Resilient modulus and segregation potential estimation from simplified laboratory procedure

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Abstract: Design of flexible pavements in regions submitted to seasonal freezing conditions requires a good knowledge of the soil resilient modulus and frost sensitivity. As the tests used for a detailed characterization are complex, costly and require experienced staff, these important design parameters are too often reduced to default values. However, many estimation approaches exist to easily obtain these parameters. New tools such as portable light weight deflectometer and percometer give the opportunity to implement estimation equations based on the soils response measured by these apparatus. A simplified laboratory procedure involving a 300 mm diameter PVC mold was developed in order to obtain the resilient modulus and the segregation potential of various subgrade soils using measurements from portable light weight deflectometer and percometer. The use of the portable light weight deflectometer for resilient modulus characterization is suitable as the short pulse load obtained with this apparatus produces a deflection in the elastic range causing the materials to react similarly to what is encountered in the field. The proposed procedure also allows taking into account the stress dependency of the resilient modulus. Regarding frost susceptibility, the percometer allows obtaining rapid dielectric constant measurement, which was often associated with the segregation potential, on the same sample used for mechanical characterization. In combination with geotechnical characterization parameters, estimation equations were proposed to obtain subgrade soils segregation potential and the resilient modulus from portable light weight deflectometer and dielectric constant measurements.

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1. Introduction

Flexible pavement design in northern environments requires the determination of subgrade response to stress for heavy vehicle loading and frost action [1]. The important parameters associated with these responses are the resilient modulus and the segregation potential, both essentials to determine the layered structure thickness in order to ensure adequate performance throughout the design period. As presented in Figure 1 [2], the resilient modulus (Mr) is associated with the recoverable strain ε_R experienced under deviatoric stress σ_d for elastoplastic engineering materials such as subgrade soils. As presented in Figure 2, the segregation potential (SP) is associated with the frost sensitivity to ice lens formation of the subgrade soils and represents the proportional constant between the water intake velocity (v) in the frozen fringe and the temperature gradient (GradT) [3]. The Mr and SP values are obtained with

(1) $$\mathrm{Mr} = \frac{\sigma_d}{\varepsilon_R}$$

(2) $$\mathrm{SP} = \frac{v}{1.09 \times \mathrm{GradT}}$$

in which 1.09 is a constant that takes into account the 9% volume increase when there is a phase change from water to ice.

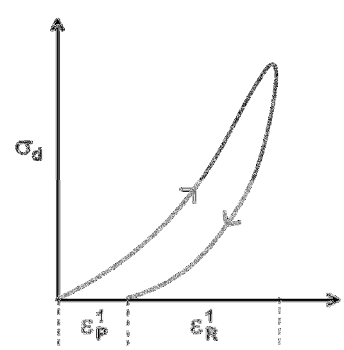

Figure 1. Soils elastoplastic behaviour [2]

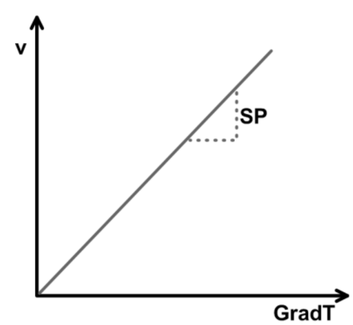

Figure 2. Relationship between water intake velocity and temperature gradient

For idealistic conditions, SP and Mr are determined through direct measurement using a triaxial cell and a freezing cell. However, these tests are costly, complex, time consuming and require experienced engineers and technicians in order to be conducted and interpreted properly. Because of these reasons, many agencies use default values in their design methods for the selection of design values associated with stiffness and frost sensitivity. Simplified estimation techniques were also proposed in order to obtain SP and Mr values based on actual measurements performed on the soils [1, 4]. Regarding frost sensitivity, dielectric constant measurements were successfully associated with this parameter as it is related to the quantity of unfrozen water content in a freezing soil. Regarding resilient modulus, laboratory tests such as CBR were intensively used in the past. The emergence of non destructive tools such as portable light weight deflectometer (PLWD) has given rise to new possibilities regarding the measurement of soils mechanical properties in the laboratory. Therefore, the objective of this paper is to develop a simplified laboratory test to estimate the Mr and SP as it would be determined through conventional procedures.

2. Materials and testing

Ten different soils from various geological regions near Quebec city (QC) were sampled in order to develop the simplified laboratory test procedure. Based on the geotechnical characterization performed on the soils, the sampled soils are SM (3), SP (2), SW-SM (1), CL (3) and CH (1).

