Analysis of the resilience modulus of a subgrade soil front of humidity variations

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Abstract. The influence of the variation of moisture content in the materials that make up the pavement has a negative impact on its performance. This variation in humidity is caused by inefficient drainage, oscillation of the water table, infiltrations, which affect the resistance and increase the deformability. The objective of this article is to evaluate the effect of moisture variation on the behavior of soils used in pavement subgrade from tests of resilience module. The subgrade of the highway BR-290/RS located in the state of Rio Grande do Sul/Brazil was evaluated. The repeated load triaxial equipment was used to perform tests of the Resilience Module (MR), varying the moisture content of the specimens by ± 2% in relation to the optimum humidity. There was a 70% decrease in MR comparing specimens above the optimum humidity with the ideal humidity conditions. A new MR equation was proposed that considers the variation in humidity, which showed high statistical significance. The results presented showed a great influence of the moisture content in soils, showing that the present article can contribute to a better understanding of the behavior of soils and a greater discussion about the effect of moisture variation in the dimensioning of pavements.

1 Introduction

The lower layers of the pavement (base, sub-base and subgrade) are compacted in unsaturated conditions and must be in their optimum moisture content. However, seasonal variations in the degree of saturation are expected during the life of the pavement, since it goes through fluctuations in the water table level, water percolation, infiltration by surface cracks, lateral movements through the shoulder, among others [1]. The occurrence of excessive humidity produces a reduction in the pavement's support capacity, starting its degradation ([2], [3], [4], [5]).

The soil resilience module (MR) is an essential property for understanding the behavior of the pavement ([6], [7]). The MR is one of the most important parameters in characterizing the mechanical behavior of soils, as it defines the resilient behavior of each material when subjected to cyclic loads. In Brazil, the first studies on the determination of the MR were carried out by Preussler and Svenson ([8], [9]).

The resilient behavior of soils is strongly affected by soil density, fines content, particle shape and maximum aggregate diameter [10]. The state of tension and the water content also perform significant roles. Because of this complex relationship between the MR, water content, stress state, type of material, it is necessary to evaluate the structure through mechanistic approaches, also considering the traffic conditions and climate. Over the years, several studies have been carried out related to the factors that influence MR, as well as the influence of resilient deformations of soils on the performance of flexible pavements ([11], [12], [13], [14], [15]).

In Brazil, where there is a predominance of humid tropical climate, the moisture content in the subgrade can vary due to several factors related to the environmental changes in the region where the pavement is built. Brazilian studies indicate that pavements with efficient drainage systems reach a state of moisture balance with the environment a few months after construction. This range of equilibrium humidity obtained is typically below the optimum humidity ([16], [17], [18], [19], [20], [21], [22], [23], [24], [25]).

Unfortunately, the recurring construction of more economical pavements often leads to unsatisfactory drainage conditions and premature defects. As a result, the consideration of bands with higher moisture content benefits the analysis of the pavement behavior.

A few studies have been carried out to evaluate the influence of humidity variation on the resilience module ([21], [24], [26], [27], [28], [29], [30], [31], [32]), and demonstrated that the humidity condition in the subgrade is an important factor and that it can strongly affect the pavement's support capacity. When there is an increase in saturation, due to external factors, there is a decrease in MR and an increase in deformability, showing the importance of having a greater knowledge of the subject.

This paper presents a study of the influence of moisture on the resilient behavior of a soil used as a subgrade on a highway in southern Brazil. The material

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was investigated for its basic and mechanical characteristics through the variation of humidity. This paper also evaluated the use of existing models that correlate MR with several factors and proposes a new model that can be used in pavements in tropical regions.

2 Materials and Methods

2.1 Subgrade Material

The soil used corresponds to the subgrade of the federal highway BR-290/RS, collected at km 14+630. This highway is located in the south of Brazil, in the state of Rio Grande do Sul and is an important connection between the state capital, Porto Alegre, and the coast.

The choice of this location considered its proximity to Lagoa dos Barros, a place close to the municipality of Osório/RS. Due to its proximity to a watercourse and because the highway has an important role in the development of the southern region of Brazil, there was a need to verify the elastic deformability of the material that makes up the subgrade of the highway, in order to evaluate whether it supports the humidity variation.

The basic properties and classification of this material are shown in Table 1.

