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Resilient Modulus of Compacted Granular and Lateritic Materials Used as Base Layers for Flexible Pavements in West Africa

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ABSTRACT

The objective of the study is to synthesize resilient modulus data available in Senegal and to propose linear and nonlinear elasticity parameters, which can be used directly for the design of flexible pavements in west Africa. The materials tested are unbound aggregates of basalt and quartzite and gravel lateritic soil from Senegal and Burkina Faso. The Repeated Load Triaxial device is used according to French and American procedures to measure resilient modulus. Different models of the resilient modulus are used to determine the parameters of the nonlinear models and the summary and/or characteristic resilient modulus used in the elastic linear calculation. For the nonlinear calculation, the parameters of the models of Seed *et al.* (1967), NCHRP (2004) and Boyce (1980) are determined. For the linear elasticity calculation, at the optimum water content and at the dry density of 95% of its maximum value, a maximum modulus of between 300 and 350 MPa is proposed for laterites in the base layer. Values of 220 MPa and 150 MPa are proposed for basalt and quartzite respectively. The moduli obtained are not correlated to the CBR values of the materials. A strong variability in the modulus of laterites is also noted, contrary to the modulus of unbound aggregates. Laterites sometimes have higher modulus than unbound aggregates due to cohesion, but they are more sensitive to water. We recommend that unbound materials (untreated gravels and laterites) be compacted in situ to 97% of the maximum dry density and, for laterite, to the optimal water content -1.5 but also to ensure a good waterproofing and good drainage of the structure.

Keywords: Resilient modulus; unbound aggregates; gravel lateritic soil; West Africa.

1. INTRODUCTION

Road pavement structures are made up of several superimposed layers which play a main role in the diffusion of stresses due to the loading of heavy vehicles. These layers are made from materials available on the route, and must meet minimum quality requirements to avoid premature failure. One of these requirements is modulus, which expresses the mechanical behavior of the material under the effect of loads. A better estimation of the module improves the resistance of the pavement and leads to more optimized thicknesses including more economical design.

In west Africa, pavement design is based on Young's modulus which expresses linear elastic behavior, most often estimated from empirical relationships or through default values included in databases of the French method of dimensioning. However, studies carried out over the past two decades in Senegal on unbound gravel and lateritic soils have shown that the behavior of these materials used in the base layer is non-linear, i.e. the modulus is highly dependent on the stress level applied (Fall *et al.*, 2002; Fall *et al.*, 2007; Ba *et al.*, 2011; Samb *et al.*, 2018; Ki *et al.*, 2022).

According to the new mechanistic-empirical design approach for pavements, the resilient modulus (M_r) is considered as the essential parameter which characterizes the nonlinear elastic behavior of untreated materials. This modulus is the ratio between the deviatoric stress and the resilient strain undergone by the material sample during a Repeated Load Triaxial (RLT) test simulating road traffic (Eq. 1).

$$\boldsymbol{M_r} = \frac{\boldsymbol{\sigma_d}}{\boldsymbol{\epsilon_r}} \qquad \text{(Eq. 1)}$$

where, M_r = resilient modulus, σ_d = deviatoric stress, et ε_r = resilient strain.

The resilient modulus of unbound materials is influenced by stresses and environmental factors such as water content and density (Ba *et al*., 2011; Ba *et al*., 2013). Several models are developed in order to take into account the dependence of this modulus on the different stress states applied. Model parameters and modulus values are available for the different unbound materials used in Senegal as a base layer. The objective of this work is to synthesize this available data and to make proposals for parameters that can be used directly for the design of flexible pavements in west Africa.

2. RESILIENT MODULUS MODELS

Several equations have been proposed to model the resilient modulus. For example, Seed *et al*. (1967) and Hicks (1971) propose a hyperbolic law of the resilient modulus as a function of the sum of the principal stresses (bulk stress). This law is better known under the name of the k - θ model and is expressed as follows (Eq. 2):

$$\boldsymbol{M_R} = \boldsymbol{k_1}\left(\frac{\boldsymbol{\theta}}{\boldsymbol{P_a}}\right)^{\boldsymbol{k_2}} \qquad \text{(Eq. 2)}$$

where M_R = resilient modulus; $\theta = \sigma_1 + \sigma_2 + \sigma_3$ is the sum of the principal stresses; P_a is the atmospheric pressure; k_1 and k_2 are the model parameters.

