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Analysis of Lateritic Soil Reinforced with Palm Kernel Shells for Use as a Sub-Base Layer for Low-Traffic Roads

Joel Koti^{1,2,*}, Crespin P. Yabi³, Mohamed Gibigaye¹, Anne Millien² and Christophe Petit²

¹LEMA, University of Abomey-Calavi, Cotonou, Benin

²GC2D, University of Limoges, 17 Bd Jacques Derche, Egletons, France

³National University of Sciences, Technologies, Engineering and Mathematics, Abomey, Benin

*Corresponding Author: Joel Koti. Email: joelkoti@yahoo.fr

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ABSTRACT

In tropical areas, palm oil production generates significant amounts of waste, including palm kernel shells. The use of this waste in the civil engineering sector, presents a very challenging task. In the present study, the production of lateritic soil (A-2 in GTR classification and A-7-6 (9) in HRB classification) reinforced with palm kernel shells is considered. In order to improve their performances, these materials are mixed using the Fuller's parabolic law. Moreover, experimental tests are used to characterize the physical and mechanical geotechnical properties of the lateritic soil. After characterizing the matrix (i.e., lateritic soil) and the inclusions (i.e., palm kernel shells) in their natural state, it is found that Avrankou's lateritic soil has a high level of fine particles (56.6%), high plasticity (PI = 21%) and low lift (ICBR = 17%); which makes it unusable in the pavement layer. Results also prove that the mixture composed of 39% of lateritic soil volume and 61% of PKS with a CBR index equals to 30 and the mixture composed of 45% of lateritic soil, 40% PKS and 15% of lagoon sand with a CBR index equals to 41 can be used as sub-base layer for roads for low and medium traffic, respectively.

KEYWORDS

Palm kernel shell; lateritic soil; subbase layer; low-traffic roads

Nomenclature

CEBTP	“Experimental Center for Research and Studies of Buildings and Public Works: <i>Centre Experimental de Recherches et d'Etudes du Bâtiments et des Travaux Publics</i> ”
HRB	Highway Research Board
ICBR	index California Bearing Ratio
LS	Lateritic Soil
MDD	Maximum Dry Density
OMC	Optimum Moisture Content
OPM	Optimum Proctor Modified



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PI	Plasticity Index
PKS	Palm kernel shell
SL	sand
MAEP	“Ministry of Agriculture, Livestock and Fisheries: <i>Ministère de l’agriculture, de l’élevage et de la pêche</i> ”

1 Introduction

In southern Benin, rural oil palm production areas are inaccessible due to the limited capacity of public investment. The maintenance or development of these roadways requires the extraction of millions of cubic meters of road material every year. These road materials, before their use in road construction, must present certain well-defined technical requirements. The lateritic gravel is the most classical and valuable road material widely used in Africa in pavement layers [1,2]. Their systematic use as construction materials is beginning to make them a scarce resource in some regions in Africa. Some of these depleted pockets require, even before their use, specific treatment with cement, lime [2], lagoon sand [3] or crushed materials [4,5] to give the materials the necessary technical requirements.

In Benin, this conventional road material is depleted and is only available in very limited quantities (724,806 m³) in the north part, mainly in Banikoara and Tchaourou cities [6]. Therefore, it becomes necessary to assess the available resources and to study the idea of extending the acceptable properties range for these soils or use alternative natural materials. In the south of Benin, where oil palms are produced, one solution consists in pouring palm kernel shells on tracks, which form with the soil on site (lateritic soil) a composite material promoting circulation, especially in rainy periods. Palm kernel shells are non-putrescible waste resulting from the exploitation and production of oil, which is one of the world’s fatty substances [7]. These residues, which represent 7% to 8% of the weight of the bunch, are generated in large quantities in tropical countries [8] and constitute in some regions an environmental nuisance. They are used in small quantities for combustion by hearths and cement industry; which has a serious issues and critical consequences on the environment. According to an MAEP report [9], over 300,000 tons of palm kernel shells are generated each year in Benin. This quantity will be constantly increasing in view of the various actions carried out by successive governments to relaunch this sector which currently contributes only 43% of the demand and needs of fatty substances of plant origin in Benin [10,11]. Recently, several studies have dealt with the problem of the use of PKS as large aggregates to replace gravel for making structural concrete for buildings [12–15]. To date, few studies have been interested in the recovery of this waste (aggregates) in road engineering. Amu and al. studied the effect of PKS in laterite stabilized with asphalt to reduce plasticity, by varying the proportions of the different components [16].