Table 1. Basic properties for the subgrade soil

Properties	Soil
Particle size	With dispersant
Gravel (%)	0.0
Sand (%)	21.0
Silt (%)	43.0
Clay (%)	36.0
Index Properties	
Specify gravity (g/cm³)	2.633
Liquid limit (%)	53
Plastic limit (%)	36
Plasticity index (%)	17
Classification	
TRB	MH
USCS	A-7-5
Compactation	Standard Proctor energy
W_{opt} (%)	28.1
Pd max (g/cm³)	1.44
Degree of saturation (%)	86.9

Notation: TRB = Transportation Research Board, USCS = Unified Soil Classification System, W_{opt} = optimum water content, ρd max = maximum dry density

The soil in question is mainly comprised of silt (43%). According to the Unified Soil Classification System (USCS), the soil belongs to the group of highly compressible silty soils (MH). For the Highway Research Board (HRB) classification, the soil is classified as A-7-5. According to the Paving Manual [33], the soils belonging to subgroup A-7-5 can be highly elastic and subject to high volume changes.

2.2 Methods

2.2.1 Resilient Behavior Analyses

The specimens were compacted following the procedures presented by the Brazilian standard DNIT 134 [34], but with the humidity above and below the optimum content, in a range of ± 2%.

Table 2 presents the test program with the humidity variation used and the respective dry specific weight obtained in the compaction of the sample. Five humidity variations were performed, with samples in duplicate.

Table 2. Test program performed

Molding Moisture Content	Compaction Humidity (%)	Maximum Dry Density (g/cm³)
W_{opt}	28.1	1.435
$W_{opt+1\%}$	29.1	1.420
$W_{opt+2\%}$	30.1	1.362
$W_{opt-1\%}$	27.1	1.428
$W_{opt-2\%}$	26.1	1.411

After demoulding and measuring the height of the specimen, it is then prepared inside a triaxial chamber, ensuring that it is not disturbed. The tests were performed using the triaxial equipment with repeated loads to obtain the MR of the material with different humidity. The axial deformation of the specimen is measured by a displacement transducer of the type LVDT (Linear Variable Differential Transformer). The LVDT transforms the specimen's deformations into an electrical potential that is transmitted to the reading program, which receives the confining stress and deviation as input data, automatically calculating the MR for certain stress.

The test procedures are also presented by the Brazilian standard DNIT 134 [34] and include a conditioning phase before the test, which is carried out to eliminate the imperfections of the impression and the initial contact irregularities. The test itself is performed using 18 pairs of stresses of at least 10 cycles each, with the confinement stress varying between 0.020 and 0.140 MPa and the deviation stress between 0.020 and 0.420 MPa.

2.2.2 Evaluation of literature models

The results were modelled considering the five equations presented in Table 3. Models MR1 to MR4 are more established models and consider basic aspects of resilient behavior. The MR1 and MR2 models are mostly used for granular materials, where the MR depends the bulk or confining stress. In well-graded granular soils, the resilient behavior is improved due to the interlocking of the grains. The greater the confining stress, the greater the resilient module. The MR3 model is generally used for cohesive soils, where the deviator stress has the greatest influence. The MR4 model incorporates both parameters (deviator stress and confining stress) and can be applied to both granular and cohesive materials.

This model is officially adopted in Brazil by the National Department of Transport Infrastructure (DNIT). Finally, the MR5 model was based on the behavior of fine sands in Mexico and considers the moisture content.

Table 3. Resilient modulus models from the literature

ID	Reference	Variables	Equation
MR1	[35]	θ	$MR = k_1 \times \theta^{k_2}$
MR2	[35]	σ_3	$MR = k_1 \times {\sigma_3}^{k_2}$
MR3	[8]	σ_d	$MR = k_1 \times {\sigma_d}^{k_2}$
MR4	[36]	$\sigma_3; \sigma_d$	$MR = k_1 \times {\sigma_d}^{k_2} \times {\sigma_3}^{k_3}$
MR5	[31]	$\sigma_3; \sigma_d; w$	$MR = e^{k_1 - k_2(w - w_{opt})} \times \left(\frac{\sigma_d}{\sigma_3}\right)^{k_3}$

Notation: ID = identification, θ = bulk stress, σ_3 = confining stress, σ_d = deviator stress, $w\text{-}w_{opt}$ = deviation from the optimum water content, k_1, k_2, k_3 = model parameters.

2.2.3 Statistical Analyses

Statistical analysis was performed to consolidate the results and provide a more complete analysis. A regression analysis was performed using the Minitab 17 Statistical software, indicating the analysis of variance, the summary of the model, the coded coefficients, the regression equation in non-coded units and the indications about the atypical values. Minitab also provides the option of graphically representing the results in different ways. With that, the graphs that best represented the results were verified, in order to facilitate their analysis.

3 Results and discussion

3.1 Specimen compaction

The cyclic triaxial tests were carried out aiming at determining the MR of the subgrade soil of BR-290/RS, varying the material moisture between ± 2% in relation to the optimum humidity. For each pair of deviator and confining stresses applied, a specific MR value was obtained. At the end of the test, 18 values of MR were obtained for the studied material and in the determined humidity.

