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Journal de la Société Ouest-Africaine de Chimie
J. Soc. Ouest-Afr. Chim. (2023), 052 : 32 - 43
28ème Année, 2023

ISSN 0796-6687
Code Chemical Abstracts : JSOCF2
Cote INIST (CNRS France) : <27680>
***Site Web:* http://www.soachim.org**
http://www.soachim.info

J. Soc. Ouest-Afr. Chim. (2023) 052; 32 - 43

Improvement of geotechnical and mechanical properties of laterite from Burkina Faso using sugar cane molasses for use as road structural layers

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(Reçu le 03/01/2023– Accepté après corrections le 20/11/2023)

Abstract: The objective of this study is to use sugarcane molasses up to 6 wt.% to improve the geotechnical and mechanical properties of lateritic soils (Bama, Burkina Faso) for use as road structure layers. Mineralogical and elemental chemical analysis showed that this soil is composed of kaolinite, quartz, and goethite. The results of geotechnical characterization indicated that the raw sample is suitable for the sub-base layer in road construction. The improvement of this lateritic clay by adding sugarcane molasses allowed the binding of isolated particles after drying. This formation of strong bonds significantly improves the geotechnical and mechanical properties of the mixtures obtained. However, the California Bearing Ratio (CBR) results after 96 hours of immersion show that the solid bonds formed dislocate, causing a decrease in CBR as the molasses content increases in general. In contrast, the immediate CBR value increases rapidly compared to the results after 96 hours of immersion. These mixtures containing between 2 wt.% (141% CBR) and 4 wt.% (149% CBR) in volume are optimal and suitable for a base course in road construction not subjected to flooding.

Keywords: Lateritic clay, Sugarcane molasses, Road structural layers, Geotechnical and mechanical properties.

Amélioration des propriétés géotechniques et mécaniques d'une latérite du Burkina Faso à l'aide de mélasse de canne à sucre pour une utilisation comme couches structurelles routières

Résumé: La présente étude vise à utiliser de la mélasse de canne à sucre jusqu'à 6% en masse en vue d'améliorer les propriétés géotechniques et mécaniques des sols latéritique (Bama, Burkina Faso) pour une utilisation comme couches structurelles routières. L'analyse minéralogique et chimique élémentaire a montré que cette terre est composée de kaolinite, de quartz et de goethite. Les résultats de la caractérisation géotechnique ont indiqué que l'échantillon brut est adapté pour la couche de sous-base dans la construction routière. L'amélioration cette argile latéritique par ajout de mélasse de canne à sucre a permis de lier les particules isolées après séchage. Cette formation de liaisons solides améliore considérablement les propriétés géotechniques et mécaniques des mélanges obtenus. Cependant, les résultats du California Bearing Ratio (CBR) après 96 heures d'immersion montrent que les liaisons solides formées se disloquent, entraînant une diminution du CBR à mesure que la teneur en mélasse augmente en général. En revanche, la valeur immédiate du CBR augmente rapidement par rapport aux résultats du CBR après 96 heures d'immersion. Ces mélanges contenant entre 2% (141% CBR) et 4% (149% CBR) en masse sont optimaux et adaptés pour une couche de base dans la construction routière non assugétie aux inondations.

Mots-clés : Argile latéritique, Mélasse de canne à sucre, Couches structurelles routières, Propriétés géotechniques et mécaniques.

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1. Introduction

Gravelly lateritic materials are abundant in tropical and subtropical regions, and are used to create sub-bases and/or base courses in road construction [1-5]. The use of these materials in road construction is proving advantageous in tropical countries, particularly Burkina Faso, due to their abundant availability and low operating costs. Their abundance and low operating costs make them economically attractive choices, even if their mechanical performance is sometimes mediocre and, above all, variable. Portions of the road built with natural lateritic gravel in Burkina Faso are suffering significant deterioration. This deterioration can be the result of heavy road traffic and the lack of adequate geotechnical testing when selecting these materials for road construction [4, 6].

In order to increase the mechanical properties of lateritic soils to make them suitable as road structure layer materials, various additives such as lime, cement, fly ash, silica fume and plant fibres have been experimented with [4-11].

With a view of diversifying admixtures in the context of improving the geotechnical, physical and mechanical properties of lateritic soils, this study was initiated in order to use sugarcane molasses as a reinforcement ingredient. Research by Dabakuyo et al. (2021) [3] and Malanda et al. (2017) [12] reported the use of sugarcane molasses as a stabiliser for lateritic soils and adobes respectively. These studies highlighted the improvement in the geotechnical, physical and mechanical properties of adobes and lateritic soils by this addition.

To our knowledge, there is very little scientific literature on the use of sugarcane molasses as a reinforcement in road structure layers. In fact, sugarcane molasses is rarely used as a stabiliser for lateritic gravel in road construction. However, it is very important to know its effect on the geotechnical and mechanical properties of road structure layers. Similarly, the influence of the chemical and mineralogical composition of sugarcane molasses on lateritic soils has not been the subject of scientific study. It is clear that the chemical and mineralogical nature of these organic binders (sugarcane molasses) has an effect on lateritic gravels, and this effect undoubtedly contributes to improving the usability properties of road structure layers for dry climates, such as tropical and subtropical climates.

The objective of this study is to use sugarcane molasses at varying contents of 0, 2, 4 and 6 wt.% with a view of improving the geotechnical and mechanical properties of the lateritic soil of Bama (western Burkina Faso) for a use as road structure layers. Particular emphasis will be placed on the effect of adding sugarcane molasses on the variation in the CBR bearing capacity index immediately and then after immersion.

