Search for qualified soil for the production of low-energy biobased composite materials

Abstract

The development of earth-based bio-sourced materials requires a thorough analysis of the study soil. For the present study, we took five (05) soil samples from a tunnel-digged quarry in the layer between 0.5 m and 5 m : white clay (MSB-BL), red clay (MSB-RG), weak clay or sandy clay (MSB-FB), strong clay (MSB-FR) and mixture (MSB-ME). To verify the quality of these five (05) soils samples, their intrinsic properties were determined at the National Building and Public Works Laboratory (LNBTP). These included grain size, clay content, specific weight, loss on ignition and moisture content. These analyses revealed that MSG-RG and MSG-BL clays have fine fractions of 64.28% and 47.85% respectively; clay fractions of 27.51% and 20.61% respectively ; and methylene blue values in the range [6 ; 8]. Their plasticity indices are in the range [20 ; 40]. These two (02) clays thus meet the requirements in terms of granularity, and their relatively high clay fraction will favor their adhesion with admixtures such as plant fibers. What's more, the particle size distribution of these clays is within the ideal CRAterre range for soils used in the manufacture of BTC or adobes, so they are all eligible.

Keywords : Earth, granulometry, argillosity, composite materials

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1. Introduction

The building sector, whether for residential, office or industrial use, is today at the heart of climate issues and the challenges of sustainable development. It consumes almost 30 – 40 % of the energy produced worldwide, and contributes around 35 % of greenhouse gas emissions [1]. This large share of the building sector is linked to the use of modern materials such as concrete, which is estimated to emit 74-81 % of CO_2 in cement production, which accounts for 9-10 % of global CO_2 production [2]. ***What type of biosourced composite material and what characteristics should be used to create low-energy habitats?***

To address these concerns, we need to pay particular attention to the development of alternative building materials that are environmentally friendly and suitable for bioclimatic design. A look at the use of unbaked earth in the construction of numerous archaeological sites around the world shows that these structures have a universal behavior and resist climatic hazards over time [3], [4]. The use of earth is therefore proving to be an alternative solution to modern construction. Indeed, earth's qualities - its thermal performance, its ability to absorb and reject moisture from indoor air are advantages that enable earthen building envelopes to reduce indoor microclimate fluctuations and cut energy consumption.

In addition to these advantages, earthen constructions such as adobe, cob, bauge, torchis, compressed or extruded earth bricks (BTC) and poured earth (earth concrete) have to overcome the obstacle of their mechanical resistance and low water resistance compared with constructions in conventional materials such as breeze blocks and concrete [5].

Burkina Faso, a country with a hot, dry tropical climate, abounds in large quantities of clay materials that could be used to formulate biosourced composite construction materials. In recent years, research has been carried out into earthen construction materials and techniques, with the aim of making better use of this abundant and easily recyclable local natural resource. However, raw adobes face problems of mechanical strength and water resistance. To solve this problem, a great deal of scientific work has been carried out on the incorporation of plant fibers into earth-based composite materials [6], [7], [8], [9].

MILLOGO *et al.* [10] studied the thermal behavior of Hibiscus cannabinus fiber-earth composites and found that thermal conductivity decreased with increasing Hibiscus cannabinus fiber content and length. They concluded that this decrease is linked to the lower density of the composite. Labat *et al.* [11] showed in their work that earth-straw composites could have a density ranging from 241 to 531 kg/m^3 and a thermal conductivity varying from 0.071 to 0.12 W/(m.K). They concluded that the addition of plant fibers to the soil results in a reduction in density leading to a reduction in thermal conductivity. Moussa OUEDRAOGO *et al.* [5] have shown that the thermal conductivity of adobes decreases with the addition of Hibiscus cannabinus fibers, essentially due to the presence of cellulose in the fibers, a good thermal insulator. Similar results were found by Malbila *et al.* [12] on BTC made of lateritic earth and Hibiscus cannabinus fibers.

Furthermore, in an international context marked by a growing need for energy and climate disruption, the design of sustainable bioclimatic habitats with low energy consumption for low-income populations in developing countries is essential. With this in mind, we have set ourselves the objective of researching the best qualified soil for the production of biosourced composite materials with good thermophysical and mechanical performance.

