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Full Length Research Paper

Implementation of Resilient Modulus - CBR relationship in Mechanistic-Empirical (M. -E) Pavement Design

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Abstract:

One of the most important part of mechanistic flexible pavement design, is the determination of the resilient modulus (Mr) to characterize the mechanical behavior of road structures. Because of the complexity and cost of the test, correlations have been established to predict resilient modulus. California bearing ratio (CBR) is the most used parameter to estimate resilient modulus since this parameter is not expensive and is easy to obtain. The objective of this paper is to implement Mr-CBR relationship in Cast3m, to verify the impact of correlations on the mechanistic design of the base course. In fact, correlations have been established based on statistical analysis. The predicted modulus is used to replace Young's modulus representing the stiffness modulus of the base course. The Uzan model is also implemented to compare the deformations obtained by these two structures. Tri-dimensional modeling performed on six pavements structures, shows that, the deformations obtained with the pavements resilient modulus predicted is higher than pavements with Uzan model. These excessive deformations due to the use of inadequate modulus, generate damages and premature failures in pavements.

Keyword: Mechanistic; Resilient modulus; CBR; Flexible pavement; Cast3m; Correlation; Tri-dimensional modeling.

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1. Introduction

The most important part in the mechanistic flexible pavement is the mechanical characterization of unbound granular materials. These materials are characterized by a nonlinear elastoplastic behavior and the characteristic modulus of this behavior is the resilient modulus (Mr) [1]. The resilient modulus is determined from repeated load triaxial apparatus for simulating wheel load. However, triaxial apparatus is expensive and the realization of the test requires a lot of time and qualified personnel. To reduce the cost, time road projects and to facilitate the work of engineers, finding relationships to predict resilient modulus is required [2]. In fact, many relationships have been established to estimate resilient modulus, but the most common one is the Mr-CBR relationship. Since the CBR is easy to determine in laboratory, not time consuming and it is not expensive.

However, the use of these correlations is the cause of the damage observed in our roads. Studies Boateng et *al.* [3].showed that this relationship ''over-predicted'' or ''under-predicted'' resilient modulus. In addition, an "under-prediction" of resilient modulus, cause an under-design and premature deterioration of roads. This article discusses the Mr-CBR relationship of unbound granular materials from Senegal and the influence of correlations on the mechanistic design of the base layer after numerical simulation under Cast3M©.

2. Literature Review

The first relationship between the resilient modulus and CBR was developed by Heukelom and Foster [4], further to dynamic tests on various types of soil of platform. The results led to the following relationship:

$$Mr(psi) = 1565 \times CBR \quad \text{[Eq. 1]}$$

Mr : Resilient modulus (psi)
CBR : California Bearing Ratio (%)

Later in 1962, Heukelom collaborated with Klomp to find the famous Heukelom and Klomp relationship below :

$$Mr(psi) = 1500 \times CBR \qquad \text{[Eq. 2]}$$

Mr : Resilient modulus (psi)
CBR : California Bearing Ratio (%)

This relationship can be expressed (in MPa):

$$Mr(MPa) = 10 \times CBR \qquad \text{[Eq. 3]}$$

Mr : Resilient modulus (MPa)
CBR : California Bearing Ratio (%)

This equation was developed based on dynamic impedance test and Rayleigh waves in Netherlands and UK. This relationship was derived from the results of wave propagation test at low strain levels and dynamic deflection tests. The results have been modified for suitable values of Poisson ratio and modulus varying from 2 to 200 MPa in order to establish relationships with CBR [5].