Witczak and Uzan (1988) propose a relationship where the resilient modulus is a function of the sum of the principal stresses and the octahedral shear stress (Eq. 3). This equation is called the universal model.

$$\boldsymbol{M_R} = \boldsymbol{k_1 P_a}\left(\frac{\boldsymbol{\theta}}{\boldsymbol{P_a}}\right)^{\boldsymbol{k_2}}\left(\frac{\boldsymbol{\tau_{oct}}}{\boldsymbol{P_a}}\right)^{\boldsymbol{k_3}} \qquad \text{(Eq. 3)}$$

where M_R = resilient modulus; θ is the sum of the principal stresses; $\boldsymbol{\tau_{oct}} = \frac{\sqrt{3}}{2}(\boldsymbol{\sigma_1} - \boldsymbol{\sigma_3})$ is the octahedral shear stress; P_a = atmospheric pressure = 101,4 kPa; k_1, k_2 et k_3 are the regression constants (model parameters).

The new design method based on Mechanistic-Empirical principles uses a generalized model given by equation 4 (NCHRP, 2004) :

$$\boldsymbol{M_R} = \boldsymbol{k_1 P_a}\left(\frac{\boldsymbol{\theta}}{\boldsymbol{P_a}}\right)^{\boldsymbol{k_2}}\left(\frac{\boldsymbol{\tau_{oct}}}{\boldsymbol{P_a}} + \boldsymbol{1}\right)^{\boldsymbol{k_3}} \qquad \text{(Eq. 4)}$$

Boyce (1980) proposes a nonlinear elastic law which takes into account a coupling between the volumetric and deviatoric parts of the behavior to express the modulus of volumetric compressibility (Eq. 5).

$$\boldsymbol{E} = \frac{9G_a \cdot \left(\frac{p}{p_a}\right)^{1-n}}{3 + \left(\frac{G_a}{K_a}\right)\cdot\left(1 - \beta\cdot\left(\frac{q}{p}\right)^2\right)} \qquad \text{(Eq. 5)}$$

where Ka, Ga, n et β are model parameters. $q = \sigma_1 - \sigma_3$= deviatoric stress; p = average pressure (p = $(\sigma_1 + \sigma_2 + \sigma_3)/3$).

The model parameters are determined by nonlinear regression analysis according to the models cited above. In the mechanistic-empirical design procedure, the parameters k_i are used as input parameters in the calculation codes. For the French rational method which uses linear elasticity calculation, the isolated values of Young's moduli are used as input parameters. These values are given here as the summary resilient modulus (M_rS) and the characteristic modulus (E_c).

3. MATERIALS & METHODS

The materials in this study are those commonly used as base layers for flexible pavements in Senegal and tropical countries. These are unbound crushed basalt, quartzite, and lateritic gravelly soils from Sindia (Senegal), Lam Lam (Senegal), and Dedougou (Burkina Faso). Table 1 presents the basic geotechnical characteristics of the materials tested.

Tableau 1 Physical properties of untreated materials used as base layers

Materials	Granulometry			Classification (USCS)	Plastic Index PI	Modified Proctor		CBR
	Gravels (%)	Sands (%)	Fines (%)			$\gamma_{d\ max}$ (kN/m^3)	w_{opm} (%)	
Basalt	65.00	28.0	7.00	GP	NP	23.74	4.20	-
Quartzite	62.00	30.0	8.00	GW	NP	21.05	5.00	-
Sindia laterite	40.54	41.6	17.86	GC - CL	9.2	19.70	9.66	55
Lam Lam laterite	42.51	39.3	18.19	GC - CL	10.1	17.52	11.8	30
Dedougou laterite	64.59	25.2	10.21	GM - GC	7.2	22.50	8.05	65

Specimens were prepared in the mould of 150 mm diameter and 300 mm height and compacted into 5 layers. The density after preparation was at least 95 % close to the maximum dry density obtained from the modified Proctor compaction test. The Repeated Load Triaxial (RLT) system used consists of applying cyclic loads to a cylindrical specimen of material and measuring the axial strains of the specimen. The device includes the triaxial cell, the loading system and the stress and strain measurement system (figure 1). The standards used in tropical Africa are the European standard EN 13286-7: 2004 and the USA Protocol 1 - 28 A of « National Cooperative Highway Research Program » (NCHRP). These procedures begin by conditioning the specimen by applying 1000 to 20,000 loading cycles to stabilize permanent deformations and achieve essentially resilient behavior. After the conditioning stage, several loading sequences, corresponding to different stress levels, are applied to the specimen and linear variable differential transformers (LVDT) measure axial resilient and plastic displacement.

