Estimation of subgrade soils mechanical properties and frost sensitivity through the use of simple tests

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ABSTRACT: Subgrade soils properties are one of the main inputs for pavement design. In cold climates, these subgrade properties are associated with stiffness, water sensitivity and frost susceptibility and can be obtained through reliable but complex and costly resilient modulus and segregation potential laboratory tests. Portable instruments such as light weight deflectometer (LWD) allow to rapidly and easily quantifying mechanical properties of soils to a limited extent. The mathematical models associated with these measurements are poorly adapted to take into account stress state and water content on the mechanical properties determination. Regarding the frost susceptibility of soils, a default value is often used or it is often estimated with charts or estimated from its physical properties. Therefore, the project focused on the development of simple tests using portable tools (LWD and percometer) to perform a reliable estimation of resilient modulus and segregation potential. Ten typical subgrade soils were sampled and a laboratory deflection based test (using a LWD and a 300 mm diameter mold), validated with field measurements, and was correlated with triaxial resilient modulus test results to take into account non linearity. Percometer measurements (dielectric value) were also performed on the laboratory samples for various water contents. The water sensitivity measured with the percometer data were correlated with laboratory segregation potential values of the tested soils. The developed resilient modulus and segregation potential estimation techniques allowed obtaining an adequate estimation of these important pavement design properties based on soils in situ characteristics.

KEY WORDS: Light weight deflectometer, Percometer, Resilient modulus, Frost susceptibility, Mathematical models.

1 INTRODUCTION

In the context of mechanistic-empirical pavement design, the reliable characterization of subgrade soils mechanical properties and frost susceptibility is complex, costly and time consuming. The development on new technologies has led to progress in the field of indirect characterization of soils. On the one hand, techniques involving the use of equipment such as the triaxial cell and frost heave cell are usually recommended for measurements of reliable laboratory parameters required for pavement design. However, their use is often limited to research projects. On the other hand, portable equipment facilitates the routine characterization of soil (or pavement layers) through the acquisition of deflection or dynamic penetration data, which are correlated with a value of elastic modulus or resilient modulus (Boutet et al. 2008; Gudishala 2004). The development of techniques and equipment for the assessment of soil physical properties and its correlation to the results of frost heave cell (the segregation potential) has been studied by several researchers as Konrad (1999) and (Doré et al. 2004) .

The difference between measurements with portable equipment and those in the laboratory is still considerable (Puppala 2008). Only a few models link laboratory measurements with measurements obtained by indirect portable equipment. Moreover, there is not a recognized and standardized protocol to obtain reliable parameters associated with the mechanical or the frost heave behavior through the use of portable equipment.

2 OBJECTIVE

The main objective of this research is to develop mathematical models which would allow obtaining a reliable estimation of the resilient modulus and of the segregation potential from the measurements of the back-calculated modulus with Light Weight Deflectometer (LWD) and the Dielectric Value (DV) with a percometer.

3 EXPERIMENTAL PROGRAM

The experimental program includes subgrade soils sampling, geotechnical characterization and laboratory tests for mechanical and frost heave characterization.

3.1 Sampling and geotechnical characterization

Sampling was carried out in a 100 km radius of Quebec city (Quebec, Canada), which includes three geological provinces of Quebec: the “Grenville”, the “Plate-forme du Saint-Laurent” and the “Appalaches”. Geological Map of Quebec (MRN 2002) and pedological studies (IRDA 2008) were used to identify ten various sampling sites. Geotechnical characterization performed on the soil samples includes the following tests: grain size analysis (NQ 2501-025), Atterberg limits (CAN/BNQ 2501-092-M-86), specific gravity of soils grains (CAN/BNQ 2501-070-M-86), modified Proctor (CAN/BNQ 2501-255-M-86) and methylene blue method for surface area estimation (BNQ 2560-255).

3.2 Mechanical tests

Subgrade soils tests for mechanical properties determination involves two steps: resilient modulus testing in triaxial cell and deflection tests with LWD.