Green and Hall [6], the U.S. Army Corps of Engineers proposed relations 4 and 5 resulting from the comparison of measurements of vibration wave propagation measurements in-situ CBR on experimental roads.

$$Mr\ (psi) = 5409 \times CBR^{0.71} \qquad \text{[Eq.4]}$$

$$Mr\ (MPa) = 37.3 \times CBR^{0.71} \qquad \text{[Eq.5]}$$

Mr : Resilient modulus
CBR : California Bearing Ratio (%)

The South African Council on Scientific and Industrial Research (CSIR), adopted equations of the form **Mr = k.CBR**, by modifying the k factor which depend on the nature of the material and laboratory tests [7]. It offers equation 6 to estimate the resilient modulus.

$$Mr(psi) = 3000 \times CBR^{0.65} \qquad \text{[Eq.6]}$$

Mr: Resilient modulus (psi)
CBR: California Bearing Ratio (%)

Powell et *al.* [8] found the relation 7, based on in-situ CBR test and wave propagation. This relationship is only valid for CBR values included between 1 and 12:

$$Mr(ksi) = 2554 \times CBR^{0.64} \qquad \text{[Eq. 7]}$$

Mr : Resilient modulus (ksi)
CBR : California Bearing Ratio (%)‘

Transportation and Road Research Laboratory (TRRL) establish the relations 8 and 9 as follows:

$$Mr(psi) = 2555 \times CBR^{0.64} \qquad \text{[Eq. 8]}$$

$$Mr(MPa) = 17.6 \times CBR^{0.64} \qquad \text{[Eq. 9]}$$

Mr: Resilient modulus
CBR: California Bearing Ratio

The analysis shows that there are a numerous of relationships between the resilient modulus and CBR, the most used one is the Heukelom and Klomp relationship [5]. The literature tells us that these relationships are very limited. Indeed, most of these relationships are applied to fine soils with very low values of CBR.

However, the Mr-CBR relationship has interested by many authors and this study creates many discussions on scientific community. Angell [9] noted that the relationship of Heukelom and Klomp is not suitable for estimating the resilient modulus. He indicated that this relationship ‘’under-estimates’’ the modulus for an CBR less than 5 % and ‘’over-estimates’’ it for CBR greater than 5 %.

Fall [10] suggested that the CBR test is arbitrary and therefore its results are difficult to link with a stiffness parameter of soil. Hopkins et *al.* [11] reported that, Lotfi [12] suggested that the dispersed values of resilient modulus predicted from Heukelom and Klomp's equation are owed only to the absence of the deviatoric stress in the expression and that the relationship is valid for less than 10 or 20 CBR values.

Sukumaran et *al.* [13] studied a finite element analysis of the CBR test to correlate the resilient modulus. The results show that the CBR is not suitable for estimating the resilient modulus. Indeed, they consider that the CBR is a measure of strength so it is not correlated with the resilient modulus which is a measure of stiffness. In addition, the resilient modulus is strongly dependent on the stress state.

They suggested estimating the resilient modulus from unconfined compressive test. Brown et *al.* [14] showed that the resilient modulus is not a simple function of CBR, but depends on the soil type and the level of the applied deviatoric stress. Drumm et *al.* [15] suggested that the CBR is a measure of strength, thus is not allowed to be correlated with the resilient modulus which is a measure of stiffness. Kumar et *al.* [5] have done significant work on the relationship between the resilient modulus and CBR.

This work shows that these two parameters are significantly different in nature. Indeed, Mr is determined from a dynamic load test, while the CBR corresponding to a force measurement results from a monotonous test. Furthermore, the resilient modulus depends on the state of stress.

3. Methodology

4. Experimental work

1. - Grain size distribution

The particle size analysis is carried out according to the standard NF P 94-056 [16] and the curves of Figures 1, 2 and 3 were obtained. These curves are based on specification defined by CEBTP [17]. These figures show that all these curves are spread and therefore, the materials have the advantage of having high densities and mechanical properties, and low permeability and easily compactable.

Table 1 summarizes the characteristics of various particle size materials studied.