Concluding that no mixture can be used as a pavement layer, it is observed that certain characteristics such as the compressive strength of the asphalt stabilized optimal mixture (by weight of 75% of lateritic soil and 25% of PKS) was greater than that of the asphalt stabilized lateritic soil [16]. Madjadoumbaye concluded that PKS improves CBR index by 26% (95% of OPM) when it mixed (20% of PKS and 80% of gravel laterite) [17]. No author has yet been interested in the mixture of fine soil (clay soil) and PKS for use as sub-base layer. Inspired by studies of improvement of lateritic soils with crushed and the traditional technique of treatment of the population (Fig. 1), this work reports on the experimentation and development of a composite based on the lateritic soil of Avrankou and the PKS of Misserete in order to produce a composite (alternative material) that can be used as a subbase layer based on locally available natural resources.

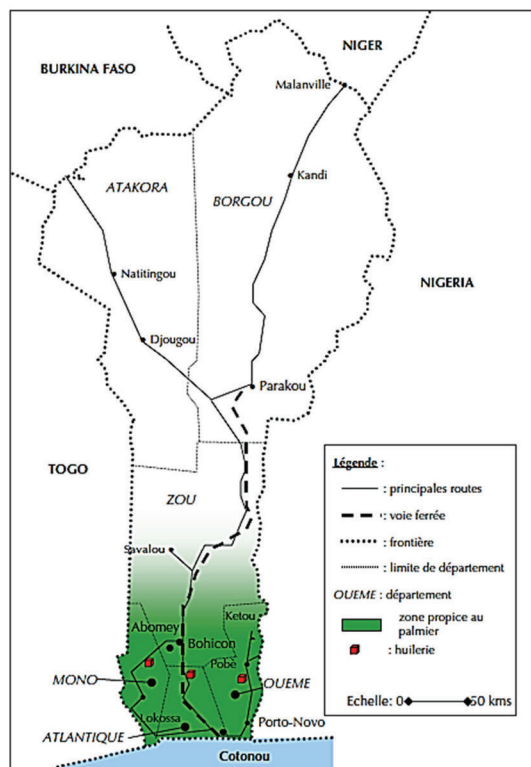
2 Properties of the Composite Components

In Benin, the oil palm is widely cultivated in the southern coastal fringe (Fig. 2). PKS are obtained using traditional processes by crushing palm nuts with artisanal machines. For this study, they are collected at “Gome Sota” (Misserete city) 6°35’39.0”N; 2°35’20.5”E. This zone is favorable to the cultivation of oil

palm because of its pedology located in the seven plateaus of South Benin. These plateaus are rich in lateritic soil (commonly called bar soil) in large quantities (minimum 10,410,949 m³) [6]. The lateritic soil is taken about ten kilometers from “Misserete” in a quarry at Avrankou 6°32'24.5"N and 2°39'3.6"E.



Figure 1: Entrance of treated house using the PKS



(a)



(b)

Figure 2: a) Oil palm cultivation area in Benin [18]; b) Pile of PKS in Misserete

At first glance, the initial and natural characteristics and properties of the basic materials were studied.

The results of the identification tests for palm kernel shells and lateritic soil are presented in [Tables 1](#) and [2](#), respectively.

Table 1: Properties of PKS

Properties	PKS	PKS used elsewhere
Specific weight (kg/m^3)	1370	1170–1370
Apparent weight (kg/m^3)	530	500–620
Water absorption (%) after 24 h immersion	22	19–24

Palm kernel shells (PKS) are coarse aggregates, the identification parameters are generally: granular distribution, specific weight, apparent weight and water absorption after 24 h after immersion [[12,14,19](#)]. PKS has an thickness rang of 1.50 to 2.5 mm, a specific weight 1370 kg/m^3 , an apparent weight 5300 kg/m^3 and 620 kg/m^3 . These different parameters show that PKS are light aggregates, 50% to 60% lighter than conventional aggregates [[8,20](#)]. The granular distribution conducted in accordance with standard NF EN 933-1 [[21](#)], the apparent weight with standard NF EN 1097-3 [[22](#)], specific weight, and water absorption with standard NF EN 1097-6 [[23](#)].