3.2.1 Triaxial resilient modulus tests

Sample preparation and testing were performed according to AASHTO T 307-99 methodology for subgrade soils. Tests were performed at two degrees of saturation: saturation at optimum moisture and saturation at 85%. Samples were prepared at optimum moisture for sands and clays. Second degree of saturation for sands was changed in triaxial cell; for clays, a second sample was compacted at Sr=85%. Results were modeled with (Uzan 1985):

$$M_R = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\sigma_d}{p_a}\right)^{k_3} \tag{1}$$

Where k_1, k_2 et k_3 are model constants; M_R (MPa) is the resilient modulus; p_a is the atmospheric pressure; θ (kPa) is the bulk stress ($\sigma_1 + \sigma_2 + \sigma_3$; principal stresses in kPa); σ_d

(kPa) is the deviatoric stress (σ_d=σ_1- σ_3). Resilient modulus corrections for saturation effects (Sr expressed as a decimal) were done according to the model developed by Drumm et al. (1997):

$$M_{R(wet)} = M_{R(opt)} + \frac{dM_R}{dS}\Delta S \quad (2)$$

Where $M_{R(wet)}$ (MPa) is the resilient modulus at a high water content; ($M_{R(opt)}$ in MPa) is the modulus at optimum moisture content and maximum dry density; (dM_R/dS) is the gradient of resilient modulus with respect to saturation and ΔS is the change of degree of saturation expressed as a decimal. $M_{R(opt)}$ and dM_R/dS were calculated from measured values in triaxial cell tests for two degrees of saturation.

3.2.2 Deflection tests with LWD

Deflection tests were performed with Light Weight Deflectometer (LWD) PRIMA 100 on a sample compacted in a mold; dielectric value (DV) was measured with a Percometer. Figure 1 presents a scheme of the test. The mold is a 300 mm x 350 mm (diameter x height) hollow tube fixed to a 25.4 mm thick aluminum base. The wall thickness of the PVC mold is 18.5 mm. The mold dimensions were chosen in order to minimize the wall effect during the application of the stress with the LWD.

