The Quebec Ministry of transportation, in collaboration with the Laboratoire central des ponts et chaussées (LCPC, France) and Laval University, has undertaken a major research project based on the monitoring of instrumented test sections. Four heavily circulated test sections were constructed and instrumented. Pavement instrumentation includes thermistors, moisture sensors, frost gages, piezometers and heave gauges. Several techniques were used to monitor pavement response during spring. One of the outcomes of the project is the development of a new mechanistic index likely to help predicting the bearing capacity loss during spring thaw in specific climatic and soil conditions. The index is based on the three important factors of thaw weakening: the quantity of ice accumulated in the soil by frost action, the rate of thaw and the rate of thaw consolidation. The new index was found to correlate well with measured loss of bearing capacity at several test sites.

1. INTRODUCTION

The Quebec Ministry of Transportation in collaboration with the Laboratoire central des ponts et chausses (LCPC, France) and Laval University has undertaken an important study on pavement performance during spring thaw. The objective of the study is to improve the understanding of the process of pavement weakening during spring thaw in order to help optimizing pavement design and load restriction policies. The study is based on five years of intensive monitoring of pavement condition, response under load and associated performance at the St-Celestin test road. It also includes two years of monitoring of two test sections in the test pit at the Laval University Road Experimental Site (Site Expérimental Routier de l'Université Laval: SERUL). Based on the results of the experimental work, a new mechanistic index has been developed to help predict pavement behavior during spring thaw.

2. FIELD STUDY

The study reported in this paper is focusing on pavement response data recorded during spring, between 2001 and 2003 in section 1 (flexible pavement structure) of the St-Celestin test road. The test road is located on Highway 155, 25km south of the city of Trois-Rivieres in the province of Quebec, Canada. It is a major transportation route carrying an average of 5500 vehicles per day. Test section 1 (the reference section for the test road) is 150 m long and is followed by three other sections including a cement stabilized base and insulation layers. The normal freezing index for the area is 1130°C*d resulting in an average frost penetration of 1500 mm. The pavement structure for section 1 is composed of 180 mm of asphalt concrete over a 300 mm thick crushed-rock granular base and a 450 mm thick granular subbase. The pavement structure is underlain by a 300 mm thick layer of silty sand over clay.

Section 1 of the St-Celestin test site is the most heavily instrumented section of the project. It includes 7 thermistor strings and 2 series of moisture sensors (time domain reflectometry (TDR) and Tetha probes) installed along a cross section of the pavement. It also includes a frost tube, a frost heave reference and a piezometer. Pavement response sensors were also installed in section 1. As shown on Figure 1, they include two fiber-optic strain gages and a multi-depth deflectometer (Déflectomètre Multi-Niveau: DMN). The strain gages were retrofitted in the asphalt concrete layer. The DMN system is composed of three rods anchored at the interface between each layer and a fourth (reference) rod anchored at a depth of 2.5 m.

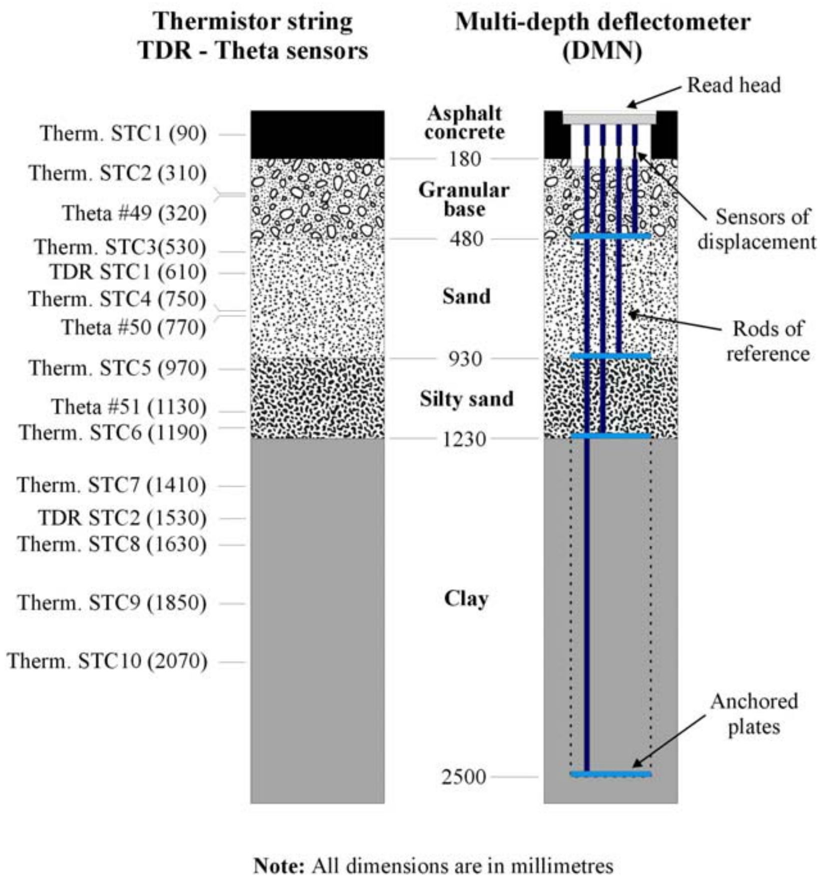

Figure 1: Description of pavement layers and position of instruments in the pavement structure of the section 1 of St-Celestin test road

The study also includes data collected at the Fosse-A and Fosse-B sections of the Laval University Road Experimental Site (SERUL). The test road is part of the Forest Road 33, 75km north of Quebec City. It is a major wood hauling route carrying an average of 35 heavily loaded trucks per day. The test sections are 30 m long and are built in a 2,5m deep concrete test pit. The normal freezing index for the area is 1600°C*d resulting in an average frost penetration of about 3000 mm. The pavement structure for the Fosse-A section is composed of 100 mm of asphalt concrete over a 200 mm thick granular base and a 500 mm thick granular subbase. The pavement structure is underlain by a 1200 mm of clayey sand. The Fosse-B section has a similar pavement structure but the subgrade soil is composed of silty till.

