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Thermomechanical Characterization of Three Soils of Abeche in Chad

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Abstract

The study carried out concerns the valorization of agricultural waste for the development of biosourced materials that can be used as insulation in homes. This article is devoted to the influence of gum arabic on the mechanical and thermal properties of clay soils in the town of Abéché. The mechanical tests were carried out using the CBR press equipped with two devices (bending device and compression device). Thermal property such as thermal conductivity was determined by the hot wire method and thermal resistance was derived by calculation. Thus, the tests were carried out on test pieces made from a mixture of clay and gum arabic in solution. The experimental program includes seven formulations (0%, 2%, 4%, 6%, 8%, 10% and 12%). The results obtained showed that the best flexural and compressive strengths are obtained by using gum arabic with a rate of 8% and a maximum stress of 4.3 MPa. In addition, the thermal results also showed that the thermal conductivity decreases when the percentage of gum arabic increases, which makes it possible to increase the thermal resistance, thus confirming the capacity of gum arabic to provide thermal insulation.

Keywords

Soils, Mechanical Characterization, Thermal Characterization, Thermal Conductivity, Thermal Resistance

1. Introduction

The increase in population generates high demand and an increase in fossil fuel consumption and economic activities as well as contamination due to air pollution and the instability of oil prices and gas emissions greenhouse effect [1]. In addition, the demand for housing continues to increase given the population explosion on a global scale. However, in recent decades the trend in construction is based much more on cementitious materials. Thus, the use of the latter releases more CO2 which contributes to global warming. Indeed, in the field of construction, it is estimated that 10 billion tonnes of concrete are used each year; concrete is the most used material in the world [2]. This significant consumption of concrete is accompanied by a strong demand for cement, which is its essential constituent [3]. In this particular context, the development and research of new alternative materials with low operating costs and environmental impacts appear as a priority problem in Africa and developing countries such as Chad, which is a country where agricultural waste is very important [4]. Thanks to this context, a renewed interest is focused on the development of alternative construction materials that respect the environment and are well adapted to the type of construction with such ecological characteristics, available locally and whose implementation is less energy consumers [5]. In addition, housing built using ecological materials has great inertia, which also promotes energy saving [6]. However, to ensure the maintenance of climatic balance, the development of sustainable construction practices by integrating systems into structures, which ensure thermal comfort therefore remains essential, not only in order to comply with current objectives for reducing the greenhouse effect, but reduce the need for conventional energy and also to limit energy consumption on a global scale [7]. Therefore, reducing the thermal loads of buildings is one of the gigantic means for combating the effects of climate change and maintaining a healthy environment [8].

Throughout the world, several construction technologies exist, but the technological development that humanity has experienced in recent years, particularly in the field of construction, through various varieties of materials, we see a favored return to construction in raw earth throughout the world [9] [10]. According to UNESCO, approximately 20% of the number of sites registered as world heritage are entirely or partially built from earth material (Anger *et al.* 2011) [11]. This proves that the latter occupies a more important place in the construction field.

However, the earth has disadvantages due to the fact that it has low mechanical resistance and high sensitivity to water [12]. However, with the evolution of technology, some researchers have used several adjuvants in order to improve the mechanical characteristics of stabilized BTC based on raw earth [13] [14]. Thus several studies have shown that the stabilization of BTCs with natural fibers makes it possible to reduce the cracking of BTCs due to shrinkage, which makes it possible to improve their durability and their resistance to bending [15] [16] and, to reduce their thermal conductivity [17] [18]. Furthermore, other researchers have shown that amending the earth with gum arabic makes it possible to increase the mechanical characteristics and thermal conductivity.

It is with this in mind that this study aims on the one hand to study the mechanical characteristics of the specimens amended with gum arabic on the one hand and the thermal resistance of the latter on the other hand. Thermal conductivity measurements using the hot wire method were carried out.

2. Material and Methods

2.1. Location of Material Sampling Sites

The geographic coordinates are given in Table 1.

Table 1. Different sites and their geographic coordinates.