2. Raw materials, methods and experimental procedures

2.1. Raw materials

Clayey raw material referenced as ALB was collected in the locality of Bama (**Figure 1.A**) (11°20' North and 04°21' West), located 25 km from Bobo Dioulasso, in western Burkina Faso. The site studied is an old quarry that was formerly exploited for road layers by some companies. The red brick clayey soil **(Figure 1.B)** suggests the presence of iron oxides.

The molasses used in this study is a by-product of sugar production, supplied by the New Comoe Sugar Company “Nouvelle Société Sucrière de la Comoé” (SN SOSUCO) in the rural commune of Bérégadougou (10°46' North and 04°43' West) in south-west Burkina Faso.

This molasses is used to stabilize dirt roads against dust during the agricultural campaign and in the dry season. It is also used as a fertilizer in fields (Vinasse), as animal feed, as a raw material for alcohol production, and in many other areas. Malanda et al. (2017) [12] and Crueger et al. (1984) [13] provided the average chemical composition of sugarcane molasses (**Table I**). These results show a similarity in the chemical composition of sugarcane molasses regardless of the variety of sugarcane plant.

2.2. Manifacture of specimens

Lateritic soil from Bama, used for the elaboration of specimens, was crushed to a diameter of less than 12.5 mm. The elaboration of specimens was carried out by mixing ALB sample and sugarcane molasses at 0, 2, 4, and 6 wt.%. The amount of water was determined using the modified Proctor test. This test provided optimal water contents : 20 wt.% for 0 wt.% admixture, 15.7 wt.% for 2 wt.%, 16 wt.% for 4 wt.%, and 18.5

wt.% for 6 wt.%. Due to the liquid aspect of sugarcane molasses, it was used to substitute a portion of the hydration water and considered as an admixture in the same way as mixing water. The proportions of mixtures used for each formulation are presented in **Table II**. Each mix design, after homogenization, was compacted in a CBR mould according to the requirements of NF P94-078 [14] to form samples for geotechnical and mechanical characterization.

2.3. Experimental procedures

The particle size distribution of ALB sample was determined by dry sieving for grains with a diameter ≥ 80 µm and by sedimentation for grains with a diameter < 80 µm, respectively, according to NF P94-056 [15] and NF P94-057 [16]. These tests allow the determination of the weight percentage of different particle families contained in the sample.

The limits of Atterberg, namely liquidity limit (WL), plasticity limit (WP), and plasticity index (IP), were determined according to NF P 94-051 [17]. The plasticity index, which is the difference between the liquidity limit and plasticity limit, provides an indication of the clay content in the sample.

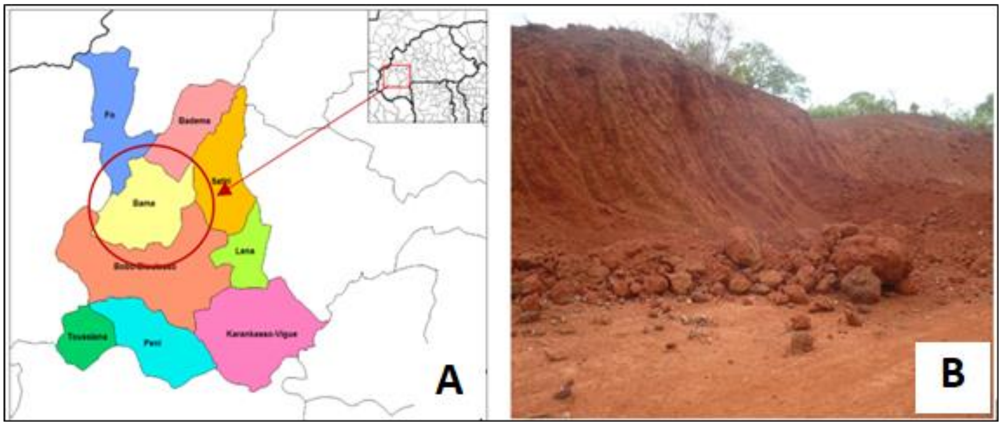

Figure 1 : Location of the city of Bama (A), Clay sampling site in Bama (B)

Table I : Average chemical composition of sugarcane molasses [12, 13]

	Water (wt.%)	Sugar Total (wt.%)	Nitrogenous matter (wt.%)	Non-nitrogenous organic matter (wt.%)	Mineral matter (wt.%)	Dry matter (wt.%)
Sugarcane molasses (Crueger et al., 1984)	18	54	7	6	13	82
Sugarcane molasses (Malanda et al., 2017)	27	64	6	-	14	73

Table II : Proportions of mixtures used for the elaboration of specimens

Code	Description of specimens	Clay mass (g)	Molasse mass (g)	Hydration water mass (g)
ALB	ALB + 0 wt.% molasses	36602	0	7320
ALB2	ALB + 2 wt.% molasses	36502	730	5001
ALB4	ALB + 4 wt.% molasses	36146	1446	4337
ALB6	ALB + 6 wt.% molasses	34337	2060	4292

The methylene blue test was carried out according to NF P 94-068 [18]. The purpose of this test is to determine the quantity and the activity of the clay fraction of a soil in a global way. It measures the ionic adsorption capacity of soils and aggregates using methylene blue. The result of the test depends directly on both the quantity and the mineralogical nature of this fraction [19].

The optimum water content (OWC) and maximum dry density (MDD) of clay materials were determined through the modified Proctor test performed according to NF P94-093 [20].