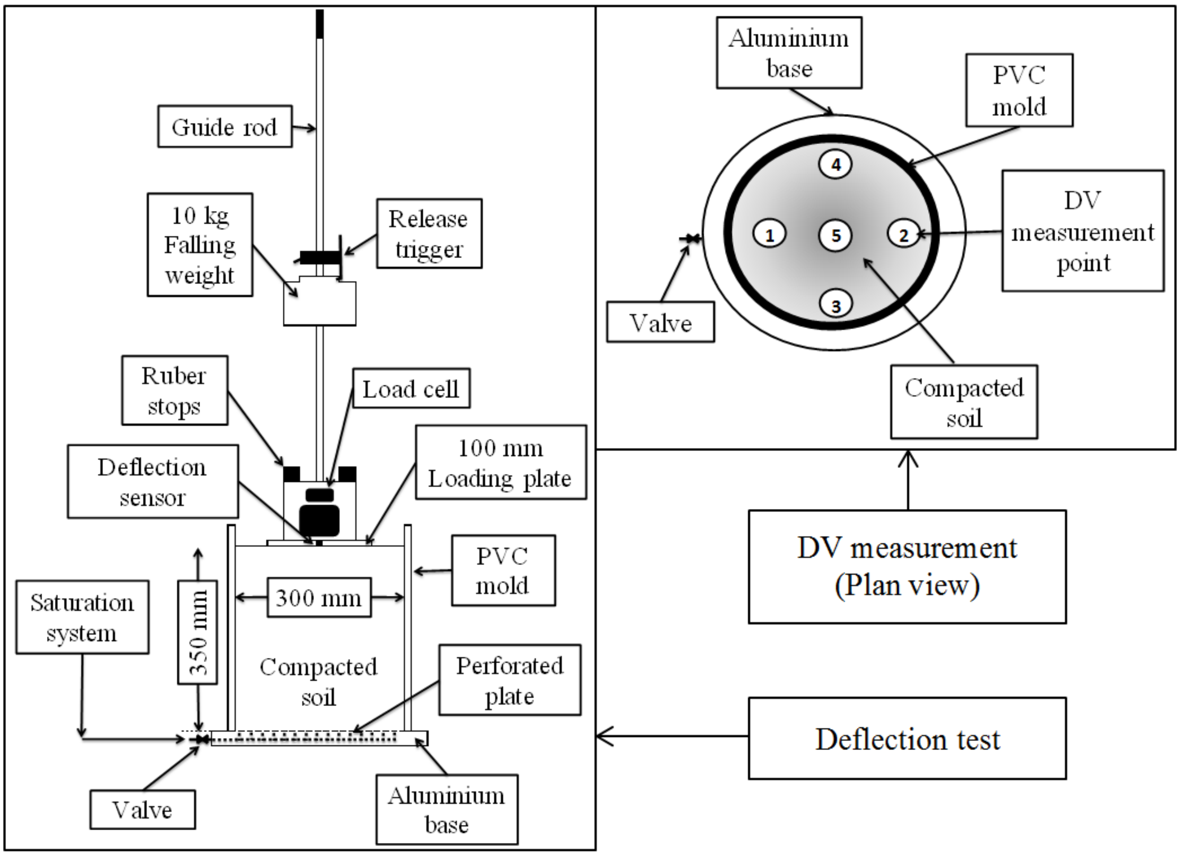

Figure 1: Deflection test with LWD and Dielectric Value measurements

LWD is composed of a falling weight which moves along a guide rod to a 100 mm diameter loading plate provided with a deflection sensor. The falling weight applies a pulse load on the plate which is transmitted through the soil as vertical stress causing a deflection on the sample's surface. The load cell records the values of vertical force (converted to stress σ_v, in kPa) applied on the loading plate (radius a=0,05m) and the deflection sensor records the deflection of the sample's surface (d_0, in micrometers). Poisson's ratio is set to υ=0.35. These values are used to determine the surface modulus or back-calculated modulus in the mold (E_{mold} in MPa):

$$E_{mold} = \frac{2(1-\upsilon^2)\sigma_v a}{d_0} \tag{3}$$

Three sets of deflection tests are performed on each sample; each set is executed at different degree of saturation (Sr). A set consist of a calculation of E_{mold} for five drop heights of the falling weight (50 mm, 75 mm, 100 mm, 125 mm and 150 mm). Each test is done following the measurement of the dielectric value (DV). According Scullion and Saarenketo (1997), dielectric value is the ratio of the electrostatic capacity of condenser plates separated by the given material to that of the same condenser with a vacuum between the plates. The DV was calculated as the average of five measurements taken on selected positions on the sample's surface (Figure 1). In order to compare the $M_{R(wet)}$ versus the E_{mold} at a given degree of saturation, the soil loading inside the PVC mold was modeled with SIGMA/W (finite element stress-deformation analysis software). Modeling was used to estimate the vertical stress (σ_1 in kPa) and the radial stress ($\sigma_2 = \sigma_3$ in kPa) generated by the falling weight (σ_v in kPa) as experienced by the soil in the mold; finite element modeling allows the calculation of $M_{R(wet)}$ at equivalent stresses in the PVC mold during deflection tests:

$$\sigma_1 = \sigma_v \tag{4}$$

$$\sigma_3 = \sigma_2 = 0.53396\sigma_v + 0.7258 \tag{5}$$

3.3 Frost heave tests

The frost susceptibility of soils was evaluated according to the LC 22-331 standard, which is used by the Ministry of Transportation of Quebec. Samples were compacted similarly to the ones tested for $M_{R(wet)}$ and E_{mold} determination. The method is based on the concept of segregation potential (SP in $mm^2/(°C*day)$), developed by Konrad and Mongenstern (1980), according to which the velocity of water flow to the ice lens (ν in mm/day) is directly proportional to the temperature gradient in the frozen fringe (gradT in °C/mm) :

