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Assessment of the Mechanical and Thermal Properties of Local Building Materials Stabilised with Gum Arabic in the Drâa-Tafilalet Region, South-East Morocco

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Abstract. Morocco enjoys a very remarkable earthen architectural heritage throughout the southeast of the country, earthen constructions which are characterized by its ability to absorb and reject moisture from the indoor air according to the fluctuations of the microclimate of the building guarantees a passive indoor comfort that would save energy. Unfortunately, earthen structures suffer from rapid degradation due to climatic changes (temperature, air humidity, water...). This study concerns mechanical, thermal characterization and durability of compressed earth blocks manufactured (CEB) with clay, gum arabic with different proportions. For this purpose, the mass percentages of 1%, 2%, 3%, 4% and 5% of gum arabic by contribution to the total mass are retained for this research work. cylindrical bricks of CEB are manufactured to carry out mechanical tests, and those of prismatic form are adapted for the determination of thermal conductivities with the method "house has high insulation". The use of gum arabic as a binder in construction has given satisfactory results. At a rate of 5% of gum arabic the bricks are associated with a compaction stress of 5.78 MPA for the compressive strength, allow us to obtain CEB with an acceptable mechanical strength and a better resistance to rainwater. In addition, the values of thermal conductivity measured, show that when the rate of gum arabic increases, the thermal conductivity rises. The thermal conductivities of all formulations vary between 0.72 and 1.05 W/(m.K). The durability test carried out on the stabilized and non-stabilized bricks, shows that the specimens not stabilized by gum arabic are totally degraded from 5 min of immersion, On the other hand those stabilized by gum arabic kept their shape more than 5 hours. This study proved the effectiveness of CEB stabilized by gum arabic for use as new sustainable construction materials in the region of Drâa-Tafilalet (southeast of Morocco).

1. Introduction

The demand for natural resources has increased globally due to spatial development and population growth, resulting in ecological imbalance and global warming. The construction sector alone consumes 40% of the planet's material and energy flows, making it one of the least sustainable sectors worldwide [1]. In Morocco, the construction sector is the largest energy consumer, accounting for over 33.6% of total energy consumption, followed by the transport sector at 38% [2]. This sector's impact on the environment is significant, necessitating the urgent need for sustainable housing solutions that meet both environmental and structural stability criteria.

Studies have shown that sustainable design, material production, construction, maintenance, and the reuse of construction materials can reduce the carbon footprint of buildings by an average of 25% [3]. One promising solution is the use of earthen soil, a natural and historical material, which can significantly reduce energy consumption and CO_2 emissions. Earthen materials offer excellent energy performance and are a cost-effective alternative to materials such as cement, lime, bitumen, and steel, which have high energy and environmental costs. It is estimated that one-third of the world's population resides in earth-constructed structures [5].

In Morocco, particularly in the Draa Tafilalet region, earthen constructions are still prevalent, with many heritage sites, such as Ksar d'Aït-Ben-Haddou, listed as UNESCO World Heritage sites [4]. Earthen construction materials align perfectly with environmental standards in arid climates with hot summers and cold winters. They possess numerous advantages, including excellent insulation properties that reduce the need for heating and cooling energy[5,6]. Additionally, earthen materials have the ability to store moisture and heat, contributing to a comfortable indoor environment. While the thermal conductivity of earth ranges from 0.3 to 1 W/(m.K) [7,8], which is not as low as conventional insulators, it still outperforms many conventional construction materials, making it advantageous in such environments.The low cost, availability, recyclability, and low embodied energy of these materials make construction particularly sustainable; the lifespan of earthen constructions is over 100 years. Therefore, earthen soil has been proven to be ecologically sustainable[9]. According to Minke[10], buildings constructed with earth can reduce global pollution by approximately 30% in 2009. Earth construction materials offer the potential to significantly reduce energy consumption during the production phase, with potential savings ranging from 80% to 90%. This efficiency tends to increase as production scale increases [8]. However, it is important to acknowledge that earth materials also have certain drawbacks, including low mechanical strength and high sensitivity to water. Humanity has always sought solutions to the shortcomings of earth material using various stabilization methods, including mechanical, chemical, and physical methods, which have led to the improvement and invention of different earth products. In our modern society, it seems important to ensure the safety of residents by providing minimum wet strengths. Thus, scientific studies have been conducted on the stabilization of raw earth. Among the different products of raw earth construction materials, rammed earth, or compressed earth blocks (CEB), is a recent version of adobe, which has the advantages of low shrinkage, high strength, low water sensitivity, and well-defined shape with straight edges. To improve its characteristics, various stabilizers are used, such as cement, lime, bitumen, natural or synthetic fibers, and biopolymer materials. The use of mineral binders in large proportions can question the ecological nature of the material [11]. In parallel, some traditional practices, especially in developing countries, and recent scientific studies have shown that the use of natural organic binders, namely biopolymers, could be a more environmentally virtuous alternative [12]. These organic products have great diversity and thus significant research potential, reflecting the variety of practices worldwide [13]. The accessibility and the effects of stabilization and reinforcement of biomaterials by environmentally friendly additives, such as hydrocolloid gums, also known as natural polysaccharides, have attracted considerable attention from researchers [14]. The use of biopolymer stabilizers can significantly improve the technical properties of soils and enhance their resistance to environmental soil conditions. Experimental tests have shown that soil strength tends to increase with an increase in biopolymer concentration [15], [16]. Research findings indicate that the incorporation of biopolymers in civil engineering projects can enhance the engineering properties of construction materials [17]. Specifically, the biopolymer b-1,3/1,6-glucan has been shown to effectively aggregate soil particles, leading to improved soil compression. Additionally, this biopolymer has demonstrated positive effects on compactness, Atterberg limits, and soil swelling index when applied to treated soil. However, it should be noted that the same biopolymer may have a negative impact on soil consolidation [18,19]. It can be observed that even with small amounts of biopolymer, the erosion reduction effect and improvement of inter-particle soil cohesion remain significant. The effect of xanthan gum on soil properties has been studied by various researchers, and it has been found that xanthan gum can significantly increase the compression and shear strength of soils, especially soils containing a significant amount of fine-grained aggregates [20,21,22]. Studies have shown that Persian gum is a biopolymer used to improve soils, and the results obtained are acceptable in terms of strength compared to xanthan and guar gums due to its property of reducing permeability and consequently high thermal stability for the treated soil. Our study aims to propose a low environmental impact method of stabilizing raw earth using local biopolymer materials through two approaches. First, we aim to limit the amount of mineral binders, namely cement and lime, and verify that the resulting solution meets sustainability and mechanical and thermal performance criteria suitable for the climatic and architectural conditions of the Draa Tafilalet region in Southeastern Morocco (fig. 1). Second, we aim to identify potential biopolymer binders that can effectively stabilize raw earth for construction. To do this, we will use a type of soil collected in Errachidia, from which we will determine its physico-chemical, mineralogical, and geotechnical characteristics to assess the impact of biopolymer binder (Arabic gum) stabilization on material efficiency. Therefore, starting from this article, we aim to propose a new local biobased material based on raw earth for contemporary construction.

