Open Journal of Civil Engineering, 2022, 12, 370-389
https://www.scirp.org/journal/ojce
ISSN Online: 2164-3172
ISSN Print: 2164-3164

Geotechnical Characterization of Termite Mound Soils of Congo

Louis Ahouet[1,2,3,4]*, Mondésire Odilon Ngoulou[2], Sylvain Ndinga Okina[3], Sorel Dzaba[3]

[1]Higher Institute of Architecture, Urbanism, Building and Public Works, Denis Sassou Nguesso University, Brazzaville, Congo
[2]Laboratory of Materials and Energies (LME), Faculty of Sciences and Technics, Marien Ngouabi University, Brazzaville, Congo
[3]Higher Polytechnic National School (ENSP), Marien Ngouabi University, Brazzaville, Congo
[4]Building and Publics Works Control Office (BCBTP), Brazzaville, Congo
Email: *louisahouet2@gmail.com

How to cite this paper: Ahouet, L., Ngoulou, M.O., Okina, S.N. and Dzaba, S. (2022) Geotechnical Characterization of Termite Mound Soils of Congo. *Open Journal of Civil Engineering*, **12**, 370-389.
https://doi.org/10.4236/ojce.2022.123021

Received: July 20, 2022
Accepted: August 29, 2022
Published: September 1, 2022

Abstract

This study is to determine the activities and correlations in the fundamental properties of the termite mounds soils *Cubitermes* spp and *Macrotermes* sp. The Intrinsic properties depend on the mineralogy, organic composition and texture of soil. Grain size, Atterberg limits and soil blue values are geotechnical properties that were used to characterize the two soils. On the basis of the geotechnical properties, specific surface area, cation exchange capacity, relative activity, surface activity and soil activity were determined. The correlations obtained in the intrinsic soil properties are linear and polynomial fits. Indeed, the relationship between the plasticity index and the blue value of a soil on the one hand and between the specific surface area and the cation exchange capacity on the other hand, is a linear fit for all soils in general. The relationship between plasticity index and specific surface area is a linear fit for the soils (C, M). Correlations in intrinsic soil properties that have a coefficient of determination close to 1 can be used in geotechnical engineering to predict one of the two desired parameters.

Keywords

Activity, Relative Activity, Surface Activity, Cation Exchange Capacity, Specific Surface, Termite Mound Soil

1. Introduction

Termite mound soils are widespread in many ecosystems, from Africa south of Sahara to Americas and Asia [1] [2]. Termites that build termite mounds include species with different feeding and nesting habits. Carbon mineralization influences soil properties and structure [3] [4]. The technical performance of termite mounds is related to their shape and results from ecological needs. Termites largely control the flow of energy and matter in tropical savannas [5] [6] [7]. The shapes of the termite mounds depend on the properties of soil which have no impact on the size or age of the colony. Termite mounds often last for more than ten years after the termites have left [7]. The nests of *Macrotermes* sp termite mounds are cathedral-shaped and have a diameter of 2 - 3 m at the base and a height of up to 5 m. In contrast, the nests of *Cubitermes* spp termite mounds are mushroom-shaped and have a diameter of 30 - 50 cm at the base and a height of up to 60 cm. The presence of termite mounds per unit area from site to site is highly variable, generally low in forest areas and in wetland soils [7] [8]. The abundance of *Cubitermes* spp termite mounds and their particular physic-chemical properties justify their use in agricultural soil fertilization [9] [10] [11]. Termite mound soils are used in earth road construction because of their consistency, CBR and compressive strength [12]. However, *Macrotermes* sp termite mound soils are also used in the manufacture of mud bricks, pottery, flooring and wall plasters in traditional houses [11]. Many studies have been carried out to understand the impact of termite mounds on their environment. Inconsistencies reported in the literature may be due to variations in site characteristics, species, genus of termites, land use on site and sampling location [3] [9] [12] [13]. Tropical termites in savannahs and temperate forests emit methane, fix nitrogen and change the structure of forests [14]. Termites can search for soil grains up to ten meters deep to build their nests. Termites modify the structure and content of soil clays by injecting saliva containing certain minerals [15]. The granulometric distribution of a soil is one of the determining factors used to classify soils and define standards of use in geotechnics [16]. It is important to have the geotechnical properties of soils and interactions with the local environment [17]. Indeed, the behavior of the material depends not only on its granularity but also on its mineralogy. Several studies on geotechnical properties have been carried out to characterize termite mounds soils [12] [18]-[24]. Despite the diversity of these studies, they have not exhausted the subject. To our knowledge, the activities and correlations between the basic properties of termite mound soils have not yet been reported. Indeed, the activity provides a method for distinguishing fine soils by mineralogy. The clay fraction indicates the variation of the physic-chemical potential in terms of plasticity index as the clay fraction increases. The variation in plasticity along the line reflects the effect of the amount and type of clay, whereas the plasticity index is not a fundamental soil property. The relationship between cation exchange capacity activity and surface activity can provide a basis for describing the mineralogical composition of fine soils [25]. Specific surface area and cation exchange capacity are intrinsic soil properties that influence the behavior of fine soils. By combining these two parameters with the clay fraction, new soil activity values are defined. The plasticity index is the range of the water content over which a soil exhibits plastic behavior. It is expected that for two soils with the same clay fraction, the more active mineral soil will have the higher plasticity index [25]. The relative activity defines the role of the specific surface on the plasticity of soil. In other words, for two soils with the same plasticity index and different clay fractions, different specific surface areas can be expected depending on the mineralogy of the soil. The specific surface area in combination with the clay fraction gives an insight into the mineralogy; whereas the clay fraction does not identify the clay mineral species present in the soil [26]. The specific surface area used in conjunction with the plasticity index can help identify the mineralogy of clays. Activity and surface activity are normalized by the clay fraction. In other words, a linear plot of activity versus surface activity suggests that a plot of plasticity index versus specific surface area should be linear [27].

The objective of this study is to determine the activities and correlations between the fundamental properties of the termite mounds soils *Cubitermes* spp and *Macrotermes* sp.

2. Materials and Methods

2.1. Materials

The location of sample collection sites is shown in **Table 1**. At each site, about 20 kg of *Macrotermes* sp termite soil and 3 - 5 *Cubitermes* spp termite mounds were collected from an area of up to 400 m^2. The color of soils of *Macrotermes* sp termite mounds ranged from grey to yellow and those of *Cubitermes* spp termite mounds from black to yellowish grey (**Figure 1**). Soil samples from *Cubitermes* spp termite mounds will be marked with the letter C followed by an index (C1-C14), and those from Sp Macroterms with the letter M followed by an index (M1-M13) (**Table 1**).

2.2. Methods

The samples collected in situ are transported to laboratory where the soils are crushed and sieved with a 2 mm sieve before testing. The particle size, Atterberg limits, methylene blue value of soil are geotechnical properties that were determined to characterize two soil types (C and M).

On the basis of geotechnical properties thus defined, the intrinsic properties of soil are determined, namely: specific surface area, cation exchange capacity, relative activity, surface activity, soil activity.

From the physical and chemical properties of grains, the termite mound soils (C, M) are classified according to the AASHTO T88-70 and USCS classifications.

Origin Pro 2019b software was used in the process of developing correlations between the intrinsic properties of soils (C and M).

2.2.1. Particle Size Analysis

The granulometry represents the percentage distribution of solid grains according to their dimensions. For particle separation, two types of tests were performed

Table 1. Location and soil sampling of termite mounds *Cubitermes* spp (C) and *Macrotermes* sp (M).

