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Modelling of the Resilient Modulus (Mr) of Lateritic Soils in Tropical Africa (Burkina Faso and Senegal): Determination of Model Parameters K1, K2 and K3 (Thom and Brown (1987), Uzan (1985) and the NCHRP 1-28A (2004) (National Cooperative Highway Research Program)

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Keywords: lateritic soil; cyclic triaxial repeated loading (TCR); measured (Mrm) and predicted (Mrp) resilient modulus; k1, k2, k3 model parameters.

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Modelling of the Resilient Modulus (Mr) of Lateritic Soils in Tropical Africa (Burkina Faso and Senegal): Determination of Model Parameters K1, K2 and K3 (Thom and Brown (1987), Uzan (1985) and the NCHRP 1-28A (2004) (National Cooperative Highway Research Program)

KI Bibalo Ida Josiane[α], BA Makhaly[σ] & COULIBALY Mory[ρ]

ABSTRACT

The study of the cyclic behavior of materials has been very successful with the development of increasingly powerful computer tools that allow to limit costly experimental studies in favor of numerical models. This development has led to an increasing demand from the scientific community in terms of accuracy of numerical simulations and in terms of calculation time. The numerical tool allows to simulate the material behavior based on plastic, viscoplastic or elastoplastic behavior models [1]. Our study will focus on the determination of the parameters of three models used for the determination of the reversible moduli (Mr). These models are those of Thom and Brown [2], Uzan [3] and the NCHRP [4] (National Cooperative Highway Research Program) of the MEPDG (Mechanistic-Empirical Pavement Design Guide) which are a function of the loading level (the confining stress (σ_3), the deviatoric stress (σ_d), the octahedral stress and the total stress (θ)). The research will be carried out on 4 samples of lateritic gravelly soils, 2 of which are from Burkina Faso (the Badnogo and Dédougou sites) and 2 from Senegal (the Sindia and Lam-lam sites). We carried out cyclic triaxial tests with repeated loading (TCR) according to the European standard Nf EN-13286-7 [5]. The tests were performed at variable confining stress to calculate the measured Reversible Modulus (Mrm = $\sigma_d / \varepsilon_{1,r}$).

The materials studied have a maximum diameter of 20 mm and a percentage of fines lower than 20%. The samples are compacted to three water contents (w_{opm} - 2%, wopm and w_{opm} + 2%) and to an optimum dry density (γ_{dopm}) equal to 95% and 100%. The methodology used was least squares ($\Sigma(\Delta Mr)^2$) and iteration by the "non-linear GRG" solving method used by the Solver calculation engine in Excel software. This allowed us to determine the values of the parameters k_1 (in kPa and > 0), k_2 (unitless and < 0), k_3 (unitless and > 0) of the above numerical models. It is found that the k_1, k_2, k_3 parameters and correlation coefficients are on average equal to 3511.540 kPa, -0.420, 0, and 0.91 for Thom and Brown's model [2]; 4988.974 kPa, -0.289, 0.536, and 0.97 for Uzan's model [3]; and 2436.959 kPa, -0.398, 1.864, and 0.91 > 0.90 for NCHRP [4] respectively. The predicted summary reversible modulus (MRSP) by the NCHRP model [4] is on average equal to 377.543 MPa. On the other hand, for the materials Ded/9.93/95.42 and Ded/8.16/95.39 the parameter k1 increases by 37.83% and the modulus MRSP also increases by 39.26%.

Moreover, for Ded/8,16/95,39 and Ded/6,23/95, 52 the k1 parameter increases by 65,77% and the MRSP module also increases by 39,11%. This justifies that the parameter k1 tells us about the hardening effect of the material.

Keywords: lateritic soil; cyclic triaxial repeated loading (TCR); measured (Mrm) and predicted (Mrp) resilient modulus; k_1, k_2, k_3 model parameters.