Instrumentation in each test section at the SERUL include a thermistor string and a series of moisture sensors (TDR and Theta probes) installed vertically in the pavement structure as indicated in Figures 2 and 3. Each section also includes a DMN for the measurement of pavement response under load.

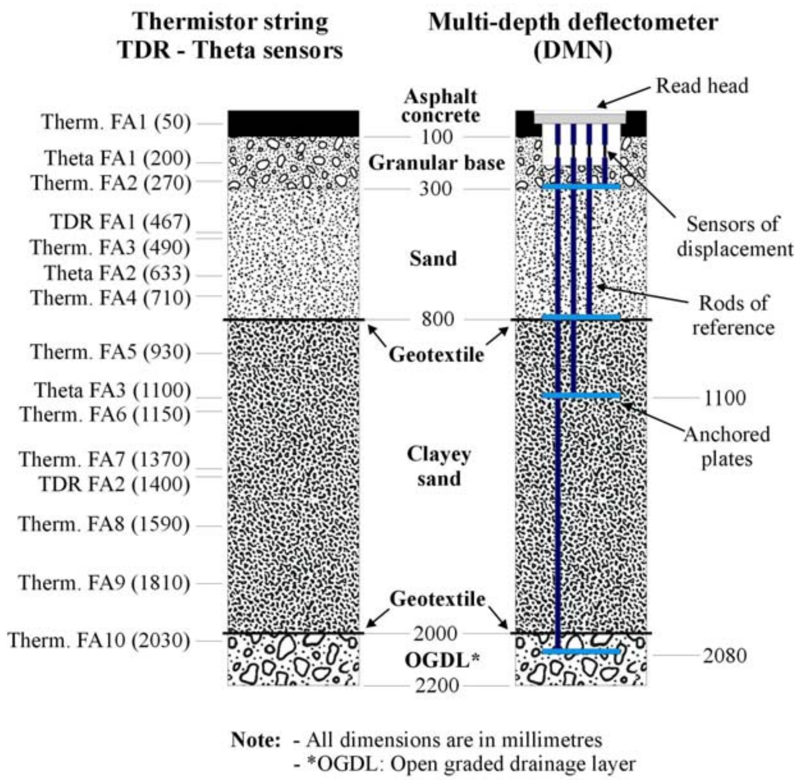

Figure 2: Description of pavement layers and position of instruments in the pavement structure of the Fosse-A section of the SERUL

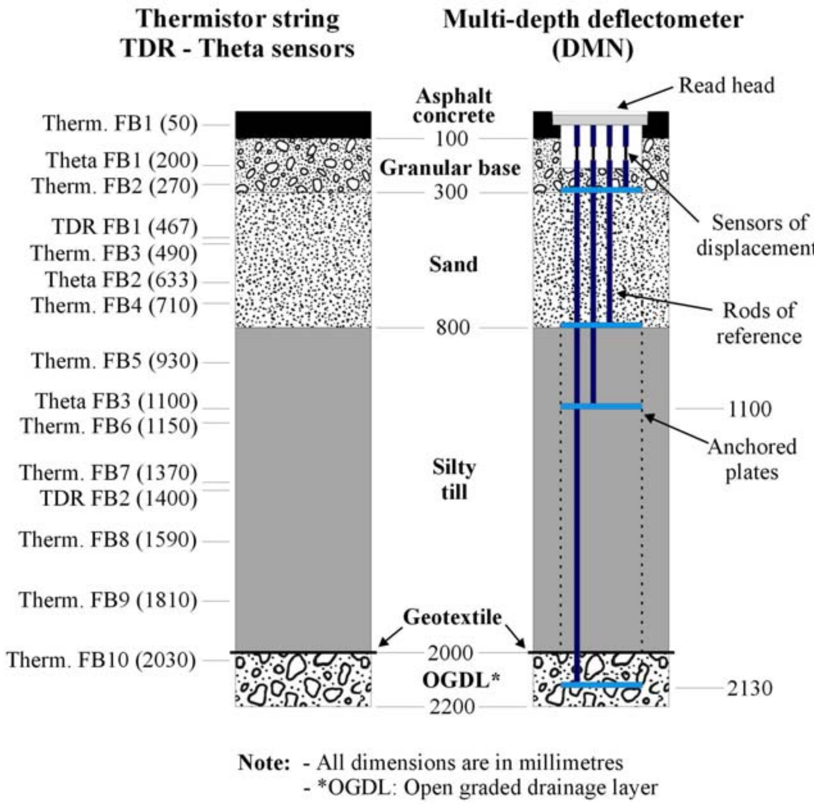

Figure 3: Description of pavement layers and position of instruments in the pavement structure of the Fosse-B section of the SERUL

The St-Célestin test site has been intensively monitored since fall 1998. The SERUL test sections were added to the monitoring program project starting in fall 2002. The pavement evaluation program includes pavement condition monitoring (temperature and moisture) and pavement response tests under controlled loading. These pavement response and pavement conditions monitoring activities were performed twice a week during spring thaw, every week during the first month of the recovery period (May) and every second week afterwards. A truck loaded to 8125 kg on the rear dual-tire wheel single axle (Benkelman Beam standard) moving at 50 km/h was used as standard load for the pavement response tests. Each test consisted of five valid[1] truck passes that were used to compute the average deflections and strains. Typical DMN signals are shown in Figure 4. The deflection was measured by subtracting the peak displacement value recorded from the baseline value measured between the two axles of the truck. The deflection measured using the reference rod was considered to be the total deflection of the pavement structure. The deflection in each layer was obtained by subtracting the deflections measured on the rods anchored at the top and at the bottom of the layer. The vertical strain for a specific layer was then readily obtained by dividing the deflection measured in the layer by the layer thickness.