Soils	Localities	Sampling	Collection site
Termite mound soils *Cubitermes* spp	BARA	C1	15˚54'E; 1˚04'S
	BOKOSONGHO	C2	13˚35'E; 4˚25'S
	BRAZZAVILLE	C3	15˚17'E; 4˚16'S
	GAMBOMA	C4	15˚51'E; 1˚52'S
	LOUIGUI	C5	14˚45'E; 4˚28'S
	LOUTETE	C6	13˚50'E; 4˚17'S
	MBE-NGABE	C7	for the northern area
	MPOUYA	C8	16˚11'E; 2˚37'S
	NGO-CENTRE	C9	15˚45'E; 2˚29'S
	NGO-NORD	C10	15˚45'E; 2˚29'S
	NTOMBO M.	C11	−4.86S; 14.40E
	ODZIBA-MBE	C12	for the northern area
	OLLOMBO	C13	15˚55'E; 1˚15'S
	YENGOLA	C14	4˚20'25"S; 13˚52'25"E
Termite mound soils *Macrotermes* sp	BARA	M1	15˚54'E; 1˚04'S
	BOKOSONGHO	M2	13˚35'E; 4˚25'S
	BRAZZAVILLE	M3	15˚17'E; 4˚16'S
	GAMBOMA	M4	15˚51'E; 1˚52'S
	LEKANA	M5	15˚48'E; 1˚54'S
	LOUTETE	M6	13˚50'E; 4˚17'S
	MPOUYA	M7	16˚11'E; 2˚37'S
	NGO-CENTRE	M8	15˚45'E; 2˚29'S
	NGO-NORD	M9	15˚45'E; 2˚29'S
	NGO-SUD	M10	15˚45'E; 2˚29'S
	ODZIBA-MBE	M11	for the northern area
	OLLOMBO	M12	15˚55'E; 1˚15'S
	YENGOLA	M13	4˚20'25"S; 13˚52'25"E

Figure 1. The *Cubitermes* spp and *Macrotermes* sp termite mounds.

by: sieving for grains of the size $\phi > 80$ µm according to NF P94-056 [28] and the sedimentation for the grains of diameter $\phi \leq 80$ µm according to NF P94-057 [29]. The grain size fraction is deduced from the recommendations of grain size nomograms, considering clays as particles < 0.002 mm, silts 0.002 - 0.06 mm and sands 0.06 - 2 mm. The grain distribution of a soil is characterized by the uniformity coefficient C_u and the curvature coefficient C_c, defined by the following formulae:

$$C_u = \frac{D_{60}}{D_{10}} \tag{1}$$

$$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} \tag{2}$$

D_x—is the particle size corresponding to x% by weight of sieving.

2.2.2. Atterberg Limits

The Atterberg limits are determined by the Casagrande method, in accordance with NF P 94-051 [30]. The plasticity index characterizes the extent of the water content range in which soils behave plastically. The limits of liquidity (L_L) and plasticity (P_L) are determined on the fraction of soil (mortar) passing a 0.40 mm sieve. The plasticity index (PI) is expressed by the following relationship:

$$\mathrm{PI} = L_L - P_L \tag{3}$$

2.2.3. Blue Value of a Soil

The measurement of methylene blue adsorption capacity of a soil consists of measuring the quantity of methylene blue adsorbed by the 0/5 mm fraction of material suspended in water. This test makes it possible to characterize the clay content (or cleanliness) of a soil. It is a quantity that is directly linked to the specific surface of soil and reflects the overall quantity and quality (activity) of the clay fraction. The methylene blue value of a soil (BVS) is determined by the standard N FP 94-068 [31].

2.2.4. Specific Surface of a Soil

Specific surface area (SSA) refers to the actual surface area of a soil particle as opposed to its apparent surface area. It is of great importance for phenomena involving surfaces, such as water adsorption and absorption. This parameter allows the interpretation of physical characteristics such as shrink-swell potentials. Depending on the geotechnical properties, the specific surface is determined by the following formula:

$$\mathrm{SSA} = 20.93 * \mathrm{BVS} \tag{4}$$

SSA (m^2/g)—specific surface, BVS (g/100g)—blue value of a soil.

2.2.5. Cation Exchange Capacity

The cation exchange capacity is the number of cations in the double layer that can be easily replaced or exchanged by other cations per 100 grams of soil. It is determined by the formula:

$$\text{CEC} = \frac{\text{BVS} * 1000}{374} \tag{5}$$

CEC (meq/100)—cation exchange capacity; BVS (g/100g)—blue value of a soil.

2.2.6. Activity

The "Ac" activity characterizes the mineral constituting the fine particles. When the clay content is sufficiently high, grains larger than two micrometers are embedded in the clay and barely touch each other. The activity can be related to the mineralogy and geology of the soil and defined as the ratio between the plasticity index PI and the clay content CF [32]:

$$\text{Ac} = \frac{\text{PI}}{\text{CF}(\%) < 0.002\ \text{mm}} \tag{6}$$

Ac—activity, PI—plasticity index, CF—clay fraction.

2.2.7. Relative Activity

The relative activity is the ratio of the plasticity index to the specific surface area, which defines the role of the specific surface area on the plasticity of soil [26]:

$$\text{RA} = \frac{\text{PI}}{\text{SSA}} \tag{7}$$

RA—relative activity, PI (%)—plasticity index, SSA (m^2/g)—specific surface area.

2.2.8. Surface Activity

Kaolinite and Illite minerals are defined according to the surface activity Sc which is the ratio of the specific surface area to the clay fraction CF, defined by the following formula:

$$\text{Sc} = \frac{\text{SSA}}{\text{CF}} \tag{8}$$

Sc (m^2/g * 102)—surface activity, SSA (m^2/g)—specific surface, CF (%)—clay fraction.

2.2.9. Cation Exchange Capacity Activity

The minerals Illite and Montmorillonite are defined according to the Cation Exchange Capacity Activity CECA which is the ratio of the cation exchange capacity to the clay fraction is defined by the following formula:

$$\text{CECA} = \frac{\text{CEC}}{\text{CF}} \tag{9}$$

CECA—cation exchange capacity activity, CEC (meq/100)—cation exchange capacity, CF (%)—clay fraction.

3. Results

3.1. Soil Identification and Classification

Figure 2 shows the particle size distribution of the different termite mound soils (C, M). The contents of clay, silt, sand, the percentage of fines passing the 80 µm sieve and the Atterberg limits are shown in Table 2. The grain sizes corresponding to D10, D30, D60 by sieve weight deduced from the sieve curves are used to determine the uniformity coefficients Cu and curvature coefficients Cc of soils.

3.2. Geotechnical Properties of Soils (C, M)

According to Table 2, the coefficients of uniformity Cu and curvature Cc of soils C1 - C4, C6, C8 - C11, C13 - M2, M4 - M6, M9 - M13 are not measurable. The soils (C5, C7, C12) have uniformity coefficients that vary from Cu (1.03 - 51.3 mm) and curvature Cc (0.04 - 7.4). For the soils (M3, M7, M8), their uniformity coefficients vary from Cu (30 - 116) and curvature Cc (5.42 - 14.82). The soils (C5, C7, C12, M3, M7, M8) have uniformity coefficients Cu > 2, that is, they have a spread grain size. However, the grain distribution of these soils is poorly calibrated. Indeed, their curvature coefficients do not integrate the recommended spindle for this purpose (1 < Cc < 3). Soils C4, C7, C12, M3, M6, M8, M12 are low plastic silts, soils C1, C3, C6, C8-C11, C13, C14, M2 are moderately plastic clays; soil C2 is a very plastic clay and soils C5, M1, M4, M5, M7, M9-M11, M13 are low plastic clays.