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I. INTRODUCTION

The resilient behavior of granular materials is affected by several factors, the most important of which is the level of stress applied. It is so essential that the stress-deformation relationship be modelized exactly with mathematical laws to predict the long and short term behavior as well as the performance of granular materials. The simplicity of the material response analysis procedure makes it difficult to establish models that respect the theoretical principles of soil mechanics [6]. The resilient modulus (MR) of road materials is one of the most important parameters in the analysis and design of pavements.This parameter is used in empirical and mechanistic-empirical methods as the main parameter to express the stiffness and behavior of road construction materials. To determine this parameter in the laboratory, it is necessary to perform a dynamic triaxial loading test under different confinement and deflection constraints, which is a costly and time-consuming approach [7]. To overcome these very exorbitant costs, several researchers have developed digital models such as Thom and Brown [2], Uzan [3] and the NCHRP (National Cooperative Highway Research Program) [4] that we studied in our research.

However, the objective of this work is to determine their parameters. For this we based ourselves on the experimental results to calculate the measured resilient modulus (Mrm), in order to predict the resilient modulus (Mrp) by the aforementioned digital models and determined their parameters. One of the most important aspects for the design and sizing of pavements is the elastic or resilient modulus (MR) which allows to characterize the mechanical behavior of materials necessary for the sizing of a pavement (AASHTO American Association of State Highway and Transportation Officiais 1986 [8]). Studies on gravelly lateritic rocks have rarely been reported in the literature. The only works to be found are those of ((Sikali et al. (1980) and Sweere et al. (1990) in [9]). To this can be added the work carried out in Senegal during the last two years. decades to discover the advanced parameters of granular materials (Fall, Ba, Samb, Dione, and Aïdara [10]) have contributed to deepening knowledge on the advanced mechanical behavior of road materials used in Senegal. In order to contribute to the improvement of the technical documents used for the design and dimensioning of pavements in tropical Africa, we carried out cyclic triaxial repeated loading tests (TCR) of the SCHENCK brand at the Gustave Eiffel University in Nantes in s " based on European standard EN 13286-7 [5] while maintaining the variable confinement pressure (method A). The measured stress-strain results are interpreted for the resilient part by applying the Boyce model, extended to the axial anisotropy [10]. The materials used come from Burkina Faso and Senegal and are of a gravelly lateritic nature, class B4-B6 according to the GTR classification.

II. MATERIALS AND METHOD

About two hundred years ago the term "laterite" first appeared in the scientific literature. Despite various vicissitudes, this term is still widely used. We could think that it covers perfectly recognized and defined facts. However, a study, even a brief one, of synthetic works dealing with this problem shows that, under the brevity of the term, sometimes very different objects are hidden. It is therefore useful to first look at the definitions that have been given to this term. We will then discuss the soil formation processes called "laterites" and their location in the world [11]. In local dialects these formations are called "brick earth". The name "laterite" is therefore only the Latin translation of a vernacular terminology.

2.1 Classification of materials used

- *General information on lateritic soils*

Laterite has the root "later" which means brick in Latin, this only by reference to the use of these blocks (Maignien, 1966; Autret 1983; Bourgeon & Gunnell, 2005 in [12]).

Theories dealing with the origin and formation of laterites are varied. Nowadays, the definition which seems to be unanimous among authors is that of Schellman in 1986 in [13] because it is based on the conditions of alteration of the bedrock and the mineralogical composition. For this author: "Laterites are products of intense meteoric weathering and are made up of a mineral assemblage that can be made of goethite, hematite, aluminum hydroxide, kaolinite and quartz" figure 1 ". The SiO2 / (Al2O3 + Fe2O3) ratio compared to that of the parent rock must be such that the laterite formation does not contain more silica than that which is retained in the remaining quartz and that which is necessary for the formation of kaolinite "[13].

Laterites are widely distributed throughout the world, but more particularly in intertropical regions of Africa, Australia, India, Southeast Asia and South America. Laterites extend beyond subhumid tropical climates and can be observed even in desert regions (African and Australian deserts) where they point to wetter past influences. Considering that the intertropical zone covers 40% of the terrestrial surface of the globe, the lateritic cover is estimated at 33% of the surfaces of the continents, in addition to the desert zones and the steppe zones where laterite does not form (Tardy, 1997 in [14] “figure 2”.

