# Potentials of an Eco-Friendly Composite in Hot-Dry Climate

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**ABSTRACT:** This study aims to show the aptitude of a locally made composite for providing thermal comfort and mechanical resistance in buildings in hot-dry climates. The thermal characterization reveals that the thermal diffusivity of the studied material is lower than that of commonly used materials such as agglomerated and full cinderblocks and laterite blocks and therefore is a better insulating material. In addition, its thermal inertia is the highest compared to commonly used materials of agglomerated and full cinderblocks, laterite blocks and compressed earth blocks, which implies a longer time lag. On the basis of mechanical resistance, with a compression resistance of 3.61 MPa, the studied material meets the requirement of CRATerre and NBF 02-003 (2009) as a material for construction of single-storey buildings. Therefore, this material, containing 1% *Hibiscus sabdariffa* fibers and compacted by vibration, is a suitable material for the walls of standing buildings and for thermal comfort in hot dry climates.

**KEYWORDS:** Local composite, vibration, characterization, single-storey building envelope, thermal comfort

## 1 INTRODUCTION

The construction sector is indeed a major contributor to greenhouse gas emissions. According to a 2007 statement of the experts on the Intergovernmental Panel on Climate Change [1], 46.9% of global greenhouse gas emissions arise from energy supply and transport, residential and commercial buildings, sectors which encompass the construction sector. On behalf of high energy consumption practices, there is, among others, the production of cement which requires a substantial amount of combustible substances; the *Afrique Expansion Magazine* revealed that 110 million tons of cement were produced in Africa in 2015 to meet the demand of the construction sector [2]. Moreover, air conditioning used for comfort in buildings is the biggest energy consumer. Estimates indicate a range of between 40% and 80% of total electricity consumption in buildings for space cooling in tropical climates [3]. A previous study [4] in Burkina Faso reported that 3.4 billion CFA francs were spent each year to ensure air conditioning in public buildings, which is a huge burden on the local economy.

Therefore, there is a need to rethink strategies for sustainable constructions that promote the use of local ecological materials and way(s) of mastering energy consumption to reduce its negative impact on the ecosystem. For this purpose, more and more research projects are focusing on developing more locally available environmentally friendly materials.

Toukourou *et al*. [5] developed a composite material of compressed earth bricks mixed with 10% cement and 2% straw, which was improved by the organic material, leading to good thermal comfort compared to the case without straw. Moreover, the investigation of Millogo *et al*. [6] on pressed adobe blocks, stabilized with natural fibers such as fibers of *Hibiscus cannabinus*, has shown that there are suitable building materials which contribute to thermal comfort due to the presence of fibers which reduce propagation of cracks, enhance tensile strength and lower the thermal conductivity. In addition, there are some experimental projects like that of Wyss and Sauret [7], who built a house with adobe and a Nubian vault roof in the Sahel region of Africa; the results have shown that it is possible to achieve an acceptable level of comfort without resorting to air conditioning [7].

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In this work, we present a composite material made of earth and vegetal fibers, free from industrial binders such as cement, that offers better properties for thermal comfort (than commonly used materials) and enough resistance for application in the envelope (walls) of buildings.

## 2 MATERIALS AND METHODS

### 2.1 Choosing Materials

#### 2.1.1 Mineral Matrix (Ceramic Matrix)

In Burkina Faso, a variety of tropical soils such as lateritic soil types and sandy clays are widely found, depending on the locality. So, to get a suitable material for a hot-dry climate without industrial additives like cement, it is important to define an appropriate earth material independently of the types of soils present but based on appropriate characteristics. These are:

- Plasticizer power for good workability in the presence of water.
  In order to facilitate the mixing, a mixture should be plastic rather than solid; this characteristic is the prerogative of fine particles and according to GTR soil classification, soils with granulometry (particle size distribution) of $D_{max}$ (largest size) inferior to 50 mm, particles smaller than 80 µm (D ≤ 80µm) representing more than 35% of the total soil and plasticity index (Ip) between 12 and 25 behave like the fine fraction [8]. Moreover, the soil classification proposed by LCPC [9] and CRR [10] indicates that soils with a plasticity index between 10 and 20 and between 12 and 25, respectively, are moderately plastic, which is sufficient for workability of the soil in the presence of water. So to determine particle sizes and plasticity of a soil, respectively, a granulometry test and the determination of Atterberg limits are indicated.
- Dense, coarse particles to withstand the mechanical loads.
  This role is incumbent on particules larger than 80 µm (D ≥ 80 µm), so the higher their portion in soil, the more the resistance will be. In this case, the granulometry test will make it possible to detect the particles concerned and their proportion in the soil.
- Porous structure to take advantage of the insulating air power.
  The studies of Maison *et al.* [11] have shown that the majority of clays (particle sizes smaller than 2 µm) display porous structure and therefore are good candidates for the choice of soil based on insulation criteria. According to GTR soil classification [8], soils with methylen blue value (VB) between 6 and 8 are identified as clay soils. Granulometry and methylene blue tests are used to know the nature of soils.

To sum up, the criteria for an appropriate soil are:

- particles smaller than 80 µm should correspond to more than 35% of soil;
- particles larger than 80 µm should represent at least 50% of soil;
- plasticity index should be more than 20% (Ip ≥ 20%);
- methylen blue value (VB) should be between 6 and 8 (6 < VB < 8).

Apart from these criteria, the clay (particle sizes smaller than 2 µm) proportion in soils definitely should not be less than 5% or exceed 30% and particle sizes should not be larger than 5 mm [12].

Therefore, some geotechnical testing, such as granulometry [13], Atterberg limits [14], and methylene blue tests, were conducted on different soils from different locations in Burkina Faso (Figure 1). It was determined that the soil with 48% of grains of diameter smaller than 80 µm and 52% of grains of diameter larger than 80 µm (Figure 2), with plasticity index (Ip) of 22% and methylen blue value (VB) of 6.97, is appropriate as earth material for the purpose of this study.

However, as the granulometry may vary even at the same extraction site, to facilitate the selection of particles, for practical reasons and due to the fact that granulometry of a soil is linked to the criteria defined above, the following requirements have been established:

Select different soils (e.g., by sieving) with particle sizes smaller than 80 µm on one hand and soils whose particle sizes are larger than 80 µm on the other hand. Then, make samples with 48% of the particle sizes smaller than 80 µm mixed with 52% of particle sizes larger than 80 µm for geotechnical testing. The mix that meets the criteria cited above is appropriated.

#### 2.1.2. Vegetal Reinforcement

*Hibiscus sabdariffa* fibers used as reinforcement in the formulated material are from an herbaceous plant that belongs to the family Malvaceae. The stems, depending on the variety, can reach one meter (1 m) long and exhibit a thick cortex.

*Hibiscus sabdariffa* is a flowering plant whose flowers are mainly used in the preparation of a beverage named "Bissap," and then the rest of the plant, such as stems, constitutes green waste. Hence the interest