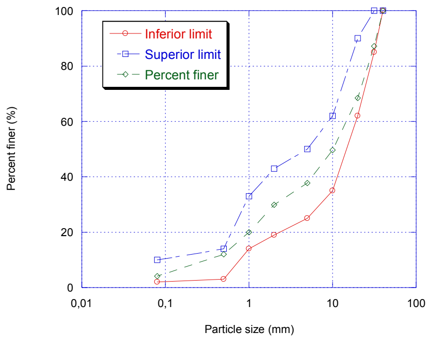

Figure 1. Grain size distribution curve of Bandia limestone

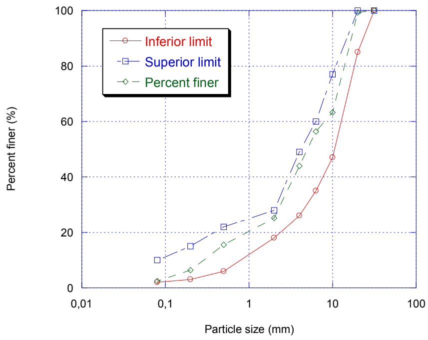

Figure 2. Grain size distribution curve of Bargny limestone

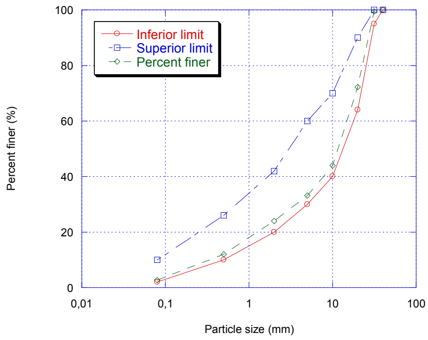

Figure 3. Grain size distribution curve of Diack basalt

Tableau 1. Grain size distribution characteristics of materials

Materials	Grain size distribution characteristics				
	% fines	< 2 mm	< 4,75 mm	D_{max}	USCS
Bargny limestone	2.50	24	48	20	GW
Bandia limestone	4	30	38	31.5	GP
Diack Basalt	2.70	24	34	31.5	GW

2. Compaction characteristics

The ability of compaction of unbound granular materials is evaluated by modified Proctor test in accordance with French standard NF P 94-093 [18]. The principle is to compact the material at different water contents and compaction energy corresponding to 55 blows per layer. For each moisture content, the maximum dry density is determined. From these two parameters, we plotted compaction curve. Figure 4 and Table 3 represent respectively the curves of compaction and compaction parameters. Figure 4 shows that the Diack basalt has a higher density than limestones, but absorbs less water. It also shows that the limestones are very sensitive to water, particularly Bargny limestone. This property of Bargny limestone results from plasticity and its cohesive structure (VBS = 11.2).

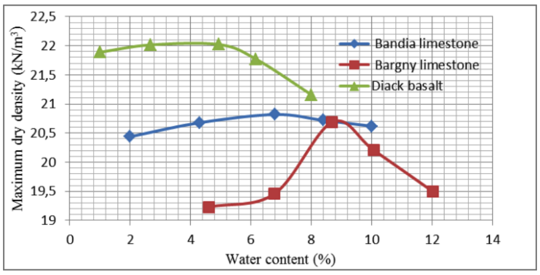

Figure 4. Compaction curves for materials

3. CBR results

The test is performed according to standard NF P94-078 [19] only CBR after immersion is performed to predict the evolution of the lift under different water conditions. CBR is obtained from the maximum value of the following expressions :

$$\frac{Load\ \ per\ unit\ area\ \ of\ \ penetration\ \ at\ 2.5\ mm\ (kN)}{13.35}\times 100$$

$$\frac{Load\ \ per\ unit\ area\ of\ \ penetration\ at\ 5\ mm\ (kN)}{19.93}\times 100$$

Tableau 2. Compaction characteristics of materials

Materials	Compaction characteristics	
	W_{opt} (%)	$\gamma_{d\ max}$ (kN / m^3)
Bargny limestone	8.9	20.60
Bandia limestone	6.9	20.83
Diack basalt	4.4	22.05

Table 3 shows that the variation of CBR according to the materials studied. It shows a very high CBR with Bandia limestone useful on base layer, a low CBR with Bargny limestone suitable for a foundation layer and a high CBR for basalt used in the base layer.