Swelling potential is the linear volume change of soil due to water absorption. For this purpose, soils C7, M10 are low swelling, soils C1, C2, C4, C5, C11 - C14, M6, M9, M11, M12 are medium swelling and soils C3, C6, C8 - C10, M1 - M5, M7, M8, M13 are swelling. Soils C2, C6, C8 - C10, C12, C14, M2 are class A-7 (A-7-6) clays. Soils C1, C3, C5, C11, C13, M9 - M11, M13 are clays and M6 is a

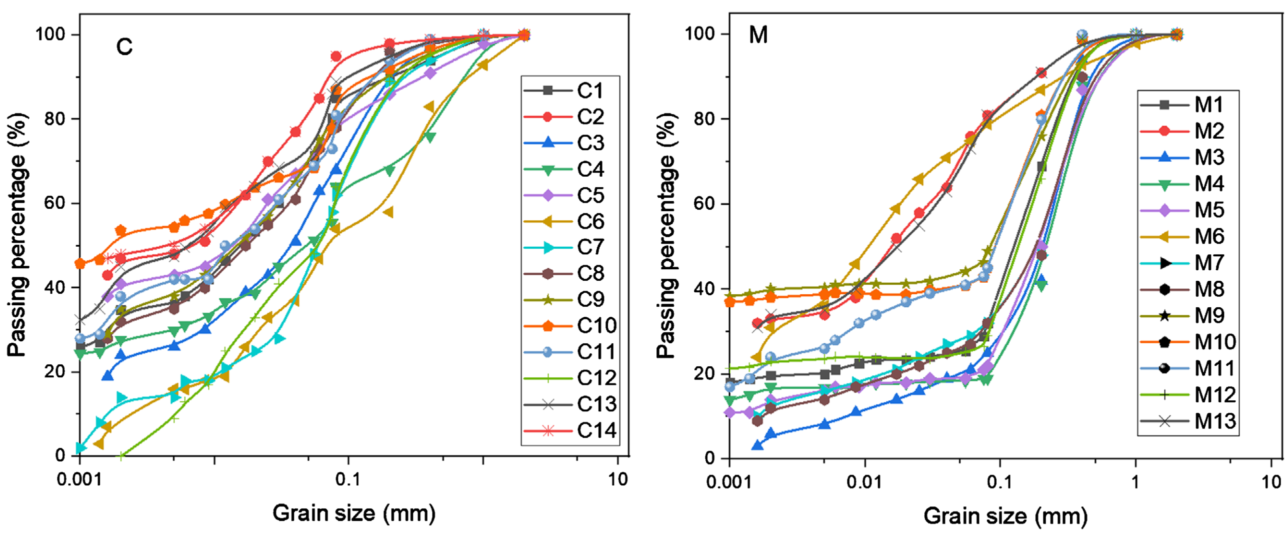

Figure 2. Particle size distribution of termite mound soils.

Table 2. Classification of termite mound soils (C, M).

Samples	Sand (%)	Silt (%)	Clay (%)	Cu	Cc	LL (%)	PL (%)	PI (%)	Classification	
									AASHTO	USCS
C1	23	48	29	-	-	30.5	17	13.4	A-6	Clay
C2	13	44	43	-	-	50.8	23.6	27.2	A-7 (A-7-6)	Clay
C3	37	44	19	-	-	32.9	19.9	12.6	A-6	Clay
C4	47	28	25	-	-	11.6	2.1	9.5	A-4	Silt
C5	40	37	23	3.87	0.371	26.4	14.8	11.6	A-6	Clay
C6	27	37	36	-	-	48.2	23.1	25.1	A-7 (A-7-6)	Clay
C7	41	32	27	51.3	7.4	27.1	19.6	7.5	A-4	Silt
C8	26	46	28	-	-	41.4	18.7	22.7	A-7 (A-7-6)	Clay
C9	24	46	30	-	-	40.7	19.8	20.9	A-7 (A-7-6)	Clay
C10	29	23	48	-	-	45	12	33	A-7 (A-7-6)	Clay
C11	63	4	33	-	-	32.2	16.1	18.6	A-6	Clay
C12	39	38	23	1.025	0.041	41.4	20.7	12.1	A-4	Silt
C13	25	38	37	-	-	40	20	18	A-6	Clay
C14	50	4	46	-	-	45.4	22.7	26.2	A-7 (A-7-6)	Clay
M1	73	8	19	-	-	15.9	0	15.9	A-2 (A-2-6)	Clayey sand
M2	24	45	31	-	-	42	19.9	22.1	A-7 (A-7-6)	Clay
M3	77	19	04	30	5.42	18.5	13.6	4.9	A-2 (A-2-4)	Silty sand
M4	81	5	14	-	-	21.2	8.4	12.8	A-2 (A-2-6)	Clayey sand
M5	79	8	13	-	-	15.5	0	15.5	A-2 (A-2-6)	Clayey sand
M6	24	51	25	-	-	38	27.5	10.5	A-6	Clayey silt
M7	88	2	10	78	14.82	23.4	13.6	10.4	A-2 (A-2-4)	Clayey sand
M8	73	17	10	116	11.07	24	13.6	9.8	A-2 (A-2-4)	Silty sand
M9	55	7	38	-	-	23.2	12	14.4	A-6	Clay
M10	58	5	37	-	-	19.6	11.4	11.8	A-6	Clay
M11	58	23	19	-	-	27.9	9	10.6	A-6	Clay
M12	74	5	21	-	-	41.31	14.9	13	A-2 (A-2-6)	Clayey sand
M13	26	43	31	-	-	26.4	20.1	21.2	A-6	Clay

Size fraction (sand, silt, clay), Cu—coefficient of uniformity, Cc—coefficient of curvature, LL (%)—liquidity limit, PL (%)—plasticity limit, PI (%)—plasticity index.

clayey silt, all class A-6. Soils M1, M4, M5, M7, M12 are clayey sands of class A-2 (A-2-6), soils C4, C7, C12 are silts of class A-4 and soils M3, M8 are silty sands of class A-2 (A-2-4).

In order to further characterize the soils (C, M) in accordance with the objective, the following paragraph deals with the intrinsic properties of the soil.

According to Table 3, the relative activity, which is the ratio between the plasticity index and the specific surface area RA (PI/SSA), is no other than the ratio between activity and surface activity (Ac/Sc). The C14 and M13 soils have the

Table 3. Basic soil properties (C, M).

Sample	BVS (g/100g)	Ac	Sc (m^2/g * 102)	SSA (m^2/g)	CEC (meq/100g)	RA	Ac/Sc	CECA
C1	0.41	0.462	0.296	8.58	1.096	1.56	1.56	0.038
C2	0.80	0.630	0.389	16.74	2.139	1.62	1.62	0.050
C3	0.35	0.664	0.386	7.33	0.936	1.72	1.72	0.049
C4	0.25	0.38	0.209	5.23	0.668	1.82	1.82	0.027
C5	0.30	0.504	0.273	6.28	0.802	1.85	1.85	0.035
C6	0.70	0.697	0.407	14.65	1.872	1.71	1.71	0.052
C7	0.21	0.278	0.163	4.40	0.561	1.70	1.71	0.021
C8	0.66	0.81	0.493	13.81	1.765	1.64	1.64	0.063
C9	0.60	0.697	0.419	12.56	1.604	1.66	1.66	0.053
C10	0.95	0.688	0.414	19.88	2.54	1.66	1.66	0.053
C11	0.53	0.564	0.336	11.09	1.417	1.68	1.68	0.043
C12	0.33	0.526	0.30	6.91	0.882	1.75	1.75	0.038
C13	0.52	0.486	0.294	10.88	1.390	1.65	1.65	0.038
C14	0.72	0.570	0.327	15.07	1.925	1.74	1.74	0.042
M1	0.54	0.837	0.595	11.30	1.444	1.41	1.41	0.076
M2	0.71	0.713	0.479	14.86	1.898	1.49	1.49	0.061
M3	0.22	1.225	1.15	4.60	0.588	1.07	1.07	0.147
M4	0.47	0.914	0.703	9.84	1.257	1.30	1.30	0.09
M5	0.52	1.192	0.837	10.88	1.39	1.42	1.42	0.107
M6	0.41	0.42	0.343	8.58	1.096	1.22	1.22	0.044
M7	0.37	1.04	0.774	7.74	0.989	1.34	1.34	0.099
M8	0.33	0.98	0.691	6.91	0.882	1.42	1.42	0.088
M9	0.45	0.379	0.248	9.42	1.203	1.53	1.53	0.032
M10	0.42	0.319	0.238	8.79	1.122	1.34	1.34	0.030
M11	0.39	0.558	0.429	8.16	1.043	1.30	1.30	0.055
M12	0.43	0.619	0.428	8.99	1.150	1.45	1.45	0.055
M13	0.72	0.684	0.486	15.07	1.925	1.41	1.41	0.042

BVS—Blue value of a soil, Ac—Activity, Sc—Surface activity, SSA—Specific surface area, CEC—Cation exchange capacity, RA—Relative activity, Ac/Sc—relationship between activity and surface activity, CECA—Cation exchange capacity activity.

same specific surface area SSA (15.07 m^2/g), different clay fractions CF (46%, 31%) and plasticity indices PI (26.2%, 21.2%). Similarly, the C13, M5 soils have a specific surface area SSA (10.88 m^2/g), the C1, M6 soils have a SSA (8.58 m^2/g) and the C12, M8, soils have a SSA (6.91 m^2/g). Although soils may have the same specific surface area, they differ in their clay fraction and plasticity index.