$$SP = {}^{v}/_{GradT} \tag{6}$$

4 MODELS DEVELOPMENT

4.1 Geotechnical characterization

Based on geotechnical characterization and according to USCS classification, three silty sands (SM), two poorly graded sands (SP) and one well graded silty sand (SW-SM) were sampled. Moreover, four clays were sampled, three of low plasticity (CL) and one of high plasticity (CH). The optimum water content of sands is between 5.9% and 11.0%; for the clays, it varies between 14.7% and 21.0%. The clay content (particles smaller than 2 µm) varies between 0% and 67.3% depending on the soil type.

4.2 Mechanical tests

Figure 2 shows the values of $M_{R(wet)}$ versus E_{mold}. It is possible to identify two types of trends for the tested subgrade soils.

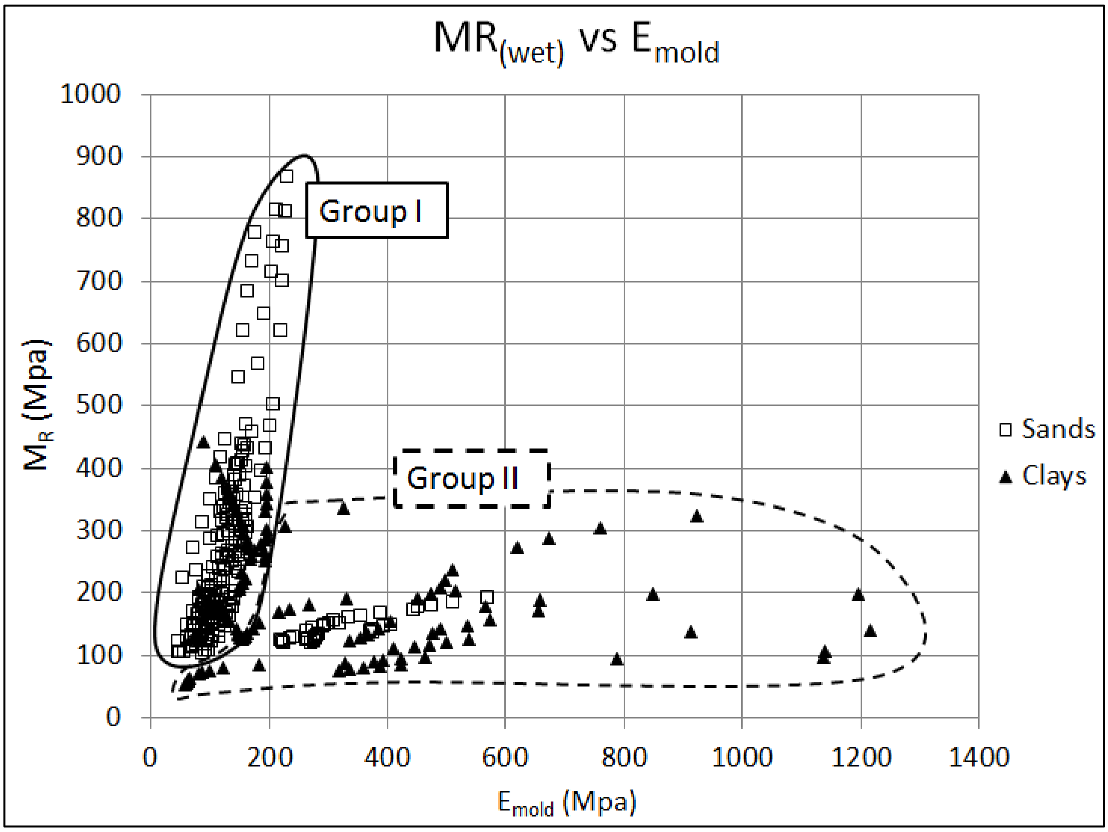

Figure 2: Resilient modulus ($M_{R(wet)}$) vs. back-calculated modulus in the mold (E_{mold})

The “Group I” shows a linear trend and the “Group II” a logarithmic trend. Group I consist of five of the six sampled sands: two SM, two SP and one SW-SM. Group II describes the behavior of clays (three CL and one CH), as well as a silty sand. Therefore, it appears to be difficult to separate the two groups as sands and clays as a silty sand can belong to Group I or Group II.