Table 4 shows the results obtained for specimen preparation and the results of dynamic triaxial tests, with the MR values being the average of each test. Table 4 also shows that uniform conditions of the specimens were obtained during compaction. In relation to the MR values, it appears that it increased with the decrease of the moisture content, as was already expected. Many researchers observed similar behavior and indicated that the MR can be predicted by assessing this humidity variation in relation to optimum humidity ([21], [26], [27], [28], [31], [37], [38]).

The wetest specimens, with +1 and +2% did not reach the end of the test, indicating that soils are moisture sensitive materials and that they do not perform satisfactorily in excessive humidity conditions.

Table 4. Summary of specimens parameters and MR results

Specimen	Compaction			DC	S	MR
	w	Maximum dry density	*e*			
	(%)	(g/cm³)	(-)	(%)	(%)	(MPa)
1	26.1	1.410	0.87	99.9	79.2	39.7
2	25.9	1.408	0.87	99.8	78.4	41.7
3	26.9	1.426	0.85	99.9	83.7	32.5
4	27.2	1.429	0.84	100.1	85.0	40.1
5	28.3	1.434	0.84	99.9	89.1	31.5
6	28.0	1.435	0.83	100.0	88.3	27.8
7	28.9	1.422	0.85	100.1	89.4	12.8
8	29.1	1.420	0.85	100.0	89.7	10.6
9	30.2	1.360	0.94	99.9	85.0	10.1
10	30.3	1.358	0.94	99.7	85.0	7.5

Notation: DC = degree of compaction, w = water content, e = void ratio, S = degree of saturation, MR = resilient modulus

3.2 Evaluation of literature models

The performance of the five models presented in Table 3 was evaluated using the results obtained in the triaxial tests with specimens varying the humidity by ± 2%. The first three models (MR1, MR2 and MR3) were analyzed for historical reasons, where in the past they have proven their usefulness. These models only consider a tension state variable and have limited resources.

The MR4 model combines the effects of confining stress and deviator stress, but disregards the moisture content. The MR5 model introduces the effect of water content and can be more representative with that verified in the field. The values obtained for the parameters of these models are shown in Table 5.

Table 5. Parameters obtained with the literature models

ID	Reference	k_1	k_2	k_3	R^2
MR1	[35]	22.75	-0,11	-	0.02
MR2	[35]	29.40	0.018	-	0.00
MR3	[8]	15.16	-0.22	-	0.10
MR4	[36]	32.63	-0.45	0.43	0.21
MR5	[31]	3.37	0.24	-0.51	0.67

Notation: R^2 = coefficient of determination, k_1, k_2, k_3 = model parameters

According to Table 5, the model that best adapted the material used was the MR5, presented by Pérez-García et al. (2015), which takes into account the variation in moisture content. The models that showed lower performance were the MR1 and MR2, which are better adapted for granular materials, than for cohesive materials. The MR3 4 MR4 models showed better behavior than the MR1 and MR2, but still with a low R^2.

It is perceived through the use of the models in the literature, that the consideration of the variation of the moisture content can present significant relevance and that this parameter directly interferes in the resilient behavior of the material under study.

3.3 Development of new model for the resilient modulus

Many studies have discussed the importance of incorporating the moisture content in the models, allowing a correct correlation with the MR ([39], [40], [41]). The analysis of the models in the literature presented in the previous section showed that the model that incorporates water content as an independent variable can produce better results than traditional models.

Based on the results obtained in the previous section, it was verified that the new equation to be proposed in the present work should consider this moisture content variable. For that, using the Minitab software, the results obtained in the repeated load triaxial tests related to the proper humidity of each sample were plotted, in order to obtain a general model that considered this variable.

Linear regression analysis was performed to assess the dependence of the deviator stress, confining stress, saturation and variation of the moisture content in the MR results. First, an analysis of the result was performed, excluding non-significant factors (variables and interactions) and correcting values identified as atypical, when necessary. At the end of this analysis, a model was arrived at, for predicting the Resilience Module.

Equation 1 represents this model mathematically:

$$MR = -0{,}18\ \sigma_d + 0{,}36\ S + 47{,}8\ (w - w_{opt}) + 0{,}15\ \sigma_3 - 0{,}69\ S \times (w - w_{opt}) \qquad (1)$$

Where σ_d = deviator stress, S = saturation, $w\text{-}w_{opt}$ = the deviation from the optimum water content, σ_3 = confining stress.

The coefficient of determination R^2 provided by the Minitab software is a measure of the statistical significance of the regression in relation to the adjustment of the sample data [42]. For the model obtained, an R^2 of 0.92 and an adjusted R^2 of 0.91 were achieved, which demonstrates the high degree of reliability of the results.