3.3. Mineralogy of Termite Mound Soils (C, M)

Figure 3 and Figure 4 refer to the minerals in soils (C, M).

From Figure 3, Sc—represents the directing coefficients of the lines delimiting

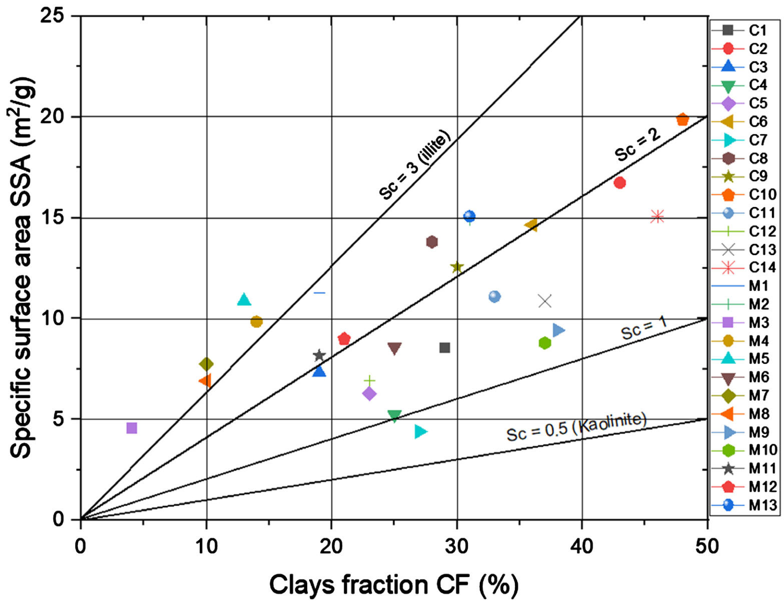

Figure 3. Surface activity of termite mound soils (C, M).

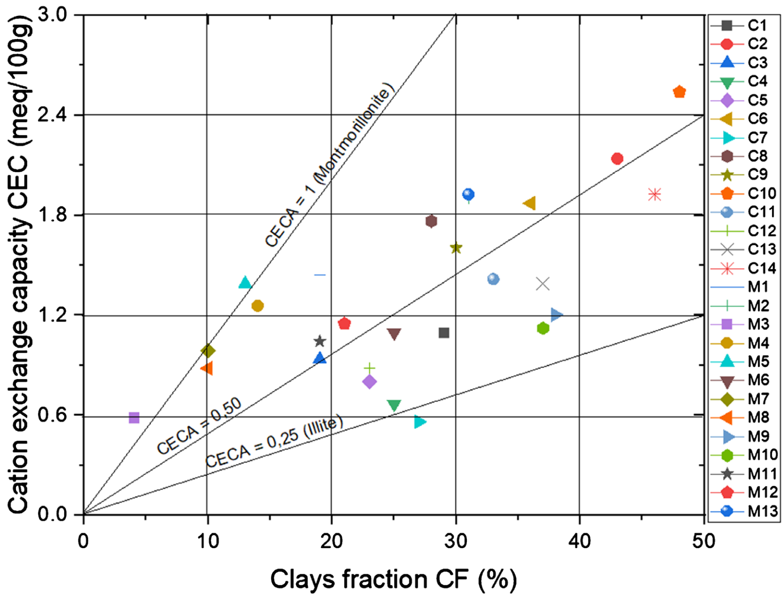

Figure 4. Cation exchange capacity activity of soils (C, M).

the zones of the mineralogical formations (kaolinite, illite). The specific surface area SSA is controlled by the particle size distribution and mineralogy of the clay and can be considered as an "inherent" soil property. By using the specific surface area as a function of the clay fraction, new activity values can be defined. Despite the fact that the soil samples come from a very wide geographical area, the (C) soils have a surface activity that varies from Sc (0.50-3), while the Sc surface activity of the (M) soils is higher than 1, but lower than 3. Soils C1 - C6, C8 - C14 contain kaolinite and illite, soil C7 contains illite and all these soils have a specific surface area that varies from SSA (4.40 - 15.07 m^2/g). Soils M1, M2, M3, M6, M9-M11, M13 contain kaolinite and illite and have specific surface areas that vary from SSA (4.60 - 15.07 m^2/g) and soils M4 and M12 all contain illite and have respective specific surface areas of SSA (9.84, 8.99 m^2/g).

From **Figure 4**, CECA—represents the directing coefficients of the straight lines delimiting the zones of mineralogical formations (illite, montmorillonite). A CECA greater than 1 should indicate the presence of montmorillonite, while a CECA greater than or equal to 0.25, but less than 1, would indicate the presence of illite. The kaolinite samples have CECA values below 0.25. According to **Figure 3** and **Figure 4**, soils M3, M5, M7 contain illite and montmorillonite, they have specific surface areas that vary from SSA (4.60 - 10.88 m^2/g). The C1-C14 soils have a cation exchange capacity that varies from CEC (0.668 - 2.54 meq/100g) and that of the M1-M13 soils, varies from CEC (0.588 - 1.925 meq/100g). In the C1-C6, C8-C14, M1, M2, M6, M9-M11, M13 soils kaolinite and illite are present and they have an activity cation exchange capacity of CECA (0.027 - 0.076); and that of the illite-containing M4, M8, M12 soils varies from CECA (0.055 - 0.09). In soils M3, M5, M7 illite and montmorillonite are found and their cation exchange capacity varies from CECA (0.099 - 0.147), the soil C7 contains kaolinite and they all have a cation exchange capacity of CECA (0.021). For a given clay fraction, the specific surface area SSA and the cation exchange capacity CEC are proportional to the mineralogy in the order kaolinite-illite-montmorillonite [32].

3.4. Correlations between Geotechnical Soil Properties (C, M)

From **Table 2** and **Table 3**, correlations between some geotechnical soil parameters (PI, BVS, LL, SSA, CEC, CF, RA, Ac/Sc) were determined.

According to **Figure 5**, the blue value of a soil (BVS) shows the amount and activity of the clay fraction in the soil. The plasticity index PI is very strongly related to the specific surface area, quantity and nature of the clay minerals present in the soil. This justifies the principle that the blue value of a soil and the plasticity index are strongly correlated in a linear way. The relationship found is a straight line valid for all soils in general:

$$Y = A + BX \tag{10}$$

Correlation between the plasticity index and the blue value of a soils (C).