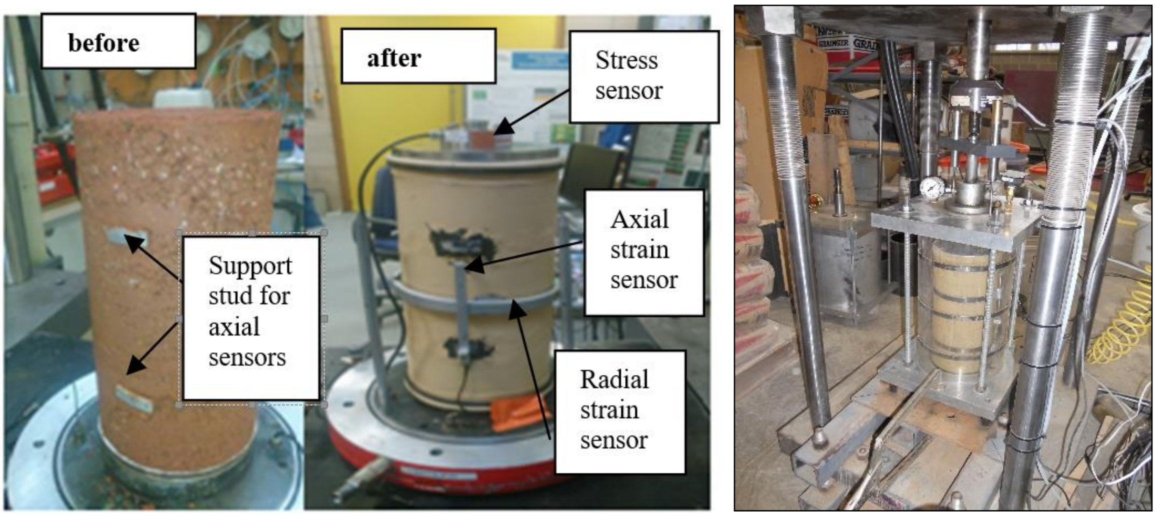

Figure 1 Experimental device for Triaxial Repeated Loading Test (Ba *et al.*, 2011; Ki *et al.*, 2022)

4. RESULT AND DISCUSSION

4.1. For nonlinear calculation

The Unbound Granular Materials (UGM) used as base and/or foundation layer in Senegal come mainly from basalt quarries in the region of Thies. Since 2015, Bakel quartzites have been exploited to meet the increasingly growing demand for aggregates, especially in eastern Senegal, reducing also the costs of transport (Ba, 2012). For a non-linear calculation, Table 2 presents the input parameters of these UGM compacted at the optimum water content and at 97% of the maximum dry density.

Two models are proposed: the k - θ model (Seed et al., 1967) and the NCHRP (2004) modified universal model. According to the k - θ model, the parameter k_1 varies between 100 for quartzite and 150 for basalt, while the parameter k_2 varies between 0.49 and 0.5. The positive value of k_2 of this model proves the hardening effect of the sum of the principal stresses on the sample, therefore an increase in the resilient modulus of granular materials at depth. According to the NCHRP (2004) model, the parameter k_1 is 950 MPa for quartzite and 1300 MPa for basalt. The parameter k_2 takes a positive value of 0.85 because of the hardening effect of θ. On the other hand, k_3 is negative and varies between -0.55 and -0.60, respectively for quartzite and basalt, which shows the softening effect of the octahedral shear stress and the deviatoric stress on the resilient modulus.