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2. Presentation and characterization of the soil

2.1. Origin of the land studied

The basic raw material used in this study is soil. It comes from a quarry in central Burkina Faso, at Malgsombo (latitude 12°52', longitude -1°.34' and located in zone 30P at an altitude of 302 m) in the rural district of Saaba, provincial of Kadiogo.

Figure 1 shows a map of the communes where the land is harvested.

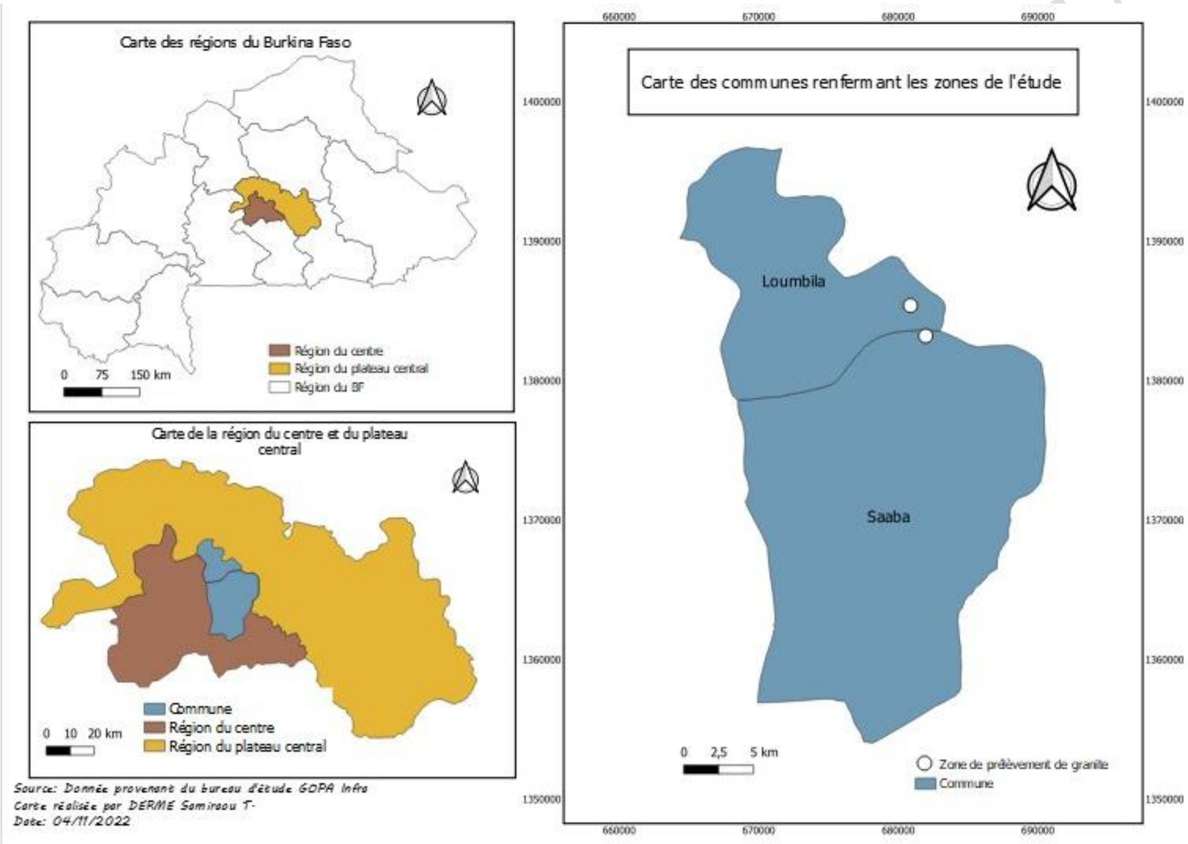

Figure 1 : Map of communes containing sampling areas in the study area

2.2. Soil particle size analysis

❖ **Aim and principle of the test**

This test is used to determine whether the soil's particle size curve falls within CRAterre's ideal range for stabilization with plant fibers. The complete particle size analysis test is carried out in two stages: dry sieving and sedimentometry. ***Figure 2*** illustrates the general composition of a soil and shows the limits of intervention for each stage of particle size analysis.