The laterite soil is identified with the habitual geotechnical road test namely: distribution granular, soil limits liquidity and plasticity, water content and dry density for Optimum Proctor Modified (OPM), bearing CBR, after 4 days of immersion and swelling after immersion [[24–27](#)].

Table 2: Summary of the results of the tests carried out on the lateritic soil

Physical and mechanical parameters	Notation/Unity/Standard	Lateritic soil
% fine particles [28]	–	56.6%
Plasticity index [29]	PI	21
Organic materials [30]	MO	0.63
GTR classification [31]	NF P 11-300	A-2
HRB classification	–	A-7-6 (9)
Modified Proctor [32]	γ_{dmax} (kg/m^3) NF P94-093	1890
	Wopt (%)	13.67
CBR soaked at 96 h [33]	CBR at 95% OPM NF P94-078	17
	Swelling (%)	0.013
Specific density [23]	(kg/m^3) NF EN 1097-6	2650
Loose bulk density [22]	(kg/m^3) NF EN 1097-3	1050
Blue value [34]	NF P94-068	0.7

3 Mixture Proportioning for the Composite

Granular mixtures, especially in the field of road materials, are generally produced by the trial and error technique [3–5,16,17]. This technique consists in varying the proportion of a component, then carrying out physico-mechanical tests on the mixtures in order to retain the mixtures with the best results. This groping technique leads to a lot of unnecessary testing. To overcome these difficulties, studies have been carried out on particle size distribution functions [35] in order to find optimal mixtures. For each system considered, there are parameters to optimize the distribution and lead to the most compact stack. But at this stage the difficulty is to set one of these real distribution functions, particularly for large grain sizes [36]. In 1907, the influence of particle size distribution on the density of granular materials was studied by Fuller et al. [37] and expressed as Eq. (1).

$$P_{FT} = 100 \cdot \left(\frac{d}{D_{\max}} \right)^n \quad (1)$$

where $P(d)$ the percentage of material passing a sieve with opening d ; $D_{\max}$ maximum size of particle in grading; n is a variable exponent, taken as 0.5 for maximum density.

With an exponent set at 0.5, this model lacks versatility. This is why it was improved by Andreasen and Andersen in 1929 which replaced the constant 0.5 by a variable q [38]. Even though Andreasen and Andersen came to the conclusion that the exponent q must be between 0.33 and 0.5 to obtain a dense mixture, the value of q which must be considered in this light constitutes a real debate [36]. For Peronius et al. [39], the porosity decreases when q evolves from 3 to 0.5 then begins to increase for q from 0.5 to 0.4 [39]. Aberg [40] and Tsirel [41] have shown that a decrease in q leads to a decrease in voids. In summary, the authors agree that it produces a decrease in porosity when q goes from 3 to 0.5. Below 0.5, opinions diverge.

In view of these variations on the exponent, a parametric study was carried out on the variation of “ n ” in this paper. The method used consisted in finding the volume proportions of components forming the densest possible mixture. The maximum diameter D of the aggregates is fixed and known. For a given variable n , the study percentage P is determined corresponding to the passing of the granular fraction of mean diameter d . A parametric optimization study is carried out by varying “ n ”. It appears that for n less than 0.2 the proportion of PKS is very low and for values of n superior to 0.5 the proportion of PKS is high, which would make the mixture incompressible. For values of n between 0.2 and 0.4, we obtain the following five mixtures (see Table 3):

Table 3: Proportions of lateritic soil and PKS

Mixture	Value of n	Volumetric proportion of lateritic soil (%)	Volumetric proportion of PKS (%)
Mixture 37	0.2	63	37
Mixture 46	0.25	54	46
Mixture 54	0.3	46	54
Mixture 61	0.35	39	61
Mixture 67	0.4	33	67

Each mixture is designated by its proportional volume of PKS. The different grain size curves are shown in Fig. 4 and it is noted that the curves of the different mixtures lie between the curve of the PKS and that of the lateritic. PKS being light aggregates, the objective sought here is to have mixtures with better compactness (see Eq. (2)) and with better geotechnical characteristics.

$$compactness = \frac{\gamma_d}{\gamma_s} \quad (2)$$

γ_d : dry density

γ_s : grain specific gravity of the material.