A detailed analysis of deflection parameters and samples physical properties allowed identifying a variable that can be used to determine to which Group a SM soil should be included. The stresses applied by the LWD cause deflections in the elastic range. Therefore, the relationship between the stress and the deflection is given by a straight line defined by a slope “m” and an intercept point “b”. In the case of soils SM, positive values of b ($b > 0$) implies a Group I behavior; if $b < 0$, it is associated with Group II behavior (Figure 3). Different multivariate linear regression models were evaluated to find simple but reliable models to estimate M_R using a limited number of independent variables into the models.

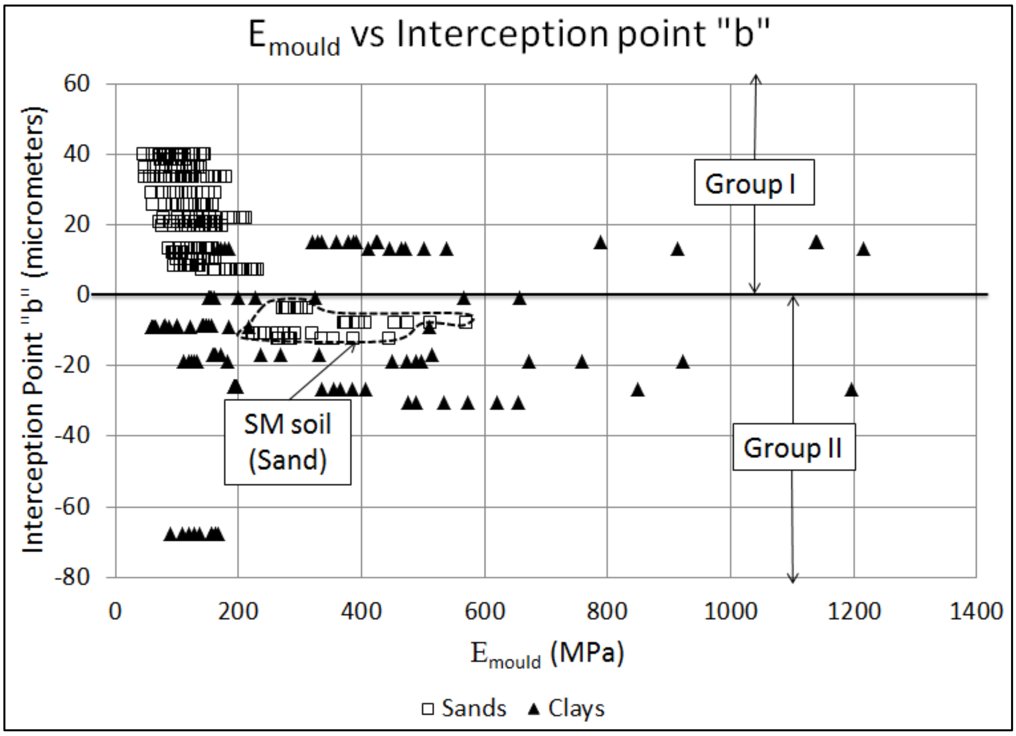

Figure 3: Interception point (b) vs. Back-calculated modulus in the mold (E_{mold})

4.2.1 $M_{R(wet)}$ models for Group I soils

Group I models include sands with b > 0. The mathematical model developed is:

$$\log\left(M_{R\,(wet)}\right) = 0.00514E_{mold} + 0.8278Sr - 0.298P080^{0.615} + 1.288 \tag{7}$$