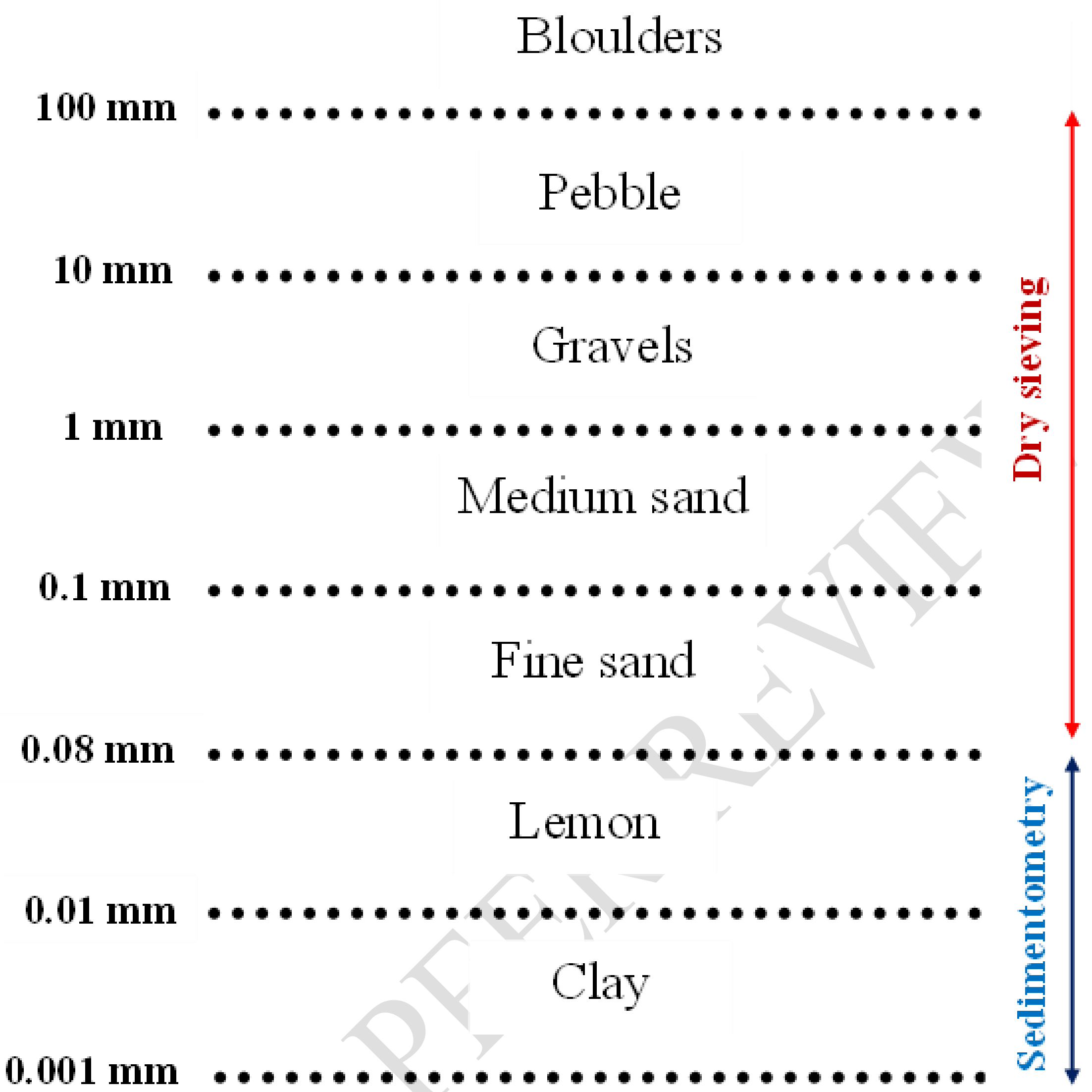

Figure 2 : Soil particle size classification

Particle size analysis by dry sieving (in accordance with standard NF P 94-056) [13] is carried out using square-meshed sieves with dimensions less than or equal to 100 mm and greater than or equal to 0.08 mm. The test consists in separating and classifying the various grains making up a sample of a given mass of material, using a series of sieves (100 mm to 0.08 mm) nested one on top of the other, with openings decreasing in size from top to bottom. The sample studied is placed in the last sieve at the top of the chain, and grain classification is obtained by vibrating the sieve column. The cumulative mass of the rejects from each sieve is recorded on a sieve analysis sheet, so that the percentages of the sieves in relation to the total mass of the sample analyzed can be calculated. This stage of the particle size analysis only provides information on grain sizes greater than or equal to 80 µm ; it is completed by sedimentometry (in accordance with standard NF P 94-057) [14].

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Sedimentometry is used to analyze the particle size of the sample passing through an 80 µm sieve. The principle behind this test is linked to the fact that in a solution at rest, the settling speed of fines is a function of their size. It is based on Stokes' law, which relates the settling velocity of spherical fines of the same density in a fluid to the intensity of gravity, provided the fluid's viscosity is known:

$$v = \frac{2r^2 g\Delta(\rho)}{9\mu} \quad \text{[E. 1]}$$

where v is the speed of fall (m/s) ; g is the intensity of gravity (m/s^2) ; r is the radius of the spherical material (m) and μ is the viscosity of the liquid $(Pa.s)$. $\Delta(\rho) = \rho_p - \rho_f$ is the difference in density between the particle and the liquid (kg/m^3) .

To carry out the sedimentometry test, remove 40 g of the 80 µm sieve passings from the sample under study ; add 60 cm^3 of deflocculating solution, sodium hexametaphosphate, HMP (Na_6 $(PO\ )_{36}$, $10H_2$ O), to prevent particle agglomeration, and 440 cm^3 of distilled water ; then leave to stand for at least 15 hours. The mixture is then stirred for 5 minutes on the electric stirrer, before being transferred to a tube and made up to the 2000 cm^3 mark with distilled water. At the start of the measurements, the mixture is stirred manually to separate the particles, which settle at different speeds according to their size. Finally, a densimeter is used to measure changes in solution density over time, and the depth of immersion of the densimeter. Sedimentometry relates the density read to the diameter of the grains still in suspension, and to their weight percentage in relation to the total mass of the sample in suspension.