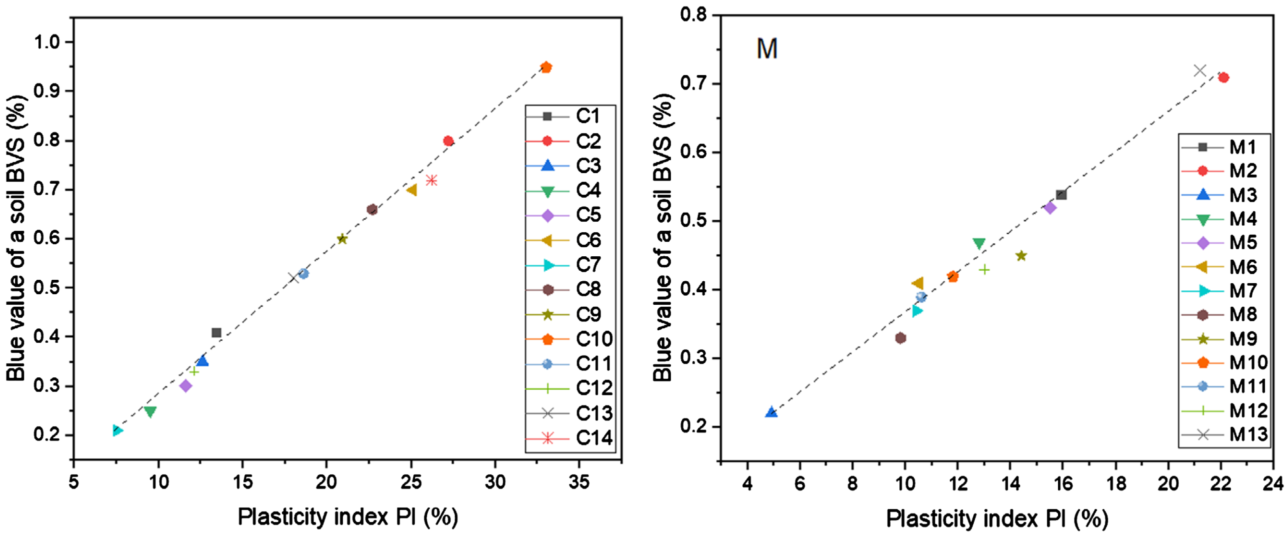

Figure 5. Correlation between the blue value of a soil BVS and the plasticity index PI.

$$A = -0.01578 \pm 0.01294; \quad B = 0.02922 \pm 6.50905\text{E}-4; \quad R^2 = 0.994$$

Correlation between the plasticity index and the blue value of a soils (M).

$$A = 0.06812 \pm 0.001973; \quad B = 0.02946 \pm 0.00141; \quad R^2 = 0.976$$

R^2—coefficient of determination, BVS (g/100g)—blue value of a soils, PI (%)—plasticity index.

Figure 6 shows the correlation between the plasticity index PI and the specific surface area SSA of the soils (C, M). The evolution of the two parameters is of the form:

$$Y = A + BX \tag{11}$$

For the plasticity index as a function of the specific soil surface (C);

$$A = 0.63981 \pm 0.42853; \quad B = 1.62599 \pm 0.03614; \quad R^2 = 0.994$$

For the plasticity index as a function of the specific soil surface (M);

$$A = -1.92378 \pm 0.75664; \quad B = 1.5815 \pm 0.07547; \quad R^2 = 0.976$$

The evolution of the plasticity index as a function of the specific surface of soils (C, M) is linear and their coefficient of determination is R^2 (0.994, 0.976) respectively.

Figure 7 shows the correlations between the specific surface area SSA and the cation exchange capacity CEC as a function of the clay fraction.

According to **Figure 7**, the specific surface area SSA and the cation exchange capacity CEC as a function of the clay fraction CF are correlated. This correlation depends on the geological formation of the sample sites and the nature of the termite mound soils. The correlation between specific surface SSA and cation exchange capacity CEC is a polynomial fit:

$$Y = B + B_1 X + B_2 X^2 \tag{12}$$

Correlation between specific surface area SSA and cation exchange capacity

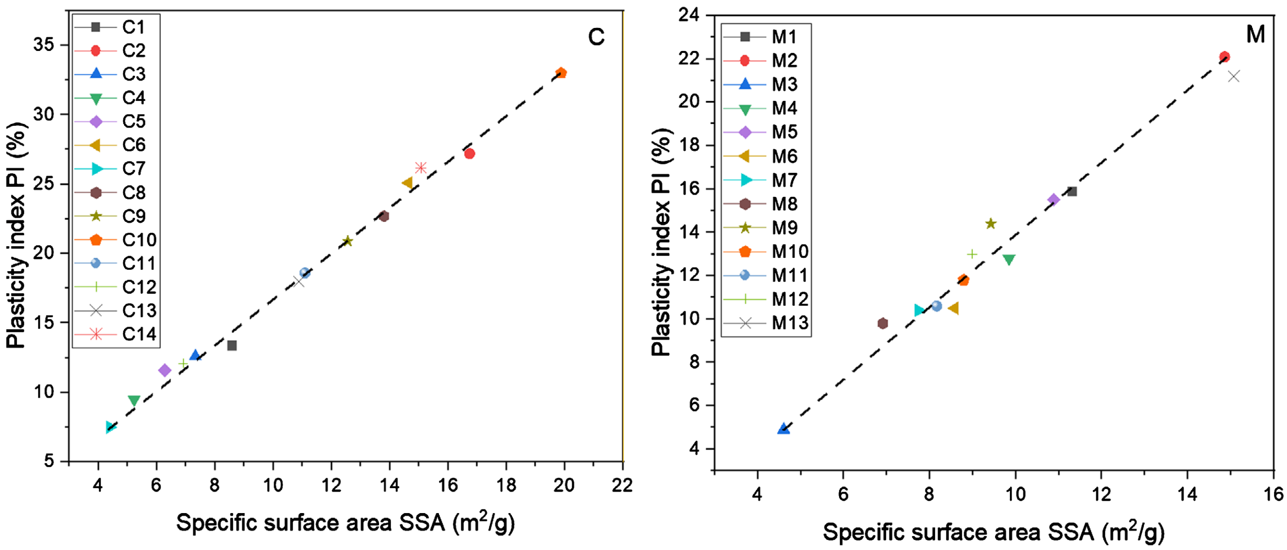

Figure 6. Correlation between plasticity index and specific soils surface (C, M).

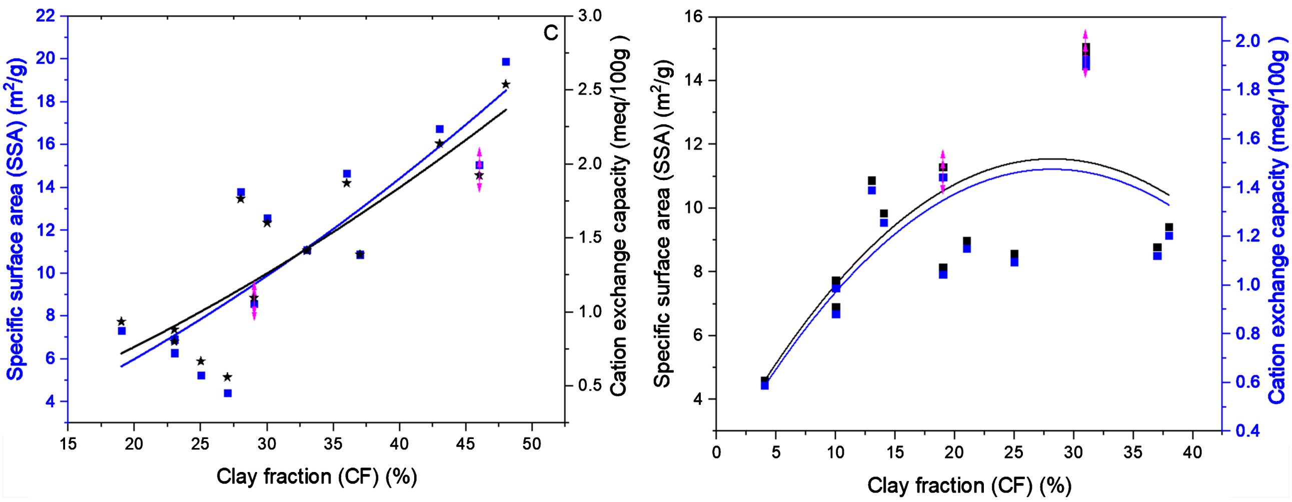

Figure 7. Correlation between specific surface and cation exchange capacity as a function of clay fraction.