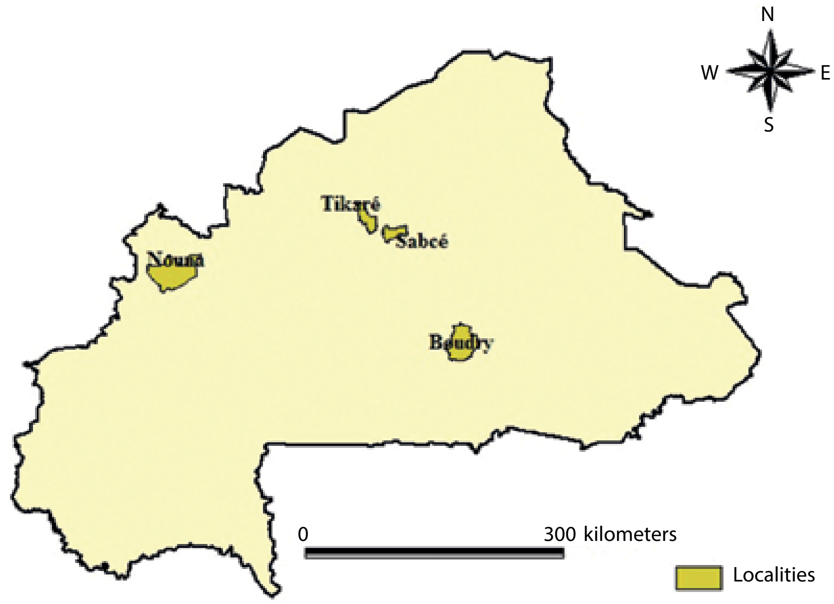



**Figure 1** Locations of the soils on which geotechnical testing was applied.

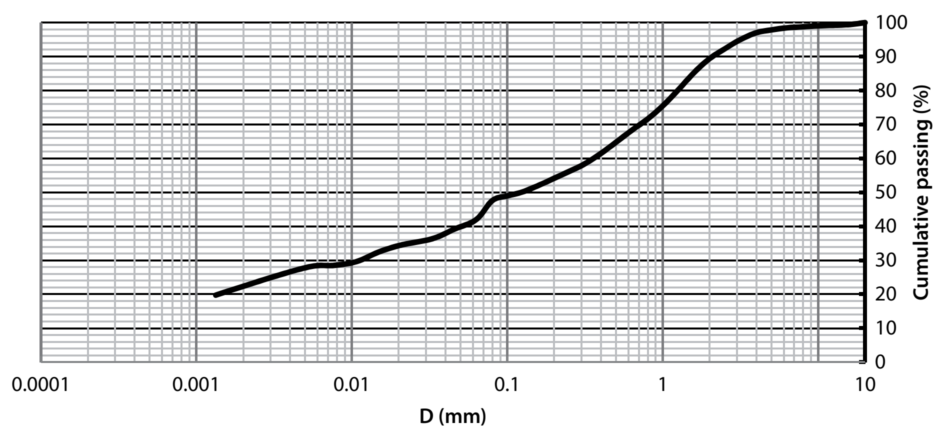



**Figure 2** Granulometry (NF P 18-560; NF P 94-057) of a soil which meets the appropriate characteristics for the study.

in valorizing the fibers of that hibiscus (Figure 3a,b) as reinforcement in mineral matrix.

## 2.2 Sample Preparation

To perform the different characterization tests, we made samples from earth material (48% grains of diameter ≤ 80 µm and 52% grains of diameter > 80 µm) blended with 1% *Hibiscus sabdariffa* vegetal fibers and 30% water in weight, following a mixing process by shearing (125 rev/min by means of a FLOTT M3 ST drilling machine which has been provided with a finned rod [Figure 4]). Then the resulting mixture is spilt in a mold into three (03) layers, with each layer being vibrated for five (05) seconds at 980.2 Hz.

## 2.3 Characterization

### 2.3.1 Thermal Characterization

The thermal characterization was conducted on prismatic-shaped samples. The analysis was performed on a Decagon Devices KD2 Pro Thermal Properties Analyzer which is composed of a dual needle probe and handheld controller. The measurement principle consists of applying heat flux in the sample and then recording temperatures respectively by means of heated needle and temperature sensor, which both form the dual needle probe (Figure 5). Then the KD2 Pro device proceeds to the analysis of the data (temperatures) collected to determine the thermal properties needed. In fact, it consists of using a

(**a**)

(**b**)

**Figure 3** (**a**) The cortical fibers of *Hibiscus sabdariffa* soaked in water. (**b**) *Hibiscus sabdariffa* cortical fibers cut into an average 1 cm pieces.