References soils	Site	Geographic coordinates
EE	Seidou1	Latitude 13˚50'52"N Longitude 20˚48'54"E
EM	Seidou2	Latitude 13˚50'52"N Longitude 20˚48'30"E
EO	Djarwa	Latitude 13˚50'12"N Longitude 20˚48'29"E

2.2. Study Materials

a) Clay

The different physical and geotechnical quantities of Abéché clay are given in the article [19]. All these physical parameters contributed to the classification of clays from three quarries in the town of Abéché as "Low plastic clay".

b) Gum arabic

It is a solidified sap exudate. Gum arabic is a product obtained naturally or following an incision, on the trunk and at the base of trees. It is generally harvested in Saharan Africa (Maghreb, Egypt, Senegal, Mali, Chad, Sudan, etc.). This diversity of gum arabic makes it the most used among many others and takes the name "kami" by the Egyptians who used it around 2650 BC. The latter was very useful in ensuring the cohesion of mummy bandages [20] [21]. **Figure 1** shows an image of gum arabic collected in its raw state.

Figure 1. Gum arabic.

The chemical compositions of gum arabic vary slightly depending on certain parameters such as climate, season, the age of the tree, etc. However, typical analytical data are given in Table 2.

Table 2. Characteristics of gum arabic from acacia seyal and acacia Senegal [22] [23].

Settings	Acacia Senegal	Acacia Senegal
Galactose (%)	44	38
Arabinose (%)	27	46
Rhamnose (%)	13	4
Glucuronic acid (%)	14.5	6.5
4-O-methyl-glucuronic acid	1.5	5.5
Nitrogen (%)	0.36	0.15
Specific rotations (degrees)	−30	+51
Average molecular mass (kDa)	380	850
Galactose (%)	44	38

Formulation of Test Pieces

The 4 × 4 × 16 cm^3 parallelepiped specimens are used for mechanical tests (flexion and compression) and the 4 × 5 × 8 cm^3 for thermal tests. The different formulations are presented in **Table 3**.

Table 3. Formulation of 4 × 4 × 16 cm^3 test pieces of different materials with gum Arabic.

Soil	Clay (%)	%GA	l (cm)	b (cm)	h(mm)	Number
EE	100	0	16	4	4	4
	98	2	16	4	4	4
	96	4	16	4	4	4
	94	6	16	4	4	4
	92	8	16	4	4	4
	90	10	16	4	4	4
	88	12	16	4	4	4
Soil	**Clay (%)**	**%GA**	**l (cm)**	**b (cm)**	**h(mm)**	**Number**
EM	100	0	16	4	4	4
	98	2	16	4	4	4
	96	4	16	4	4	4
	94	6	16	4	4	4
	92	8	16	4	4	4
	90	10	16	4	4	4
	88	12	16	4	4	4
Soil	**Clay (%)**	**%GA**	**l (cm)**	**b (cm)**	**h(mm)**	**Number**
EO	100	0	16	4	4	4
	98	2	16	4	4	4
	96	4	16	4	4	4

Continued

EO	94	6	16	4	4	4
	92	8	16	4	4	4
	90	10	16	4	4	4
	88	12	16	4	4	4

2.3. Soil Preparation

First, a mass of clay (450 ± 1 g) is taken and weighed with a balance as shown in Figure 2 below. We weigh the different percentages of gum arabic (0%, 2%, 4% 6%, 8% 10% and 12%) of the mass of clay taken initially and dissolve them in water for 24 hours to have a completely homogeneous solution. Then we subtract 2% from 450 g of clay and we complete with the gum arabic solution, so this operation is done for the other percentages. The clay is then put in a cup, and then the gum solution arabique is poured gradually onto the clay, kneading with a trowel until an almost homogeneous mixture is obtained. Finally, pour the mixture (clay + gum arabic) into a plastic bag and set aside for 15 to 20 minutes to mix well.

Figure 2. (a) Clay, (b) Gum arabic, (c) Gum arabic in solution, (d) Mixture (clay + gum arabic).

