Estimation of resilient modulus for compacted unbound granular materials used as base and subbase layers in Canada

Jean-Pascal Bilodeau, ing., Ph.D.
Research associate, department of civil engineering, Laval University

Guy Doré, ing., Ph.D.
Professor, department of civil engineering, Laval University

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Abstract: One of the main flexible pavement design input is the resilient modulus of the granular layers such as the base and the subbase. Unfortunately, this value is too often approximated using default values, or estimated from indirect and non representative tests, as performing resilient modulus testing is complex and costly. Using a database of reliable resilient modulus laboratory tests performed at the Quebec’s Ministry of Transportation, an estimation model was developed for typical Canadian granular materials commonly used in pavement bases and subbases, which allow obtaining a more representative stiffness value for this important design parameter. The proposed model is based on easily and commonly obtained aggregate characteristics. A two step approach was considered which consists in first determining the resilient modulus at the saturated state followed by the determination of the resilient modulus at any degree of saturation using two different models. The model adequately predicts the resilient modulus for the three different tests moisture contents.
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Guy Doré, ing. Ph.D.

1. Introduction

Pavement design is a process of layers thickness optimization that ensures that the structure will meet its design life without excessive deterioration, considering a given traffic and climate [1,2,3]. Through the use of various design methods, one of the main input parameters is layers stiffness, characterized by the resilient modulus, which is unfortunately not often known for unbound granular materials (UGM). This is mostly due to the fact that the equipment for the resilient modulus characterization is costly and the test complex. Because of that, the resilient modulus of the granular layers is often estimated from indirect tests such as CBR, fixed with typical values based on universal soil classification or estimated from typical model parameters. Some estimation models allowing resilient modulus estimation from soils and aggregates index and physical properties are available in the literature [4,5], mostly for subgrade soils. As the aggregate source has a significant influence on the resilient modulus of unbound granular materials [6,7], having an estimation model developed on Canadian granular materials is of great importance.

The resilient modulus $M_R$ is defined as the ratio of the deviatoric stress to the resilient axial strain (Figure 1) as in

$$[1] \quad M_R = \frac{\sigma_d}{\varepsilon_R}$$

in which $\sigma_d$ is the deviatoric stress and $\varepsilon'_R$ is the resilient axial strain [8]. As a matter of fact, when UGM are submitted to a deviatoric axial stress, a complex non linear elastoplastic behaviour is observed. For UGM, the $M_R$ is mainly proportional to the total stress $\theta$, as an increase of $\theta$ increases the stiffness. Several models are proposed to adequately model the resilient modulus stress dependency, such as the K-$\theta$ model, the Uzan model and the linear model [8,9,10]. Most of the $M_R$ estimation models propose in various ways to use stress dependent constitutive equations as the basis of the estimation models. Therefore, it is proposed to use such an approach to develop an estimation model for Canadian UGM, which could become a useful tool for mechanistic-empirical flexible pavement design.
2. Database

The first step of this research process was to gather resilient modulus test results obtained on typical UGM from Canada. Certain selection criteria were imposed in order to ensure a good homogeneity of the database. These criteria are: Canadian UGM, well characterized UGM, laboratory resilient modulus test results, tests performed with the same standard. Two studies performed at the Quebec’s Ministry of Transportation laboratory were selected since they met these criteria. The tests from the selected studies were performed according to the Quebec’s Ministry of Transportation resilient modulus characterization standard LC 22-400 [10], which allows characterizing $M_R$ at three water contents. These three water contents are initial water content (fixed 2% above the aggregate absorption value), saturated water content and drained water content (obtained after gravitational drainage). As moisture content was identified as the parameter having the greatest influence on granular materials mechanical properties [11], the quantification of the effect of moisture content is of great importance. The first study [6] consists in 22 resilient modulus tests on C-LTPP base and subbase granular materials obtained across Canada. The second study from [7] consists in 21 resilient modulus tests performed on three different aggregate sources at various grain-size distributions. Therefore, while the former study was focused on the effect of the aggregate source, the latter study focused on the effect of grain-size distribution. Thus, an interesting complementarity exists between both studies. The variability of some characteristics of the samples included in the database is presented in Table 1.