**Figure 4** Mixing by shearing with a FLOTT M3 ST drilling machine which has been provided with a finned rod.

fitting method, based on the Levenberg-Marquardt nonlinear least-squares algorithm, between measurements and temperatures obtained following these equations:

$$T_C = b_0 \times t + b_1 \times E_i \frac{b_2}{t} : \text{During heating,} \quad (1)$$

$$T_C = \frac{4\pi (T - T_0)}{b_2} : \text{After heating,} \quad (2)$$

where $T_c$ [°C] is calculated temperature; T [°C] is measured temperature; $T_0$ is ambient temperature measured at the beginning of the measurements; $E_i$ is the exponential integral (Abramowitz and Stegun, 1972);

**Figure 5** Thermal characterization in process with Decagon Devices KD2 Pro Thermal Properties Analyzer.

and $b_0$, $b_1$, $b_2$ are constants whose values minimize the sum of square errors between measured and calculated temperatures.

At the end of the process, the correspondent thermal conductivity (λ [W/m.K]) and diffusivity (α [m²/s]) are determined as follows:

$$\lambda = \frac{1}{b_1} \tag{3}$$

$$\alpha = \frac{r^2}{4b_2} \tag{4}$$

### 2.3.2 Mechanical Characterization

A compression test was conducted according to the standard NF P 18-406 on cubic-shaped samples (Figure 6a,b). It is meant to determine the highest stress a material can withstand when being pressed:

$$R_C = \frac{F_{\max}}{S} \pm \frac{\Delta R_C}{R_C} \tag{5}$$

where $R_c$ [MPa] is maximal stress; $F_{max}$ [N] is maximum load; and S [m2] is surface where the load is applied.

### 2.3.3 Physical Characterization

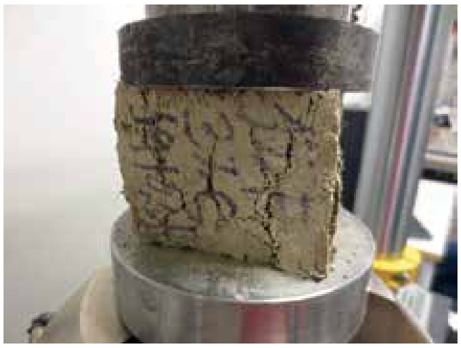
A material is composed of three phases: solids, water and air. Water and air occupy the voids called pores. Thus, porosity (φ [%]) represents the percentage of voids in a material:

$$\varphi = \frac{V_v}{V_T} \tag{6}$$

where $V_v$ [m³] is volume of voids or pores; and $V_T$ [m³] is total volume of the sample.

The interest in knowing the porosity lies in the fact that the pores are where mass and heat transfers take place. The studies of Chen *et al.* [15] clearly show the impact of porosity on material strength. Moreover, it is also thanks to the pores that the material breathes. Indeed,

(**a**)



(**b**)

**Figure 6** (**a**) Compression testing on a cubic-shaped sample with an Instron 8516 machine. (**b**) Sample being compressed showing the appearance of lateral cracks.

the network of pores, particularly opened ones, impact on the thermal properties due to the presence of air. For that purpose, we determined the porosity of the material employing volumetric and gravimetric methods.

Gravimetric methods are based on direct mass measurements using precision analytical balance when volumetric methods are concerned with volume measurements. Indeed, according to the phase diagram:

$$V_v = V_T - V_s = V_a + V_w \tag{7}$$

Where:

$$V_w = \frac{M_w}{\rho_w} \tag{8}$$

$$M_w = M_T - M_s \tag{9}$$

$$V_s = \frac{M_s}{G_s \rho_w} \tag{10}$$

$$G_s = \frac{M_s}{M_{w'}} = \frac{KM_s}{M_s + M_{1t} - M_{2t}} \tag{11}$$

$$V_a = V_T - (V_w + V_s) \tag{12}$$

where $V_T$ is the volume of the sample obtained through Archimedes principle [16] (Figure 7a–c); $V_v$ is volume of voids; $V_s$ is volume of solid particles; $V_a$ is volume of air in the sample; and $V_w$ is volume of water in the sample;