Table 3. CBR values at optimum water content of materials

Materials	CBR (%)
Bargny limestone	32
Bandia limestone	138
Diack basalt	86

4. Resilient modulus (Mr)

Resilient moduli were obtained from the work of Ba [20]. The test consists of two phases. In the first phase, a conditioning is applied: it means the application, in a deviatoric stress of 207 kPa and a confining stress of 103.5 kPa, a high number of load cycles 1000 cycles of loading is generally applied. This phase allows the stabilization of permanent deformation in order to measure only the reversible deformation the actual conditions that will suffer on action of traffic loading are also taken into account. During the second phase, the specimen is loaded cyclically under different stress states for the study of reversible behavior. In the NCHRP [21] protocol, 30 sequences of 100 cycles are applied for the sample. The resilient modulus is calculated from the reversible deformation of the last five cycles recorded by each LVDT.

5. Methodology

Correlation analysis

Correlations were made from Uzan [22] and NCHRP [21] models. They are based on statistical analysis and significance tests for their eventual establishment. The results allow to establishing the following relationship with an R^2 of 0.69 for the Mr predicted from the Uzan model and an R^2 of 0.66 for the NCHRP model.

$$Mr = 91.226 + 0.017\times(CBR)^2 \quad \text{Uzan} \qquad \text{[Eq. 10]}$$

$$Mr = 92.720 + 0.019\times(CBR)^2 \quad \text{NCHRP [Eq. 11]}$$

These results indicate that the resilient modulus predicted from the Uzan model is more efficient than the model NCHRP [2]. This module predicted from the Uzan model is implemented in the base layer for design using finite element method.

6. Finite element analysis for implementing the resilient modulus relationships

After the establishment of correlations, the predicted resilient modulus is implemented in Cast3m software in order to apply the mechanistic design of the base layer. The resilient modulus is predicted from the Uzan model and depending only on CBR. It will replace the Young's modulus at the base layer. The 3D modeling is carried out on 6 structures according to characteristics and structures defined by Tables 4, 5, 6, 7, 8 and 9. The mesh is shown in Figure 6 and the vertical and horizontal displacements are blocked the base of the platform and the horizontal displacements are blocked in the transversal direction of the structure.

The simulation is conducted by considering a nonlinear behavior with as stiffness modulus for the resilient modulus of the base layer. For the other layers, the linear behavior is used with a Young modulus. The implementation of the modulus correspond to equations 12 and 13, representing respectively to Uzan model and predicted model from CBR of limestones.

$$Mr = k_1 Pa\left(\frac{\theta}{Pa}\right)^{k_2}\left(\frac{\sigma_d}{Pa}\right)^{k_3} \qquad \text{[Eq. 12]}$$

Mr: *resilient modulus* (MPa),
θ : bulk stress (kPa),
τoct: *octahedral shear stress* (kPa);
Pa: *atmospheric pressure* (kPa);
σ_d: *deviatoric stress* (kPa);
ki: *model parameters* (kPa).

Mr -CBR model implemented

$$Mr = 91.226 + 0.017\times(CBR)^2 \qquad \text{[Eq. 13]}$$

Mr: *resilient modulus* (MPa), *CBR: California Bearing Ratio*

Table 4. - Characteristics of structure 1 with base course at predicted modulus

Layers	Thickness (m)	E (MPa)	υ	Properties
Surface	0,08	23 000	0.35	*Linear elastic*
Base	0,25	545	0.25	*Predicted resilient modulus* *CBR (%)* *105*
Subbase	0,25	300	0.25	*Linear elastic*
Subgrade	-	250	0.25	*Linear elastic*

Table 5. – Characteristics of structure 2 with base course at predicted modulus

Layers	Thickness (m)	E (MPa)	υ	Properties
Surface	0.08	23000	0.35	*Linear elastic*
Base	0.25	440	0.25	*Predicted resilient modulus* *CBR (%)* *88*
Subbase	0.25	340	0.25	*Linear elastic*
Subgrade	-	250	0.25	*Linear elastic*

Table 6. – Characteristics of structure 1 with base course at predicted modulus

Layers	Thickness (m)	E (MPa)	υ	Properties
Surface	0.08	23000	0.35	*Linear elastic*
Base	0.25	340	0.25	*Predicted resilient modulus* *CBR (%)* *68*
Subbase	0.25	300	0.25	*Linear elastic*
Subgrade	-	250	0.25	*Linear elastic*

The pavement is loaded with a half axle with a load equal to 0.662 MPa for dual tire. The wheel load will be applied to both on imprint finely meshed located at the area of the asphalt layer. The implementation of the resilient modulus predicted consists in replacing the initial Young modulus with the predicted model defined by Equation 11. For the Uzan model, the implementation is more complicated; it is done according to Figure 5.