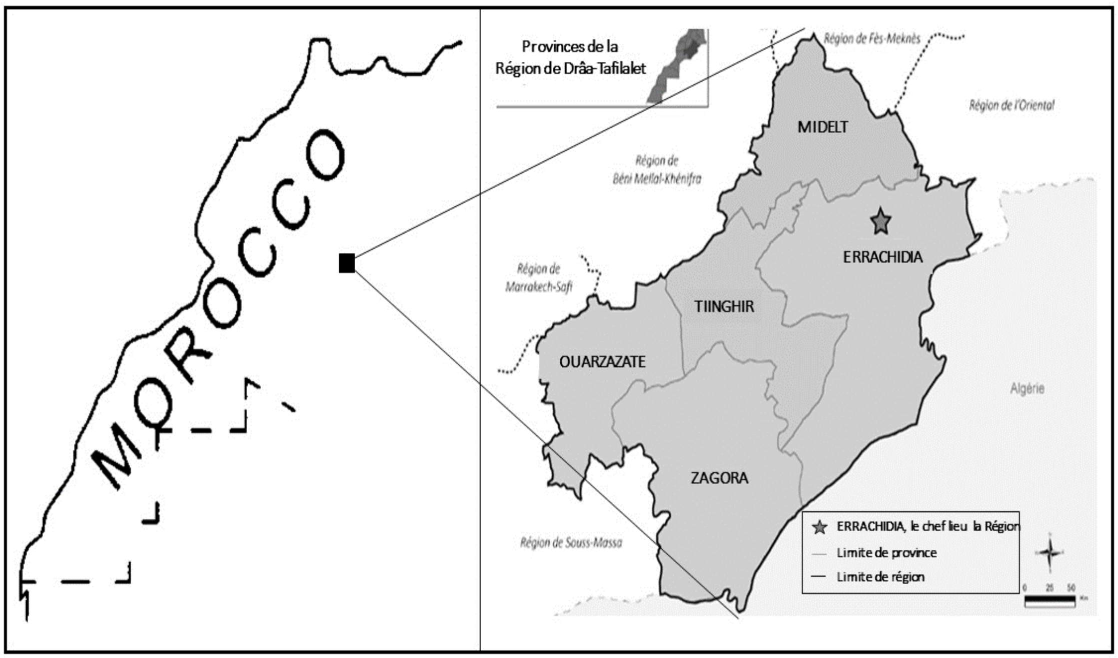

Fig.1: South-eastern Morocco (Errachidia Province)

2. Matrials and Methods

2.1 Materials

2.1.1 Soil

The soil used in our study comes specifically from the Ksar Ait Ben Omar Tinejdad region, located in Errachidia. This choice was made because of the availability and abundance of this soil in the region (fig.2). In selecting this soil, we took into account its composition and characteristics, which are essential for our research. In addition, the Ksar Ait Ben Omar Tinejdad region has particular geographical and climatic conditions that make it suitable for our study.

Fig.2 : Studied soil

2.1.2 Gum Arabic

Gum arabic, also known as "Gomme Sénégal", is a plant biomass obtained from the exudate of sap, solidified naturally or by incision, from the trunks and roots of trees in the acacia family. It is harvested mainly in Saharan Africa (Maghreb, Mali, Senegal, Chad, Egypt, Sudan, etc.). Gum arabic is commercially available in powder or crystal form. It is pale yellow to brownish yellow in color, odorless, soluble in water and insoluble in alcohol, but soluble in glycerol and propylene glycol with prolonged heating. The visible part of the crystals is "matt", with fine cracks that are difficult to see with the naked eye [26].

The gum used in our study was collected on the road between Risani and Tazarine (Morocco). This region is semi-Saharan (fig.3).