2.3.1. Manufacturing of Specimens for Mechanical Tests

To manufacture the test pieces, we first measure the masses composed of clay and gum arabic for the different formulations using a balance. Then we introduce the mixture (clay+ gum arabic) into the molds whose dimensions are 4 × 4 × 16 cm^3 through a crucible, we close the molds and compress with a hydraulic press to obtain the test pieces with measuring 4 × 4 × 16 cm^3. Figure 3 shows an image of the manufacturing stage of different test specimens.

Once these test pieces are manufactured, their extraction is done very carefully once the upper cover is removed and action on the jack. Drying is carried out in the shade at the ambient temperature of the laboratory of the National School of Public Works (ENSTP) of approximately 30˚C ± 2˚C. After 3 days of conservation of the latter in the laboratory, they are then put in an oven and subjected to a temperature of 105˚C for 24 hours to have a stable mass.

2.3.2. Manufacturing of Specimens for Thermal Tests

The specimens for thermal characterization were manufactured out with the same hydraulic press as well as the drying process. Figure 4(a) is that of the press used for the manufacture of the test specimens and Figure 4(b) is that of the specimens manufactured.

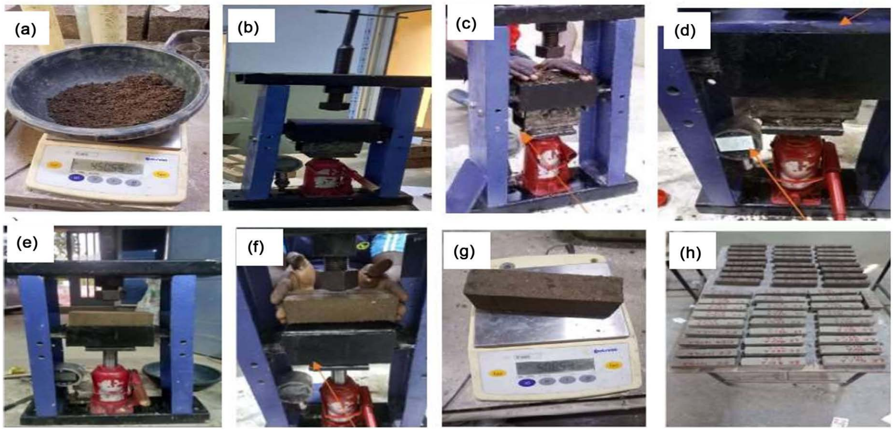

Figure 3. (a) Mixture (clay +gum arabic in solution) weighed, (b) Hydraulic press, (c) Mold, (d) Pressure gauge, (e) Manufactured sample, (f) Extraction, (g) Weighed sample, (h) Dried samples.

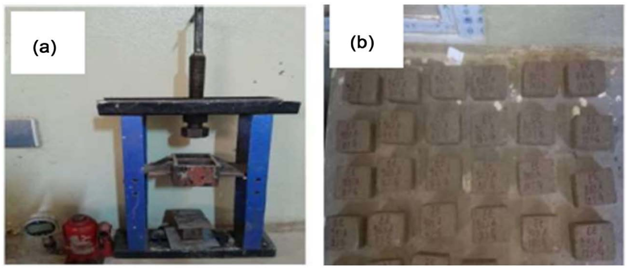

Figure 4. (a) Hydraulic press, (b) 4 × 5 × 8 cm^3 specimens.

2.3.3. Mechanical Characterization of Specimens

a) Three-point bending test

The manufactured specimens are first dried to have a stable mass before being subjected to the crushing operation. This crushing operation is carried out with a 30 KN CBR press shown in **Figure 5(a)** and the bending device is shown in **Figure 5(b)**. This press is designed to evaluate the CBR value of working capitals and underlayments in the laboratory, as well as to determine the strength of materials. The force F is then applied at a speed of 1.27 mm/min, *i.e.* until the specimen suddenly breaks. Force measurement is carried out with a 50 kN electronic force sensor. The weight of the press is 98 kg. Firstly, they are subjected to the three-point bending test according to French standard EN 1015-11 [24].

The device for bending tests on 4 × 4 × 16 cm^3 mortar prisms, according to EN 196.1. He is composed of two lower knives 100 mm apart and one upper knife, and the diameter of the knives is 10 mm. This device weighs 11 kg. The bending resistance is determined according to the following expression:

$$R_f = \frac{\frac{3}{2} * F * L}{h^3} \quad (1)$$

With, R_f the breaking strength (MPa), F the breaking load (N), h the height of the specimen (mm) and L the distance between the two supports (mm).