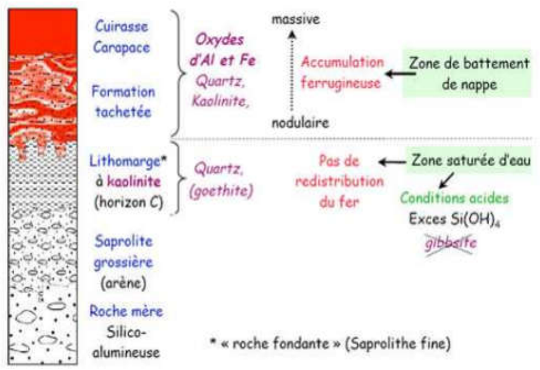

Fig. 1: Lateritic profile (Retallack, 1997 in [14])

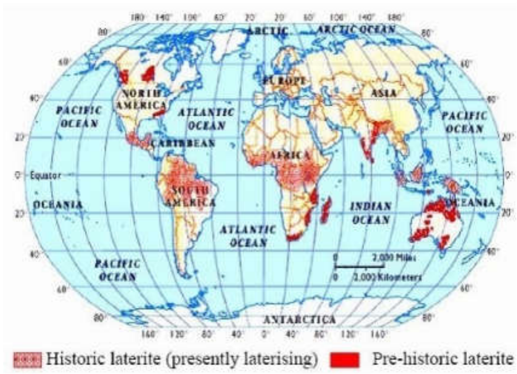

Fig. 2: current and prehistoric laterites (Persons, 1970 in [12])

- *Characterization of laterites from Senegal and Burkina Faso used*

The study as a whole focused on the laterites of two borrowings sites in Burkina Faso (Badnogo and Dédougou) “figure 3” and of two (2) quarries in Senegal (Sindia and Lam-Lam) “figure 4”. The laterites and many other soils of the intertropical regions are located in areas where it is very hot and where the rains are abundant, either all year round or during a wet season (Legros, 2013 in [15]).

The summary of the material characterization tests is presented in "Table 1". It appears that:

After analysis of the materials, it can be seen that the samples, despite the diversity of their origin, are gravelly materials with little clay (lateritic gravels with little clay) and of class B4, B5 and B6 "table 1" according to the book of the "Guide of Road Earthworks "[10].

Fig. 3: location of borrowing sites in Burkina Faso (Dédougou et Badnogo)

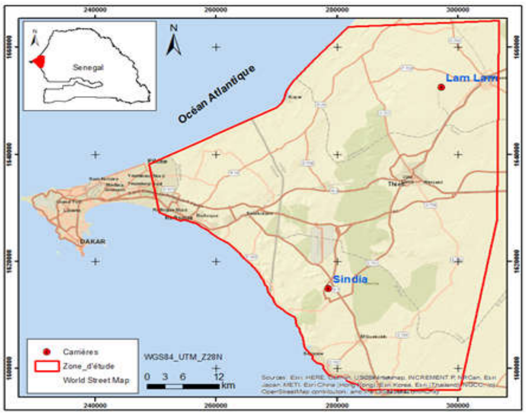

Fig. 4: location of borrowing sites in Senegal (Sindia et Lam-Lam

Table 1: Physical and mechanical characterization of lateritic soils samples [10]

Designation of borrow sites	Particle size Analysis				Materials classification				Parameters of the Atterberg limit			CBR compactness and lift parameters				
	Sand (%)	Fines (%)	Ratio									Water content	Dry density	Parameters of the Modified Proctor		CBR after 4 days of immersion
	2 mm	80 µm	Cu	Cc	GTR	LCPC	AASHTO	USCS	LL (%)	PI (%)	Ic	wn (%)	Gs	γd max (kN/m3)	wopm (%)	95% OPM
Sindia	41.6	17.86	207	0.34	B5	GA	A2-4a (0)	GC - CL	29.85	9.2	2.7	4.7	2.76	19.7	9.66	54.8
Lam-Lam	39.3	18.19	130	0.28	B5	GA	A2-4a (0)	GC - CL	30.3	10.1	2.4	5.6	2.69	17.52	11.8	30.5
Dedougou	25.2	10.21	763	29.5	B4	GA	A2-4a (0)	GM - GC	27.5	7.2	3.2	4.3	2.82	22.5	8.05	65
Badnogo	34.6	16.63	129	11.6	B6	GA	A2-6 (0)	GC - CL	28	13	1.8	4.6	2.76	21.45	9.7	58