CEC as a function of soil clay fraction (C): For the specific surface

$$B = 0.20598 \pm 11.12921;\quad B_1 = 0.22411 \pm 0.68664;$$
$$B_2 = 0.00329 \pm 0.01002;\quad R^2 = 0.686$$

For cation exchange capacity;

$$B = 0.02383 \pm 1.42308;\quad B_1 = 0.02875 \pm 0.0878;$$
$$B_2 = 4.18423\text{E}{-4} \pm 0.00128;\quad R^2 = 0.686$$

Correlation between specific surface area SSA and cation exchange capacity CEC as a function of soil clay fraction (M):

For the specific surface;

$$B = 2.07494 \pm 2.76486;\quad B_1 = 0.67222 \pm 0.28586;$$
$$B_2 = -0.01192 \pm 0.00636;\quad R^2 = 0.384$$

For cation exchange capacity;

$$B = 0.26454 \pm 0.35306\,; \quad B_1 = 0.08597 \pm 0.0365\,;$$
$$B_2 = -0.00153 \pm 8.11725\text{E}-4\,; \quad R^2 = 0.384$$

SSA (m^2/g)—specific surface, CEC (meq/100g)—cation exchange capacity, CF (%)—clay fraction, R^2—coefficient of determination.

The specific surface area and the cation exchange capacity are normalized by the clay fraction, which can justify the soil determination coefficients (C, M) of R^2 (0.686, 0.384) respectively. Figure 8 shows the correlation between the specific surface area SSA and the cation exchange capacity CEC.

The specific surface area SSA and the cation exchange capacity CEC as a function of the clay fraction are correlated (Figure 7). The specific surface area versus the cation exchange capacity is linearly fitted for the soils (C, M) (Figure 8). The linear fit seems to be general for all soils. The evolution of the two parameters is given below:

$$Y = A + BX \tag{13}$$

For soils (C): $A = 0.00717 \pm 0.00213\,; \quad B = 7.82312 \pm 0.0014\,; \quad R^2 = 1$

For soils (M): $A = -0.0025 \pm 0.00506\,; \quad B = 7.82964 \pm 0.00395\,; \quad R^2 = 1$

SSA (m^2/g)—specific surface, CEC (meq/100g)—cation exchange capacity, R^2—coefficient of determination.

3.5. Relationship between Activity and Surface Activity, Relative Activity

Figure 9 shows the relationship between activity and surface activity for the 27 termite mound soils (C, M). The 27 soils follow the C line at approximately Ac = 0.005 (Locat *et al.* 2003). The relationship between activity and surface activity is none other than the relative activity, defined by Quigley *et al.* 1985 [26]. Figure 10 shows the plasticity index as a function of the specific surface, that is, the

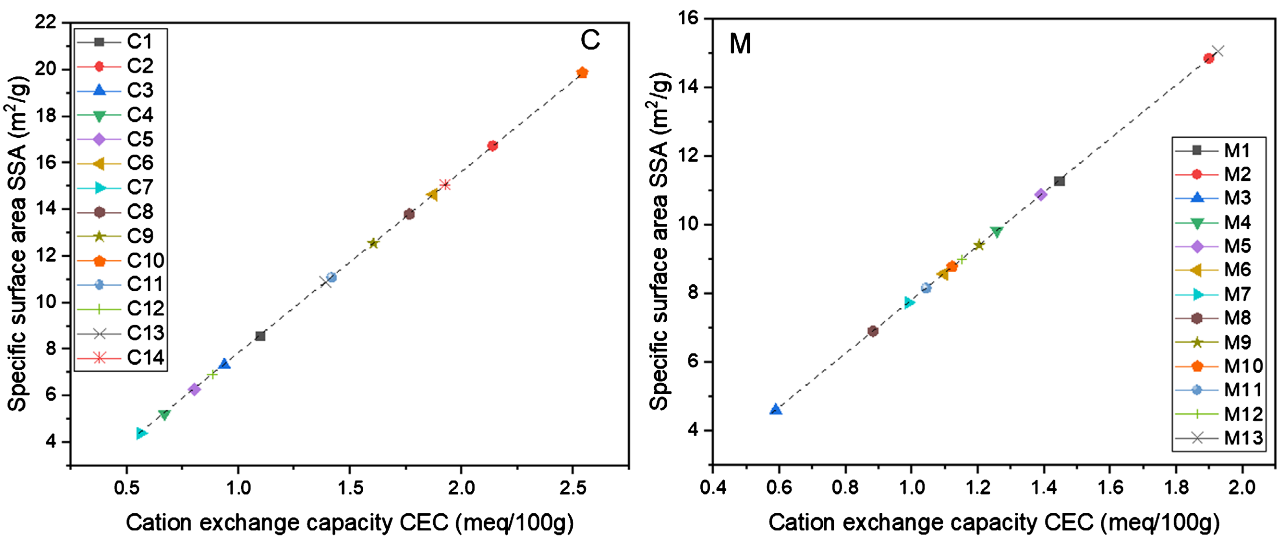

Figure 8. Correlation between cation exchange capacity and soil specific surface area (C, M).

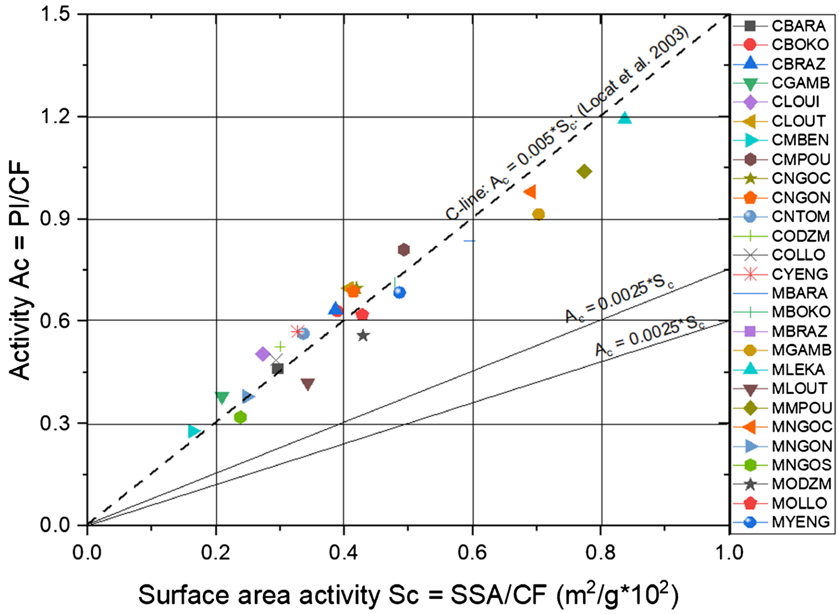

Figure 9. Relationship between activity and surface activity.

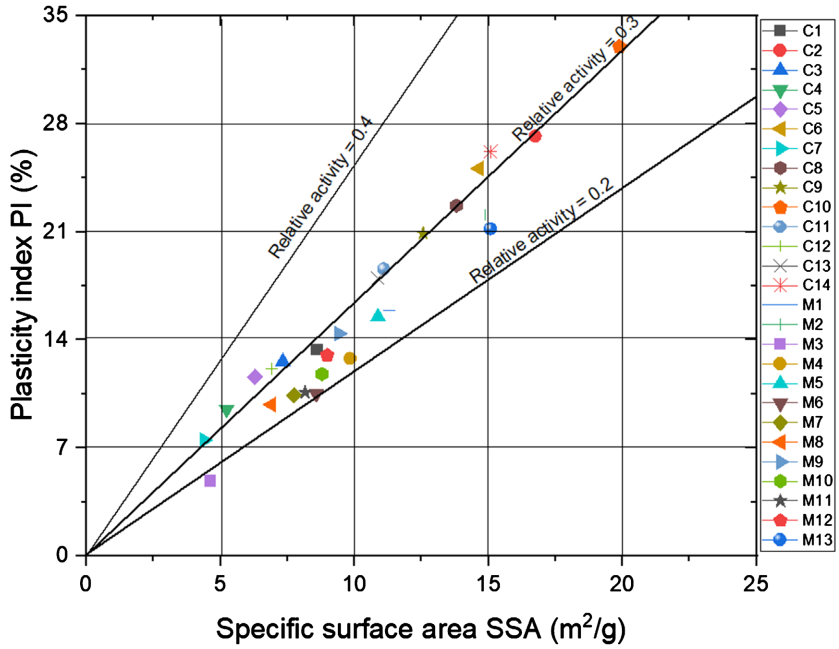

Figure 10. Relative activity of termite mound soils (C, M).

relative activity.