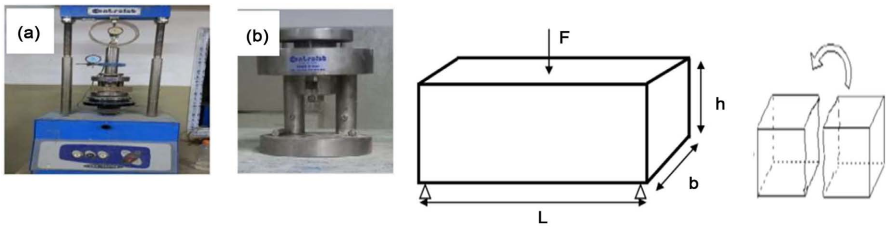

Figure 5. (a) CBR press, (b) Bending device.

b) Compressive strength

After the test piece breaks, the two pieces are recovered and subjected to a compression test.

The device for compression tests on mortar half-prisms 40 × 40 × 160 mm (to be inserted into the test space of a machine) with dimensions: Ø 140 × 180 mm. The weight of the device is 7 kg. The device is established according to standard EN 196-1/EN ISO 679/ASTM C349. The CBR press is shown in Figure 6(a) and the compressive device is shown in Figure 6(b). However, the compressive strength is determined according to the following formula:

$$R_c = \frac{F_c}{a^2} \tag{2}$$

With, R_c the compressive strength (MPa), F_c the breaking load (N) and a edge of the support surface (mm).

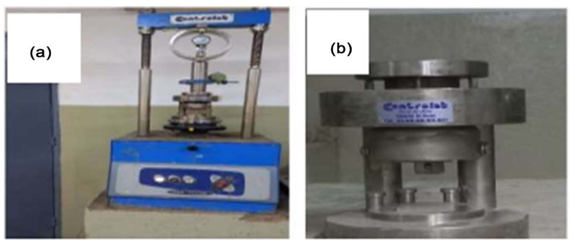

Figure 6. (a) CBR press, (b) Compression device.

2.4. Thermal Characterization

For thermal characterization, 5 × 4 × 8 cm^3 specimens are manufactured. To determine the thermal conductivity we used the hot wire method. The other thermal characteristics are deduced by calculation. However, Figure 7(a) shows us the FP2C device connected to the computer to determine the thermal conductivity of test samples made from different formulations. Figure 7(b) shows us the hot wire probe.

Figure 7. (a) FP2C device + computer, (b) Hot wire probe.

This FP2C device includes and is equipped with:

- a probe for determining thermal conductivity using the hot wire method
- Simulation software
- An acquisition box

For implementation, the probe is first connected to the acquisition box and sandwiched between the two identical test pieces (same material), and a heat flow is sent. The following equation relating thermal conductivity to the change in temperature with respect to time is:

$$\Delta T = \frac{q}{4p} * \left(\ln\left(t\right) + cste\right) \tag{3}$$

With λ: $Wm^{-1}\cdot K^{-1}$ thermal conductivity, q the injected linear flow in W/m, ΔT the temperature difference in K and the duration of the test in s. For reliability of results, testing is recommended. The principle of the probe and the device were developed by the CSTB. They derive from the ASTMD5930-97 standard and the RILEM AAC 11-3 recommendation [25].

2.5. Thermal Resistance

Thermal resistance (R_{th}) is used to quantify the insulating power of materials for a given thickness. It is expressed in $m^2\cdot KW^{-1}$. A wall is all the more insulating, as its thermal resistance is high. This size is particularly used in thermal insulation applications. It is calculated by the following relationship:

$$R_{th} = \frac{e}{\lambda} \tag{4}$$

R: $m^2\cdot K\cdot W^{-1}$ thermal resistance;

e: (m) thickness of insulation λ: $Wm^{-1}\cdot K^{-1}$ thermal conductivity.