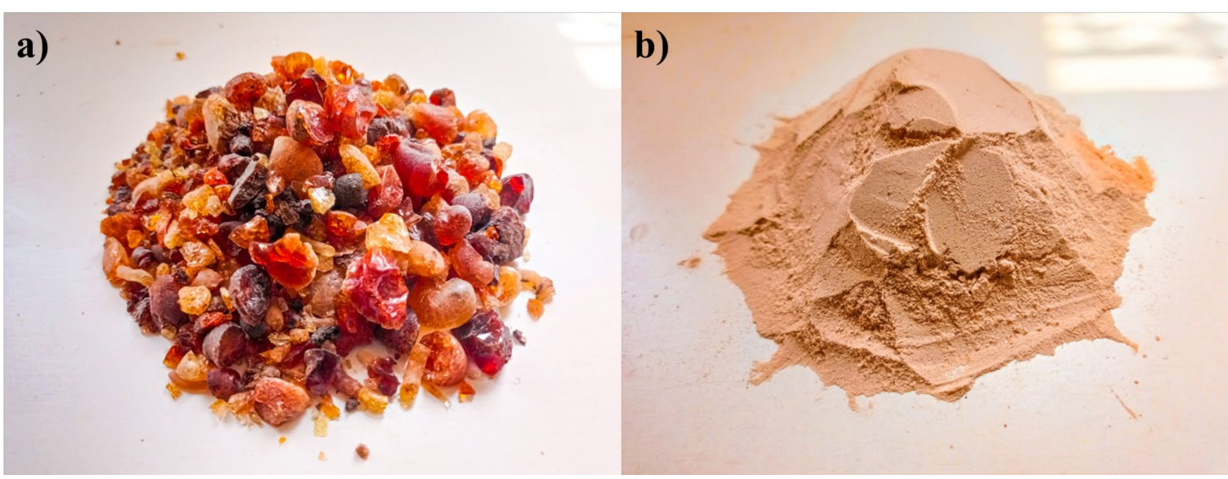

Fig.3: Gum arabic: a) form crystals, b)form powder

2.2 Methods

2.2.1 Exploring Soil Properties: Particle Size Analysis and Methylene Blue Values Examination

The particle size analysis of the soil samples in our study was conducted in accordance with established protocols outlined in French standards. The first standard utilized was NFP94056 (NF P94-056, 1996) [29], which is primarily concerned with particle size analysis through sieving for soil particles larger than 80 µm. To perform this analysis, the soil samples were initially soaked in water for 24 hours to ensure they reached a wet state. Subsequently, the samples underwent sieving, and the retained soil particles were then subjected to drying in an oven at 105°C until a constant mass was attained. The weight of the residue from each sieve was subsequently measured.

The second standard employed was NFP94057 (NF P94-057, 1992) [30], which complements the sieve-based particle size analysis by utilizing sedimentation for particles passing through an 80 µm sieve. This method entailed filling a test tube with distilled water to a precise volume of two liters. The suspended particles in the water settled at the bottom of the test tube based on their diameters. By utilizing a hydrometer, density measurements were regularly taken over time and at specific heights. These measurements allowed for the calculation of the proportions of particles of each diameter, which were recorded in a table and used to construct the grain size distribution curve. In addition to the particle size analysis, we also employed the methylene blue test to assess the clay fraction within the soil samples. The methylene blue test is commonly used in geotechnical engineering to determine the quantity and quality of clay present. Clay particles exhibit a strong affinity for methylene blue molecules, enabling the measurement of their adsorption capacity and, consequently, their water retention properties. The methylene blue values were determined following the guidelines outlined in the French standard NFP94068 (NF P94-068, 1998)[31].

2.2.2 Atterberg limits

Atterberg limits are employed to predict the behavior of materials, particularly soils that have been sieved to a size of 400 µm. This test involves varying the water content of the soil sample to assess its consistency. The procedure for this test adhered to the Moroccan standard NM 13.1.007 (NM 13.1.007, 1998) [32]. The test consisted of two stages. In the first stage, we identified the water content at which a groove formed in the soil sample placed in a bucket with specific characteristics closes when the bucket and its contents undergo repeated shocks. This closure indicates the plastic limit of the soil. In the second stage, we determined the water content at which the soil sample, when manually rolled, develops cracks. This particular water content corresponds to the liquid limit of the soil.

2.2.3 Specimen preparation

For the preparation of the test specimens, the mixture is prepared as follows: We collected the particles that passed through a 5 mm sieve for the clay and those that passed through a 2 mm sieve for the gum arabic. The mixture is prepared in a dry state, combining the clay and gum arabic, and then water is added. For the gum arabic, mass percentages of 1%, 2%, 3%, 4%, and 5% were chosen to prepare the mixture.

The mixture (clay + gum arabic) is prepared in a dry state. Subsequently, the entire mixture is manually kneaded with water. The mass of the dry mixture for making CEB test specimens is 13.50 kg for each dosage. The moisture content is monitored during the preparation of the test specimens. Once the mixture is well homogenized, it is placed in a plastic bag for about 4 hours for proper saturation. The press used for the production of CEBs is a manual press. The prepared material mixture is poured into the mold to obtain regular CEBs. After demolding, the bricks are dried in the laboratory of FST Errachidia to prevent rapid drying (see figure 7). In total, 18 bricks were manufactured (3 test specimens for each dosage).