The soils were first submitted to standard tests to determine their frost sensitivity (SP) according to standard LC 22-331 and resilient modulus Mr according to standard AASHTO T307-99. Regarding the frost sensitivity, the results were interpreted according to equation 2 in order to calculate the segregation potential. The Mr was determined for various stress state as specified by AASHTO T307-99 and it was modelled according to stress parameters using (Uzan 1985)

(3)
$$Mr(MPa) = k_1 Pa\left(\frac{\theta}{Pa}\right)^{k_2}\left(\frac{\sigma_d}{Pa}\right)^{k_3}$$

in which Pa is the atmospheric pressure (kPa), σ_d the deviatoric stress (kPa), θ the total stress (kPa) and k_1, k_2 and k_3 regression parameters. The triaxial resilient modulus tests were conducted at optimum water content and at wet conditions (degree of saturation at approximately 85%). In order to determine the resilient modulus for any degree of saturation Sr, the model of Drumm et al. [5] was used. It is expressed as

(4)
$$Mr(wet) = Mr(opt) + \frac{dMr}{dSr}\Delta Sr$$

in which Mr(opt) is the Mr at optimum water content, Mr(wet) is the Mr at a wet water content, dMR/dS is the gradient of resilient modulus with respect to the degree of saturation and ΔS is the change of degree of saturation expressed as a decimal. The values of Mr(opt) and dMR/dS were computed from measured values in triaxial cell tests for two degrees of saturation.

In order to estimate the Mr and SP values obtained from standard tests, a simplified test procedure was developed using PLWD and dielectric measurements. The simplified procedure is performed on a soil sample compacted in a PVC hollow cylinder as presented in Figure 3. The cylinder has an internal diameter of 300 mm and the compacted sampled height is set at 350 mm. The cylinder is fixed on a perforated aluminium base connected to a drainage line. This drainage line is used to modify the water content of the compacted samples using a water reservoir. The elastic modulus in the mold *E*mold is calculated using

(5)
$$Emold = \frac{2\left(1-\mu^2\right)\sigma_0 a}{d}$$

in which μ is the poisson coefficient (set to 0.35), σ_0 the vertical stress under the loading plate, a the plate radius and d the measured deflection. A loading plate diameter of 100 mm was selected and five drop heights (50, 75, 100, 125 and 150 mm) were used to obtain various vertical stresses.

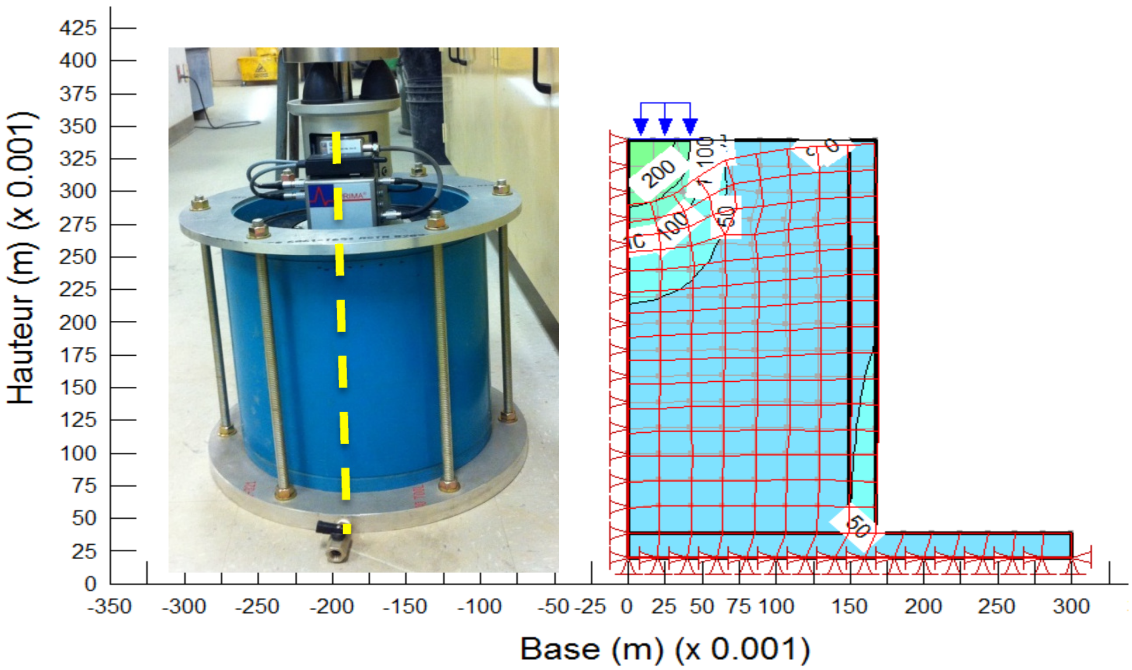

Figure 3. Simplified test procedure using PLWD for resilient modulus estimation

As presented in Figure 3, in order to take into account the particular loading conditions encountered in a confined environments such as a plastic mold, finite element simulations using SIGMA/W were performed to determine the stress conditions of the soil samples inside the mold. These simulations were performed to determine the confining stress level σ_3 occurring when a vertical stress σ_1 is applied under the loading plate. This vertical stress is calculated from the fall height and the loading plate diameter. The simulations allowed obtaining a relationship between the vertical stress and the average confining stress developed during vertical loading over a depth of significant stress. This relationship is expressed