From **Figure 10**, RA—represents the directing coefficients of the lines delineating the geological zones of soils. The respective relative activity values of 0.2, 0.3, 0.4 represent the geology of samples locations. Soils C1-C14 has a relative activity of about RA (0.3), which may resemble a geological formation that appears to be uniform. Soil M3 has a relative activity of RA < 0.2, soils M1 - M8, M11 have a relative activity that varies from RA (0.2 - 0.3) and that of M12 is RA (0.3 - 0.4). These soils have geological formations that change from one sampling site to another.

4. Discussion

From **Figure 2** and **Table 2**, the termite mound soils in Congo are spread out and poorly graded like those in Nigeria. Indeed, the particle size distribution of the Nigerian termite mound soils [19] have uniformity coefficients that vary from Cu (3.75 - 7.50), higher than 2. The coefficients of curvature of C5, C7, C12, M3, M7, M8 soils are Cc (0.371, 7.4, 0.041, 5.42, 14.82, 11.07) respectively, do not incorporate the recommended spindle (1 < Cc < 3).

The plasticity indices of the Nigerian termite mounds vary from PI (10.83% - 28.45%) [19], close to the plasticity of the Congo (C) soils which have plasticity indices that varies from PI (7.5% - 27.2%), but differ from the termite mound soils south-western Nigeria studied by Adekunle 2021 which have of plasticity index of IP (18.2% - 49.5%).

C2, C6, C10, C14, M2 soils have specific surface areas that vary SSA (14.65 - 19.88 m^2/g) and are close to those of clay soils with specific surface areas that vary from SSA (10 - 50.51 m^2/g) [25] [33]. Despite the fact that clays represent the largest surface area of all mineral constituents, they have different specific surface areas [25].

Figure 6 simply suggests that a plot of the plasticity index against the specific surface area is linear, that is, the range of water content between the liquidity limit and the plasticity limit depends on the specific surface area which is related to the liquidity limit [27].

Two soils M10 and M12 have the same clay fraction of CF (37%), soil M12 is the most active with an activity of Ac (0.486) and has the highest plasticity index of PI (18%), while soil M10 has a plasticity index of PI (12%) and an activity of Ac (0.319). The C3 and M1 soils of different nature have a clay fraction of CF (19%), the M1 soil is the most active with an activity of Ac (0.837) and has the highest plasticity index of PI (15.9%), however, the C3 soil has a plasticity index of PI (12.6%) and an activity of Ac (0.664) [25].

According to **Figure 5** and **Figure 8**, the correlations between the plasticity index and the blue value of a soil on the one hand and the specific surface and the cation exchange capacity on the other hand are linear fits for all soils [34].

According to **Figure 10**, the M6 and M11 soils have different clay fractions CF (25%, 19%), both soils have the same plasticity index PI (11%) with different specific surface areas SSA (8.58 m^2/g, 8.16 m^2/g) [26].

From **Table 3**, the relationship between activity and surface activity presented by [27], simplifies to a relative activity defined by [26] as the ratio of plasticity index to specific surface area.

For the practical use of soils in the manufacture of adobes, mud bricks or compressed earth bricks, the standards recommend on average a clay fraction CF (10% - 30%), and a sand content of at least 30% [16]. Only the Australian standard (HB 195, 2002) [35] sets the maximum clay fraction at 40%. Soils C2, C10 and C14 have clay fractions CF (43% - 48%), higher than 40% and soils C1, C6, C8 - C10, C13, M2, M3, M6, M13 have sand contents SC (13% - 27%), lower than 30%. In fact, high clay contents and low sand contents are likely to generate cracks during the drying of the bricks (high shrinkage) and in general do not allow to obtain the high mechanical resistances (poorly graded soils). To correct this imbalance without generating the high cost of bricks, an addition of sand or local plant fibers may be necessary [36] and the ecological cost ratio of such a solution is advantageous [37].

5. Conclusion

Six (6) soils (C, M) have a spread grain size with poorly graded grains and the remaining twenty-one (21) are not measurable. The (C, M) soils include clays, clayey sands, silts and sandy silts of classes A-7 (A-7-6), A-6, A-4, A-2 (A-2-4) and A-2 (A-2-6). Soils C4, C7, M9, M10 have low swelling potential, soils C1 - C3, C5, C6, C9 - C14, M1, M2, M6, M11 - M13 have medium swelling and C8, M3 - M5, M7, M8 are swelling. The C8 soil has a normal activity of 0.81, the C1 - C7, C9 - C14, M2, M6, M9-M13 soils are inactive, their activities vary from Ac (0.278 - 0.713) and the M1, M3-M5, M7, M8 soils have a normal activity Ac (0.914 - 1.225). The plasticity index is very strongly related to the specific surface and the blue value of a soil and represents a linear fit for (C, M) soils. Specific surface area and cation exchange capacity are two strongly related parameters and can be considered as inherent soil properties. Specific surface area and cation exchange capacity is a linear fit with a determination coefficient R^2 (1) for (C, M) soils. The plasticity index and blue value of a soil is a linear fit for all soils and their coefficients of determination vary from R^2 (0.994 - 0.976). The relationship between plasticity index and specific surface area is a linear fit for the soils (C, M), their coefficients of determination vary from R^2 (0.994 - 0.976). The specific surface and the cation exchange capacity as a function of the clay fraction is polynomial fits. Their coefficients of determination are R^2 (0.686) and R^2 (0.384) for the soils (C and M) respectively. The soils (C, M) follow the C line of Locat *et al.* 2003.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Maynard, D.S., Crowther, T.W., King, J.R., Warren, R.J. and Bradford, M. (2015) Temperate Forest Termites: Ecology, Biogeography, and Ecosystem Impacts. *Ecological Entomology*, **40**, 199-210. https://doi.org/10.1111/een.12185

[2] Wesceslau, A.L., Teixeira, G., Riha, S.J., Johannes Lehmann, E. and Fernandes, C.M. (2007) The Impact of Mound-Building Termites on Surface Soil Properties in a Secondary Forest of Central Amazonia. *Applied Soil Ecology*, **37**, 267-276. https://doi.org/10.1016/j.apsoil.2007.08.005

[3] Bignell, D.E. and Eggleton, P. (2000) Termites in Ecosystems. In: Abe, T., Bignell, D.E. and Higashi, M., Eds., *Termites*: *Evolution*, *Sociality*, *Symbioses*, *Ecology*, Sprin-

ger, Dordrecht, 363-387. https://doi.org/10.1007/978-94-017-3223-9_17

[4] Khan, M.A., Ahmad, W. and Paul, B. (2018) Ecological Impacts of Terminates. In: Khan, M. and Ahmad, W., Eds., *Termites and Sustainable Management*, Springer, Cham, 201-216. https://doi.org/10.1007/978-3-319-72110-1_10

[5] Semhi, K., Chaudhuri, S., Clauer, N. and Boeglin, J.L. (2008) Impact of Termite Activity on Soil Environment: A Perspective from Their Soluble Chemical Components. *International Journal of Environmental Science & Technology*, **5**, 431-444. https://doi.org/10.1007/BF03326039

[6] Fall, S., Brauman, A. and Chotte, J.L. (2001) Comparative Distribution of Organic Matter in Particle and Aggregate Size Fractions in the Mounds of Termites with Different Feeding Habits in Senegal: *Cubitermes niokoloensis* and *Macrotermes bellicosus*. *Applied Soil Ecology*, **17**, 131-140. https://doi.org/10.1016/S0929-1393(01)00125-1

[7] Jouquet, P., Mamou, L., Lepage, M. and Velde, B. (2002) Effect of Termites on Clay Minerals in Tropical Soils: Fungus-Growing Termites as Weathering Agents. *European Journal of Soil Science*, **53**, 521-528. https://doi.org/10.1046/j.1365-2389.2002.00492.x

[8] Lal, S., Saxena, D. and Lal, R. (1987) Effects of DDT, Fenitrothion and Chorpyrifos on Growth, Photosynthesis and Nitrogen Fixation in Anabaena (Arm 310) and *Aulosira fertilissima*. *Agriculture*, *Ecosystems & Environment*, **19**, 197-209. https://doi.org/10.1016/0167-8809(87)90001-6

[9] Trapnell, C.G., Friend, M.T., Chamberlain, G.T. and Birch, H.F. (1976) The Effect of Fire and Termites on a Zambian Woodland Soil. *Journal of Ecology*, **64**, 577-588. https://doi.org/10.2307/2258774

[10] Dangerfied, J.M. (1990) Abundance, Biomass and Diversity of Soil Macrofauna in Savanna Woodland and Associated Managed Habitats. *Pedobiologia*, **34**, 141-150.