2.2 *Methodology of the cyclic triaxial test with repeated loading*

Like Untreated Graves, laterites are natural granular materials without binder, which exhibit a highly non-linear behavior, depending on the stresses applied and the number of loading cycles. The triaxial repeated loading test is widely used to study the mechanical behavior of these types of materials [16]. The TCR consists in subjecting a cylindrical specimen of untreated granular material to cyclic loadings, simulating the stresses existing in a road bedding layer, and in measuring the axial and radial deformations of the specimen produced by these phase loads. The standard used is EN 13286-7 [5] and defines three different test procedures (method B with constant confining pressure σ3, method A with variable confining pressure σ3 and stepwise method the one we have used). From the identification and characterization tests (particle size, Atterberg limit, Proctor, etc.) we notice that the laterites are close to the GNT. This justifies the choice of this aforementioned standard [10].

For entering the input data for the confinement stress, we deduce 2kPa. This corresponds to the weight of half the height of the water contained in the cell. The test pieces after preparation to the desired water content and density of compactness are assigned the sensors for measuring axial and radial deformations "figure 5" and "figure 6".

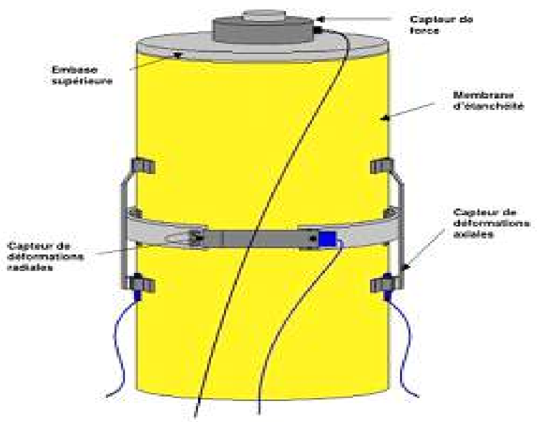

Fig. 5: Complete device for measuring axial and radial deformations [16]

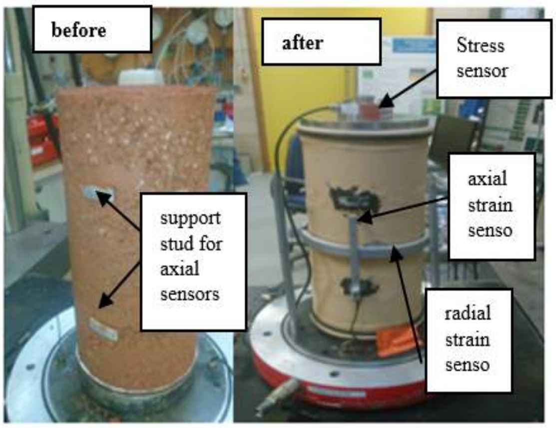

Fig. 6: Test specimen with sensor fixing studs (before) and with sensor installation (after)

III. MODELING BY SEVERAL NO LINEAR MODELS OF THE RESILIENT MODULUS

The resilient behavior of granular materials is affected by several factors, the most important of which is the level of stress applied; where they exhibit no linear behavior. It is essential that the stress-strain relationship be modelized exactly with mathematical laws to predict the long and short term behavior as well as the performance of granular materials. The simplicity of the material response analysis procedure makes it difficult to establish models respecting the theoretical principles of soil mechanics (Lekarp et al., 2000 in [17]).

To take into account the non-linearity of bass behavior, the modulus of elasticity is replaced by the Resilient Modulus (Seed et al., 1965 in [17].). The term "resilient" refers to the portion of the recoverable energy of a material that is stressed, when it is discharged. This is how the resilient modulus concept was developed to allow better simulation of the loading of pavements by rolling loads [14].

Lekarp, Isacsson, & Dawson [6] reported on numerous studies carried out since 1960 in order to characterize the resilient behavior of granular materials. The studies found in the literature, show that this behavior can be affected, with different degrees of importance, by several factors such as the level of stress, the history and number of loading cycles, the loading frequency, the effect of density, grain fraction and grain shape, water content. However, the most important parameter affecting the resilient response is the level of stress applied to the sample (Table 2.1) [14].