The bearing capacity of different clayey materials (raw and improved) was evaluated through the Californian Bearing Ratio (CBR) test according to NF P94-078 [21]. Three types of bearing capacity were evaluated: the immediate CBR bearing capacity without immersion (CBRim0), the CBR bearing capacity after 24 hours of curing without immersion (CBRim24), and the CBR bearing capacity after 96 hours of immersion (CBR96). After demoulding, specimens formulated in a hollow cylindrical mould with a diameter of 152 mm and a height of 152 mm were kept for 21 days at the ambient temperature of the laboratory (30 ± 5°C) to be subjected to a mechanical characterization through a compression test according to the NF P18-406 [22] standard. The test was performed using a Controlab hydraulic press equipped with a load cell with a capacity of 200 kN and a displacement speed of 0.5 mm/min.

The chemical composition of ALB was determined by Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES) after digesting the sample in fluxes. A sample of the starting material was ground into particles smaller than 80 µm and melted with lithium tetraborate ($Li_2B_4O_7$) to form a glass bead. The glass bead was dissolved in nitric acid, and the resulting solution was analyzed by ICP-AES to determine its chemical composition. Loss on ignition was determined after calcining the sample at 1000°C.

X-ray diffraction (XRD), infrared spectrum, and differential scanning calorimetry (DSC) coupled with thermogravimetric analysis (DSC-ATG) were used to determine the mineralogical composition of the samples.

The diffractometer used was a Siemens D5000 equipped with a monochromator using a cobalt anticathode (Kα= 1.789 Å).

Infrared spectra of the raw materials were performed using a Perkin Elmer UATR1 Frontier FT-IR spectrometer.

DSC-ATG thermograms were performed on a Netzsch SATA 449 F3 Jupiter with a temperature rise rate of 10°C/min up to 1000°C.

By combining the results of chemical analysis with those of mineralogy, the semi-quantitative composition of mineral phases of ALB clay was evaluated using relation 1 [23]:

$$T(a) = \sum MiPi(a) \qquad (1)$$

Where T(a) is the percentage of the constituent oxide of element "a"; Mi is the percentage of mineral "i", and Pi(a) is the percentage of oxide of "a" in "i".

3. Results and discussion

3.1. Caracterization of raw clayey material and Sugarcane molasses

3.1.1. Chemical and mineralogical characterization of raw clayey material

Table III shows the chemical composition of the ALB sample. Analysis of these results reveals that the ALB sample contains a high silica content, a medium alumina content, and a considerable iron oxide content, giving it a reddish hue. Based on these results, the sample is likely to be rich in quartz and clay minerals and would contain an appreciable amount of iron minerals.

X-ray diffraction (**Figure 2**) confirms the presence of kaolinite ($Al_2(Si_2O_5)(OH)_4$), quartz (SiO_2), and goethite (FeO(OH)) in the sample. This result is consistent with the chemical composition previously mentioned.

The infrared (IR) spectrum of the clay raw material (**Figure 3**) exhibits several characteristic bands corresponding to different mineral components. Specifically, the spectrum shows kaolinite bond vibration bands at 3697, 3650, and 3621 cm^{-1} (corresponding to O-H elongation vibrations) [24, 25], 1115 and 1002 cm^{-1} (corresponding to Si-O vibrations) [22, 24], and 911 and 756 cm^{-1} (related to Al-OH and Si-O-Al deformation vibrations) [26, 27]. The presence of a band at 1030 cm^{-1} indicates the presence of quartz (Si-O vibration) [28], while bands at 794 and 681 cm^{-1} are related to Si-O-Si deformation vibrations [28, 29]. Additionally, a band at 1648 cm^{-1} is attributable to hygroscopic water [25].

The absence of the kaolinite band at 3672 cm^{-1} confirms its low crystallinity in the sample [30, 31]. These various results are in agreement with the findings from X-ray diffraction, confirming the presence of kaolinite, quartz, and other relevant components in the clay sample.

DSC-ATG thermograms of the sample are presented in **Figure 4**. Examination of the DSC-ATG curves reveals an endothermic peak around 85 °C, which corresponds to a mass loss of 1.2 wt.% attributable to the departure of hygroscopic water from the sample. Another endothermic peak observed at around 335 °C can be attributed to the dehydroxylation of goethite and its transformation into hematite. Furthermore, a very intense endothermic peak at 520 °C is observed, which is attributed to the dehydroxylation of kaolinite into an amorphous phase called metakaolinite [32, 33] following relation 2:

$$Si_2Al_2O_5(OH)_4\ (kaolinite) \rightarrow Si_2Al_2O_7\ (metakaolinite) + 2H_2O \qquad (2)$$

Table III : Chemical composition of the soil (ALB) used in this study.

Oxides	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	LOI[a]	Total
wt.%	49.24	22.75	16.01	-	0.1	0.25	-	11.13	99.48