$r^2 = 0.78$; RMSE = 68; N = 215

This equation allows the assessment of $M_{R(wet)}$ (MPa) as a function of E_{mold} (MPa), obtained with a LWD deflection test on a soil compacted in the 300 mm mold. The use of the degree of saturation of the sample (Sr expressed as a decimal) and of the fine particles percentage P080 (expressed as decimal) has significantly improved the precision associated with the estimation of $M_{R(wet)}$. Such physical parameters are often used to estimate the soils mechanical properties (Rahim and George 2005)

4.2.2 $M_{R(wet)}$ models for Group II soils

Group II soils are clays and the sands with b < 0. In order to estimate $M_{R(wet)}$, The same explanatory variables were used than for Group I soils. The model is expressed as:

$$log\left(M_{R\,(wet)}\right) = 0.2967\,log(E_{mold}) - 3.0152Sr^{10} - 0.3642P080^{3} + 1.505 \tag{8}$$

$r^2 = 0.81$; RMSE = 24; N = 111

4.3 Frost heave tests

The proposed models have been implemented for coarse-grained soils (sands) and fine-grained soils (clays).

4.3.1 Models for coarse-grained soils

The parameter that showed the best correlation with the segregation potential (SP in $mm^2/(°C*day)$) was the percentage passing 80 µm sieve (P080 expressed as a decimal). An initial model was developed based on P080 parameter. The regression model was improved by the addition of dielectric value (DV) as a second explanatory variable. Correlation analysis indicate that the selected variables are in good agreement with the studies of Konrad (1999) regarding the use of physical properties to estimate the SP and with the studies of Guthrie and Scullion (1999) regarding the use of DV to assess the frost susceptibility of soils:

$$SP = 211.5P080 + 6.28 \tag{9}$$

$r^2 = 0.79$; RMSE = 14.6; N = 6

$$SP = 18.34ln(P080) + 2.14DV + 59.77 \tag{10}$$

$r^2 = 0.99$; RMSE = 2.9; N = 6

4.3.2 Models for fine-grained soils

The best explanatory variable for the estimation of SP for fine-grained soils was given by the liquid limit (LL expressed as a decimal). Liquid limit was used by Tice and al. (1976) to predict the unfrozen water content; this concept was also used by Doré et al. (2005) for indirect calculation of SP for subgrade soils. Therefore, a regression model was developed to estimate SP using LL. A second model was implemented using LL and DV, the latter variable improve the correlation of the model:

$$SP = 137.55LL^{-0.5} - 150.66 \tag{11}$$

$r^2 = 0.80$; RMSE = 6.8; N = 4

$$SP = 202.76LL^{-0.5} + 1.8DV - 287.7 \tag{12}$$

$r^2 = 0.99$; RMSE = 1.6; N = 4

5 DISCUSSION

The development of the proposed models was conducted on the premise of using the lowest number of variables in order to generate more reliable correlation models. The resulting models can be used to validate previous research on the use of geotechnical soil properties to assess resilient modulus and frost heave. The selection of independent variables was analyzed as a function of the absence of correlation between them; a correlation threshold of $r = 0.7$ between two variables used in the same equation was determined as a criterion for rejecting the use of one of the two variables.

The straight stress-deflection line provides additional information on the sample properties. The intercept point "b" can be used for: (i) identifying in which Group the sands should be considered (ii) determination of the values of stresses, which may be used to assess $M_{R(wet)}$. Principal stresses can be calculated using (4) and (5) obtained by finite element modeling with SIGMA/W. The calculation of $M_{R(wet)}$ at small strains for soils of Group II is limited by the value of the stress at which $b = 0$ in the straight stress-deflection line. For stress values of σ_v corresponding to $b < 0$ the relationship is asymptotic, as shown by the dotted lines in figure 4, because it is not possible to obtain negatives values for interception point (b) from positives values of vertical stress (σ_v).