3.1 No linears models of resilient modulus used

An elastic constitutive law is chosen, can be elastic linear isotropic (from the normative point of view), hypo elastic (model K-θ) or hyper elastic (model of Boyce) [18]. There are several digital models used in the bibliography for the digital modeling of the resilient module. These models are either according to the level of loading or according to the physical parameters. The methodology used is that of least squares (Σ (ΔMr) ²) and iteration by the "no linear GRG" resolution method used by the Solver calculation engine in the Excel software. This allowed us to determine the values of the parameters k_1 (in kPa and> 0), k_2 (without unit and <0), k_3 (without unit and> 0) of the aforementioned numerical models.

We determine the residual (Ri) by equation 1 which will be the objective to be defined in the Solver and the variable cells which correspond to the cells of the parameters k_i to be determined.

$$Ri = \frac{\left(\sum_{i=1}^{n} (\Delta Mr)_i^2\right)}{Nb} = \frac{\left(\sum_{i=1}^{n} (Mr_m - Mr_p)^2\right)}{Nb} \qquad (1)$$

Ri is the residual, Mrm the measured modulus, Mrp the modulus predicted by the chosen model and Nb corresponding to the matrix of cells (number of sequences).

Several models have been developed for the prediction of the resilient modulus of untreated bass (GNT). Among which we have:

Uzan [3] proposes a modification of the k - θ model to take into account the effect of the deviatoric stress. This relationship is expressed by equation (2) as follows:

$$M_r = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\sigma_d}{p_a}\right)^{k_3} \qquad (2)$$

k_1, k_2 et k_3 are parameters of model pa is atmospheric pressure in kPa;

θ = sum of principal stresses in k Pa is the deviatoric stress in kPa

Uzan's model seems to agree well with the experimental results on GNT even at confinement stresses greater than the deviatoric stress

Thom and Brown [2] experiment the Resilient Modulus as a function of the following stress ratio according to the equation:

$$M_r = k_1 \left(\frac{p}{q}\right)^{k_2} \qquad (3)$$

k_1, k_2, are the parameters of the model, $q = \sigma_d = \sigma_1 - \sigma_3$ deviatoric stress, p = average pressure ($p = (\sigma 1+\sigma 2+\sigma 3) / 3$).

A new "harmonized" test protocol for the resilience module has been developed as part of the NCHRP project 1-28A [4]. This model, called either the NCHRP model or the MEPDG model, is implemented in the new "Mechanistic-Empirical Pavement Design Guide" (MEPDG). This new protocol uses the universal nonlinear model which is applicable to unbound base or subbase materials given by equation (4) [17]. This equation combines the hardening effect of the sum of the principal stresses and the softening effect of the shear stress; thus, the value of k2 must be positive and that of k3 negative. But in our study for severe lateritics the value of k2 will be negative and that of k3 positive. To properly identify the model constants, the multiple correlation coefficients determined for the test must exceed 0.90. It should be noted that the use of this model is proposed for both the granular materials of the base layers and for the fine soils of the foundation layers.

$$M_r = k_1 pa\left(\frac{\theta}{pa}\right)^{k_2} \cdot \left(\frac{\tau_{oct}}{pa}\right)^{k_3} \quad (4)$$

k_1, k_2, k_3 are the parameters of the model. ($k_1 > 0$; $k_2 < 0$; $k_3 > 0$ for our lateritic materials.

3.2 The results obtained and interpretations

It appears that:

- After the analysis of the materials, it can be seen that the samples, despite the diversity of their origin, are gravelly materials with little clay (lateritic gravels with little clay) and of class B4, B5 and B6 according to the book of the "Guide de Terrassement Routier "Table 1»
- Table 2 and figures 7 (a), 7 (b) and 7 (c) show that the parameter k1 is positive and varies according to the type of material and the type of model. Their maximum, average and minimum values are represented by diagrams in « Box »
- Table 2 and figures 8 (a), 8 (b) and 8 (c) show that the parameter k2 is negative and varies depending on the type of material and the type of model. Their maximum, average and minimum values are represented by diagrams in « Box »
- Table 2 and figures 9 (a), 9 (b) and 9 (c) show that the correlation coefficient R varies according to the type of material and the type of model. Their maximum, average and minimum values are represented by diagrams in « Box ». We deduce that:
- Figure 10 shows a regression curve of the measured Resilient Modulus (Mrm) against the predicted Resilient Modulus (Mrp) of the models: (Uzan [3], Thom and Brown [2], NCHRP [4]) of the sample Sin 12.10 / 95.75. We deduce that the Uzan model is closer to the line of equation Y = X, from which it correlates well especially for the material Sin / 11.7 / 95.71 with a correlation coefficient equal to 0.994.
- The parameters k_1, k_2, k_3 are on average respectively equal to 3511.540 kPa, -0.420, 0, and 0.91 for the model of Thom and Brown [2]; 4988.974 kPa, -0.289, 0.536 and 0.97 for that of Uzan [3] and 2436.959 kPa, -0.398, 1.864 and 0.91 for the NCHRP [4] « Table 2 ».
- The summary resilient modulus predicted by the NCHRP model [4] is on average equal to 377.543 MPa for the four samples « table 2 ».
- In addition, table 2 shows us that for the materials Ded / 9.93 / 95.42 and Ded / 8.16 / 95.39 the parameter k1 increases by 37.83% and the MRSP modulus also increases by 39.26 %. In addition, for Ded / 8.16 / 95.39 and Ded / 6.23 / 95.52, the parameter k_1 increases by 65.77% and the MRSP modulus also increases by 39.11%. This justifies that the parameter k_1 tells us about the hardening effect of the material.

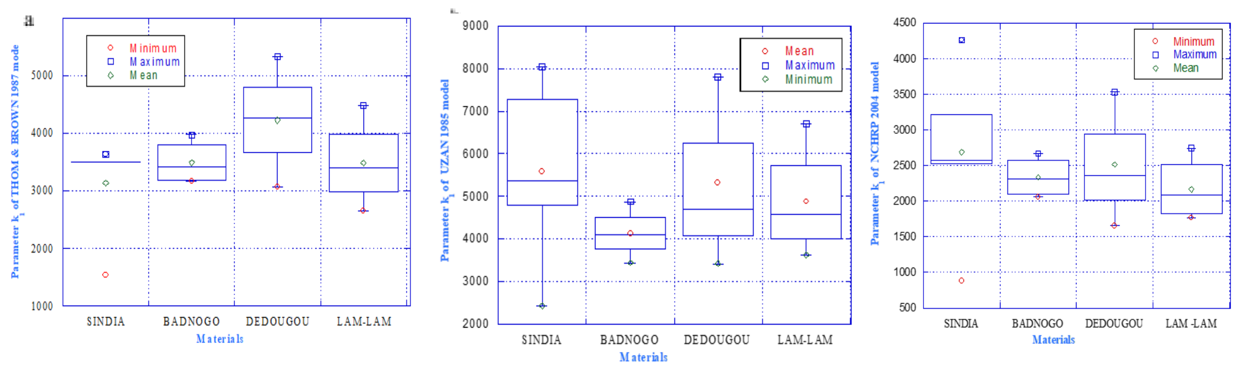

Fig. 7: Parameter k_1 (a) of the Thom and Brown model [2]; (b) of the Uzan model [3]; (c) of the NCHRP model [4]

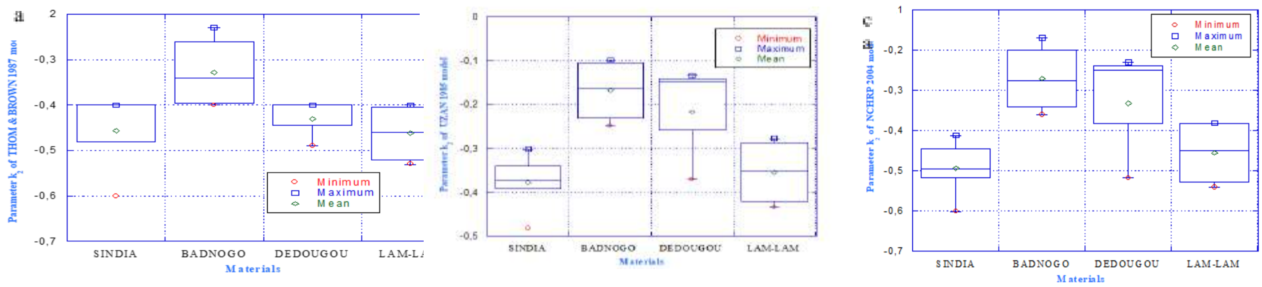

Fig. 8: Parameter k_2 (a) of the Thom and Brown model [2]; (b) of the Uzan model [3]; (c) of the NCHRP model [4]