Table 1. Variability of some characteristics of the tested samples included in the chosen database

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Minimum</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Cu$</td>
<td>Uniformity coefficient</td>
<td>3</td>
<td>44</td>
<td>27</td>
</tr>
<tr>
<td>$n$ (%)</td>
<td>Porosity</td>
<td>13</td>
<td>19</td>
<td>4</td>
</tr>
<tr>
<td>$w_{opt}$ (%)</td>
<td>Opt. water content</td>
<td>4.3</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>$\rho_{max}$ (kg/m$^3$)</td>
<td>Maximum dry density</td>
<td>1579</td>
<td>2206</td>
<td>147</td>
</tr>
<tr>
<td>$\rho_d$ (kg/m$^3$)</td>
<td>Dry density</td>
<td>1686</td>
<td>2142</td>
<td>103</td>
</tr>
</tbody>
</table>

3. Model development
The multiple linear regression analysis, in combination with the least squares criterion, was used to develop the resilient modulus estimation model for unbound granular materials used in pavement base and subbase. After the determination of the basic statistics, correlation matrixes were calculated between the dependent variable, which is the resilient modulus (characterized by model parameters), and the independent variables, which are associated with gradation, moisture content and density. Through the statistical process, efforts were made to ensure that the proposed model uses only easily obtained aggregate characteristics. As proposed in other researches, it is suggested to express $c_1$ and $c_2$ as a function of aggregate blend properties. These values are the regression material parameters obtained from the linear model defined by

$$ \theta = R_M c_1 + c_2 $$

in which $\theta$ is the bulk stress expressed in kPa. Preliminary regression analyses were made on three constitutive laws, which are the K-$\theta$ model, the Uzan model and the linear model. This analysis revealed that more satisfying results are obtained using the linear model for the selected data set. In order to isolate the effect of aggregate characteristics such as gradation and density, the effect of the water content was considered separately. This approach is also privileged in the MEPDG. Therefore, it is proposed to estimate the resilient modulus at an equivalent degree of saturation for each sample. As saturated samples were tested in the considered studies, those samples represent the same matrix suction of approximately zero. As it was previously demonstrated [6], matrix suction adequately represents the changes in resilient modulus with the changes of the degree of saturation as it affects the aggregate blend effective stress. Therefore, the regression analysis and model development was first performed on the saturated samples. Thus, the resilient modulus estimation is a two step process: 1. Saturated resilient modulus estimation based on the aggregate characteristics; 2. Changes of resilient modulus with a decrease of the degree of saturation. Therefore, the proposed estimation model is defined by

$$ \Delta M_R = c_{1s}\theta + c_{2s} + \Delta M_R = M_{Rsat} + \Delta M_R $$

in which $c_{1s}$ and $c_{2s}$ are material regression parameters at saturated state, $\Delta M_R$ is an increase of resilient modulus with a decrease of the degree of saturation and $M_{Rsat}$ is the resilient modulus at the saturated state. Two different approaches [6,7,12] developed Canadian studies were considered to evaluate the $\Delta M_R$ value.

4. Results and analysis

4.1. Resilient modulus estimation at the saturated state

In order to determine the resilient modulus at the saturated state, correlation matrix were computed between the measured $c_{1s}$ and $c_{2s}$ values and explanatory variables associated with density grain-size distribution and moisture content. This statistical analysis allowed
identifying the explanatory variables that are more associated with the $c_1s$ and $c_2s$ values. Multiple linear regression analysis result is estimation equations defined by

\[ c_1s = -6.259 - 0.508 \left( \frac{Cu}{n_f} \right) + 7.725 \left( \frac{\rho_{d_{\text{max}}}}{\rho_d} \right) - 0.107 \times w + 0.168 \times w_{\text{opt}} \]  
\[ (R^2 = 0.73) \]  

\[ c_2s = 879.476 + n \times (14.353 + 0.00557 \times \rho_s) - 0.557 \times \rho_s - 6.213 \times n_c + 0.253 \times \rho_{d_{\text{max}}} - 27.533 \times w \]  
\[ (R^2 = 0.80) \]

in which $Cu$ is the uniformity coefficient, $n_f$ the fine fraction porosity (%) as defined by Côté and Konrad [13], $\rho_{d_{\text{max}}}$ is the maximum dry density (kg/m³), $\rho_d$ is the dry density (kg/m³), $w$ is the water content (%), $w_{\text{opt}}$ is the optimum water content (%), $n$ is the porosity (%), $\rho_s$ is grain density (kg/m³) and $n_c$ is the coarse fraction porosity (%) as defined by Côté and Konrad [13]. The values of $n_f$ and $n_c$ are defined by

\[ n_c = n + (1 - n)\%F \]

\[ n_f = \frac{n}{n + (1 - n)\%F} = \frac{n}{n_c} \]

in which $\%F$ is the fines content (<80 µm). Using the proposed estimation equations for $c_1s$ and $c_2s$, a predicted versus measured saturated resilient modulus values for 375 data was produced in Figure 2. An estimation error of 15% was found for the saturated state using the estimation model. I should be emphasized that, in order to use the proposed approach, it is only necessary to perform grain-size distribution analysis, grain density and modified proctor tests, which are commonly performed on pavement granular materials.