[1] A test was considered valid when the center of the dual tires (rear axle) was within 50 mm of the center of the instruments.

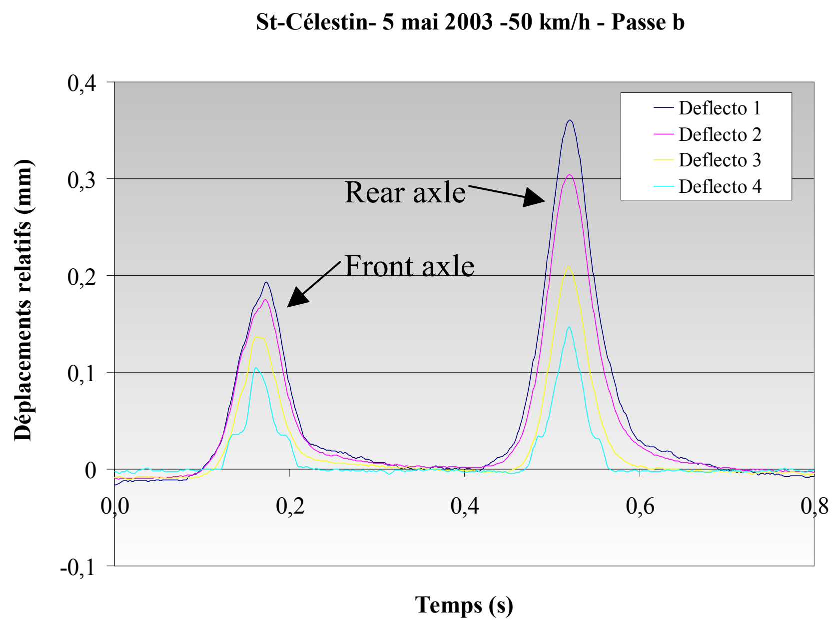

Figure 4: Typical DMN signal

3. PRELIMINARY FIELD RESULTS

The equipment installed at the three test sections monitored as part of the research project are providing very useful and interesting information of the thermal, hydric and mechanical behavior of the pavement structures during spring thaw.

Figure 5 illustrates typical data collected at the St-Celestin test section in the spring of 2001. As shown on the figure, vertical strains measured in the granular subbase tend to be high and to vary much during spring. Strain evolution during spring correlates fairly well with moisture contents observed in the layer. The figure shows that it took about 16 days to thaw completely the subbase layer. During that period, the recorded strains have increased by a factor 10, reaching a peak level of 160με. Moisture contents measured at the bottom of the layer were then high and remained high for at least 20 days after complete thawing of the layer. The recorded strains remained high during that period and an important reduction was observed afterward. The strain reduction occurred when water contents returned to "normal" levels.

The amount of frost heave occurring in a specific layer and the rate of consolidation of the layer subjected to thawing are likely to explain, at least in part, the weakening process in pavement structures. Figure 6 illustrates frost heave and thaw consolidation recorded at each pavement interface and in subgrade soil during winter and spring 2003.

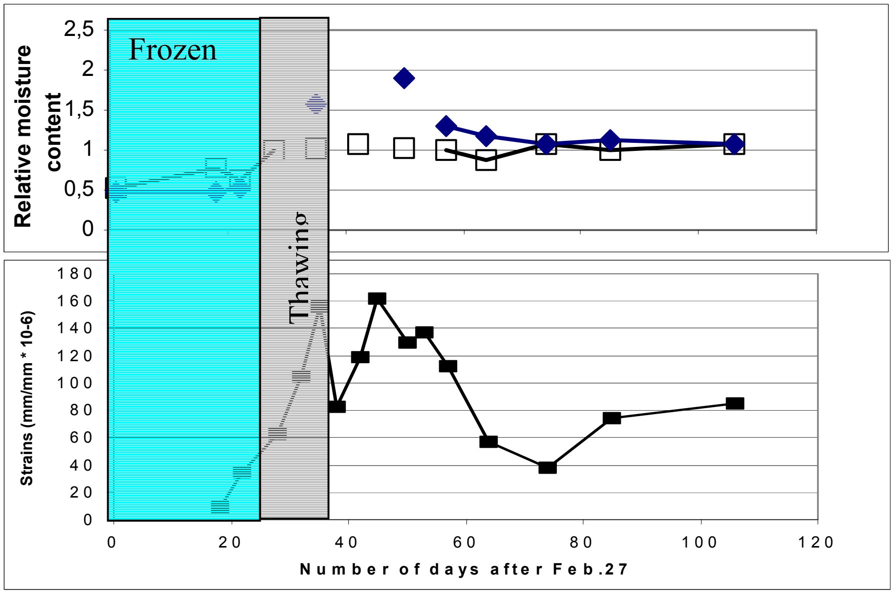

Figure 5: Example of vertical strains and moisture contents in the subbase layer of the St-Celestin test road during spring 2001. Solid diamonds and empty squares indicate moisture contents (normalized by the fall value) measured in the bottom part and the top part of the layer respectively.