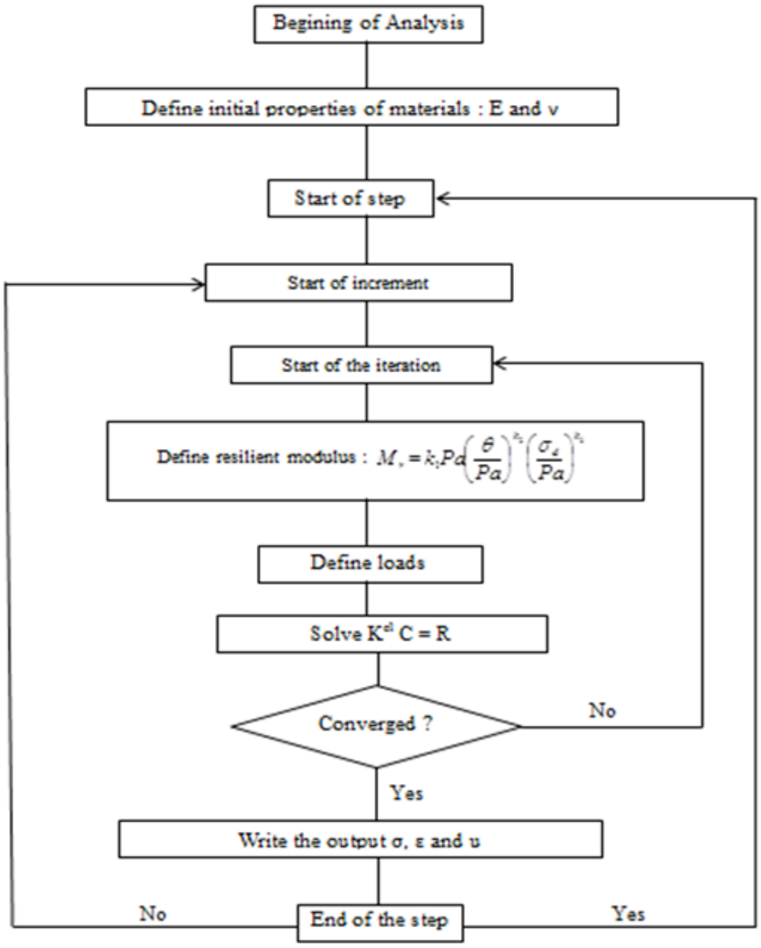

Figure 5. Algorithm for implementing resilient modulus in Cast3m (Kim, [23] modified)

Tableau 7. – Characteristics of structure 1 with base course at Uzan model

Layers	Thickness (m)	E (MPa)	υ	Properties
Surface	0.08	23000	0.35	*Linear elastic*
Base	0.25	545	0.25	*Resilient modulus* *k_1 (kPa)* *k_2* *k_3* *109852* *1.29* *-0.81*
Subbase	0.25	300	0.25	*Linear elastic*
Subgrade	-	250	0.25	*Linear elastic*

Table 8. – Characteristics of structure 2 with base course at Uzan model

Layers	Thickness (m)	E (MPa)	υ	Properties
Surface	0.08	23000	0.35	*Linear elastic*
Base	0.25	440	0.25	*Resilient modulus* k_1 *(kPa)* k_2 k_3 *70485* *1.2* *-0.55*
Subbase	0.25	340	0.25	*Linear elastic*
Subgrade	-	250	0.25	*Linear elastic*

Table 9. – Characteristics of structure 3 with base course at Uzan model

Layers	Thickness (m)	E (MPa)	υ	Properties
Surface	0.08	23000	0.35	*Linear elastic*
Base	0.25	340	0.25	*Resilient modulus* k_1 *(kPa)* k_2 k_3 *63570* *1.13* *-0.36*
Subbase	0.25	300	0.25	*Linear elastic*
Subgrade	-	250	0.25	*Linear elastic*