2.3. Atterberg limits

Atterberg limits are geotechnical parameters used to identify and characterize soil by means of its plasticity index (PI). Depending on its water content, a reworked soil has different consistencies: liquid, plastic, solid with shrinkage and solid without shrinkage. Soils pass from one state to another, and the boundaries are defined by the Atterberg limits (standard NF P 94-051) [15].

2.3.1. Liquidity limits

This test is used to determine the water content of a soil as it changes from a liquid to a plastic state. To do this, a soil sample is washed through a 0.4 mm sieve to recover the sieved

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material. The sieves, moistened for at least 24 hours and transformed into a homogeneous paste, are placed in the dish of the Cazagrande apparatus. Using the groove tool, it is divided into two (02) equal parts. The cup is then struck with the crank until the groove is closed over a length of one centimeter (1 cm) of dough. Two (02) slices of this dough are wet-weighed and then oven-dried to determine its water content. The operation is repeated five (05) times, ensuring that the range of strokes within the closed interval [15-35] is respected. Finally, a straight line W=f(logN) is plotted with the water contents obtained at the end of the five (05) operations; the liquidity limit (W_L) is determined graphically and corresponds to the 25ème blow made on the cup.

2.3.2. Plasticity limits

This test is used to determine the water content of a soil as it changes from a plastic to a solid state. It consists in rolling 10 to 15 g of the paste sample used to calculate the liquid limit with the palm of the hand, forming a thin cylindrical stick with a diameter of 3 mm. By rolling it, we should be able to observe breakage of the stick to conclude that the plasticity limit has been reached. The pieces of each stick are weighed wet and dried in an oven to obtain the water content corresponding to the plasticity limit (W_p). The plasticity index (PI) defines the extent of the plastic range and enables us to assess the quantity and type of clay present in a soil sample, i.e. its argillosity.

$$IP = W_L - W_P \qquad [E. 2]$$

The possible land states and their various limits are illustrated in ***Figure 3***.