$M_w$ is mass of water in the sample; $M_s$ is mass of oven-dried sample; $M_T$ is mass of the sample; $M_{1t}$ is mass of pycnometer filled with distilled water up to ¾ of its capacity; and $M_{2t}$ is mass of pycnometer and sample soaked in distilled water after boiling to remove the rest of the trapped air;

G*s*, obtained following ASTM C128 standard [17], is the specific gravity of soil particles and ratio of density of soil particles to the density of a reference substance (water in our case) having the same volume (Figure 8).

## 3 RESULTS AND DISCUSSIONS

Table 1 below summarizes the thermal and physical properties of the formulated material (A), full cinderblock (B), agglomerated cinderblock (C), compressed earth block (BTC) and laterite block (BLT).

Comparing (A) to (B) and (C), which are commonly used in construction of walls, we noticed that the thermal conductivity of (A) is lower than that of (B) but higher than that of agglomerated cinderblock, BLT and BTC. Air being the best insulator (in the case of low thickness and low external ventilation influence), explains these remarks about thermal conductivities.

Moreover, material (A) has the highest thermal effusivity and the lowest thermal diffusivity (Table 1), which are predictive of better thermal inertia [21]. Indeed, on a thermal comfort basis, an appropriate material for a hot-dry climate, like a sub-Saharan one, should have a high inertia.

On one hand, thermal effusivity and diffusivity are the thermal properties that best reflect the inertia of buildings [21]. Thermal diffusivity represents the ability of a material to let the heat spread faster. Therefore, lower thermal diffusivity means that the heat will be transmitted more slowly through the wall. As for the thermal effusivity, it represents the capacity of the material to absorb heat without getting warmed, which implies a capacity to store a large amount of heat. Therefore, the best material for comfort in a hot climate like ours (no overheating) is one that has the lowest thermal diffusivity and the highest thermal effusivity for storing the maximum heat. Therefore, it implies that material (A) has a longer time lag [22] than commonly used materials (B), (C) and BLT.

(**a**) (**b**) (**c**)

**Figure 7.** (**a**) Sample wrapped in paraffin to prevent water infiltration or particle loss. (**b**) Weight of the sample when hung by a string so that it does not sink into the water. (**c**) Applying Archimedes principle to a sample wrapped with paraffin.