[a] Loss on ignition at 1000 °C

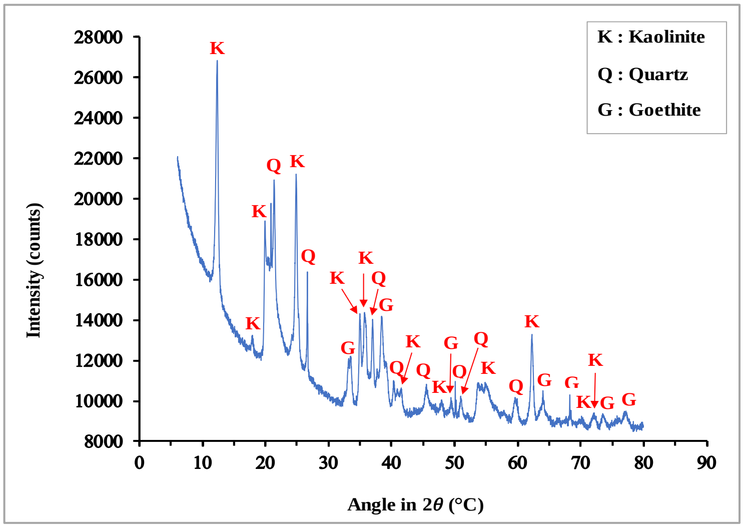

Figure 2 : XRD pattern of the soil (**ALB);**

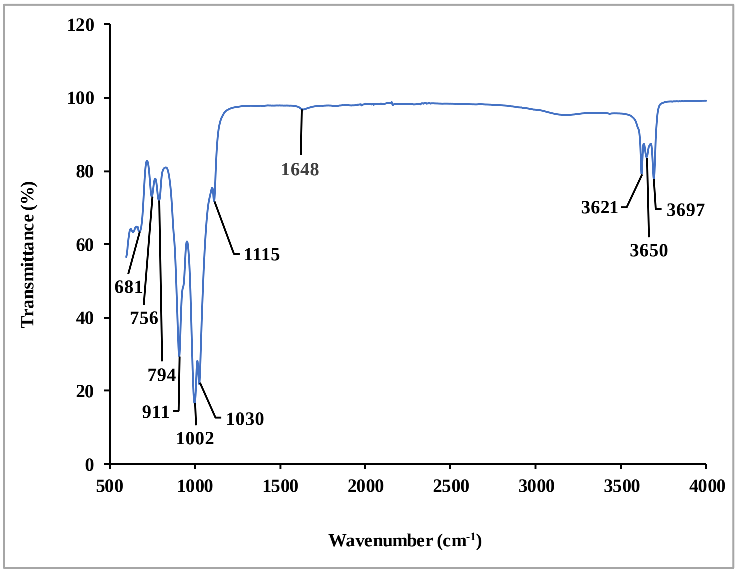

Figure 3 : FTIR spectrum of the raw material

This transformation is associated with a weight loss of 8.1 wt.%.

The dehydroxylation temperature of an ordered kaolinite is typically around 600 °C, whereas for a disordered kaolinite, it occurs at a lower temperature [34]. Given that the dehydroxylation temperature of kaolinite in our sample is 520 °C, it indicates that the kaolinite is disordered.

The only exothermic peak observed at around 970 °C corresponds to the structural reorganization of metakaolinite [34, 35]. This reorganization involves the transformation of metakaolinite into the spinel phase (Al-Si-spinel) and amorphous silica, as described by the relation 3 [36]:

$$2[2SiO_2.Al_2O_3] \text{ (metakaolinite)} \rightarrow Si_3Al_4O_{12} \text{ (Al-Si-spinel)} + SiO_2 \text{ (amorphous)} \qquad (3)$$

The mineralogical composition of the clayey raw material, evaluated using relation 1, reveals that the ALB sample mainly consists of kaolinite (58 wt.%), quartz (22 wt.%), and goethite (18 wt.%). The remaining 2 wt.% is comprised of amorphous minerals and/or mostly organic matter (likely carbonates) [37].

3.1.2. Geotechnical and mechanical characterization of the raw sample (ALB)

A close examination of the particle size distribution curve (**Figure 5**) reveals that ALB clay mainly consists of 63 wt.% gravel (> 2 mm), 36 wt.% skeleton (< 2 mm), 20.3 wt.% mortar (< 0.425 mm), 10.6 wt.% fine particles (< 80 µm), and 4 wt.% clay fraction (< 2 µm). Liquid limit (WL), plastic limit (WP), and plasticity index (IP) of the studied sample are 59, 32, and 27%, respectively. The value of the plasticity index shows that the ALB sample is a plastic clay. This high plasticity is probably due to the presence of clay minerals such as kaolinite, which makes it plastic, and the low quartz content, which normally contributes to the decrease of plasticity [38].

The methylene blue value of ALB clay is VBS = 1.6 g/100 g. This value indicates that the ALB sample belongs to the silty type of lateritic clay, which is plastic and contains fine clay and silica sand [34]. This result corroborates well with those of the Atterberg limits. The values of the plasticity index and methylene blue value obtained in this study are higher than those reported by Millogo et al. (2008) [2] for lateritic gravels from Sapouy (PI = 10.5% and VBS = 0.17 g/100 g). This difference can be explained by the predominance of clay in our sample, in contrast to the Sapouy sample, which consists mainly of gravels and is therefore low in clay minerals.

The Modified Proctor Test (MPT) is used to obtain the optimum characteristics (dry density and moisture content) of samples used in road construction. The Modified Proctor Optimum (MPO) curve, as a function of the maximum dry density (MDD), is represented in **Figure 6**. As can be observed, the water content at Modified Proctor Optimum (Wopm) and the maximum dry density (MDD) of ALB clay are respectively 19.8 wt.% and 1.67. The optimum high water content of the ALB sample and its low density comparen to with those reported by Millogo et al. (2008) [3] for lateritic gravels from Sapouy are justified by the presence of clay minerals of the ALB sample. These values corroborate those of the Atterberg limits and the methylene blue value.