Table 6 presents the coefficients of the regression model and their respective "p" values. The "p" value allows to verify if the effect is considered significant when it is less than the 5% significance level.

Table 6. Coefficients and p-values of the regression model

Term	Coef	p-value
$W\text{-}W_{opt}$ (%)	47.8	0.042
Deviator Stress (kPa)	-0.18	0.000
S (%)	0.37	0.000
Confining Stress (kPa)	0.15	0.046
$W\text{-}W_{opt}$ (%) * S (%)	-0.69	0.016

According to the p values obtained for each of the model's parameters, it appears that all of them had a significance level below 5%. Considering the interaction between them, only the interaction between deviation from the optimum water content and saturation was significant and was maintained in the proposed equation.

Fig 1 shows the 3D surface with the effects of the variables deviation stress and deviation from the optimum water content in relation to the MR. As the graph shows, when increasing the deviator stresses during the test and also when increasing the humidity in addition to the optimum humidity, the resistance of the material decreases, resulting in a lower MR. The humidity variation appears to be the factor that most impacts the resistance drop considering this material.

4 Summary and conclusions

This article presented a study of the resilient behavior of a subgrade soil on the BR-290/RS highway, collected at km 14+670, near Lagoa dos Barros, in the state of Rio Grande do Sul - Brazil.

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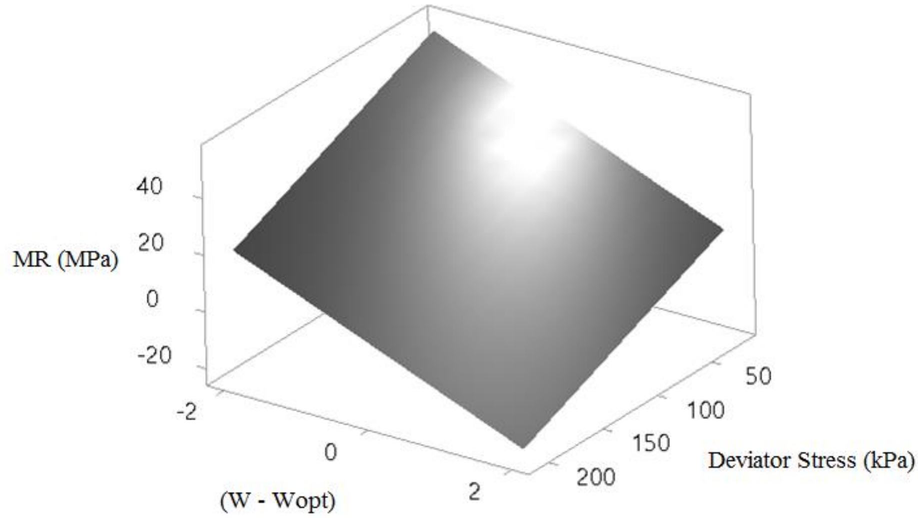

Fig 1. 3D surface considering deviation from the optimum water content (%) and deviator stress (kPa).

A new MR model was introduced which considers the influence of the variation of moisture content in the material resistance. The study was based on laboratory tests, evaluation of models in the literature and statistical analysis.

Laboratory tests were performed varying the moisture content of the material between ± 2% in relation to the optimum moisture content. After the specimen conditioning phase, with higher moisture content in relation to the optimum, the specimen broke before the end of the test, showing that the deformability in these conditions was significant. The increase in the moisture content strongly influenced the MR values, making it decrease up to 70% when compared to the MR obtained in the optimal humidity. It is important to note that small variations in the degree of saturation caused great variations in the deformability of the analyzed soil.

The low values of MR obtained for the soil in both the dry and wet branches show the low support capacity of the studied material. This becomes evident when evaluating the structure of the pavement built in BR-290/RS, considered as robust.

The classic models ([36], [9], [37]) that do not incorporate the parameters related to the water content, presented relatively poor performance for this studied soil, under conditions of variable moisture content. The model which incorporates water content variables [32], showed superior performance, but also has some limitations.

A new equation of resilience module has been proposed considering the humidity variation in relation to the optimum moisture content and saturation, in addition to the parameters already consolidated, such as the deviator stress and confining stress. The regression analysis indicated that the consideration of the moisture content variation factor was significant, as well as the other factors included in the new equation. The proposed new equation showed high statistical significance (R^2 of 0.92) showing a good adjustment.

The results presented show the great influence of the moisture content in the soils. The practical impact of the MR model proposed in this article must be evaluated later, assessing the variation of the water content of the pavement under different pavement structures, materials and drainage conditions. These additional studies can assist in the introduction of models in a mechanistic method of pavement design.

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