The mixes are done manually; PKS and lateritic soil being dry (illustrated in Fig. 3). Geotechnical tests are carried out with each mixing (granular distribution, soil limits liquidity and plasticity, water content and dry density for Optimum Proctor Modified (OPM), bearing CBR, after 4 days of immersion and swelling after immersion).



Figure 3: Study images of mixtures (lateritic soil + PKS)

4 Results and Discussion

The recommendations of the specifications related to road materials depend on the nature of said materials, the standards and regulations in force in the country, the traffic, the considered layer and the type of treatment. In West Africa, the CEBTP guideline [42] is considered as the most widely used material in the civil engineering of roads; which has evolved over time (1972, 1980 and 1984). The major criteria are the CBR index and the plasticity index (PI). Based on the shape of PKS (polygonal shapes with angular edges, surfaces smooth enough for concave and convex faces), the composite (Lateritic soil + PKS) could be assimilated or compared to conventional materials such as lateritic gravelly (if the PKS play the role of lateritic nodules), clayey sand or shell materials from the CEBTP guideline.

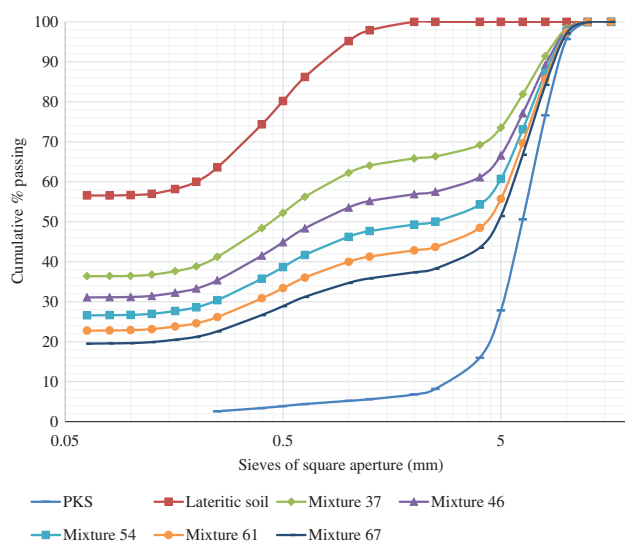


Figure 4: Sieves of PKS, Lateritic soil and the 5 mixtures

The geotechnical characteristics of the various mixtures are presented in [Table 4](#) and the various criteria for the use of natural soils, according to the CEBTP approach, are summarized in [Table 5](#).

Table 4: Characteristics of the different mixtures (PKS + LS)

Geotechnical characters	Lateritic soil	Mixture 37	Mixture 46	Mixture 54	Mixture 61	Mixture 67
% of fine particles P_{80} ($<80 \mu\text{m}$)	56.6	36	31	27	23	20
OMC (W_{OPM} en %)	13.67	12.42	15.43	19.32	16.72	20.64
MDD γ_{dmax} (kg/m^3)	1890	1670	1650	1600	1530	1380
Density of solid particles (kg/m^3)	2650	2180	2060	1950	1870	1790
Compactness (%)	71.3	76.6	80.2	81.9	82.0	77.1
Liquid limit (W_L)	47	46	38	49	43	43
Plastic limit (W_P)	26	24	19	26	23	20
Plasticity index	21	22	19	23	20	23
Blue value	0.7	1.57	1.29	1.28	1.41	1.42
CBR (95% OPM)	17	31	20	18	30	20
Swelling (GL %)	0.013	0.07	0.41	0.22	0.16	0.35

The lateritic soil used is a fine soil with 56.6% fines. It is class A-2: clay soil (GTR classification) and A-7-6 (9) and (HRB classification) with a CBR index after immersions of 17.