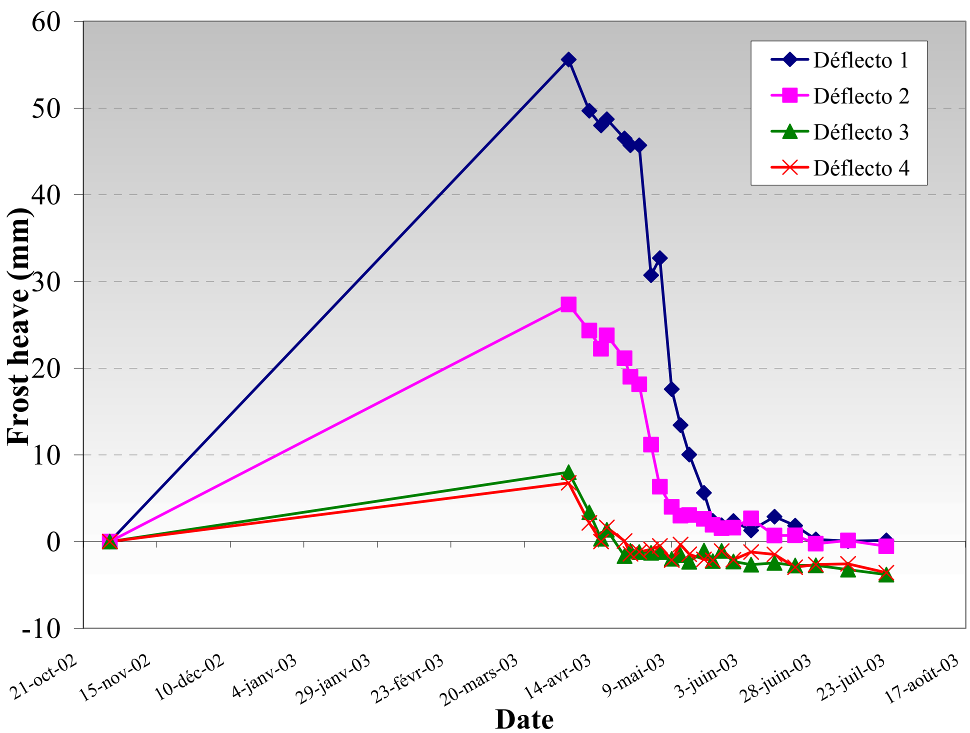

Figure 6: Frost heave and thaw consolidation in pavement layers of Fosse-B section

In Figure 6, “deflecto 1” illustrates total frost heave for the pavement structure. Deflecto 3 and deflecto 4 illustrate frost heave at the subbase-subgrade interface and at the base-subbase interface respectively. Deflecto 2 illustrates frost heave occurring at a 300-mm depth in the subgrade soil. It is interesting to note that approximately 8 mm of heaving is occurring in the granular base (deflecto 4) while none is occurring in the subbase layer (deflecto 3 – deflecto 4). Approximately 50 mm of heaving is occurring in the subgrade soil (deflecto 1) of which, 20 mm is attributable to the top 300 mm (deflecto 2 – deflecto 3). Thaw consolidation of the structure occurs over a 50-day period starting around April 1st.

Figures 7 and 8 show the vertical displacements and gravimetric water content measured in the base layer and the top 300 mm of the subgrade soil in the Fosse-B section during 2003 spring thaw. It can be seen on the figures that both layers undergo drastic increases of vertical displacement, when subjected to the standard loading, immediately after the beginning of thawing. These increases in measured displacements coincide with significant increases in water contents in the layer.

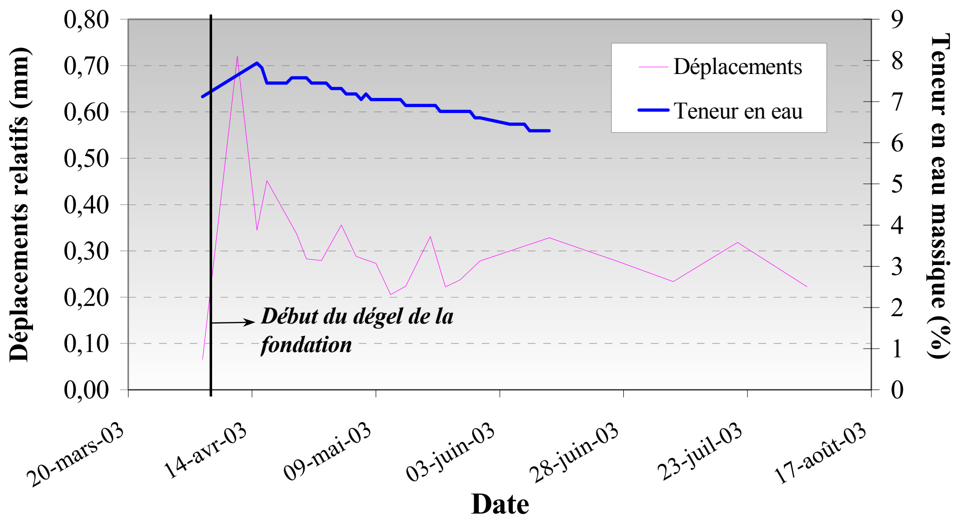

Figure 7: Evolution of gravimetric water content and vertical displacements in the granular base in Fosse-B section during spring 2003.

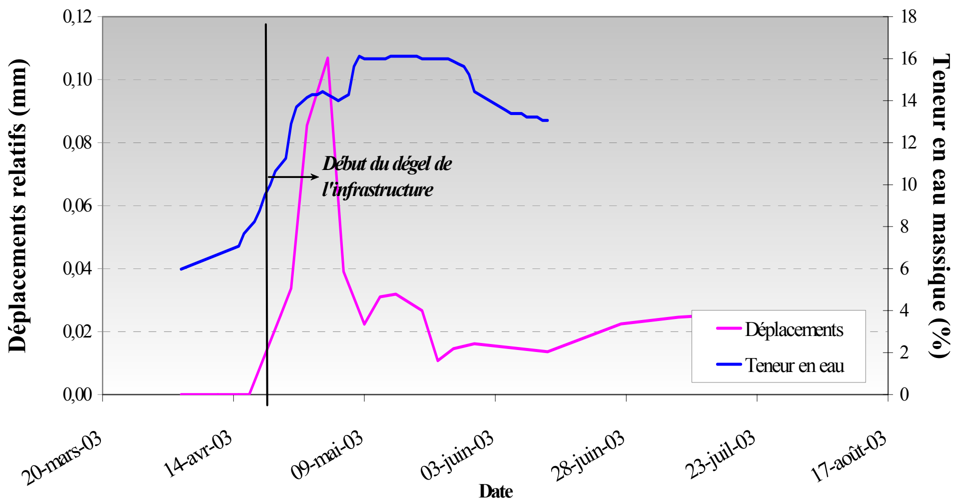

Figure 8: Evolution of gravimetric water content and vertical displacements in the top 300 mm of the subgrade soil in Fosse-B section during spring 2003

As the information from the 2004 monitoring season becomes available, a thorough analysis of available data will be done in order to mechanistically explain thaw weakening of pavement structure. Displacements and strains will be normalized as a function of transmitted stresses in order to obtain information on elastic modulus and its variation during spring thaw. Water contents will also be transformed into suction-pressure values in order to evaluate the variations of effective stresses in pavement materials.