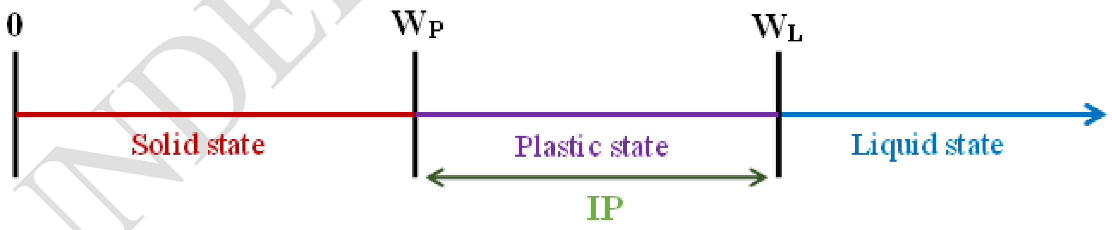

Figure 3 : representation of Atterberg limits

2.4. Methylene blue test : VB

This test is an identification method that measures the overall quantity and activity of the clay fraction contained in a clay soil. ***Figure 4*** shows an illustration of the apparatus and two examples of positive and negative tests.

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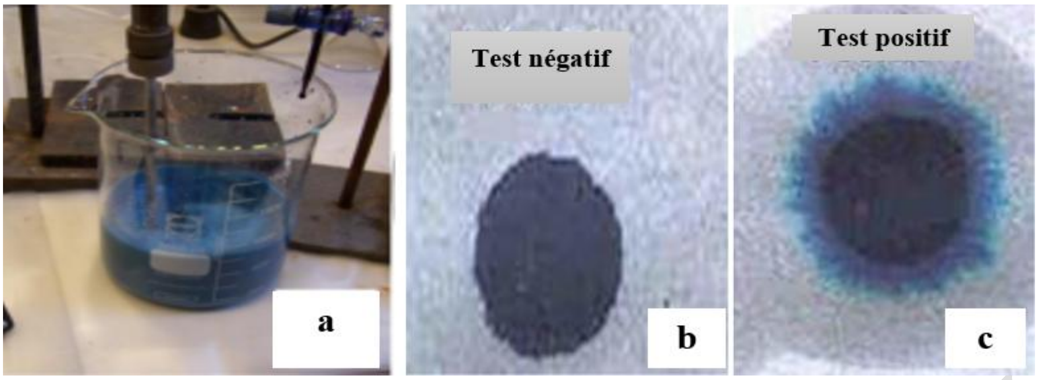

Figure 4 : (VB measurement) : a) equipment and BM assay ; b) negative test ; c) halo formation (positive test)

The methylene blue test involves measuring the quantity of methylene blue that can be adsorbed by a soil. This quantity of blue is directly proportional to the 0/5 mm fraction of the soil. The blue value (VB) is directly linked to the specific surface area of the particles making up the soil, which is primarily governed by the importance and activity of the clay materials present in the fine fraction of the soil (NF P94-068 standard) [16]. Dosing is carried out by successively adding different quantities of methylene blue and checking absorption after each addition. To do this, a drop of the suspension is taken and placed on filter paper, creating a stain. Maximum adsorption is reached when a persistent light blue halo (***Figure 4*****c**) occurs at the periphery of the stain (positive stain). The methylene blue value (VB) of the material is determined according to equation 3 :

$$VB = \frac{V(cm^3) * CBM(g/cm^3)}{M_{sol}(g)} * 100 \qquad [E. 3]$$

Where :

- ✓ VB is blue value for 100 g of soil,
- ✓ V is number of cm^3 of titration solution used,
- ✓ CBM is concentration of methylene blue,
- ✓ M_{sol} is mass of dry soil, kg.

2.5. Air pycnometer specific weight

This test enables us to determine the weight by volume of solid grains in a soil. The sample is taken directly without washing, and each sample is weighed between 600 g and 900 g directly into the pycnometer tared on a balance. Next, distilled water is added in a quantity greater than 300 cm^3, the device is closed and air is injected using a small pump built into the device.