$$\sigma_3 = 0.53396 \times \sigma_1 + 0.7258 \tag{6}$$

Using equation 3 and 4, this procedure allows determining Mr(wet), which is based on triaxial measurements, at similar stress state and degree of saturation than the ones experienced in the PVC mold for *E*mold.

Each test is followed by the measurement with a percometer (Figure 4) of the dielectric value (DV), which 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 4. DV measurement at 5 points on the compacted sample surface using a percometer

3. Model development

<u>Resilient modulus</u>

The laboratory test results allowed investigating the relationship between triaxial resilient modulus Mr(wet) and backcalculated elastic modulus Emold for equivalent stress state and degree of saturation as presented in Figure 5. This analysis clearly shows two different trends which were associated with two soils groups. With some exceptions, a general tendency tends to associate Group I soils with sands and Group II with clays. Following a comprehensive and detailed analysis, these soils groups were differentiated on the basis of the intercept point associated with the relationship between Mr(wet) and Emold as presented in Figure 6. The use of this parameter clearly allowed differentiating soils from Group I and Group II.

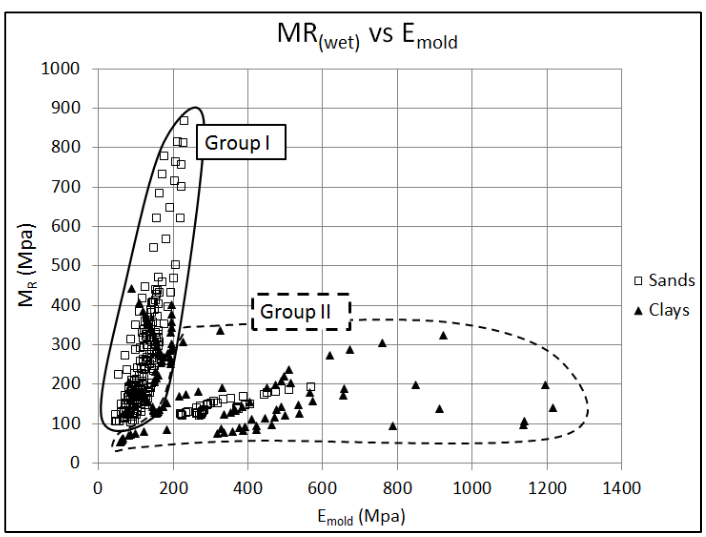

Figure 5. Relationship between Mr(wet) and Emold [6]

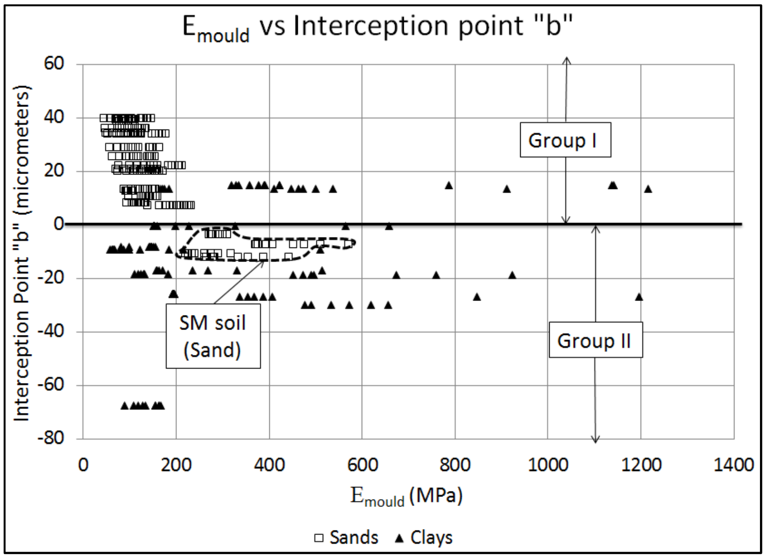

Figure 6. Intercept point values for Group I and Group II soils [6]

A linear multiple regression analysis was performed between Mr(wet) as a dependent variable and Emold as an independent variable. Geotechnical characterization parameters were included in the analysis to improve the estimation the resilient modulus using the proposed simplified procedure. The results of the linear multiple regression analysis are estimation equations expressed as