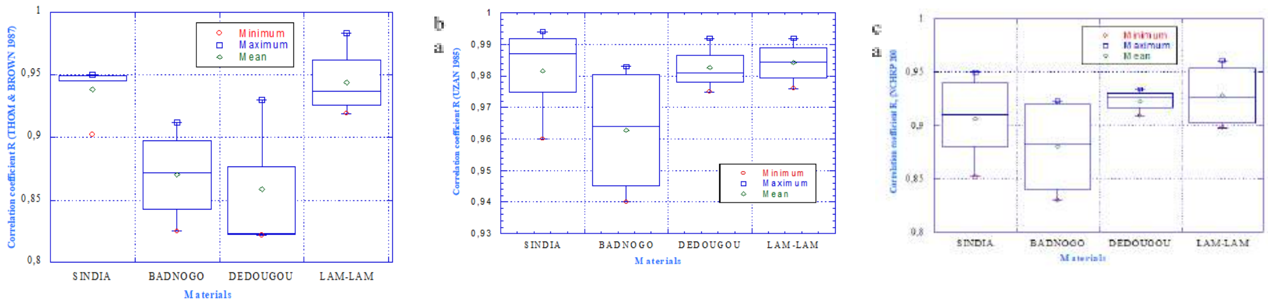

Fig. 9: correlation coefficient (a) of the Thom an Brown model [2]; (b) of the Uzan model [3]; (c) of the NCHRP model [4]

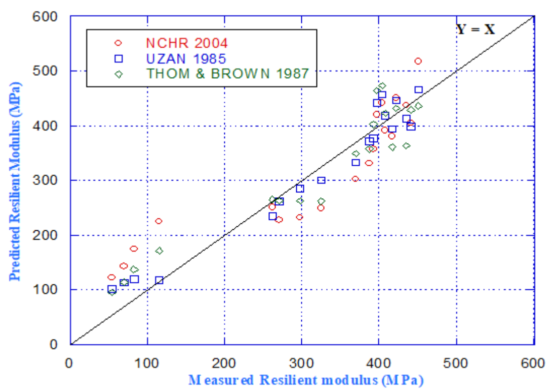

Fig. 10: Resilient Modulus measured / Resilient Modulus predicted by the models (UZAN [3], THOM and BROWN [2], NCHRP [4]) of the Sin sample 12.10 / 95.75

Table 2: Summary of the parameters and correlation coefficient and determination of the digital models of the resilient module