4. DEVELOPMENT OF THE THAW WEAKENING INDEX

Several authors have indicated the importance of three important factors on the behavior of pavements during spring thaw:

1. The amount of frost heave occurring per unit thickness in the considered layer
2. The rate at which the layer is thawing
3. The rate at which the layer consolidates

Dysli (1991a) has identified the three factors as being directly related to thaw-weakening. Experimental work by Dysli (1991a and b) has demonstrated the importance of the thaw rate on pavement damage during thawing. Simonsen and Isaaksson (1999) have identified the amount of frost heave per unit of frozen soil as an important factor in loss of shear strength. High pore pressures that result from segregation ice thawing and poor drainage are identified as key factors. The rate of thawing is also identified as an important factor of strength reduction.

Thaw-weakening is a complex process and those factors need to be taken into consideration for a correct assessment of the weakening potential of a pavement structure. Frost heave occurring in a layer will cause water to accumulate in pores and in ice lenses increasing thus the overall porosity of the material. Water accumulation as interstitial ice and more specifically as segregation ice can be seen as a weakening potential. During thawing, the rate at which the thaw front progresses in the layer will control the rate at which water is released in the material. The rate at which the layer consolidates is in turn an indication of the capacity of the material to drain the released water and to reduce pore pressure.

The thaw-weakening index (TWin) has been proposed by Doré and Imbs (2002). It combines the weakening potential represented by the total heave normalized by the thickness of the considered layer with the thaw-consolidation ratio developed earlier by Nixon and Morgenstern (1971) as indicated in Equation 1:

$$TWin = \frac{h}{D} \times \frac{\dot{x}}{\dot{S}} \qquad \text{(Equation 1)}$$

Where: h is the total heave resulting from frost action in the subgrade soil
D is the thickness on subgrade soil affected by frost action
$\dot{x}$ *and* $\dot{S}$ are the thawing rate and the settlement rate respectively

The dimensionless index incorporates therefore most of the factors contributing to thaw-weakening behaviour of a given material in a specific environment. Frost heave represents the weakening potential accumulated by frost action. The rate of thawing is in turn a function of the climatic conditions during spring (heat transmitted to the pavement system) and the resulting thermal response (heat absorbed) of the material. Finally, the rate of consolidation is the resulting mass transfer (drainage) and volume change (settlement) in the pavement system.

Validation of the index using field data

The field validation of the "Thaw-weakening Index" (TWin) concept requires the following specific information:

- Thickness of the frozen soil layer (frost depth)
- Total frost heave (assuming that no significant frost heave occurs in the pavement granular layers)
- Progression of the thaw front as a function of time during spring thaw
- Relative elevation of the pavement surface as a function of time during spring thaw and recovery period
- A measurement of the evolution of the pavement bearing capacity with time

Data from the three sites described above will provide detailed information on the behavior of thawing pavements but the number of observations from these sites is clearly insufficient to validate the new index. To complement the available information, data was gathered from the literature. Two sets of data were assembled from available publications. In Both cases, the variables related to thermal response of the site were determined using heave-consolidation and frost-thaw penetration history data. Figure 9 illustrates the measurements made in order to quantify the required variables. Assuming that all frost heave is occurring in the frost susceptible subgrade soil, frost heave is readily obtained by measuring maximum value on the heave time history chart (h in Figure 9). Field observations and close examination of the data available however indicate that this assumption is not valid and can induce significant errors especially for pavements with limited total frost heave. A consistent heave of approximately 10 mm occurring in the pavement granular layers was observed for all test sites. A correction was thus applied to the total frost heave to take into consideration that phenomenon. The thickness of the frozen layer is also easy to measure by subtracting the maximum frost depth from the thickness of the pavement structure (D in Figure 9). Consolidation rate is the slope of the consolidation curve measured as indicated in Figure 9. Only the portion of the curve after the date when the subgrade soils begins thawing is considered for the measurement of the slope. Finally, as indicated in Figure 9, the rate of thawing was obtained by measuring the slope of thaw front evolution line at the beginning of subgrade soil thawing. It is expected that this period represent the most critical since the top part of the subgrade soil is the most solicited by traffic action and considering the poor drainage conditions during the early stage of subgrade thawing.