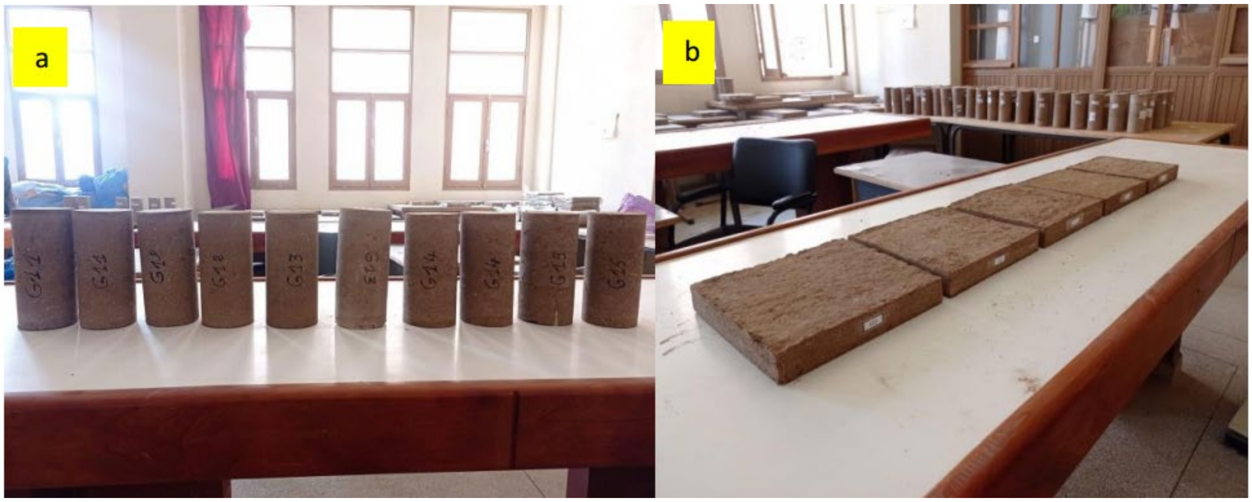

Fig.7: Samples for testing a) mechanical b) thermal

Cylindrical test specimens (CEB) measuring 11 cm in diameter and 22 cm in height were used for mechanical tests (compression and tension), and test specimens measuring 24 x 24 x 4 cm were used for thermal conductivity measurements.

2.2.4 Thermal conductivity

We conducted an experimental study to evaluate the thermal conductivity of various bricks using the highly insulated house method (PHYWE, 2012) [33], a technique previously employed by researchers like Ben Zaid et al. (2020) [34] and Medina et al. (2017) [35]. The core concept of measuring thermal conductivity involves placing the sample to be assessed within a square opening measuring 210×210 mm2. The highly insulated house consists of four identical side walls enclosed by an insulated cover that includes a 5 cm thick polystyrene plate. Inside this setup, a small black box houses a 100 W bulb as a heat source, with precautions taken to minimize the impact of radiation (refer to Figure 8). The bulb is connected to a controller programmed to maintain indoor air temperature at 50 °C, while an air conditioner is employed to regulate external temperature at approximately 19 °C. We used K-type thermocouples to measure the temperature of both the inner and outer surfaces of all test specimens, with readings recorded at 1-minute intervals. Data acquisition was facilitated through a GL840 DATA-LOGGER equipped with a PC interface, and the accompanying data reading software allowed for data display and recording in Excel.

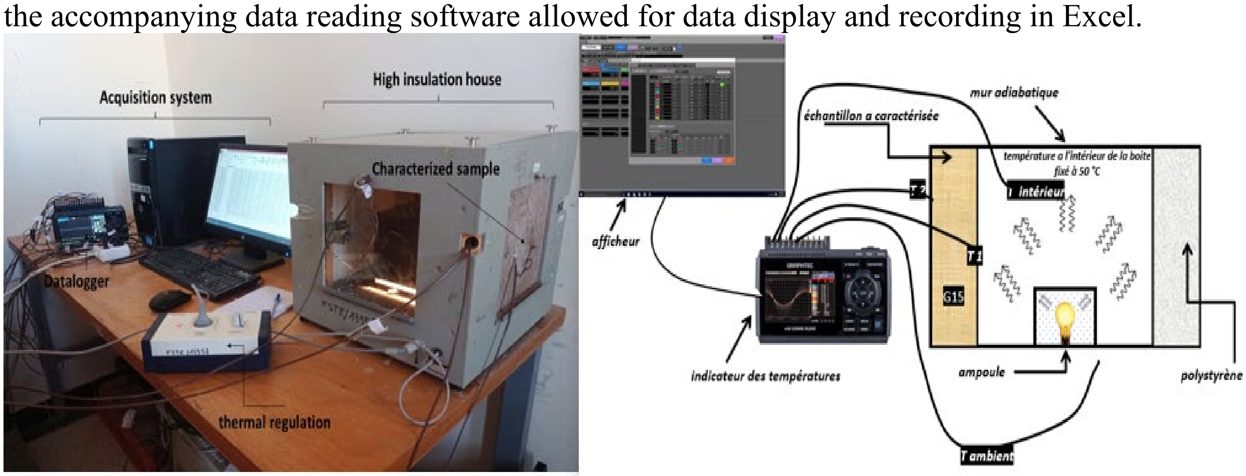

Fig.8: Thermal house connected to an acquisition system

The determination of thermal conductivity follows the procedure outlined below:

The convective heat transfer between the interior air and the surface of the inner wall of the sample is expressed by the equation:

$$\varphi = h_{int} * S * (T_{\text{interior}} - T_1) \qquad Eq.1$$

Here, h_{int} represents the convection coefficient of the interior air, S denotes the surface area of the sample wall, and $T_{interior}$ and T1 respectively represent the temperature inside the highly insulated house and the surface temperature of the interior sample wall.
The equation for φ is further defined as:

$$\varphi = \lambda * s * \frac{T_1 - T_2}{e} \qquad Eq.2$$

In this equation, λ represents the thermal conductivity, T_2 signifies the surface temperature of the outer wall of the sample, and (e) represents the thickness of the sample.
The calculation of thermal conductivity is based on the steady-state conservation of heat flux:

$$\lambda = h_{int} * e * \frac{T_{\text{interior}} - T_1}{T_1 - T_2} \qquad Eq.3$$

In the case of natural air movement in enclosed spaces, the reference value for h_int is 8.1 W/K m2 (PHYWE, 2012).