3. Results and Discussion

3.1. Mechanical Behavior of Three Soils

3.1.1. Mechanical Resistance to Bending

Table 4 below presents the results of the mechanical tests (resistance in bending) on specimens without and with gum arabic.

Table 4. Results of mechanical resistance in bending.

% gum arabic	Reference soils		
	EE	EM	EO
	R_f (MPa)	R_f (MPa)	R_f (MPa)
0	0.53	0.69	0.56
2	0.8	0.85	0.64
4	1.14	1.33	1.28
6	2.16	1.58	1.76
8	2.45	2.69	2.65
10	3.59	2.64	3.75
12	3.46	2.58	3.35

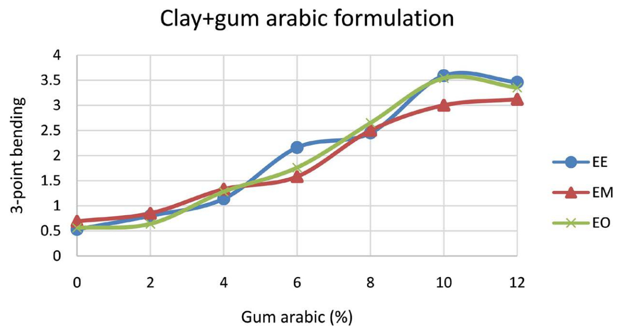

Figure 8. Influence of gum arabic on the bending strength of the specimens.

The results of the mechanical bending tests are given in **Figure 8**. These results give a representation of the variation in the bending resistance as a function of the addition of gum arabic. However, these curves show that the bending strengths vary depending on the percentage of gum arabic. Examining **Figure 8**, we see up to 4% gum arabic, the flexural strength values of three soils are close. However, at 6%, we see a slight increase in the value of the flexural resistance of the EE soil. From 6% of gum arabic, the increase in bending resistance is significant for the three soils. The maximum value obtained is 3.59 MPa for EE and 3.75 for EO with a percentage of 10% of gum arabic, but for EM soil, it is 2.69 MPa at 8% of gum arabic.

3.1.2. Mechanical Resistance to Compression

Table 5 below presents the results of the mechanical strength (compressive strength) of specimens without and with gum arabic.

Table 5. Compressive strength values.

% gum arabic	References of soils		
	EE	EM	EO
	R_c (MPa)	R_c (MPa)	R_c (MPa)
0	1.70	1.56	1.98
2	2.73	2.81	2.59
4	4.36	4.42	4.78
6	5.73	5.21	5.63
8	6.28	5.84	7.17
10	7.89	5.75	8.71
12	7.49	5.59	7.96

Figure 9 shows the compressive strength curves of three soils (**Figure 9**).

Likewise, the compressive strength also increases depending on the gum arabic content. From 2% of gum arabic in the mixture, we see a slight increase in mechanical strength. However, the compressive strength values are close to up

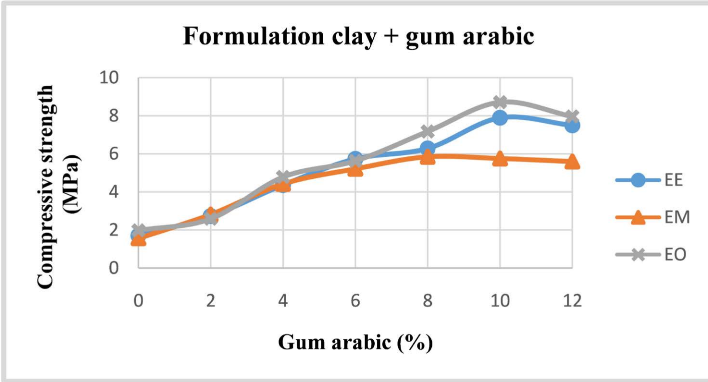

Figure 9. Influence of gum arabic on the compressive strength of the specimens.

to 6% of the addition of gum arabic in the mixture. Beyond 6% of the gum arabic we record a peak until we obtain a value of 7.89 MPa at 10% for the EE soil, 8, 71 MPa for the EO soil. For EM soil the maximal value is 5.84 Mpa at 8% of the gum arabic. Remember that beyond 10% of the gum arabic, we noted cracks on the different test pieces manufactured

In the above, we can say that:

- The analysis of the results shows us that the resistances with gum arabic reinforcement exceed all the other resistances of the specimens without gum arabic.