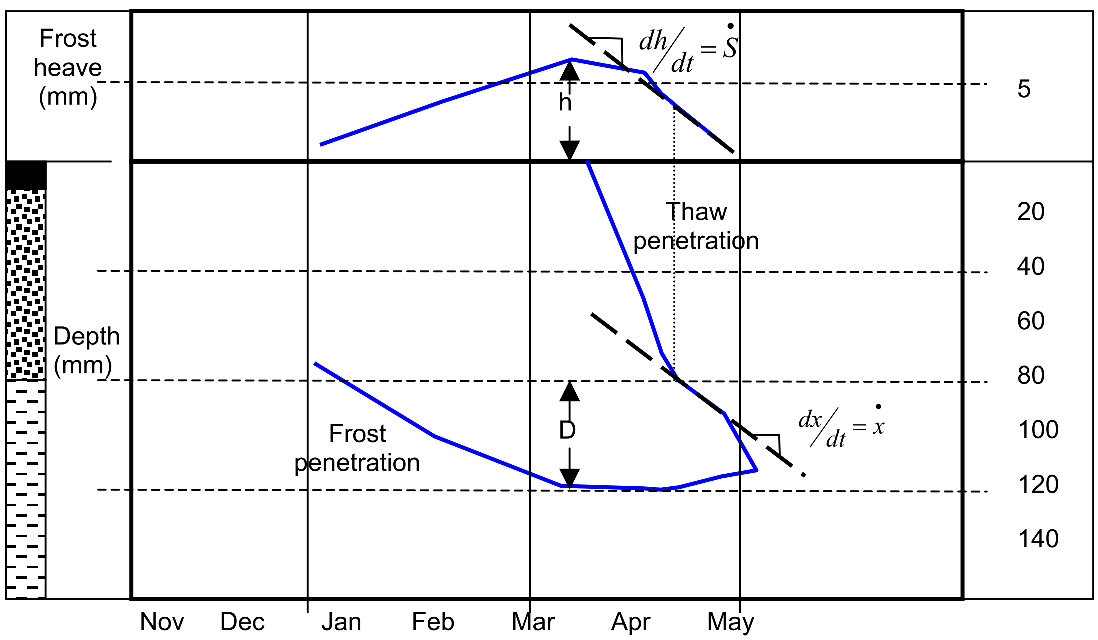

Figure 9: Determination of parameters for the Thaw-weakening Index

The first data set includes five sections where the thermal response of the site is fully documented and where bearing capacity evolution has been reported in terms of maximum deflection using either Benkelman beam measurements or FWD (d_0) measurements. The value used to quantify weakening is defined as being:

$$\frac{\Delta d}{d} = \frac{d_{sp} - d_{su}}{d_{su}} \qquad \text{(Equation 2)}$$

Where: d_{sp} is the maximum deflexion recorded during spring thaw
d_{su} is the minimum summer deflexion
$\Delta d/d$ is the normalized loss of bearing capacity due to spring thaw

Despite the fact that it is generally admitted that Benkelman beam deflections do not correlate very well with FWD deflections, it is expected that normalized values obtained from Equation 2 may be used to compare site behavior. Table 1, assembled by Imbs (2003), summarizes the characteristics of the five sections considered in this part of the study.

Table 1: TWin validation data with pavement weakening quantified using deflection data (Imbs, 2003)

	Vorsmund	Minnesota	Québec, Canada		
	Norway	USA	HW-155 St-Celestin	HW-265	HW-122
Soil type	Clay	Clay	Silty sand + clay	Silty sand	Silty sand
Thickness of frozen soil (mm)	750	750	705	1000	500
Total heave (mm)	90	16	24,4	6	58
Consolidation rate (mm/j)	1,72	0,75	0,86	0,36	2,5
Thaw penetration rate (mm/j)	21,9	50	30,4	33	25
TWin	1,53	1,42	1,22	0,55	1,16
Δd/d	0,72[(a)]	0,5[(b)]	0,42[(b)]	0,12[(b)]	0,29[(b)]

(a) From Benkelman Beam deflections
(b) From FWD deflections

Figure 10 illustrates the correlation obtained between TWin and Δd/d for those five sections. The number of observations is clearly insufficient to be conclusive but the relationship obtained is very encouraging with a coefficient of determination (R^2) of 0,97. The relationship appears to be exponential and it would take the following preliminary form:

$$\frac{\Delta d}{d} = 0{,}044e^{1{,}77 \times TWin} \qquad \text{(Equation 3)}$$

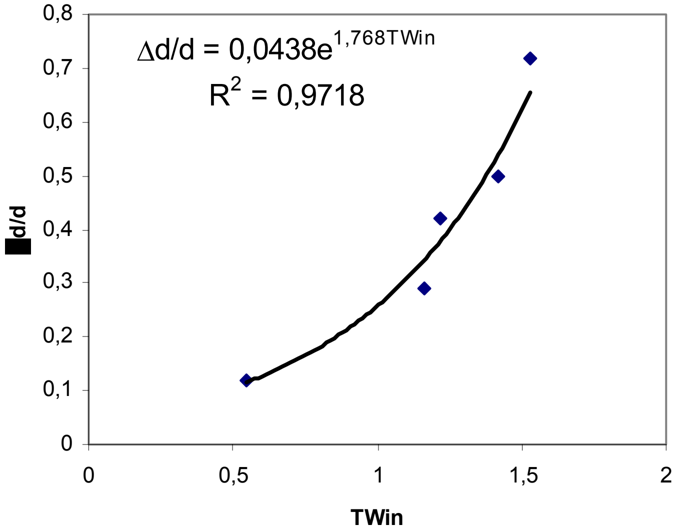

Figure 10: Relationship between the Thaw-weakening Index and bearing capacity loss as obtained from deflection measurements

It was possible to gather specific information from five additional sites including three where observations were made during two winters. Bearing capacity information from these sites is reported under the form of backcalculated modulus from FWD testing. In this case, the value used to quantify weakening is defined as being:

$$\frac{\Delta M}{M} = \frac{M_{su} - M_{sp}}{M_{su}} \qquad \text{(Equation 4)}$$

Where: M_{su} is the maximum modulus obtained from summer deflection measurements
M_{sp} is the minimum modulus obtained during spring thaw
$\Delta M/M$ is the normalized loss of bearing capacity due to spring thaw

Table 2 summarizes the characteristics of the test sites and the parameters derived from the field observations at the St-Celestin test road or obtained from data reported in the Finnish publications (Palolahti et al., 1993a and b).