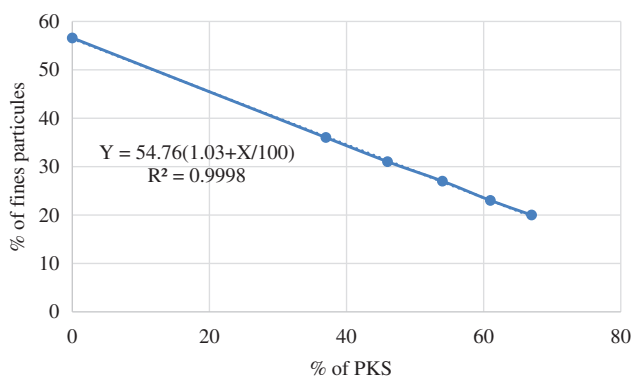
Table 5: Summary of the criteria for the use of mixtures [42]

	Criteria	Lateritic soil	Mixture 37	Mixture 46	Mixture 54	Mixture 61	Mixture 67
Platform	PI < 40	ok	ok	ok	ok	ok	ok
	$W_L < 70$						
	GL < 2%						
	OM < 3%						
Form layer (low traffic site)	CBR > 5	no	ok	ok	ok	ok	ok
	PI < 30						
	$P_{80} < 45$						
Subbase layer (low traffic site: gravelly lateritic)	$1.8 < \rho_{dmax} < 2$	no	no	no	no	ok	no
	(Corresponding to a compactness of at least 68%)						
	CBR(95% OPM) ≥ 30						
	$P_{80} < 35$						
	PI < 30						

Note: Legend: ok= usable; no= unusable.

4.1 Fines Particles

The evolution of the proportions of fine particles (passing to 80 μm) is linear (Fig. 5). The absolute linearity is that the distributions of the different granular mixtures were reconstructed from the sizes of the two materials. It is noted that the percentage of fines in the lateritic soil decreases by 10% for 10% of PKS added.

**Figure 5:** Evolution of the proportion of fines particles in function of PKS

4.2 Maximum Dry Density and Compactness

The maximum dry density is determined as a function of the wet density and the optimum water content. The compactness, for its part, represents the ratio between the maximum dry density and the density of the solid grains.

Unlike what is observed with mixtures of conventional materials (lateritic gravel and alluvial gravel) [5], the maximum dry density decreases when the proportion of PKS increases (Fig. 6). Its evolution is almost linear. The trend line of equation $y = -6.68x + 1915.1$ and its coefficient correlation of 0.9111. This observed decrease in the maximum dry density of composites is due to the fact that PKS is twice as light as lateritic soil. Despite the decrease in maximum dry densities, the compactness of composites is greater than that of lateritic soil in its natural state. This phenomenon is explained by the arrangement of fine grains in coarse grains thus forming dense mixtures. All five have a compactness greater than 72%, which gives them a usable material density in the pavement body. The compactness (Fig. 7) seems to stabilize for mixtures 46, 51 and 61. This means that the optimum proportion of PKS is between 46% and 61% (i.e., between 30% and 45% by mass proportion).

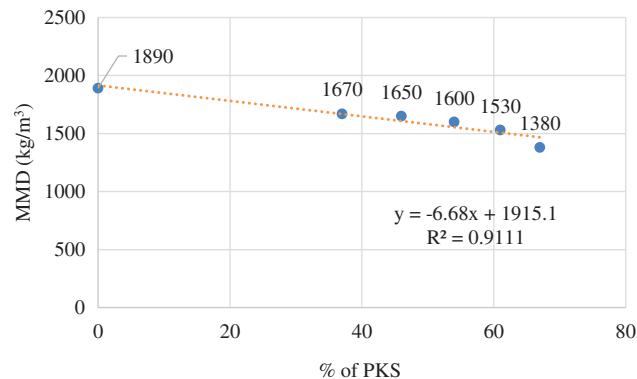


Figure 6: Evolution of maximum dry density (MMD) in function of % PKS

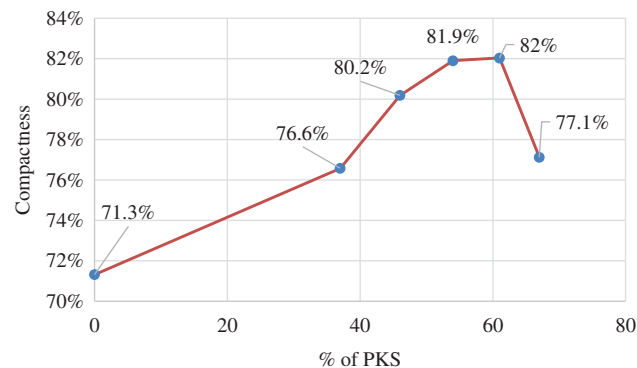


Figure 7: Evolution of compactness in function of % PKS

4.3 CBR after Immersion and Swelling

The curves in Fig. 8 show the variation of CBR (90%, 95% and 100% of the OPM corresponding respectively to 10, 25 and 56 strokes) as a function of the proportion of PKS. The curves look the same. Above 90% of the OPM, all composites have a higher CBR than the lateritic soil. However, the mixture 61 (with the best compactness) offers a considerable improvement in the CBR index compared to the CBR of lateritic soil with gains of 100%, 76% and 14% for respectively 90%, 95% and 100% of the OPM.