Lateritic soils are widely used in tropical Africa where their use is largely dependent on their CBR value. These soils show great sensitivity to water and great variability in their physical and mechanical characteristics, hence their name “problematic soils”. In nonlinear calculation, Table 2 gives the parameters of the NCHRP (2004) model and the Boyce (1980) model. For the NCHRP model, the proposed k_1 values vary between 2000 MPa for the Lam Lam and Dedougou laterites, and 2500 MPa for the Sindia laterite. The k_2 parameter is negative in these soils and varies between -0.25 and -0.60, which demonstrates the softening nature of the sum of the principal stresses, contrary to unbound granular materials. On the other hand, the parameter k_3 is positive for laterites, and varies between 1.60 and 1.65, hence a hardening effect of deviatoric and octahedral shear stresses on laterites. This behavior is typically observed in fine and coherent soils or those containing clayey fines (Table 2).

These results clearly show that lateritic soils are special materials, different from conventional unbound gravels, even if they are not treated with binders.

4.2. For linear elasticity calculation

The design method currently used in Senegal and in most French-speaking African countries uses the theory of linear elasticity. The stiffness of materials is defined by Young's modulus (E), measured in the laboratory using a monotonic loading test, or most often determined from correlation equations with the CBR value, or from given default values through catalogs and guides (SETRA-LCPC, 1994; AGEROUTE, 2015). This modulus must be determined experimentally from Triaxial Repeated Loading Test, more representative of cyclic road loading. These are the summary resilient modulus (MrS) and the characteristic modulus (Ec) determined at predefined stress levels (Table 2).

The results show that the modulus obtained are different from those predicted from the CBR values. As the CBR value is not an intrinsic mechanical parameter, it is difficult to correlate with the modulus which is a function of the applied stresses. During the tests, it is also noted a strong variability in the modulus of laterites contrary to the modulus of unbound granular materials. It is difficult to propose finite values of modulus for elastic calculation, because of its strong dependence on the conditions of implementation, humidity and compaction. However, for an optimal water content and a dry density of 95 % of its maximum value, a maximum value between 300 and 350 MPa is safer for the design of lateritic soils as a base layer. These values may increase if the materials are compacted on site at the optimum water content - 1,5 %, and at 97 % of the maximum dry density. In the subbase layer, a division into sub-layers 25 cm thick from the bottom is necessary to take into account the non-linearity. The modulus of an Ei sub-layer being equal to 2.5 times the modulus of the sub-layer imme-diately below, with a maximum value of 200 MPa (SETRA-LCPC, 1994; AGEROUTE, 2015). Modulus values of 220 MPa and 150 MPa are suggested respectively for basalt and quartzite. These materials being insensitive to water, the modulus varies little with the water content.

Tableau 2 Mechanical behavior parameters proposed for the materials tested

Materals	Nonlinear calculation			Linear elasticity calculation		Former Values (MPa) E=5CBR
	k - θ	NCHRP	Boyce	M_rS (MPa)	E_c (MPa)	
Basalt (w_{opt}, 97%γ_{dmax})	$k_1 = 150$ $k_2 = 0.50$	$k_1 = 1300$ $k_2 = 0.85$ $k_3 = -0.60$	-	220	-	600

Quartzite (w_{opt}. 97%γ_{dmax})	k_1 = 100 k_2 = 0.49	k_1 = 950 k_2 = 0.85 k_3 = -0.55	-	150	-	600
Sindia laterite (w_{opt}. 95%γ_{dmax})	-	k_1 = 2500 k_2 = -0.50 k_3 = 1.60	K_a = 30 MPa G_a = 90 MPa n = 0.42 γ = 0,50	350	200	275
Lam Lam laterite (w_{opt}. 95%γ_{dmax})	-	k_1 = 2000 k_2 = -0.25 k_3 = 1.65	K_a = 60 MPa G_a = 70 MPa n = 0.70 γ = 0,60	300	180	150
Dedougou laterite (w_{opt}. 95%γ_{dmax})	-	k_1 = 2000 k_2 = -0.45 k_3 = 1.65	K_a = 15 MPa G_a = 65 MPa n = 0.111 γ = 0,30	300	180	325

Because of cohesion, lateritic soils have modulus higher than the modulus of unbound aggregates. The latter being devoid of cohesion, only intergranular friction makes it possible to densify and increase rigidity. These unbonded materials (UGM and Laterites), because of their relatively low rigidity, are reserved for road pavement structures supporting traffic of less than 50 heavy vehicles/day/direction, according to the rational approach of the French design method which uses a linear elasticity calculation.