(7)
$$\mathrm{Log}\left[\mathrm{Mr}(\mathrm{wet})\right] = 0.00514\mathrm{Emold} + 0.8278\mathrm{Sr} - 0.298{P_{80}}^{0.615} + 1.288$$
$$R^2 = 0.78;\ \mathrm{RMSE} = 68;\ N = 215$$

(8)
$$\mathrm{Log}\left[\mathrm{Mr}(\mathrm{wet})\right] = 0.2967\mathrm{Emold} - 3.0152\mathrm{Sr}^{10} - 0.3642{P_{80}}^{3} + 1.505$$
$$R^2 = 0.81;\ \mathrm{RMSE} = 24;\ N = 111$$

in which Mr(wet) and Emold are in MPa, Sr is the degree of saturation in decimal and P_{80} is the percentage of particles finer than 80 µm in decimal.

<u>Segregation potential</u>

In the same manner than the analysis performed between Mr(wet) and Emold, an investigation was made to link the measured segregation potential (SP) measured in a freezing cell with the dielectric value (DV). For the purpose of this analysis, the tested soils were divided according to the results of the geotechnical characterization. Therefore, the two groups used to develop estimation equations are coarse grained soils (1) and fine grained soils (2). Again, linear multiple regression analysis was performed to identify significant relationships between the dependant variable SP and the independent variable DV. Easily obtained geotechnical characteristics generally associated with frost sensitivity were included in the analysis to help improve the relationships. The number of data points, in comparison with the analysis on the mechanical behaviour, is limited because only one SP test was made for each soil for one test condition. This means that this specific measurement is associated with percometer measurements in the mold for a similar test condition. In comparison, each stress state and water content is associated with a measurement of Emold.

The results of the linear multiple regression analysis are estimation equations expressed as

(9)
$$SP = 18.34LN\left(P_{80}\right) + 2.14DV + 59.77$$
$$R^2 = 0.99;\ RMSE = 2.9;\ N = 6$$

(10)
$$SP = 202.76LL^{-0,5} + 1.8DV - 287.7$$
$$R^2 = 0.99;\ RMSE = 1.6;\ N = 4$$

4. Conclusion

Design of flexible pavements in regions submitted to seasonal freezing conditions requires a good knowledge of the soil resilient modulus and frost sensitivity. As the tests used for a detailed characterization are complex, costly and require experienced staff, these important design parameters are too often reduced to default values. However, many estimation approaches exist to easily obtain these parameters. New tools such as portable light weight deflectometer and percometer give the opportunity to implement estimation equations based on the soils response measured by these apparatus. A simplified laboratory procedure involving a 300 mm diameter PVC mold was developed in order to obtain the resilient modulus and the segregation potential of various subgrade soils using measurements from portable light weight deflectometer and percometer. The use of the portable light weight deflectometer for resilient modulus characterization is suitable as the short pulse load obtained with this apparatus produce a deflection in the elastic range causing the materials to react similarly to what is encountered in the field. The proposed procedure also allows taking into account the stress dependency of the resilient modulus. Regarding frost susceptibility, the percometer allows obtaining rapid dielectric constant measurement, which was often associated with the segregation potential, on the same sample used for mechanical characterization. In combination with geotechnical characterization parameters, estimation equations were proposed to obtain subgrade soils segregation potential and the resilient modulus from portable light weight deflectometer and dielectric constant measurements.

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References

[1] Doré, G. and Zubeck, H. 2008. Cold regions pavement engineering. McGraw-Hill, NY.

[2] Bilodeau, J.-P., Doré, G. and Poupart, J. 2012. Permanent deformation of various unbound aggregates submitted to seasonal frost conditions. Accepted for the 15th International Conference on Cold Regions Engineering, Quebec, Canada, August 19-22, 2012.

[3] Konrad, J-M. and Morgenstern N-R., 1980. A mechanistic theory of ice lens formation in fine-grained soils. Canadian Geotechnical Journal. - Edmonton, Alberta, Canada : NRC, Vol. 17. - pp. 473-486.

[4] Huang, Y.H. 2004. Pavement analysis and design. Pearson Prentice Hall, New Jersey.

[5] Drumm, E.; Reeves, J.; Madgett, M. and Trolinger, W., 1997. Subgrade resilient modulus correction for saturation effects. Journal of Geotechnical and Geoenvironmental Engineering, v 123, n 7, p 663-670. The University of Tennessee, Knoxville, United States.

[6] Tafur, D. S., Doré, G. and Bilodeau, J.-P. 2012. Estimation of subgrade soils mechanical properties and frost sensitivity through the use of simple tests. Ninth International Conference on Bearing Capacity of Roads Railways and Airfields, Trondheim, Norway.