The linear swellings at 95% of the OPM are 0.013% for the lateritic soil against 0.16% for the mixture 61. These swellings are lower than the maximum allowable for the use of the composite in base and sub-base layers of low traffic pavements.

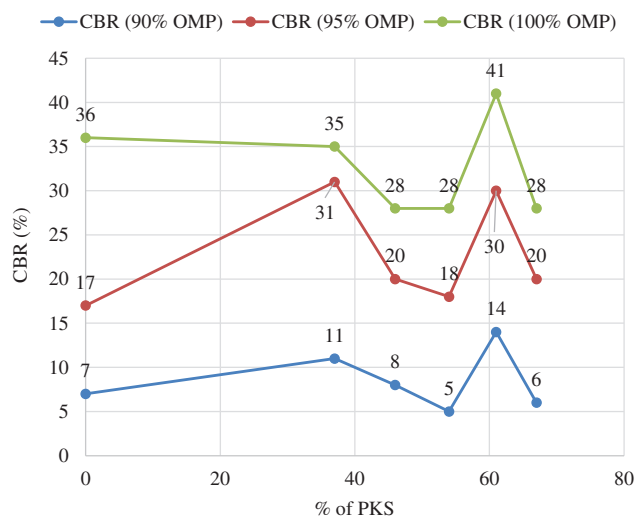


Figure 8: Evolution of CBR after immersion in function of PKS

4.4 Use of Composites in Road Construction

According to the technical recommendations of CEBTP [42] summarized in Table 5, the five mixtures can be used as materials for the platform and for subgrade for low and medium traffic sites.

Whatever the nature of the structure, the materials used in the sub-base layer must have a CBR at least equal to 30 obtained for a dry density corresponding to 95% of the OPM (25 may be accepted for low traffic, T1). The mixture 61 is the most dense and compact mix with a compactness of 82% with CBR 30 (at 95% of OPM) and 41 (at 100% of OPM). In view of these different technical requirements, only the mixture 61 (39% lateritic soil + 61% PKS) has all the characteristics as a sub-base layer materials for low traffic roads (T1 < 300 vehicles per day).

The optimal composite 61% of PKS (45% by weight) is different that of Amu (25% of PKS and 75% of laterites), that of Madjadoumbaye (20% of PKS and 80% of grave lateritic) and of Ahouet (30% alluvial gravel and 70% lateritic gravel [5,16,17]. These differences demonstrate that the optimum of composites and their geotechnical characteristics strongly depend on intrinsic characteristics of the matrix (type of laterites) and inclusion.

4.5 Composite PKS/Lateritic Soil/Sand

In order to consider their use as a subbase layer for medium traffic (T2 and T3), it will be necessary to decrease by reducing the plasticity index. The addition of sand is considered as one of the less expensive mechanical treatment improvements, recommended by CEBTP guideline. This solution was chosen in this work because of the availability of river sand in the study environment. This solution was adopted by Ndiaye et al. [3] as part of his lithostabilization study in which he has concluded that the sand not only reduces the plasticity index but also helps in increasing lift. The proportion of sand was fixed and kept constant (15%). The used sand is taken from Agassa-Godomey in the municipality of Abomey-Calavi, in which their physical and mechanical characteristics are summarized in Table 6.