![Figure 2. Predicted versus measured resilient modulus using the proposed estimation equations](image)

4.2. Calculation of resilient modulus variations with changes of the degree of saturation

The estimation of the resilient modulus at the saturated state theoretically represents the lower stiffness value for a pavement granular material. As the degree of saturation
decreases, an increase of resilient modulus should be measured. The $\Delta M_R$ value in the proposed approach takes into account this phenomenon and allows adjusting the saturated resilient modulus values for any degree of saturation. The two studies used to gather data for the model implementation propose two different approaches that allow quantifying the effect of the degree of saturation on the resilient modulus. The first approach [6] considers the relationship between the degree of saturation and the matrix suction in order to evaluate the effect of moisture content on the resilient modulus value. The proposed relationship between $\Delta M_R$ and the matrix suction is

$$
\Delta M_R (kPa) = -8700(u_a - u_w) - 17000
$$

in which $(u_a - u_w)$ is the matrix suction (kPa). The study presented by Doucet and Doré introduced a general relationship between the degree of saturation and the matrix suction which was quantified by Mellizo [14] with

$$
S_R (%) = 57.483 \times e^{-\frac{(u_a - u_w)}{-21.879}} + 38.353 \times e^{-\frac{(u_a - u_w)}{1.596}} - 7.858
$$

in which $(u_a - u_w)$ is in kPa. Therefore, for the degree of saturation measured in both considered studies at initial and drained water contents, it was possible to quantify the matrix suction and, therefore, compute $\Delta M_R$.

The second method [7,11] directly considers the variations of resilient modulus with the changes of the degree of saturation. With this method, the $\Delta M_R$ is expressed

$$
\Delta M_R (MPa) = S \times \Delta S_R
$$

in which $S$ (MPa/%) represents the slope of the relationship between $\Delta M_R$ (MPa) and $\Delta S_R$ (%), the latter being the change of the degree of saturation. For the purpose on the proposed estimation model, since the estimation of the resilient modulus is first made at the saturated state, $\Delta S_R$ is in that case equal to $S_R - S_{Rsat}$ or approximately equal to $S_R - 100$. The $S$ value was found to be adequately estimated with the granular materials fine fraction porosity $n_f$ and found to be a function of bulk stress $\theta$. Using the procedure proposed by Bilodeau [7], a $S$ parameter determination equation was adapted using the considered data in this study. For the data used in the model, $S$ is defined by

$$
S (\frac{MPa}{\%}) = (0.00003 \theta + 0.0206)(n_f - 113.636) + 0.31818
$$

in which $\theta$ is the bulk stress (kPa) and $n_f$ the fine fraction porosity (%). Figure 3 presents the predicted versus measured plots at initial and drained water contents using both $\Delta M_R$ evaluation methods, as well as predicted versus measured plot at the saturated water content to ease the comparison. For the 375 data points considered, the estimation error remains at 15% for the $\Delta M_R$ evaluation method proposed by Bilodeau [7], while it is 19% for the $\Delta M_R$ evaluation method proposed by Doucet and Doré [6] at the initial and drained water contents.
5. Conclusion

A resilient modulus estimation model was developed for unbound granular materials commonly used in flexible pavement bases and subbases in Canada. A reliable database was created using laboratory resilient modulus tests data obtained at the Quebec’s Ministry of Transportation. The proposed estimation model uses easily and commonly obtained unbound granular materials characteristics related to grain-size distribution, grain density and modified proctor. The model is based on a two step approach, which first allows calculating the saturated resilient modulus and, second, allows quantifying the changes of stiffness with changes of the degree of saturation. Considering the estimation error of approximately 15%, the proposed model represents an interesting alternative to the use of default values based on unified classification or to the use of default constitutive law parameters.
References