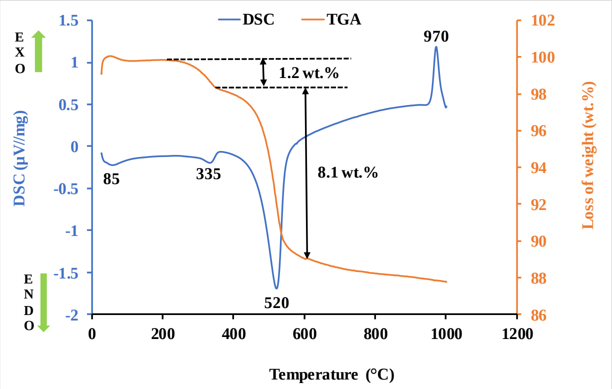

Figure 4 : DSC and TGA of Bama soil (ALB)

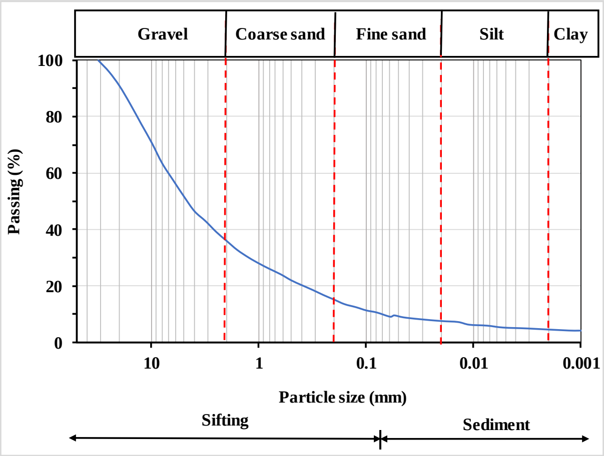

Figure 5 : Particle size distribution of the soil

The CBR bearing capacity at 95 % compaction after four days of immersion is 44 % for the ALB sample. The very high optimum water content could be explained by the predominance of fine clay particles in the ALB sample. Based on these results, we can conclude that the studied clayey raw material is suitable for road construction sub-base **[39]**. However, its potential use as a base course material requires improvement, which could be achieved through various means, such as chemical improvements (e.g., using an organic binder like sugarcane molasses).

Geotechnical properties of lateritic gravel reported in the study by Millogo et al. (2008) **[2]** are better than those reported in this study. This difference could be attributed to the mineralogy of the raw materials. In this work, the authors identified a high presence of quartz (42 wt.%) which acts as a degreaser, and a significant content of kaolinite (26 wt.%), making this material more suitable for use as a base layer in road construction.

On the other hand, the ALB soil has a better particle size distribution than that reported by Onana et al. (2015) **[38]**. This is because of the high fine fraction (18 wt.%) in its clayey raw material. However, this fine fraction may have a detrimental effect on the base course in road construction

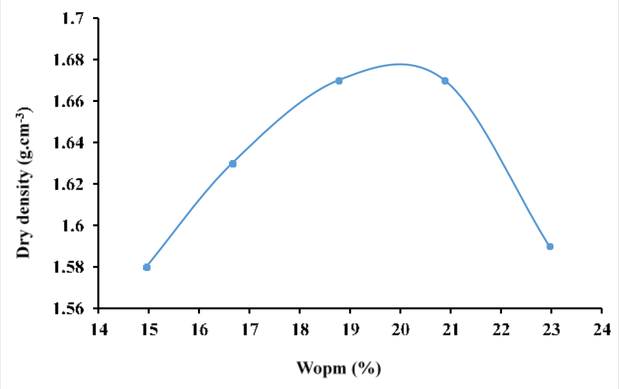

Figure 6 : Modified Optimum Proctor (MOP) curve versus Maximum Dry Density (MDD)

3.1.3. Chemical and Mineralogical Caracterization of Sugarcane Molasses

Table IV shows the overall chemical composition of sugarcane molasses. Molasses is a brownish, viscous substance with a water content usually between 15 and 25 wt.%. Its density is about 1.35, and its pH is slightly acidic. According to some authors, notably Obando et al. (1969) **[40]**, it contains 5 to 6 wt.% of organic acids, half of which are combined in the form of salts or esters. Aconitic acid is quantitatively the most important (5 to 6 wt.% in some molasses). Additionally, there would be, in small quantities, mineral acids such as nitric acid (0.15 wt.%). Its dark color is due to the action of heat on proteins, in the presence of reducing carbohydrates.

To identify any amorphous compounds formed, sugarcane molasses was analyzed using Fourier transform infrared (FTIR) spectroscopy (**Figure 7**). The infrared spectrum of sugarcane molasses shows a band around 3305 cm^{-1}, which corresponds to the stretching O-H bonds vibrations of polysaccharides (sucrose and fructose) **[41]**. This band is also attributable to the stretching O-H bonds vibrations of the water present in sugarcane molasses.

The bands observed at 2939, 1409, 1269, and 927 cm^{-1} are associated with C-H bonds vibrations of aromatic ring structures of polysaccharides. At 1636 cm^{-1}, there is a band corresponding to the C=O elongation vibrations of aromatic ring structures of polysaccharides **[41, 42]**. Another band observed around 1590 cm^{-1} is attributable to the C=C-C elongation vibrations of aromatic ring structures of polysaccharides **[43-45]**.

Additionally, the band observed around 1049 cm^{-1} corresponds to the C-O-C deformation vibrations of acetyl groups (xylans) of polysaccharides **[46]**, while the band at 993 cm^{-1} is attributable to the C-O and Si-O antisymmetric elongation vibrations of polysaccharides **[46]**.