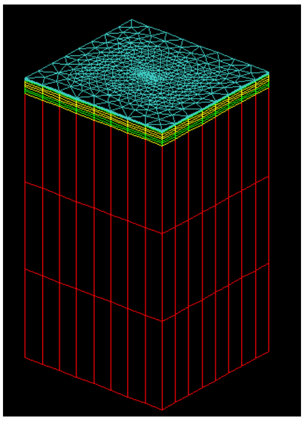

Figure 6. - Tridimensional mesh of the pavement structure

Results

After loading, the structure is deformed. Figure 7 shows a deflection amplified by 4.87 10^3.

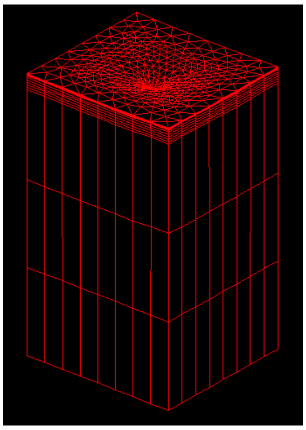

Figure 7. Amplified deflection of the pavement structure

The analysis reveals that the deformations caused by resilient modulus predicted from the CBR, are very important compared to deformations caused by the resilient modulus of Uzan model (Figures 8, 9 and 10). Indeed, these high deformations due to the used of a suitable modulus generate premature damages.

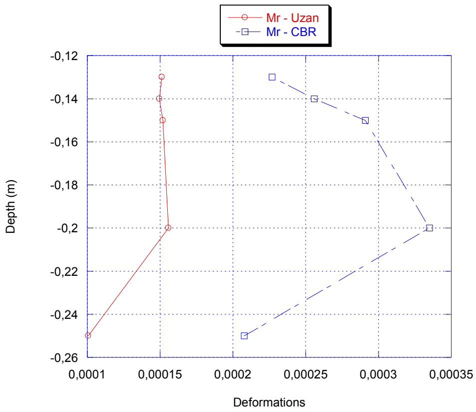

Figure 8. Deformation of base course of the pavement structure 1

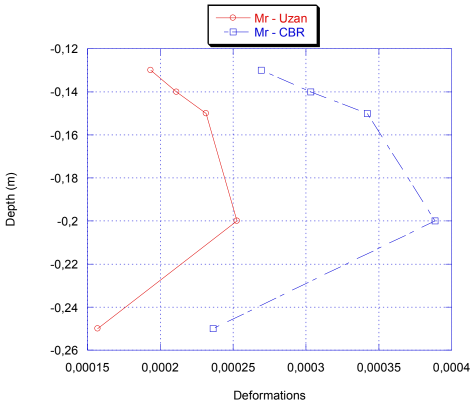

Figure 9. Deformation of base course of the pavement structure 2

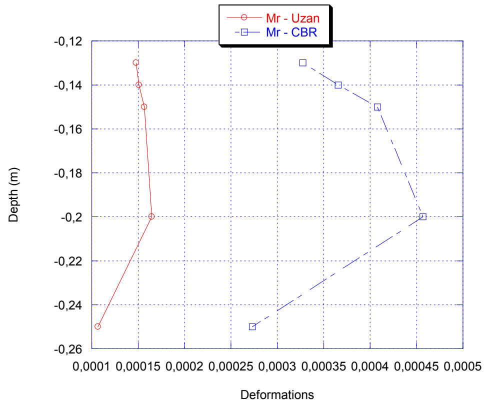

Figure 10. Deformation of base course of the pavement structure 3

Conclusion

This study shows that the Mr-CBR relationship found is not satisfactory to predict the resilient modulus of unbound granular materials of Senegal (figures 8, 9 and 10). However, implementation of this relationship in the base layer as the stiffness cause large deformations due to under-design. These large deformations observed at the base layer would cause excessive damage and premature failures. It also shows that the correlations between Mr-CBR should be used carefully because they tend to ‘’over-predict’’ or ‘’under-predict’’ the resilient modulus. The best method to determine the resilient modulus is repeated load triaxial apparatus to take into account the real behavior of unbound granular materials.

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