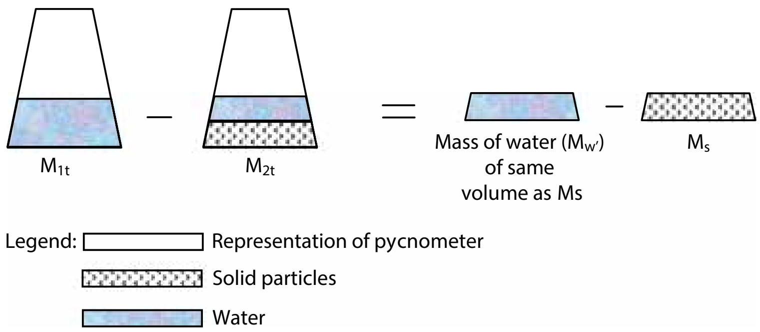



**Figure 8** Illustration of the quantity $M_{1t} - M_{2t}$.

**Table 1** Thermal and physical properties of the studied material and other known materials.

| Materials | ρ | λ | C | α (x10⁻⁷) | E | ρCλ (x10⁻⁶) | Φ |
|---|---|---|---|---|---|---|---|
| | [kg.m⁻³] | [W.m⁻¹.K⁻¹] | [J °C⁻¹ kg⁻¹] | [m².s⁻¹] | [J.m⁻².°C⁻¹.s⁻¹/²] | | % |
| (A) | 1789.48 ± 0.08% | 0.92 ± 5.73% | 1472.28 ± 4.70% | 3.49 ± 1.15% | 1556.81 ± 5.17% | 2.43 | 25.36 |
| (B)[18] | 2100 | 1.1 | 880 | 5.95 | 1425.76 | 2.03 | - |
| (C)[18] | 1250 | 0.67 | 880 | 6.09 | 858.49 | 0.74 | - |
| BTC[19] | 1835.45 ± 1.5% | 0.56 ± 1.08% | 1417 ± 1.27% | 2.14 ± 1.07% | 1202.29 ± 0.89% | 1.46 | - |
| BLT[20] | 1820 ± 3.85% | 0.51 ± 15.69% | 795.05 ± 17.28% | 3.60 ± 25% | 850 ± 28.19% | 0.74 | 30 |

ρ = density; E = thermal effusivity; C = heat capacity

On the other hand, the thermal inertia is determined following the expression $\rho C\lambda$ [23]. Results in Table 1 show that material (A) possesses the highest thermal inertia followed respectively by materials (B), BTC, BLT and (C). We can then conclude that material (A) will provide better thermal comfort than materials (B), (C), BTC and BLT.

Concerning mechanical resistance, the compression test reveals a mean compression stress of 3.61 ± 8.61% MPa (Figure 9). It is of the same order of value as those found in the literature for local and natural materials; indeed, the compressive strengths are 0.38 to 4.87 MPa for Burkinabé laterite [20] and 0.5 to 3 Mpa for Indian laterite [24]. However, a material to be used as construction material should meet some requirements.

CRATerre, a renowned organization working for the dissemination of good practices in the construction field, suggests at least a compression resistance of 4 MPa for any brick made of earth to be used in building construction. As for compressed earth blocks, a minimum of 2.4 MPa is recommended for the construction of single-storey (ground-storey) buildings and buildings R+1 [25]. Since material (A) was packed down as compressed earth blocks, but by vibration, we can affirm that it meets the requirements for use as material for construction. Moreover, 2 MPa is the minimum required for construction in Burkina Faso [26].

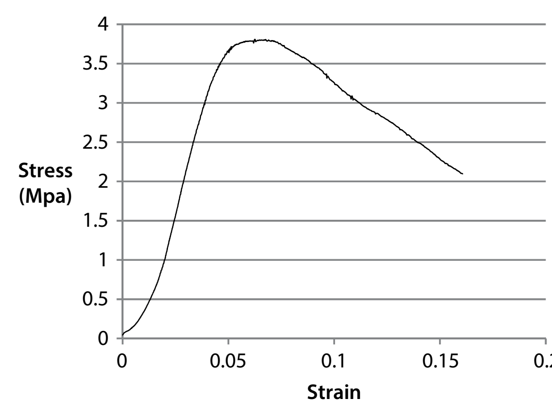



**Figure 9** Chart of the compressive test on the studied material.

## 4 CONCLUSION

This study leads to the determination of thermo-physical properties and mechanical resistance to compression of a composite material made of earth (48% of grains of diameter inferior to 80 µm and 52% of grains of diameter superior to 80 µm) and 1% *Hibiscus sabdariffa* fibers, and compacted by vibration. The results reveal that this material has the highest thermal inertia compared to commonly used materials of agglomerated and full cinderblocks, BTC and BLT. As for mechanical resistance, the material meets the minimum required as a construction material for single-storey (ground-storey) buildings. So as a material made from environmentally friendly matter, we can then conclude that material (A) would be an interesting and suitable material for comfort in single-storey buildings in hot-dry climates. However, more investigations should be performed such as water absorption factor, fire resistance and embodied energy. Most importantly, the thermal and mechanical qualities of the proposed material should be observed in the case of a real building project.

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