2.2.5 Simple compression tests

The uniaxial compression strength test of the prepared samples was carried out in accordance with the Moroccan standard for earth construction (Decree No. 2-12-666 of 17 Rejeb 1434, Decree on Seismic Regulations for Earth Construction and the Establishment of the National Committee for Earth Construction, 2013) [23]. The testing machine used was the FORM TEST SEIDNER D79400 from Germany, capable of exerting a maximum breaking load of 3000 kN. At least three samples for each soil and gum arabic mixture under the same conditions were tested, and an average value was recorded. The cylindrical specimen, measuring 100 mm in diameter and 200 mm in height, was dried in the laboratory at the Faculty of Sciences and Technology in Errachidia. It was then compressed between two flat plates (see Fig.9). The samples intended for the compression test were at least 28 days old at the time of testing and had smooth and regular end surfaces to ensure that the compression force was applied uniformly over the specimen's entire surface. Any sample with an irregular surface was coated with a thin layer of dental plaster, as specified by Walker et al. [25].

The measurement of compressive strength is given by the following formula:

$$\sigma c = \frac{F_r}{S} \qquad Eq.4$$

With: Fr (N): breaking force; S (mm^2): cross-sectional area of specimen; σ_c (MPa): compressive strength.

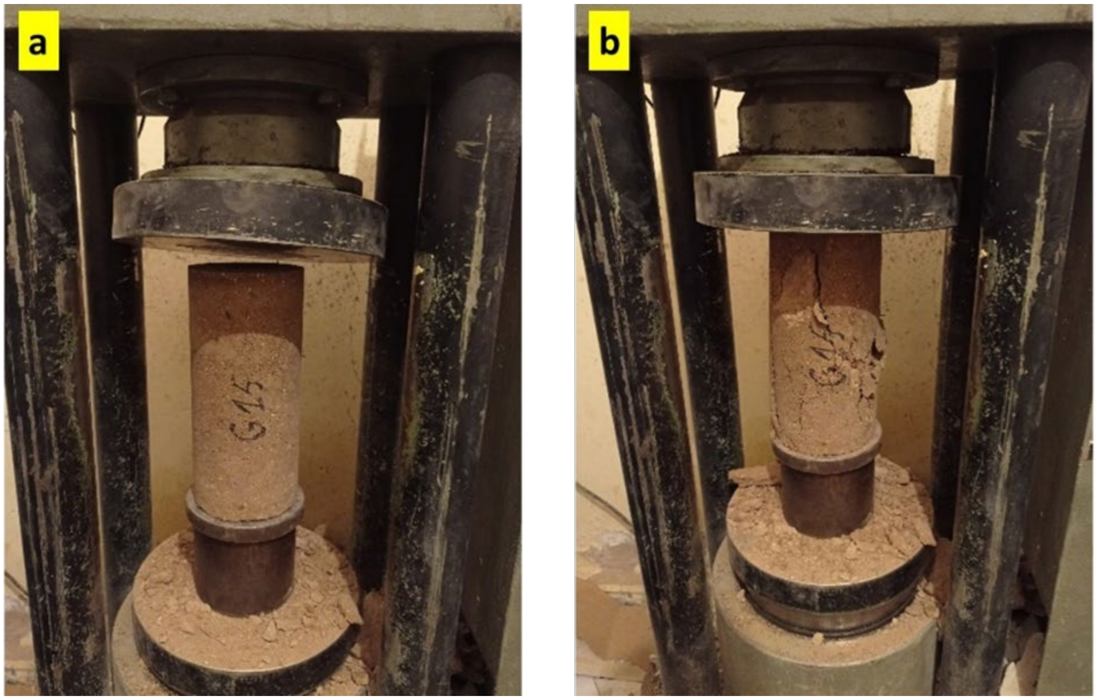

Fig.9: Mechanical test: a) before press, b) after press

2.2.6 Water erosion test

The Errachidia region receives 127 mm of rainfall during the rainy season [26]. Durability with respect to water is also a key aspect of construction materials quality.

The erosion test involves subjecting a sample of gum arabic-stabilized compressed earth block to immersion in a water basin for 24 hours. During this period, it was observed that the specimens not stabilized with gum arabic deteriorated completely (see Figure 11) after just 15 minutes of immersion. In contrast, those stabilized with gum arabic maintained their integrity in water for over 5 hours. For the specimens stabilized with gum arabic, the higher the gum arabic content, the greater the water resistance, and the better it retained its mass.

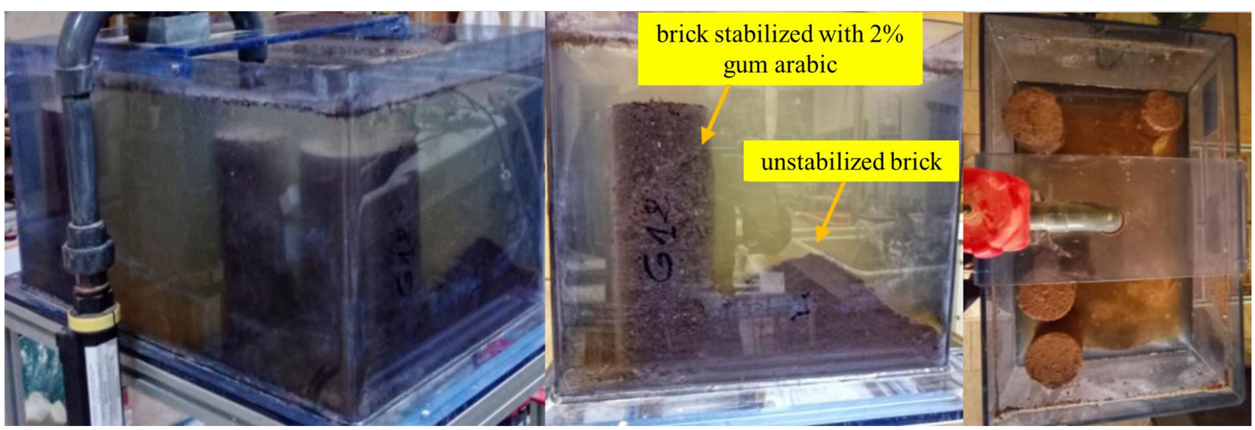

Fig.11: Cylindrical samples of clay-gum arabic mix immersed in water

In fact, in construction, the bricks only receive rainfall on one side. All other other parts are protected by the other bricks. We can say that stabilizing building materials building materials with gum arabic not only improves mechanical strength but also contributes to good resistance to rainwater.