This result is explained by the increase in gum arabic and the stickiness of the latter.

- The increase in gum arabic causes a decrease in porosity, which then becomes the main cause of the increase in flexural and compressive strength.

With a compaction force of 4.3 MPa, the results obtained are significant compared to certain works such as (Abakar Ali, 2018) with a compaction force of 2 MPa, because this compaction force makes it possible to reduce the porosity of the material. Compressive and flexural strengths are low for unstabilized bricks. Stabilization with gum arabic improves the mechanical characteristics, which is consistent with the work of certain authors (Bozabe Kornet, 2013 and Abakar Ali, 2019). Thus, the minimum compressive strengths proposed by certain countries are of the order of 2 Mpa. However, with this constraint of 4.3 MPa, even without the addition of gum arabic we obtain values of compressive strengths of BTCs in the same order of magnitude as those of the minimum compressive strengths of BTCs.

Authors Doat. P *et al.* (DOAT *et al.*, 1979a) recommend minimum mechanical resistance values for the construction of a R + 1 building:

- Compressive strength: 2 $kg \cdot cm^{-2}$ (0.2 MPa);
- Tensile strength: 0 MPa.

In the above, we can say that the analysis of the results shows us that the resistance with gum arabic reinforcement exceeds all other resistances of the specimens without gum arabic [22].

4. Thermal Characterization

4.1. Thermal Conductivity of Materials with Gum Arabic

The results of the thermal conductivity of three materials are given in the table below (Table 6).

Table 6. Variation in thermal conductivity depending on the addition of gum arabic.

% gum arabic	Reference soils/ thermal conductivity thermal ($W\cdot m^{-1}\cdot K^{-1}$)		
	EE	**EM**	**EO**
0	0.73	0.618	0.66
2	0.62	0.58	0.56
4	0.57	0.53	0.55
6	0.51	0.51	0.53
8	0.50	0.48	0.49
10	0.50	0.60	0.47
12	0.63	0.61	0.69

Figure 10 shows the evolution of thermal conductivity as function of percentage of gum arabic of three soils.

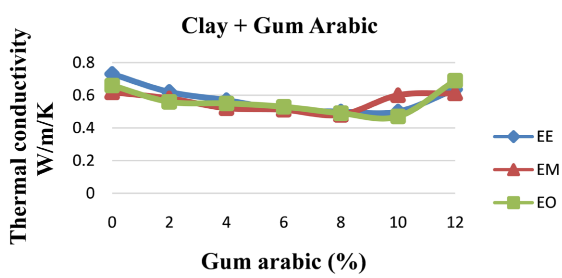

Figure 10. Influence of gum arabic on thermal conductivity.

A decrease in thermal conductivity as a function of gum arabic percentage is noted in the three different soils. However, we note:

- The test pieces with the lowest thermal conductivities are those, which are manufactured without the addition of gum arabic.

Thus, for EE and EO soils the conductivity decreases from 0% to 10% for EE and EO soil. However, for EM soil, we note a decrease in thermal conductivity up to a rate of 8% of gum arabic before increasing. This justifies the fact that thermal conductivity depends on parameters such as the particle size and nature of the soil. Beyond 10% of gum arabic, we note an increase in conductivity on both soils (EE and EO) while for EM the conductivity increases from 10% of gum arabic rate. The highest average conductivity value for the three soils is given by the formulation prepared with 88% clay and 12% gum arabic.

It is on average around 0.64 $W \cdot m^{-1} \cdot K^{-1}$. According to the authors (DOAT *et al.*, 1979b; Rafalko, 2006), a material made up of fine and coarse elements gives a much more compact final product than a material prepared only with fine elements. From a certain percentage of gum arabic, all the pores are welded and the material becomes compact. Consequently, beyond 10% of the gum arabic in the mixture on the soils (EE, EO), the pores are practically welded, which thus causes an increase in thermal conductivity. However, for EM soil the thermal conductivity increases from 8% of gum arabic.