Using the same methodology (3), the following five mixtures are obtained:

- Mixture A: 68% LS + 15% SL + 17% PKS
- Mixture B: 59% LS + 15% SL + 26% PKS
- Mixture C: 51% LS + 15% SL + 34% PKS

- Mixture D: 45% LS + 15% SL + 40% PKS

- Mixture E: 38% LS + 15% SL + 47% PKS

** LS: Lateritic soil; SL: sand; PKS: palm kernel shell.

Table 6: Characteristics of sand

Proprieties	Notation/Unity/Standard	Sand
% of fine particles P_{80}	%	3
Specific gravity	(kg/m^3) NF EN 1097-6	2560
Loose bulk density	(kg/m^3) NF EN 1097-3	1420
Blue value	NF P94-068	0.7
Sand equivalent	ES (%)	72

The results of the Modified Proctor and CBR tests, carried out on the three-phase mixtures of lateritic soil, of sand and PKS are presented in Table 7. It is observed that the addition of 15% of sand improves significantly the bearing capacity of the mixtures (i.e., their CBR index is greater than 30) and their plasticity limit (i.e., less than 20). It is noticed also that the compactness of the various mixtures is stabilized between 75% and 78%.

Table 7: Characteristics of the different mixtures (PKS + Sand+ Lateritic soil)

Geotechnical characters	Lateritic soil	Mixture A	Mixture B	Mixture C	Mixture D	Mixture E
% fine particles P_{80} ($<80 \mu\text{m}$)	56.6	39	34	30	26	23
OMC (W_{OPM} %)	13.67	11.59	12.90	12.09	12.02	14.03
MDD γ_{dmax} (kg/m^3)	1890	1830	1750	1730	1640	1580
Density of solid particles (kg/m^3)	2650	2420	2300	2200	2120	2040
Compactness (%)	71.3	75.7	76.0	78.6	77.4	77.6
Liquid Limit (W_L)	47	37	37	35	35	34
Plastic Limit (W_P)	26	21	21	21	21	20
Plasticity Index	21	16	16	14	14	14
Blue value	0.7	0.63	0.65	0.65	0.60	0.68
CBR (95% OPM)	17	32	34	31	41	34

The CBR index of the composites mix with PKS is greater than that of the lateritic soil. Therefore, the CBR index is improved by adding PKS to lateritic soil. Unlike the work of Amu et al. [16], the mixture D (45% LS + 15% SL + 40% PKS) and the mixture E (38% LS + 15% SL + 47% PKS) with a plasticity index less than 20, the fines percentage being less than 30 and a CBR index greater than 30 can be used as a subbase layer (Table 8) for medium traffic roads (T2 and T3). The mixture D (by weight of 26.1% of PKS, 55.8% of lateritic soil and 18.1% of lagoon sand) comparable to that optimal from Amu's study (25% PKS and 75% lateritic soil), confirms the reliability of the optimization method used.

Table 8: Summary of criteria for use of Mixtures in subbase layer by reference material [42]

	Criteria	Lateritic soil	Mixture A	Mixture B	Mixture C	Mixture D	Mixture E
Subbase layer (site T3: gravelly lateritic)	$1.8 < \rho_{dmax} < 2$ Corresponding to a compactness of at least 68% $CBR(95\% OPM) \geq 30$ $P_{80} \leq 30$ $PI \leq 20$	no	no	no	ok	ok	ok
Subbase layer (clayey sand)	$1.9 < \rho_{dmax} < 2.1$ (Corresponding to a compactness of at least 72%) $7 < W_{OPM} (\%) < 13$ $CBR(95\% OPM) > 30$ $10 < P_{80} < 30$ $5 < PI < 20$	no	no	no	no	ok	ok
Subbase layer (Shell materials)	$CBR(95\% OPM) > 30$	no	ok	ok	ok	ok	ok

Note: Legend: ok= usable; no= unusable.

5 Conclusion

In Benin, as in many African countries, the selection criteria for materials in road construction are based on the recommendations of the “pavement sizing guideline for tropical countries” of the CEBTP of 1972 and of 1980 (revised 1984). These recommendations are generally based on the Plasticity Index (PI) and the CBR Index.

In this work, an experimental study is presented to improve the geotechnical properties of lateritic soil (i.e., unusable in its natural state in the body of the road) by adding palm kernel shells.

According to the findings, the minimum input of 37% of PKS (by volume) enhances the clay material for its use in subgrade and road platform. The addition of PKS to the lateritic soil reduces the percentage of fines to less than 35 and increases the CBR index. Thus, the mixture composed of 39% of lateritic soil and 61% of PKS with CBR index equals 30 and the mixture composed of 40% of PKS, 45% of lateritic soil and 15% of lagoon sand with CBR index equals 41 can be used as a subbase layer for roads for low and medium traffic respectively, in the case of new constructions as well as rehabilitations.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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