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Finally, the needle is returned to the red point and the pressure reading is taken. The specific weight is then given by equation 4 :

$$\gamma_s = \frac{w_s}{V_{lu} - V_{eau}} \qquad [E. 4]$$

In this relationship, w_s is the mass of the material, V_{eau} is the volume of water added and V_{lu} is the volume read given by equation 5 :

$$V_{lu} = \left(\frac{P_m - 4,4174}{P_m - 1} \right) \times 1214,7465 \qquad [E. 5]$$

2.6. Humidity (*TH*)

Clay soils readily absorb water known as "imbibition water." [17]. Heating to 105°C in an oven causes this water to leave the soil. The moisture content (TH) is the percentage of water absorbed by a soil, and provides information on the soil's state of hydration. The principle of TH determination involves measuring a sample mass m_1 and placing it in an oven heated to 105°C for at least 24 hours. After cooling, the sample is weighed again to determine its post-steaming mass m_2 . The value of the moisture content is given by equation 6:

$$TH(\%) = 100 \times \frac{m_1 - m_2}{m_1} \qquad [E. 6]$$

For this test, we used a DHG83-A oven set at 105°C and maintained at this temperature for 24 hours, i.e. until the end of the test.

2.7. Fire loss

The loss on ignition test is a method for determining the organic matter content of a soil by calcination at 1000 °C in a kiln. A lateritic or clayey soil heated to 1000 °C undergoes successive losses of mass, which can be explained by the elimination of constitutive water, the modification of its structure or the calcination of carbonates and organic matter. [18]. Thus, the loss on ignition (LOI) or organic matter content is obtained by applying equation 7 :

$$PF(\%) = 100 \times \frac{m_3 - m_4}{m_3} \qquad [E. 7]$$

Where; m_3 is the mass of the sample subjected to a temperature of 1000 °C in an oven and m_4 is the mass of the sample after heating and cooling. For this test, we used a NABERTHERM

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C250 type furnace heated to 1000 °C and a two (02) hour stage with a rate of rise of 10 °C per minute.

3. Results of our area study

3.1. Particle size

The results of the particle size analysis of the five (05) soils sampled are shown in ***Figure 5*** and summarized in ***Table 1***. From these results, we note that these soils have a similar granulometry and are all contained within the ideal spindle (between Ref1 and Ref2) recommended by CRAterre for their use as earth brick manufacturing material. However, the MSB-FR clay, with a fine fraction of 69.82% (percentage of 80 µm sieve passings) and a clay fraction of 31.77% (percentage of 2 µm sieve passings), falls slightly outside this range, which leads us to disregard it. Further testing enabled us to assess the other four (04) more accurately.