[11] de Bruyn, L. and Conacher, A.J. (1990) The Role of Termite and Ants in Soil Modification: A Review. *Australian Journal of Soil Research*, **28**, 55-93. https://doi.org/10.1071/SR9900055

[12] Maixent Loubouth, S., Ahouet, L., Elenga, R., Okina, S. and Kimbembe, P. (2020) Improvement of the Geotechnical Properties of the Soil of Lime-Treated Cubitermes Mound Soil. *Open Journal of Civil Engineering*, **10**, 22-31. https://doi.org/10.4236/ojce.2020.101003

[13] Endubu, M., Kombele, B.M., Litucha, B.M. and Mambani, B. (1992) Perspective of Using Termite Mounds to Improve the Fertility of Tropical Soils: The Case of an Experiment in Vegetation Pots. *Tropicultura*, **10**, 51-54.

[14] Makala, S.L.O. (1977) One Note on the Apparent Density of Termites. *Australian Journal of Soil Research*, **15**, 93-94. https://doi.org/10.1071/SR9770093

[15] Evans, T.A. (2021) Predicting Ecological Impacts of Invasive Termites. *Current Opinion in Insect Science*, **46**, 88-94. https://doi.org/10.1016/j.cois.2021.03.003

[16] Delgado, M.C.J. and Guerrero, I.C. (2007) The Selection of Soils for Unstabilised Earth Building: A Normative Review. *Construction and Building Materials*, **21**, 237-251. https://doi.org/10.1016/j.conbuildmat.2005.08.006

[17] Enagbonma, B.J. and Babalola, O.O. (2019) Environmental and Replace by Sustainability: A Review of Termite Mound Soil Material and Its Bacteria. *Sustainability*, **11**, 3847. https://doi.org/10.3390/su11143847

[18] Mahaney, W.C., Zippin, J., Milner, M.W., Sanmugadas, K., Hancock, R.G.V.S. and Aufreiter, S. (1999) Chemistry, Mineralogy and Microbiology of Termite Mound

Soil Eaten by the Chimpanzees of the Mahale Mountains, Western Tanzania. *Journal of Tropical Ecology*, **15**, 565-766. https://doi.org/10.1017/S0266467499001029

[19] Momah, M. and Okieimen, F.E. (2020) Minerology, Geochemical Composition and Geotechnical Properties of Termite Mound Soil. *Journal of Ecology and the Natural Environment*, **12**, 1-8. https://doi.org/10.5897/JENE2019.0798

[20] Park, N.S., Saleh, H.-L., Algrinawi, H. and Lord, N.P. (2022) Investigating Physical and Mechanical Properties of Nest Soils Used by Mud Dauber Wasps from a Geotechnical Engineering Perspective. *Scientific Reports*, **12**, Article No. 2192. https://doi.org/10.1038/s41598-022-06162-2

[21] Adekunle, A. (2021) Influence of Leachates on Geotechnical and Geochemical Properties of Termite Mound Soils. *Environmental Engineering-Inzenjerstvo okolisa*, **8**, 26-31. https://doi.org/10.37023/ee.8.1-2.4

[22] Martinez, A., Dejong, J., Akin, I., Aleali, A., Arson, C., Atkinson, J., *et al.* (2021) Bio-Inspired Geotechnical Engineering: Principles, Current Work, Opportunities and Challenges. G*éotechnique*, **72**, 687-705. https://doi.org/10.1680/jgeot.20.P.170

[23] Olowofoyeku, A., Ofuyatan, O., Bamigboye, G. and Busari, A.A (2016) Assessment of Geotechnical Properties of Termite Reworked Soils. *ARPN Journal of Engineering and Applied Sciences*, **11**, 10327-10331.

[24] Olayiwola, H.A., Apanpa, K.A. and Ademola, A. (2020) Geotechnical Properties of Termite Mound Soil as Construction Material. *International Journal of Plant & Soil Science*, **32**, 45-58. https://doi.org/10.9734/ijpss/2020/v32i1130343

[25] Cerato, A. and Lutenegger, A.J. (2005) Activity, Relative Activity and Specific Surface Area of Fine-Grained Soils. *Proceedings of the* 16*th International Conference of Soil Mechanics and Geotechnical Engineering* (*ICSMGE*), Vol. 2, Osaka, 12-16 September 2005, 325-328.

[26] Quigley, R.M., Sethis, A.J., Boonsinsuk, P., Sheeren, D.E. and Yong, R.N. (1985) Geologic Controls on Soil Composition and Properties, Lake Ojibway Clay Plain, Matagami, Quebec. *Canadian Geotechnical Journal*, **22**, 491-500. https://doi.org/10.1139/t85-069

[27] Locat, L., Tanaka, H., Tan, T.S., Desari, G.R. and Lee, H. (2003) Natural Soils: Geotechnical Behavior and Geologic Knowledge. In: Tan, T.S., Phoon, K.K., Hight, D.W. and Leroueil, S., Eds., *Characterization and Engineering Properties of Natural Soils*, Vol. 1, Swets and Zeitlinger, Amsterdam, 3-28.

[28] NF P94-056 (1996) French Standard. Soils: Recognition and Tests. Analyse granulométrique. Method by Dry Sieving after Washing. Association Française de Normalisation, Paris, 5-15.

[29] NF P94-057 (1992) French Standard. Soils: Recognition and Tests. Granulometric Analysis. Sedimentation Method. Association Française de Normalisation, Paris, 4-17.

[30] NF P94-051 (1993) French Standard. Soils: Recognition and Tests. Determination of Atterberg Limits. Limit of Liquidity at the Cup-Limit of Plasticity at the Roller. Association Française de Normalisation, Paris, 4-14.

[31] NF P94-068 (1998) French Standard. Soils: Investigation and Testing – Measuring of the Methylene Blue Adsorption Capacity of a Rocky Soil. Determination of the Methylene Blue of a Soil by Means of the Strain Test, October 1998.

[32] Skemptom, A.W. (1953) The Colloidal "Activity" of Clays. *Proceedings of the 3*rd *International Conference of Soil Mechanics and Foundation Engineering*, Vol. 1, Zurich, 16-27 August 1953, 57-60.

[33] Mitchell, J.K. (1976) Fundamentals of Soil Behavior. John Wiley and Sons, New York.

[34] Ahouet, L., Ngoulou, M.O., Ndinga Okina, S. and Kimbatsa, F.T. (2022) Study of the Relationship between the Fundamental Properties of FNE Soils and Those of Mathematical Models of Particle Size Distribution and Geotechnical Quantities. *Arabian Journal of Geosciences*, **15**, Article No. 1173. https://doi.org/10.1007/s12517-022-10378-x

[35] Walker, P. and Standards Australia (2002) HB 195: The Australian Earth Building Handbook. Standards Australia, Sydney.

[36] Ahouet, L., Elenga, R.G., Bouyila, S., Ngoulou, M.O. and Kengué, E (2018) Improvement of the Geotechnical Properties of Lateritic Gravel by Adding Crushed Alluvial Gravel 0/31.5. *Applied Engineering Sciences*, **3**, 1-6.

[37] Van Damme, H. and Houben, H. (2017) Earth Concrete. Stabilization Revisited. *Cement and Concrete Research*, **114**, 90-102. https://doi.org/10.1016/j.cemconres.2017.02.035