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3. Results and Discussion

3.1 Soil particle size and methylene blue value

Table 4 shows the grain sizes of our material, ranging from 20 mm to 0.002 mm, with an estimated 84% passing through the 20 µm to 2 mm sieve. Soil comprises 70% sand, 9% silt and 6% clay. The material in our study is made up of grains of various sizes, a large percentage of which are extremely fine. It is therefore necessary to perform Atterberg limit tests on the clay soil in order to classify it.

Table.4: *Grain sizes of soil studied*

Constituents	Diametres	Percentage%
Pebbles (%)	20 à 200 mm	4
Gravel (%)	2 à 20 mm	11
Coarse sand (%)	20 µm à 2 mm	27
Fine sand (%)	20 µm à 200 µm	43
Silt (%)	2 µm à 20 µm	9
Clay (%)	< À 2 µm	6
Methylene blue value		0,67

The methylene blue value of our soil is: 0.67

3.2 Atterberg limits

Atterberg limits and calcification of studied soils as a function of plasticity:

- Liquid limit W_l (%): 28
- Plasticity limit W_p (%): 21
- Plasticity index I_p (%): 7
- Soil plasticity: Low
- Swelling potential: Low
- Technical recommendations: CEB and Rammed earth

3.3 Drying kinetics of compressed earth blocks

We observed that most test specimens remain stable in their drying process from day 14 onwards. However, the test tube made with 5% gum arabic retained a higher moisture content until day 20. This observation can be explained by the fact that gum arabic retains water thanks to the sugars it contains.

In the Errachidia region, we benefit from sufficient sunshine to dry building materials. All we need to do is choose the right production period, preferably during the summer. This period offers favorable climatic conditions, with high temperatures and low humidity, which speeds up the drying process. By exploiting this natural resource, we can optimize specimen drying and guarantee reliable, consistent results for our studies.