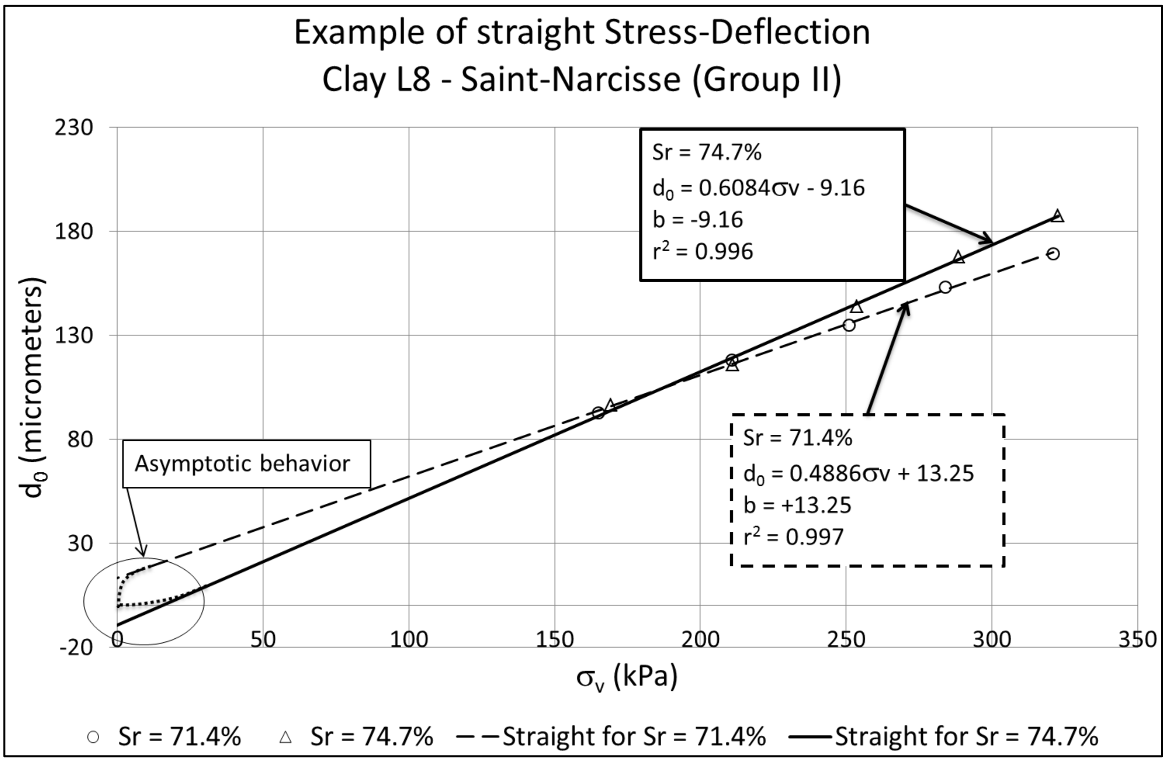

Figure 4: Example of straight stress-deflection line for a Group II soil (Clay L8 – Saint-Narcisse)

The incorporation of the dielectric value in assessing the frost susceptibility of soils has improved the reliability of the prediction of the segregation potential (SP). The parameters used to estimate the SP facilitate the use of the model, since the use with the compacted sample in the 300 mm mold is not required to obtain the variables. Deflection test and dielectric value measurements were performed in situ in order to validate the models obtained in the laboratory and to facilitate their implementation in the field.

6 CONCLUSION

New estimation models were developed for subgrade resilient modulus in combination with a new way of using simple deflection tools such as LWD to precisely obtain soil stiffness. Until now, portable devices were used to monitor subgrade soil properties in comparison with reference values. In contrast, the models presented in this paper give the possibility to calculate design modulus values for a known degree of saturation. The analysis of the resilient behavior of subgrade soils, including the stress path dependency, is now possible by indirect mechanical testing. It represents an improvement in the field of indirect characterization of the mechanical properties of soil and road materials that will allow designers to obtain values closer to those defined as level 1 by the *Guide for Mechanistic-Empirical Design* (NCHRP 2004).

The analysis of the frost susceptibility of soils was enhanced by the development of new models that have validated the results from previous research and that consider the use of the dielectric value.

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