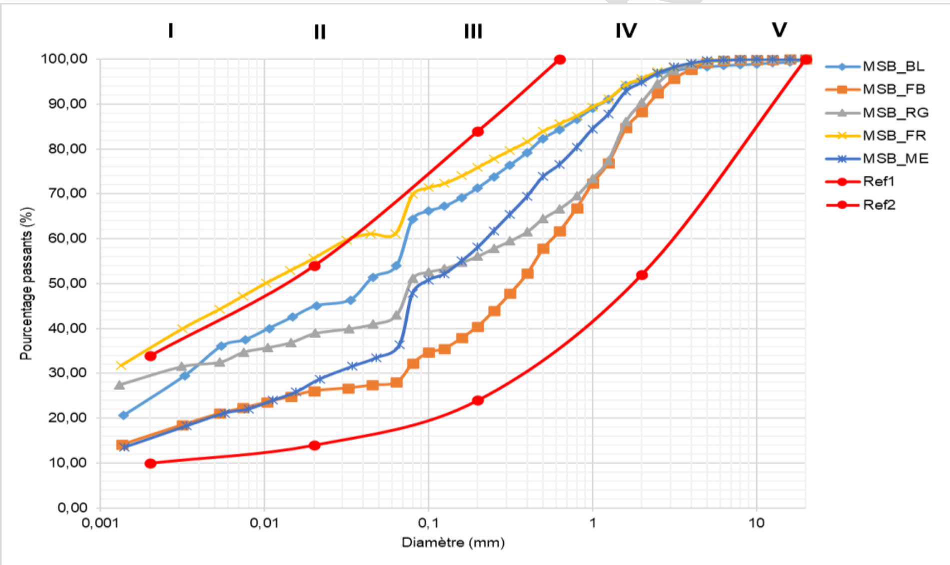

Figure 5 : Sieve size curves for the soils studied

Table 1 : Particle size distribution of the soils studied

Floors	**Fine fraction (D<0.08 mm) (%)**	**Clay fraction (D<0.002 mm) (%)**	**Mortar (D<0.4 mm) (%)**	**Skeleton (D< 2mm) (%)**
MSB-RG	64.28	27.51	61.54	90.42
MSB-FR	32.24	31.77	81.59	95.73
MSB-FB	51.16	14.1	52.27	88.33

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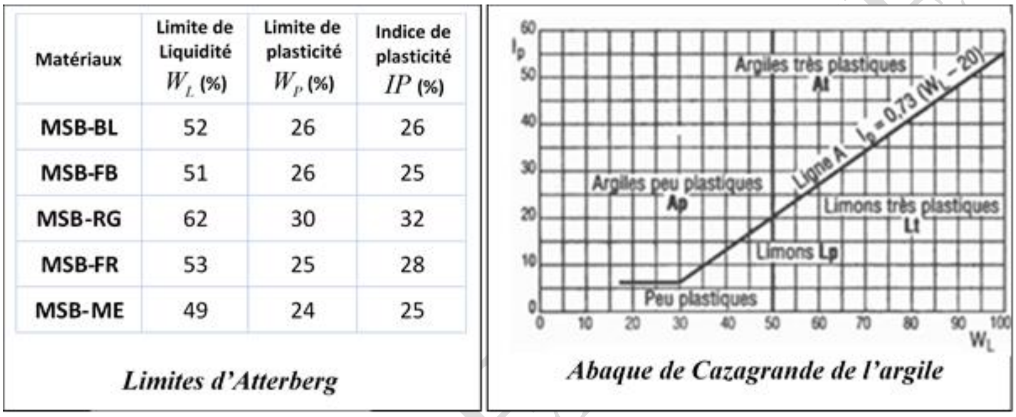
MSB-ME	69.82	13.56	69.45	94.84
MSB-BL	47.85	20.61	79.19	95.39

3.2. Argilosity

3.2.1. Atterberg limits

The results of determining the Atterberg limits of the samples studied are shown in ***Figure 6***. This figure represents our tabulated results in conjunction with the Cazagrande abacus for clay classification.



Matériaux	Limite de Liquidité W_L (%)	Limite de plasticité W_P (%)	Indice de plasticité IP (%)
MSB-BL	52	26	26
MSB-FB	51	26	25
MSB-RG	62	30	32
MSB-FR	53	25	28
MSB-ME	49	24	25

Limites d'Atterberg

Abaque de Cazagrande de l'argile

Figure 6 : Atterberg limits & Cazagrande abacus

From this figure, we note that the liquidity limit of the four (04) clays (MSB-BL, MSB-FB, MSB-RG and MSB-FR) remains above 50 % and their plasticity index is above the A line. These clays are therefore of type At (very plastic clay) according to Cazagrande's Abacus [19], based on the Unified Soil Classification System (USCS). The liquidity limit (49%) of the MSB-ME clay is below 50% and its plasticity index (25%) is above the A line; this clay is therefore of type Ap (low plasticity clay).

3.2.2. Methylene blue value : VB

Table 2 gives the methylene blue (MB) values of the five (05) soils analyzed. The blue value of a soil quantifies the adsorption capacity of the clays present in it.

Table 2 : Methylene blue test results

Materials	MSB-RG	MSB-ME	MSB-BL	MSB-FR	MSB-FB
Methylene blue (VB) values	5.99	8.26	7.66	7.50	9.33

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According to ***Table 2*** above, the methylene blue (VB) values of the soils studied are in the range [5 ; 10], and according to the results of the particle size analysis D_{max} <50 mm and the 80 µm sieve pass is greater than 35 % except for the MSG-FB clay; these soils therefore belong to the class of fine clays or very plastic, water-sensitive silts (standard NF P11 - 300) [20].