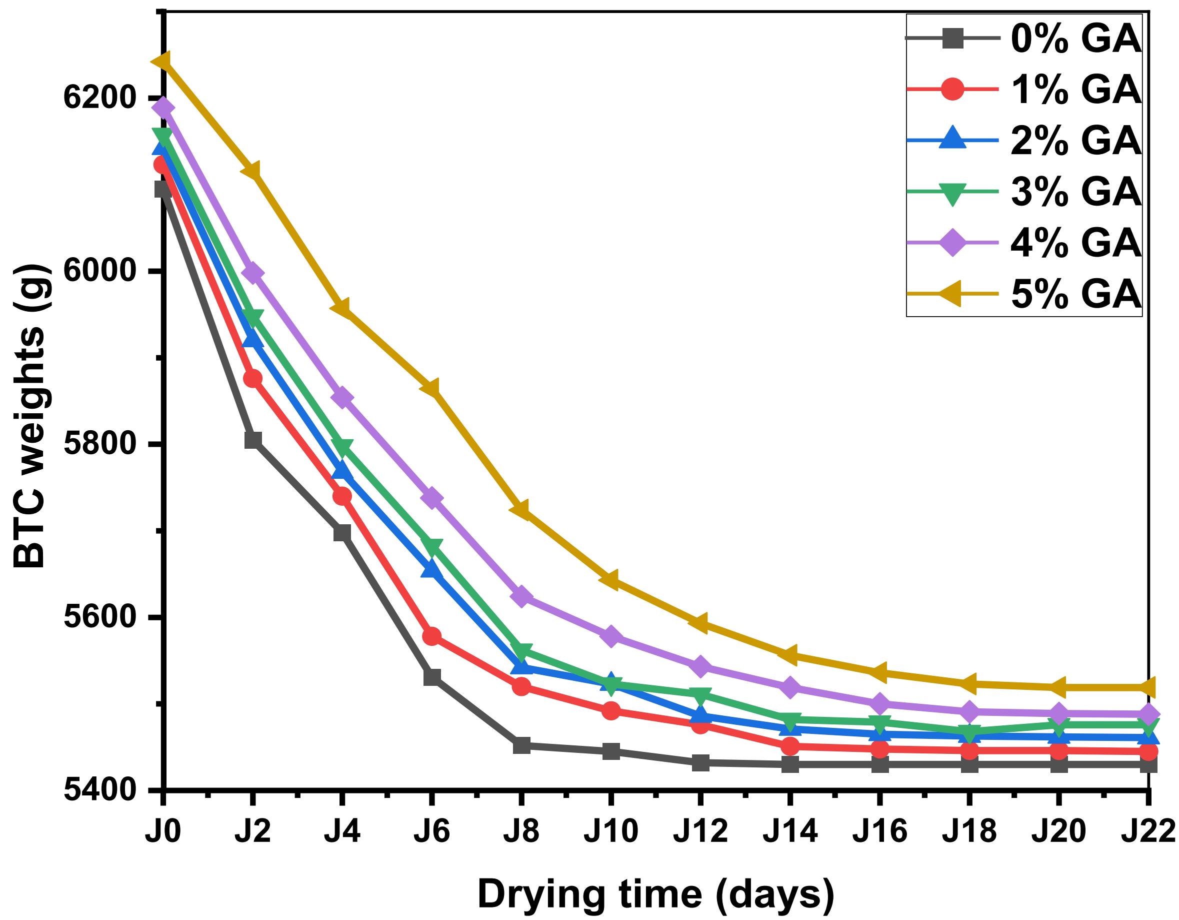

Fig.14: brick drying as a function of time

3.4 Thermal conductivity

Fig.12 illustrates the variation in thermal conductivity of the samples studied as a function of arabic gum content. Thermal conductivity values in all the formulations studied ranged from 0.72 to 1.05 $W.m^{-1}.K^{-1}$. The formulation with the highest thermal conductivity, around 1.05 $W.m^{-1}.K^{-1}$, is obtained with a composition of 95% clay and 5% gum arabic (G5).

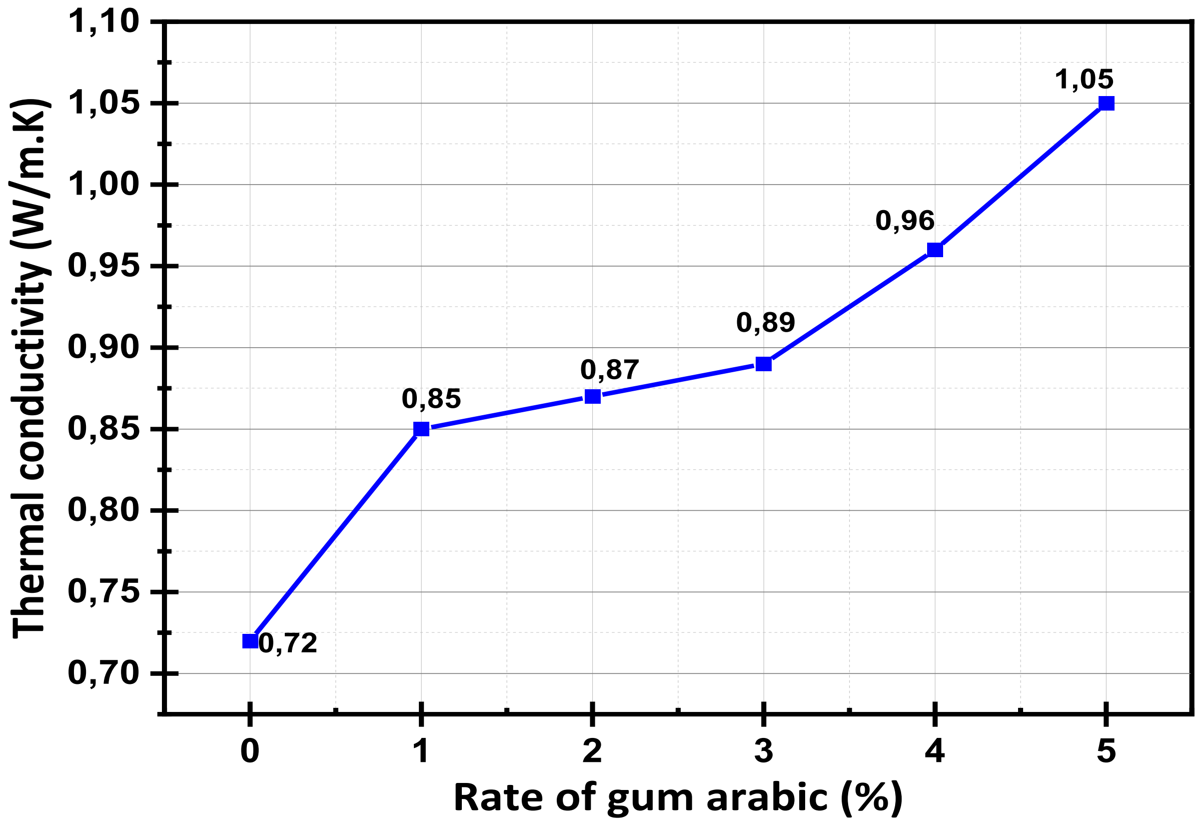

Fig.6: Variation in thermal conductivity of clay bricks as a function of Gum arabic

It was observed that for samples stabilized with gum arabic, an increase in the amount of gum arabic in the mixture is associated with an increase in the thermal conductivity value. This observation can be explained by the fact that a low proportion (1% to 3%) of gum arabic does not completely coat the grains of the materials, creating voids within the samples, leading to a decrease in thermal conductivity. However, as the proportion of gum arabic increases, all the pores are filled, leading to compaction of the material and, consequently, an increase in thermal conductivity.

3.5 Compressive strength

Tinejdad clay contains a high percentage of pores. This porosity adversely affects mechanical properties, particularly tensile strength. From the results obtained in (fig.13), we can see that Tinejdad clay stabilized with gum arabic gives satisfactory values for compressive strength. For example, clay stabilized with 1% gum arabic gives a 298% increase in simple compressive strength compared with unstabilized clay. At 3% gum arabic, we have a 437% increase, and at 5% gum arabic, strength rises by 803%. Our compressive strength results, which vary from 0.64 to 5.78 MPa, are in the same range as those obtained on Ndjamena clay in Chad, which range from 1.01 to 3.25 MPa [27], and on laterites from Burkina Faso, which range from 1.5 to 5 MPa [28].