4.2. Thermal Resistance Depending on Gum Arabic

Table 7 gives the results of the thermal resistance of three soils according to different percentages of clay and gum arabic.

Table 7. Variation in thermal resistance depending on the addition of gum arabic.

% of gum arabic	Reference soils/Thermal resistance ($m^2/K/W$)		
	EE	**EM**	**EO**
0	0.27	0.32	0.30
2	0.31	0.33	0.35
4	0.34	0.37	0.35
6	0.39	0.39	0.37
8	0.39	0.41	0.40
10	0.39	0.33	0.42
12	0.33	0.32	0.28

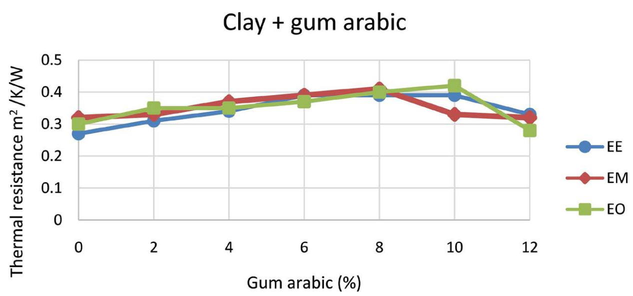

Figure 11. Influence of gum arabic on thermal resistance.

In **Figure 11**, we notice an increase in thermal resistance as a function of the increase in the percentage of gum arabic. For the three soils studied, the weak thermal resistance is that obtained without the mixture of gum arabic. Indeed, at 100% clay, the thermal resistance values are: 0.27 $m^2/K/W$ for EE soil, 0.32 $m^2/K/W$ for EM soil and 0.30 $m^2/K/W$ for EO soil. Thermal resistance is the ratio between the thickness of the specimen and the thermal conductivity. Thus, the more the thermal conductivity increases, the more the thermal resistance decreases. From 2% to 10% of gum arabic contained in the mixture, we observe an increase in the curves for EE and EO soils. While for EM soil it begins to decrease from 8% of gum arabic). However, the highest resistance values are 0.39 $m^2/K/W$ for the EE soil, 0.41 $m^2/K/W$ for the EM soil and 0.42 for the EO soil. We can deduce that the resistance thermal varies inversely with thermal conductivity.

5. Conclusions

The three clay soils were the subject of a mechanical and thermal characterization study.

However, in this study, it is a question of designing BTCs stabilized with gum arabic having better mechanical and thermal characteristic resistances. To be able to obtain this type of BTC, compression tests were carried out on test specimens. These tests made it possible to note that the specimens (EE and EO) produced with a concentration of 90% clayey soil, and 10% gum arabic, gave mechanical strengths: 3.59 MPa in flexion and 7.89 MPa in compression for the EE soil, 3.75 MPa and 8.71 MPa for EO soil. However the maximum mechanical resistance values obtained for the EM soil at 8% of the gum arabic, they are 2.65 MPa (flexion) and 5.84 MPa (compression). Likewise, the thermal conductivities increase as a function of the addition of gum arabic. The maximum value of thermal resistance at 10% of the gum arabic for the EE (Rth = 0.39 $m^2/K/W$), EO (Rth = 0.42 $m^2/K/W$) and for the EM soil (Rth = 0.41 $m^2/K/W$) at 8% of gum arabic).

The use of three soils in construction proves to be very interesting, taking into account the different results obtained during the two tests (flexion and compression). We can conclude that the results of this experimental study made it possible to identify the interesting mechanical and thermal characteristics of the new material based on clay and gum arabic. This will provide a sustainable solution to construction, particularly in areas where gum arabic is available.

Conflicts of Interest

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

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Nomenclature

Symbols	Designations	Units
EE	Seidou 1	-
E.M.	Seidou 2	-
EO	Djarwa	-
GA	Gum arabic	-
R_f	Bending resistance	MPa
R_C	Compressive strength	MPa
λ	Thermal conductivity	W/m/K
a	edge of the support surface	mm
e	Thickness	m
R_{th}	Thermal resistance	m^2/K/W
l	Length	