CONCLUSION

The main objective of this study was to suggest modulus for the design of unbound granular materials and laterites. To carry out this study, samples of unbound granular materials (basalt and quartzite) and laterites were subjected to Triaxial Repeated Loading tests according to European standard EN 13286-7: 2004 and the USA 1 - 28 A protocol of the "National Cooperative Highway Research Program" (NCHRP).

For a linear elastic calculation, values of summary resilient moduli and characteristic moduli are proposed for the materials studied (unbound granular materials and laterites) as input parameter for the calculation of the response of the pavement structure. For a nonlinear elasticity calculation, parameters k_i from the NCHRP (2004) model and parameters from the Boyce (1980) model are proposed. These modulus and model parameters can replace the old default values and CBR-correlated values currently used in african tropical countries.

Laterites sometimes have higher moduli due to cohesion, but are more sensitive to water. It is recommended that these materials be compacted in situ at 97 % of the maximum dry density and, for laterite, to the optimum water content -1.5 but also ensure good waterproofing and good drainage of the pavement structure.

Declaration by Authors

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REFERENCES

1. AGEROUTE (2015) Catalogue de structures de chaussées neuves et Guide de dimensionnement des chaussées au SENEGAL. Version 2 provisoire – Avril 2015. AGEROUTE, Senegal.
2. Ba, M., Fall, M., Samb, F., Sarr, D. and Ndiaye, M. (2011) Resilient Modulus of Unbound Aggregate Base Courses from Senegal *(West Africa)*. *Open Journal of Civil Engineering*, 2011, 1, 1-6, DOI:10.4236/ojce.2011.11001.
3. Ba, M., Nokkaew, K., Fall, M., Tinjum, J. M. (2013) - Effect of Matric Suction on Resilient Modulus of Compacted Aggregate Base Courses. *Geotech Geol Eng*, DOI 10.1007/s10706-013-9674-y.
4. Boyce, H.R. (1980) A nonlinear model for the elastic behaviour of granular materials under repeated loading. Proc Int Symp Soils Cycl. Transient Load. 285–294
5. Fall, M., Senghor, B., Lakhoune, A. (2002) Analyse de la pratique du dimensionnement rationnel des structures de chaussées au Sénégal. Influence des paramètres d'entrée dans les codes de calcul pour le renforcement

des chaussées. *Annales du Bâtiment et des Travaux Publics*, N_ 1/02 (1/9).

6. Fall, M., Sawangsuriya, A., Benson, C. H., Tuncer B. E. and Bosscher, P., J. (2007) On the Investigations of Resilient Modulus of Residual Tropical Gravel Lateritic Soils from Senegal (West Africa*). Geotechnical and Geological Engineering Journal*. Volume 26, Number 1 / February, 2008.
7. Hicks, R. G., and Monismith, C. L. (1971) - Factors influencing the resilient properties of granular materials. *Hwy. Res. Rec. 345*, 15–31.
8. Ki, B. I. J., Ba, M. & Coulibaly, M. (2022) 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). *London Journal of Engineering Research* Volume 22 | Issue 5 | Compilation 1.0
9. NCHRP (2004) Laboratory determination of Resilient Mo ulus for flexible pavement design. National Cooperative Highway Research Program (NCHRP) Project 1-28A. Transportation Research Board of National Academies.
10. Samb, F., Berthaud, Y., Ba, M., Fall, M. & Benboudjema, F. (2018) Nonlinear Mechanical Behavior Analysis of Flexible Lateritic Pavements of Senegal (West Africa) by FEM for M.-E. Pavement Design. *Geotech Geol Eng* (2018). https://doi.org/10.1007/s10706-018-0514-y.
11. Seed, H. B., Mitry, F. G., Monismith, C. L., and Chan, C. K. (1967) ‘‘Prediction of flexible pavement deflections from laboratory repeated load tests.’’ *NCHRP Rep. No. 35*, National Cooperative Highway Research Program.
12. SETRA - LCPC (1994) Conception et dimensionnement des structures de chaussées : guide technique. Ministère de l’Equipement, des Transport et du Tourisme, France. 260 p.
13. Witczak, M. W., Uzan, J. (1988) The universal airport pavement design system. Report I of V: granular material characterization, Department of Civil Engineering, University of Maryland, College Park, MD.

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