Table 2: TWin validation data with pavement weakening quantified using back-calculated moduli from deflection testing

	Oulunsuu Finland	Nummi-Pusula Finland		Jyva-skilan Finland	Kempele-Oulunsalo Finland		Hwy-155 St-Celestin Québec-Canada	
	1991	1991	1992	1991	1991	1992	2000	2001
Soil type	Silty sand	Silt		Clayey silt	Silty clay		Silty sand + clay	
Thickness of frozen soil (mm)	800	400	200	490	680	405	364	388
Total heave (mm)	82	56	40	80	70	28	15	23
Consolidation rate (mm/j)	1,77	2,07	1,56	3,59	1,74	0,52	1,0	1,52
Thaw penetration rate (mm/j)	12,13	9,51	15,16	16,39	11,56	9,02	12,1	16,7
TWin	0,70	0,64	1,94	0,74	0,68	1,19	0,50	0,65
ΔM/M	0,25	0,15	0,46	0,29	0,25	0,43	0,18	0,18

The relationship between the thaw-weakening index and bearing capacity loss as obtained from elastic moduli backcalculated from deflection measurements is illustrated in Figure 11. Despite a limited number of observations, the results show a strong correlation between the observed weakening of the pavement as defined by Equation 4 and the proposed index. Available field observations thus demonstrate the validity of the concept. The relationship obtained is the following:

$$\frac{\Delta M}{M} = 0{,}25\ln(TWin) + 0{,}33 \qquad \text{(Equation 5)}$$

The coefficient of determination (R^2) of the relationship is 0,86 confirming the strength of the correlation.

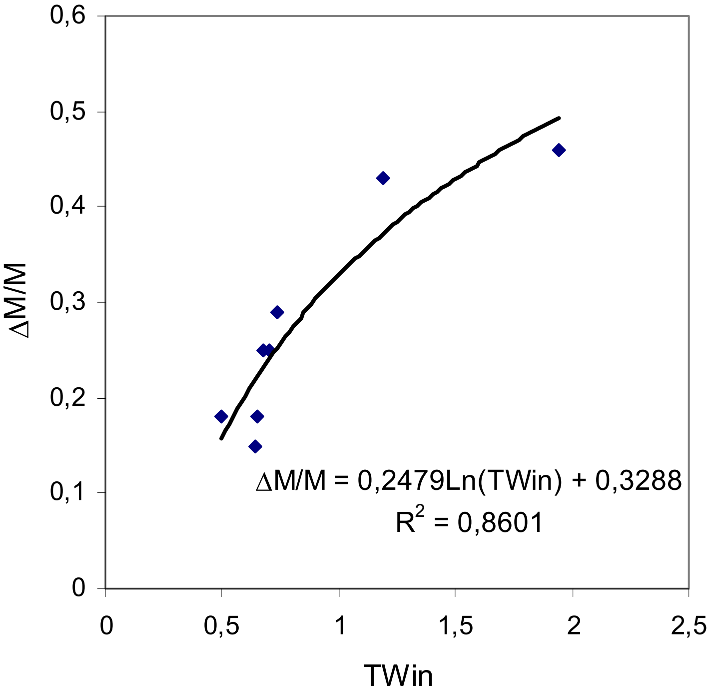

Figure 11: Relationship between the Thaw-weakening Index and bearing capacity loss as obtained from elastic moduli backcalculated from deflection measurements

The two sets of data cover a wide range of conditions going from low to high frost susceptibility soils subjected to a variety of climatic conditions. The 10 test sections from which data was obtained vary from low volume to strong flexible pavement structures with asphalt concrete layers ranging from 70 to 180 mm and with total thicknesses ranging from 480 to 980 mm. The values of TWin obtained for all observations vary from 0,5 to 2,2. The responses observed for those conditions are also highly variable. For the data set where deflection was used as pavement response measurement, weakening values obtained using Equation 3 vary from 0,1 to 0,7 following an exponential relationship. For the dataset where backcalculated modulus was used as pavement response measurement, values of weakening obtained using Equation 4 ranged from 0,15 to 0,5 following a logarithmic relationship. It is interesting to note that within the conditions of the test sites used in this study, significant weakening (0,1 to 0,15) was obtained for sites with very low sensitivity to frost action. These conditions seem to be captured by low but measurable values of TWin around 0,5. There seems to be a general trend with respect to the range of TWin values for a given type of soil. Based on all observations reported in this paper, the index tends to increase with increasing content of fines particles in the soil. TWin values for silty sand range from 0,55 to 1,22, from 0,76 to 2,23 for silt, from 0,78 to 1,62 for silty clay and from 1,42 to 1,53 for clay. The ranges are illustrated in Figure 12. It is important to note that in two cases, i.e. for silty clay and for silt, extreme values of the range were obtained for observations at the same site, showing the important influence of climatic conditions on the index.

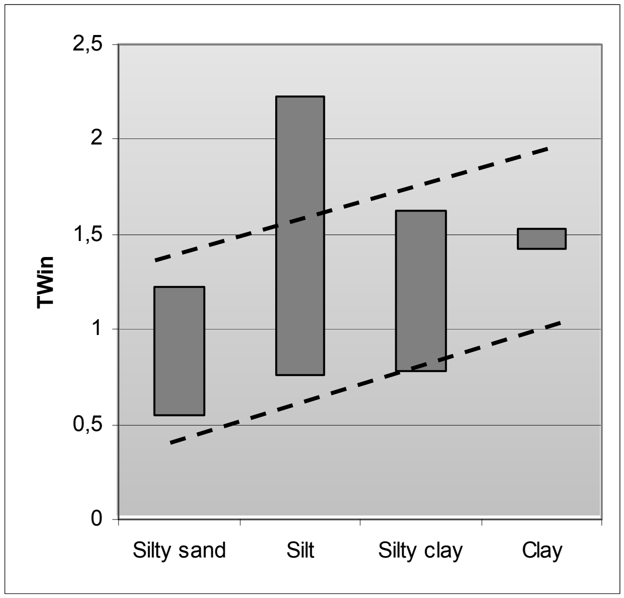

Figure 12: distribution of TWin values based on the observations reported in this paper

Based on the observations of TWin values and of corresponding pavement weakening made during this study, the following preliminary classification of TWin is proposed:

Low sensitivity to thaw weakening:	TWin < 0,8
Intermediate sensitivity to thaw weakening:	0,8 < TWin < 1,2
High sensitivity to thaw weakening:	TWin > 1,2

Implementation of the Twin

There are two important considerations for the implementation of the TWin. The first consideration is the measurement of the index and the second is its use in pavement engineering.