3.3. Air pycnometer specific weight

The specific weight of a soil, also known as its relative density or density, is the ratio of the weight of the soil to that of an equal volume of water. For a soil of given specific gravity x, this means that it weighs x times more than the same volume of water (the density of water being equal to 1).

The results of the air pycnometer test to determine the specific weights of the soils studied are given in ***Table 3***.

Table 3 : Specific weight results for the soils studied

Floors	**Dry weight of soil in tank (g)**	**Volume of distilled water added (cm)^3**	**Final tank pressure (P') "sample + chambers (mWs)**				**V value$_{lu}$ (cm)^3**	**γ_S (kN/m)^3**
			1st test	2nd test	3rd test	Average P' (mWs)		
MSB-ME	260	360	6.9	6.8	6.8	6.83	503.10	1.82
MSB-BL	220	350	6.5	6.5	6.5	6.50	459.97	2.00
MSB-FR	230	380	6.7	7	6.8	6.83	503.10	1.87
MSB-FB	260	300	6.1	6.4	6.4	6.30	431.50	2.00
MSB-RG	230	310	6.3	6.6	6.7	6.53	464.52	1.50

3.4. Moisture content (TH) and fire loss (PF)

Test results for moisture content and loss on ignition are shown in ***Table 4***.

Table 4 : Moisture content and loss on ignition of the soils studied

Floors	**Initial test mass (g)**	**Mass at 105°C (g)**	**Moisture content (%)**	**Mass at 1000°C (g)**	**Loss on ignition (%)**
MSB-RG	37.01	36.45	1.53	32.84	9.89
MSB-FR	48.77	47.35	2.90	42.60	10.04

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MSB-FB	47.22	46.04	2.50	42.76	7.12
MSB-ME	43.36	42.74	1.44	38.74	9.35
MSB-BL	39.91	39.09	2.06	35.62	8.89

According to ***Table 4***, the MSB-FR clay has the highest moisture content (2.897 %). This is consistent with the very high value of the clay fraction found (31.77 %). However, the clays MSG-FR, MSG-RG and MSG-ME have loss on ignition values of 10.04, 9.891 and 9.345 respectively. This may be linked to their mineralogical structure, which may contain goethites that are often associated with organic matter. These remarkable values are also linked to the fact that these clays are very clayey and that loss on ignition results in the elimination of the water that forms the clay sheets. The other two (02) clays have relatively low moisture content and loss on ignition values.

3.5. Choice of study site

According to the results presented in the previous paragraphs, MSB-FB and MSB-ME clays have fine fractions of 51.16 % and 69.82 % respectively; relatively low clay fractions (14.10% and 13.56% respectively) and PI values of 25 %. According to the code of good practice published by the Road Research Center [21] any soil for which the plasticity index is in the range [12 ; 25] is moderately clayey. These two soils are therefore moderately clayey. The MSG-RG and MSG-BL clays have fine fractions of 64.28 % and 47.85 % respectively; clay fractions of 27.51 % and 20.61 % respectively; and methylene blue values in the range [6; 8]. Their plasticity indices are in the range [20; 40]. These two (02) clays meet the requirements in terms of granularity, and their relatively high clay fraction will favor their adhesion with plant fiber additives. In addition, the particle size distribution of these clays is within the ideal CRAterre range for soils suitable for the manufacture of BTC or adobes. [22] so they are all eligible.

Also, these clays have higher moisture contents. This is consistent with the very high clay fraction values noted above. Their loss on ignition values are also higher. These remarkable values are also linked to the fact that loss on ignition results in the elimination of water from the clay sheets.

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4. Conclusion

The aim of this study was to present the methods and procedures for selecting a soil suitable for the production of biobased composite materials. It should be noted that, during this experimental study, we selected five (05) soils for analysis. The detailed characteristics of these soils were presented, and a quantitative and qualitative interpretation enabled us to conclude that MSG-RG and MSG-BL clays have the intrinsic characteristics required for use in the production of biosourced composite materials suitable for bioclimatic habitat design.

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