Table IV : Molasse overall chemical composition **[40]**

	Mean percentage composition (wt.%)	Extreme value percentage (wt.%)
Dry matter	76.8	71.0 - 80.0
Ash	8.4	5.5 - 11.3
Fat	0.1	0.0 - 0.3
Nitrogen free extract	64.6	51.7 - 69.0
Soluble carbohydrates	58.7	50.0 - 69.7
Sucrose	34.6	29.6 - 37.8
Reducing sugar	16.2	13.9 - 17.0
Glucose	8.6	5.5 - 14.0
Fructose	9.9	1.3 - 16.0
Crude protein	3.6	1.5 - 10.2

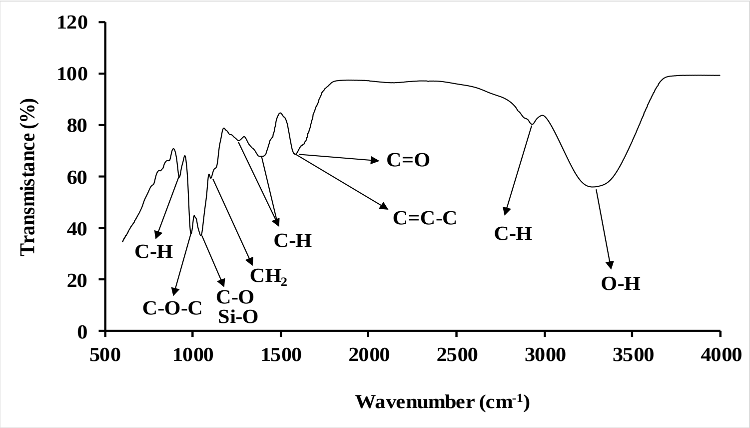

Figure 7 : Infrared spectrum of the sugarcane molasses.

3.2. Geotechnical, mechanical and mineralogical characterization of composite materials reinforced with sugarcane molasses

3.2.1. Geotechnical characterization of composite materials reinforced sugarcane molasses

The variations in optimum water content (OWC) and maximum dry density (MDD) as a function of the quantity of sugarcane molasses are shown in **Figure 8**. These two parameters evolve in opposite directions.

The results show that the OWC of the composite material decreases with the addition of sugarcane molasses to a value of around 2.5 wt.% of molasses. This decrease could probably be due to the low quantity of water in the molasses, which does not allow good hydration of the sugar particles (sucrose, fructose and educational sugars) contained in the molasses. Above 2.5 wt.% of sugarcane molasses, the OWC increases. This increase is justified by the fact that part of the quantity of water chosen to allow the two constituents to be mixed during the Modified Proctor test is used by the sugarcane molasses to dissolve the sugar particles contained in the molasses, thus increasing the actual water content of the different mixtures [1]. The MDD of the composite material increases up to an optimum value of 2.5 wt.% of sugar cane molasses. This increase is explained by the arrangement of the fine grains in the coarse grains, thus forming the denser composite material. Above 2.5 wt.% molasses, we observe a drop in MDD due to the increased water content of the soil. After drying, the water will leave the voids, resulting in a decrease in MDD. Generally speaking, the OWC and the MDD values of lateritic soils amended with sugarcane molasses are higher than those of raw lateritic gravels. The results obtained in this study are in agreement with those reported by Dabakuyo et al. (2021) [3] on the effect of sugarcane molasses on the physical properties of metakaolin-based geopolymer stabilized lateritic soil.

The Californian Bearing Ratio (CBR) bearing capacities after 96 hours of composite immersion are shown in Figure 9. They vary from 27 to 44 % depending on the sugarcane molasses content. The CBR values decrease progressively with increasing molasses content, reaching 41 % for 2 wt.% molasses, 27 % for 4 wt.%, then increase to a CBR value of 29 % for 6 wt.%. This decrease in CBR bearing capacity can be attributed to the dislocation of ALB soil particles and sugarcane molasses on contact with water. The slight increase in CBR lift with 6 wt.% molasses is due to lubrication and grain reorganisation, which optimise the compactness of the composite material [1]. The results obtained in this study differ from those reported by Sanou et al. (2023) [4] on the stabilization of a Lateric Clay from Burkina Faso with Cement-Metakaolin for an Application in Road Construction. For those authors, this difference is due to the fact that with the addition of cement-metakaolin, the CBR bearing capacities after 96 hours of immersion of the composite materials increase. This increase is essentially due to the formation of CSH (calcium silicate hydrate) following the pozzolanic reaction involving the portlandite of the cement and the amorphous silica of the metakaolin. This cementitious compound binds the isolated particles soil reducing microporosity.

According to the literature [2, 4, 7] and the CEBTP (Centre Expérimental et d'Études du Bâtiment et des Travaux Publics) standard [39], the 2 wt.% sugarcane molasses composite can be used as a sub-base in road construction.

However, the CBR bearing capacity index increases and reaches an optimum value of 88 % for ALB4 in the immediate CBR test (**Figure 10**). This can be justified by the cohesive capacity of molasses when mixed with fine clay soils, as it increases soil cohesion **[11]**. The trends observed for immediate CBR are in line with the results reported by Ako et al. (2016) **[5]** on the utilization of palm kernel shell ash as a stabilizer of lateritic soil for road construction.