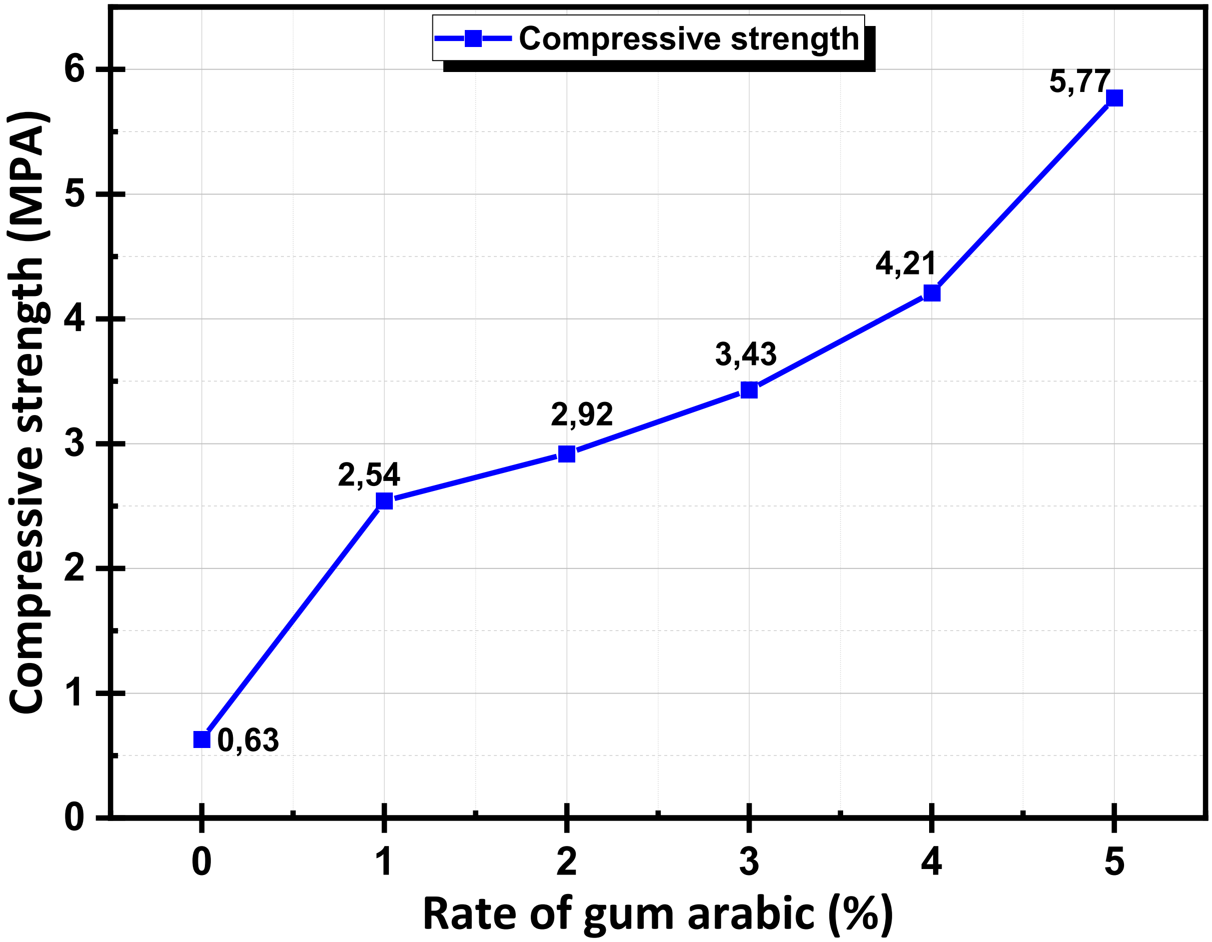

Fig.13: Variation in compressive strength of earth bricks compressed as a function of gum arabic content

The results obtained are very interesting, with a remarkable improvement in the mechanical strength of the materials. Maximum compressive strength exceeds 6 MPa.

The various characterizations made it possible to classify our clay as "Low plasticity clay". The results obtained in this work from mechanical tests are sufficient to justify its use in construction. Stabilization of the clay with gum arabic gives satisfactory results in compression. On the other hand, the sugar contained in gum arabic is responsible for the delayed setting and hardening of the composite. In fact, gum arabic can be used at a rate of 5%, where hardening is felt from the 20th day of age, or a drying method with low environmental impact can be used.

3.6 Water durability test

For gum arabic-stabilized specimens, the higher the gum arabic content, the greater the resistance to water and the greater the ability to retain its mass. In reality, in construction, bricks only receive rainfall on one side. All other parts are protected by the other bricks. We can say that stabilizing building materials with gum arabic not only improves mechanical strength but also contributes to good resistance to rainwater (fig.8).

- Bricks stabilized with biopolymers (gum arabic) can be considered suitable for use in exterior walls.

Fig.8: Cylindrical samples immersed in water

Conclusion

This research work has shed light on the significance of local materials in the field of construction. The thermal conductivity values obtained through the highly insulated construction method revealed that the various formulations examined in this study do not result in materials with high thermal insulation capacity. However, these materials possess a particularly valuable characteristic, namely, a high thermal inertia capacity. This property, while not making them top-tier thermal insulators, offers significant potential to enhance indoor comfort in construction environments.

Regarding mechanical strength, the results obtained can be described as modest, but they remain sufficient for common construction applications. It is worth noting that gum arabic-stabilized raw earth bricks are not suitable for use as building foundations. However, it is important to emphasize that these materials hold promising potential in sustainable construction. They could be advantageously employed for above-ground walls and partition construction, where their thermal inertia capacity and modest mechanical strength can bring significant advantages, both in terms of energy efficiency and building durability. This research thus paves the way for new opportunities in environmentally friendly construction.

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