Name		Model of THOM & BROWN 1987		Coefficients		Model of UZAN (1985)			Coefficients		Model of NCHRP (2004)			Coefficients		Predicted Resilient Modulus Sommary (MRSP) (MPa) $\theta = \sigma_b$ 208 kPa τ_{oct} = 48,6 kPa $\sigma_3 = \sigma_c$ = 35 kPa
		k_1	k_2	Correlation	Determination	k_1	k_2	k_3	Correlation	Determination	k_1	k_2	k_3	Correlation	Determination	
SINDIA Wop%= 9,66	Sin/11,7/95,71	1532,67	-0,60	0,902	0,814	2421,05	-0,482	0,860	0,994	0,988	874,634	-0,601	2,606	0,95	0,905	158,496
	Sin/12,10/95,75	3489,45	-0,40	0,945	0,894	4798,57	-0,301	0,454	0,975	0,950	2567,506	-0,412	1,632	0,91	0,822	363,430
	Sin/9,90/95,80	3635,15	-0,48	0,949	0,900	5356,91	-0,371	0,568	0,987	0,973	2525,042	-0,496	1,957	0,852	0,923	382,110
	Sin/9,10/94,94	3489,45	-0,396	0,945	0,894	8032,71	-0,340	0,465	0,960	0,922	4253,516	-0,446	1,644	0,880	0,775	590,010
	Sin/7,59/95,94	3489,45	-0,40	0,945	0,892	7279,08	-0,391	0,642	0,992	0,984	3210,334	-0,516	2,124	0,940	0,884	511,592
BADNOGO 2 Wop% = 9,7	Bad/11,43/95,48	3608,36	-0,23	0,864	0,746	4083,44	-0,106	0,265	0,938	0,879	2669,361	-0,225	1,175	0,835	0,697	361,414
	Bad/10,04/95,58	3167,07	-0,29	0,825	0,680	3438,19	-0,099	0,372	0,945	0,893	2058,260	-0,174	1,295	0,855	0,730	303,366
	Bad/7,57/95,32	3973,45	-0,40	0,883	0,780	4872,05	-0,215	0,516	0,983	0,967	2476,969	-0,322	1,749	0,923	0,853	392,118
	Bad/9,36/100,06	3203,82	-0,39	0,912	0,833	4119,91	-0,249	0,484	0,978	0,956	2143,762	-0,360	1,698	0,917	0,840	323,581
DEDOUGOU Wop% = 8,05	Ded/9,93/95,42	3068,14	-0,40	0,822	0,676	3413,88	-0,148	0,568	0,992	0,984	1655,390	-0,249	1,847	0,934	0,873	287,385
	Ded/8,16/95,39	4269,22	-0,40	0,823	0,677	4704,63	-0,134	0,538	0,981	0,963	2358,181	-0,231	1,757	0,909	0,827	400,204
	Ded/6,23/95,52	5329,26	-0,49	0,930	0,865	7799,18	-0,370	0,601	0,975	0,950	3530,922	-0,518	2,101	0,926	0,858	556,713
LAM-LAM Wop%= 11,8	Lam/14,56/95,21	3489,45	-0,51	0,983	0,965	4762,95	-0,434	0,579	0,992	0,983	1765,563	-0,515	2,562	0,961	0,923	334,751
	Lam/12,43/98,92	3308,74	-0,40	0,932	0,869	4403,64	-0,277	0,485	0,983	0,966	2276,177	-0,385	1,699	0,907	0,823	337,386
	Lam/13,92/96,51	2647,89	-0,41	0,941	0,885	3629,59	-0,297	0,472	0,976	0,953	1882,254	-0,382	1,655	0,898	0,807	274,747
	Lam/10,15/96,04	4483,07	-0,53	0,919	0,844	6707,81	-0,408	0,709	0,986	0,972	2743,480	-0,542	2,320	0,946	0,895	463,386

IV. CONCLUSION

At the end of our research we can conclude that the gravelly lateritic materials, despite their geographic diversity, have almost the same physical and compact characteristics; they are class B4, B5 and B6 according to the GTR classification. In addition, after testing the cyclic triaxial (TCR) by standard EN 13286-7 [5] with method A, the resilient molds obtained differ from the type of materials (percentage of fine, water content, and stress level. Three mathematical models were used in our work for analysis. The Resilient modulus measured (Mrm) with respect to the Resilient modulus predicted (Mrp) by these models (Uzan [3], Thom and Brown [2], NCHRP [4]) tells us that the Uzan model [3] presents a very good correlation whatever the material, especially for the Sin / 11.7 / 95.71 material with a correlation coefficient equal to 0.994. In addition, the parameters k1, k2, k3 are at least respectively equal to 1532.670 kPa, -0.600, 0, and 0.82 for the model of Thom and Brown [2]; 2421.050 kPa, -0.482, 0.265 and 0.94 for that of Uzan [3] and 874.634 kPa, -0.601, 1.175 and 0.84 for the NCHRP [4]. The summary resilient modulus predicted by the NCHRP model [4] is on average equal to 377.543 MPa for the four samples. We also notice that for the materials Ded / 9.93 / 95.42 and Ded / 8.16 / 95.39 the parameter k1 increases by 37.83% and the MRSP modulus also increases by 39.26%. In addition for Ded / 8,16 / 95,39 and Ded / 6,23 / 95,52 the parameter k1 increases by 65.77% and the MRSP modulus also increases by 39.11%. This justifies that the parameter k1 tells us about the hardening effect of the material.

In perspective, propose to strengthen studies by determining the SiO_2 / (Al_2O_3 + Fe_2O_3) ratio and other chemical and mineralogical mechanical tests in order to better classify our material.

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