On the other hand, when the sample is punched after 24 hours of curing in open air and without immersion, an increase in the CBR index is observed (**Figure 11**), reaching an optimum of 149 % for ALB4, and CBR indices of 60 %, 141 % , and 105 % for ALB, ALB2, and ALB6, respectively. This good performance of CBR index could be justified by the good interconnection of particles isolated lateritic clay from Bama and sugarcane molasses. The CBR index values of the ALB-sugarcane molasses mixtures are lower than those reported by Millogo et al (2012) **[6]** on cement and lime-improved lateritic gravels. This disparity is linked to the nature of the two samples. The sample used in this study has a higher plasticity (PI = 27 %) than that studied by Millogo et al. (2012) **[6]**, which is 10.5 %.

Figure 12 presents a comparative analysis of CBR indices based on the curing method used and the rate of addition of sugarcane molasses to the clay matrix. Significant differences between the results can be observed. The best bearing capacities are obtained with the 24 hours cure on a free surface without immersion, except for the 96 hours cure with imbibition.

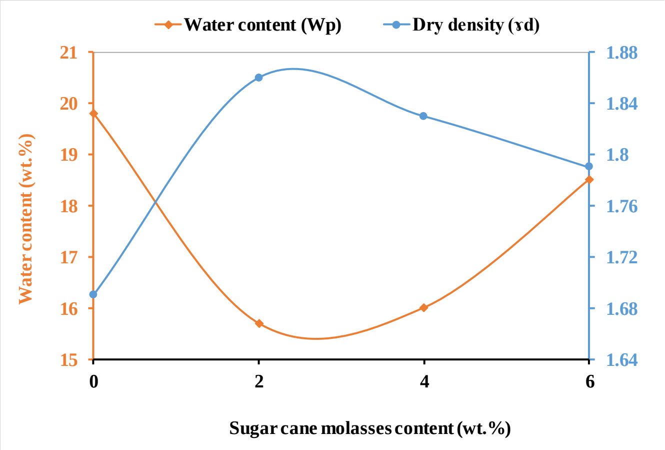

Figure 8 : Water content and dry density as a function of molasses addition

The analysis indicates that the optimum results for immediate CBR and CBR at 24 hours are obtained with an addition rate of 4 wt.% of molasses.

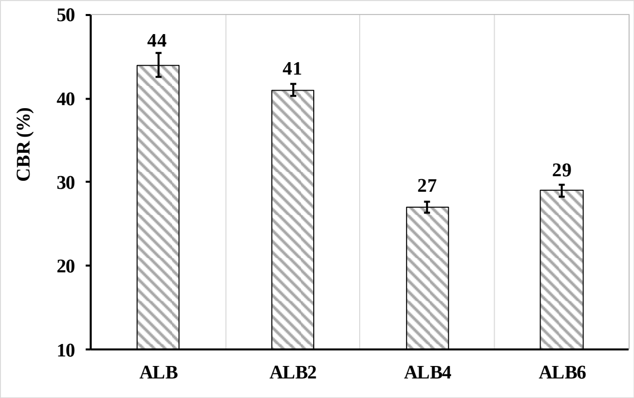

Figure 9 : Variation of CBR bearing capacity index after 96 hours of immersion according to addition of sugarcane molasses

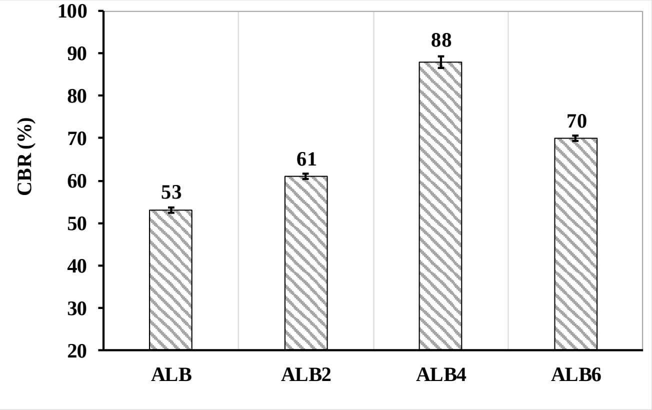

Figure 10 : Variation of immediate CBR bearing capacity index with the addition of sugarcane molasses

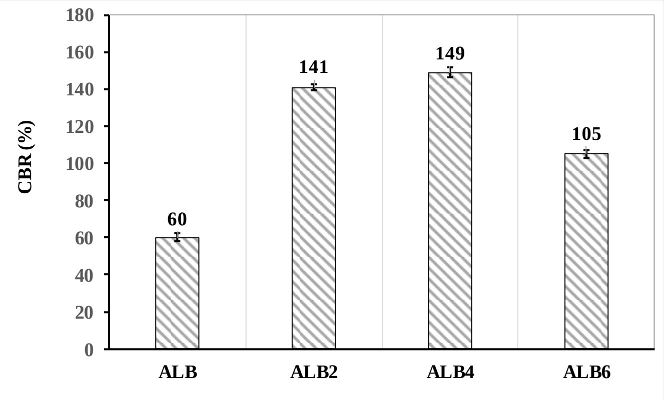

Figure 11 : Variation of the CBR bearing capacity after 24 hours of curing without immersion according to an addition of sugarcane molasses

Based on the results obtained, it can be deduced that sugarcane molasses has improved the CBR bearing capacity of ALB without immersion. However, it should be noted that this technique is not the only determining factor for the choice of materials for road layers. According to CEBTP [39] recommendations, the ALB2 composite is suitable for the sub-base layer in road construction, and the ALB4 composite is suitable for a base layer, provided that the pavement is sealed to prevent infiltration and capillary rise.