Measurement of the Thaw-weakening Index

Field observations have demonstrated that the Thaw-weakening index is a mechanistic based index that can help predict the loss of bearing capacity of a pavement structure in any given spring thaw conditions. The validation of the index has been done using field data which is difficult to find in the literature and hard to measure in the field. It will thus be difficult to implement the index based on the approach taken in this study. Moreover, the major application of the index is for the optimisation of structural design of new or rehabilitated pavements. The field approach is thus not applicable, at least for new pavements.

Research is currently being conducted to develop a laboratory approach for the assessment of the TWin. These developments are essentially based on freezing and thawing tests in a freezing cell. A simple laboratory test is required to facilitate the practical application of the index.

Applications

Several applications are foreseen for the thaw-weakening index. Among other, potential applications include optimisation of pavement design, improvement of material characteristics and management of load restrictions on highways.

- The TWin can be used as a mechanistic index to characterize soil for pavement structural design purpose. Most design methods used in cold climates, including AASHTO 1986 and most of the mechanistic empirical methods, recommend the use of a seasonal base approach to damage computation. There are currently few methods available for the prediction of the variation of resilient modulus resulting from thaw-weakening. In most cases, typical values based on field observations and laboratory testing are used to assess weakening without consideration for the effect of climatic conditions. TWin could become a very useful tool to predict the loss of rigidity of subgrade soils during spring making it possible to compute seasonal damage based on site specific characteristics. For example, based on Equation 5 or Figure 11, for a soil having a "summer" resilient modulus of 50 MPa and a TWin of 1,0, a loss of 0,3 would be expected yielding to a "spring" modulus of 35MPa. It would also be possible to limit thaw weakening by specifying a maximum allowable TWin. Since the TWin is an index which varies with climatic conditions, a probabilistic approach could be used to assess the risk of exceeding the specified allowable TWin. Limitation of frost heave would be the best way for pavement engineers to limit the TWin.
- The TWin can also be used as a criterion for soil or material improvement. For instance, soils having high TWin values can be modified and tested to minimize bearing capacity loss. Effectiveness and dosage of chemical treatment can be assessed using TWin tests. Material gradation can also be modified to minimize bearing capacity loss based on TWin testing.
- TWin can also be used to analyse the thaw-weakening susceptibility of a transportation route or road network. Field measurements or lab testing could thus be used to analyse the risk of bearing capacity loss. A probabilistic approach would allow for the estimation of the weakening under different climatic scenarios (severe winters and mild springs, etc) and assess the risk of premature pavement failure.

5. DISCUSSION

Field data have demonstrated the validity of the Thaw-weakening Index concept. The approach taken to estimate the index from field observations and from the literature was rigorous but likely to introduce errors and biases. The descriptions of the methods used for the measurement of frost and thaw depth, frost heave and consolidation and pavement response are often succinct and sometime omitted in the available literature. It is also likely that different techniques were used in the studies consulted to make the measurements. For instance, thermistors were used at certain sites while frost tubes were used at other. The use of Benkelman beam measurements for one site might have lead to an overestimation of the bearing capacity loss for the Vormsund test site. It is generally admitted that static loading of a visco-elastic system will lead to larger deformations. The very important increase in deflection measured at the Vormsund test site might be considered suspect in the circumstances. This might also explain the fact that the two relationships obtained within this study somewhat contradict each other. According to Equation 5 and Figure 11, the bearing capacity loss for an increase of TWin between 0,5 and 1 is greater that for an increase between 1,5 and 2,0. The same trend should be observed for the increase in deflection which is inconsistent with the trend observed on Figure 4. Assuming that the Vormsund observation leads to overestimated loss of bearing capacity, the trend shown in Figure 4 could very well become consistent with the trend of Figure 5. Different back-calculation techniques were also probably used by the different researchers to assess the resilient modulus. As a result, errors and biases might have been introduced in the analysis of the thaw-weakening behaviour of the test sites. The significance of these errors is however very difficult to assess with the available information. The use of normalized values for the quantification of the pavement weakening is likely to contribute to reduce some of the errors related to the use of different measurement and back-calculation techniques.

The thaw-weakening index measured for all sites is consistent with the expectations. Comparison between different types of subgrade soils shows that fine-grained soils have higher thaw-weakening indices than coarser soils. The correlations between the index and pavement weakening are very encouraging. Based on the result of this study, it can be stated that the Thaw-Weakening Index constitute a solid foundation for the analysis of pavement response and performance in freeze-thaw conditions. More field data would definitely help improving the robustness of the models presented. More research is also needed to facilitate the implementation of the new index. A laboratory test incorporating a full freeze-thaw cycle is under development based on the work previously done by Chamberlain (1988). The test will allow the characterization of the frost heave and thaw-weakening behaviour any soil or pavement material under controlled laboratory conditions. It is expected that laboratory-measured indices will be transposable to any field conditions by adjusting the thaw rate to expected site condition.

6. CONCLUSION

A new mechanistic index has been developed to predict the mechanical behaviour of soils and pavement materials in thawing conditions. The index is based on factors witch are physically linked with the loss of bearing capacity during spring thaw. It takes into consideration the amount of water accumulated by the freezing process, the rate of thawing in the subgrade soil and the rate of consolidation of the pavement structure. The index has been validated using high quality data from a limited number of well documented test sections. Good correlations have been obtained between the TWin and pavement weakening proving that the thaw-weakening index is a promising tool to characterize soils and pavement materials with respect to their spring-thaw behaviour in any given site specific conditions. The index can be derived from field measurements. It is also expected that it will be possible to assess the index using laboratory tests.

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