3.2.2. Mechanical characterization of composite materials reinforced sugarcane molasses

The simple compressive strength evolution of different composites as a function of molasses addition rate is presented in **Figure 13**. It varies from 0.94 MPa (for 0 wt.% molasses) to 3.7 MPa (for 6 wt.% molasses), depending on the rate of sugarcane molasses addition. These results demonstrate an improvement in the mechanical parameters of ALB by the addition of molasses. This finding is consistent with the scientific works of Malanda et al. (2017) [12], who observed a considerable increase in the mechanical strengths of molasses-stabilized mud bricks. In their study, they found that the mechanical strength of the bricks increased to more than 4 MPa for all formulations with 4, 8, and 12 wt.% of sugarcane molasses, regardless of the soil sampling depth used. This improvement in compression was attributed to the densification of the composite matrix by the formation of strong bonds between the polysaccharides of molasses and the fine particles of the clay material.

3.2.3. Mineralogical characterization of composite materials reinforced sugarcane molasses

The composites' diffractograms are shown in **Figure 14**. These powder diffractograms only show the presence of original minerals in the sample, indicating no formation of new phases.

The absence of new phases in the powder diffractograms of different ALB-molasses composites proves that there was no chemical reaction between the clay and molasses to create new crystalline minerals. Additionally, the peak intensities of the crystalline minerals presence did not change.The stabilisation of the lateritic clay is mainly physical in nature, involving the isolated particles of lateritic clay and the sugar cane molasses.

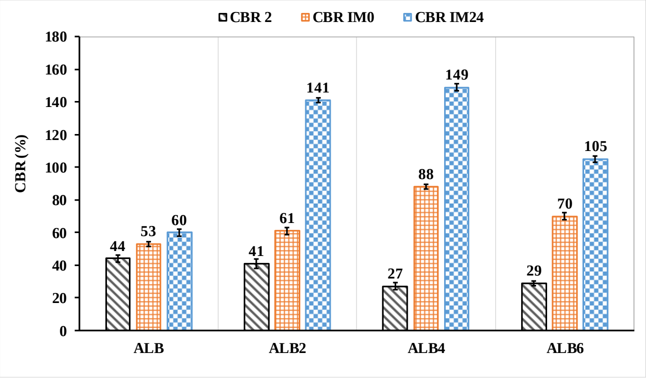

Figure 12 : Comparison of Immersion and Immediate CBR values

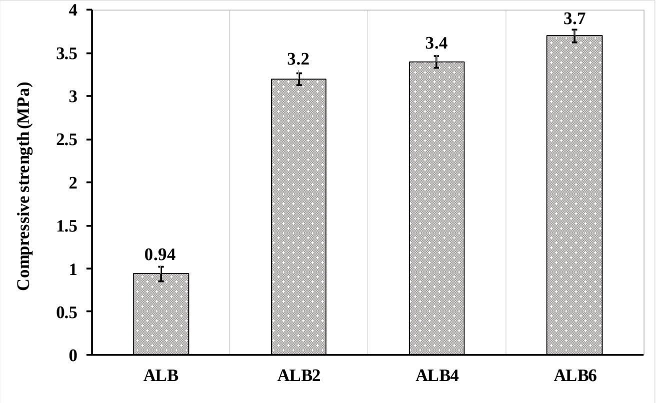

Figure 13 : Composites **c**ompressive strength after 21 days

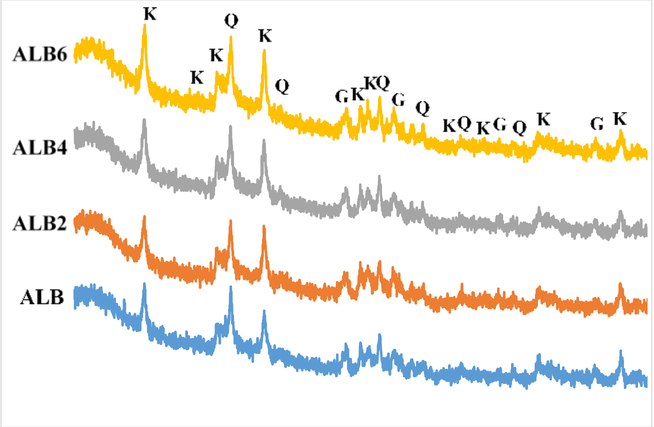

Figure 14 : X-ray diffractograms (XRD) of different ALB-molasse composites

4. Conclusion

The physico-chemical and mineralogical characterizations have shown that the raw material is a highly plastic clay, mainly composed of kaolinite (58 wt.%), quartz (22 wt.%), and goethite (18 wt.%). Geotechnical and mechanical characterizations indicated that the ALB clay (CBR 95 % at 44 %) is suitable for a use as a road construction sub-base layer. The CBR bearing capacities at 96 hours of immersion for all ALB-molasses blends at 95% compaction gradually decrease with the molasses content compared to that of the natural sample. The addition of 2 wt.% of molasses is perfectly usable as a foundation layer material. On the other hand, the immediate CBR values and those after 24 hours of curing without immersion systematically increase.

The ALB-molasses mixture is not suitable for a pavement layer that will be constructed in a flood-prone area where the pavement is unprotected. However, the immediate CBR results and the 24 hours curing show that molasses can be used for the geotechnical stabilization of well-protected pavements with well-defined shoulders and embankments for effective drainage of rainwater. Furthermore, molasses can also be used as an additive for soil stabilization for roads in urban areas. The optimal content of molasses in the ALB-molasses mixture is between 4 and 6 wt.% of the used Bama lateritic clay.

5. Acknowledgements

The authors of this manuscript would like to thank the National Laboratory of Buildings and Public Works of Burkina Faso for their constant assistance during the geotechnical and mechanical tests.

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