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Thermomechanical and Hydrous Effect of Heavy Fuel Oil in a Building Material Based on Silty Clayey Soil

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Abstract: This study focuses on the use of heavy fuel oil in construction in Burkina Faso. Mixed with silty and/or clay soil, it is used as a coating to reinforce the walls of raw soil constructions which are very sensitive to water. The interest of this paper is to shed light on the thermomechanical and above all water effects of heavy fuel oil on a sample of silty clayey soil. To achieve this, we used heavy fuel oil added in different proportions to silty clayey soil, to make sample of bricks on which tests were carried out. At the end of the experimental tests carried out on materials made (bricks) with our soil sample, it appears that heavy fuel oil moderately reduces the mechanical resistance of bricks and slightly increases thermal diffusion through them. On the contrary, we note a very good water resistance of the bricks thanks to the heavy fuel oil, in particular their water absorption by capillarity. This confirms that the mixture of heavy fuel oil and a silty-clayey soil used as a coating makes it possible to prevent the infiltration of water into the walls of raw soil constructions. However, its use as a construction material does not guarantee very good mechanical resistance, and slightly increases thermal diffusion.

Key words: Thermomechanical and hydrous effect, heavy fuel oil, building material, silty clayey soil.

1. Introduction

Housing in a decent habitat is one of the basic needs of humans. In Africa, most of the population is faced with housing problems. In Burkina Faso, the costs of modern construction materials from industrial production such as cement and steel are exorbitant for a large part of the population. Indeed, the country does not have the necessary resources to produce these materials, this is one of the reasons for their rather high costs. The importation of raw materials and the lack of energy sources are the main causes of the perpetual increase in the price of these industrial materials, making them inaccessible to many African populations living below the poverty line. Only a tiny portion of the higher-income population can use these cementitious materials. In addition, the manufacture of Portland cement, for example, generates approximately one ton of CO_2 (carbon dioxide) per ton of cement produced [1]. However, with the awareness of this strong environmental impact, which has a direct influence on global warming (production of greenhouse gases) as well as this poverty which undermines our society, it is judicious, even imperative, that current research orients towards the development of local materials that are more respectful of the environment and accessible to all

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levels of our society. Regarding the United Nations SDGs (Sustainable Development Goals), we understand that SDGs are not simply an affair of governments, we should contribute as scientists to help governments take their responsibility and make the policies that should lead to the achievement of these goals [2].

It is in this perspective that this study aims to be a contribution to help the housing sector of the Country to meet the many challenges that arise, and enable the realization of simple, cost-effective, and climate-responsive architecture using local materials such as ground, to ensure that the country's cities are inclusive, safe, resilient, and sustainable. Today, it is estimated that the habitat of a third of humanity is still in the ground, the city of Ouagadougou is not on the sidelines of this because it is marked by a great urban dichotomy, so its urban fabric is composed of urbanized areas, and others consisting mainly of spontaneous habitats [3]. Notwithstanding, the land development efforts of the State, Boyer and Delaunay estimate that in 2009, the areas with spontaneous dwellings commonly called unplanned areas housed 33% of the population of Ouagadougou and 86.7% of the habitats in these unplanned areas. Lots are made of Banco (raw ground) [4]. The major factors of this strong use of Adobe (clay used as a building material, typically in the form of sun-dried bricks) are its availability, its proximity to the site of habitat construction and especially the lack of financial means to acquire more sophisticated building materials.

Despite all the advantages that we recognize in raw ground constructions, they present in its unstabilized form such as Adobe, some defects which are: the deficit in mechanical resistance and especially its high sensitivity to water [5]. One of the major consequences of its sensitivity to water is the repeated destruction of spontaneous habitats during heavy rainfall. As the case of September 1st, 2009, most of the housing destroyed by floods in Ouagadougou city, was in the unplanned area, 67% of the victims of the city [1]. To overcome these shortcomings, the populations of these said areas generally focus on a very inexpensive construction technique. In fact, this practice frequently adopted in earthen constructions consists of mixing soil (silt and/or clay) and heavy fuel oil to use it as a coating. Although this technique is widely used by many people in our country, it is not well known by many researchers in the sub-region and no scientific study has been made until now on this practice. This is also the main reason why we are focusing on this technique to determine the thermomechanical and water effects of heavy fuel oil on raw soil. The goal is to fully understand the technique to help those people who use it to improve themselves and achieve the goal of sustainable cities and communities for their well-being.

2. Materials and Methodology

In the present study whose objective is to determine the thermal effect, water and mechanical effects of heavy fuel oil on a soil sample, we will proceed by the following method.

First, we took a sample of soil that will be used to make our materials from a site in the village of Sabtenga, municipality of Pabre in the central region of Kadiogo province, which is located at the northern exit of the city of Ouagadougou. Then, a geotechnical study of our sample is made to specify the nature of the soil used. So, the sampling by quartering is the process followed in our study, which consists of taking a representative fraction of the sample [2].

In a second step, we will proceed to make different types of bricks with and without heavy fuel oil. Finally followed the characterization phase of the bricks made, the thermomechanical and water effects are the most important in this study. Thus, the material and equipment used in the context of our research are, among others, a hydraulic press for the compression of the material (Fig. 2), a KD2-Pro device for measuring the thermal properties (Fig. 3), a device for the test of water absorption by capillary action (Fig. 4).

This flowchart describes the approach adopted in this study (Fig. 1).

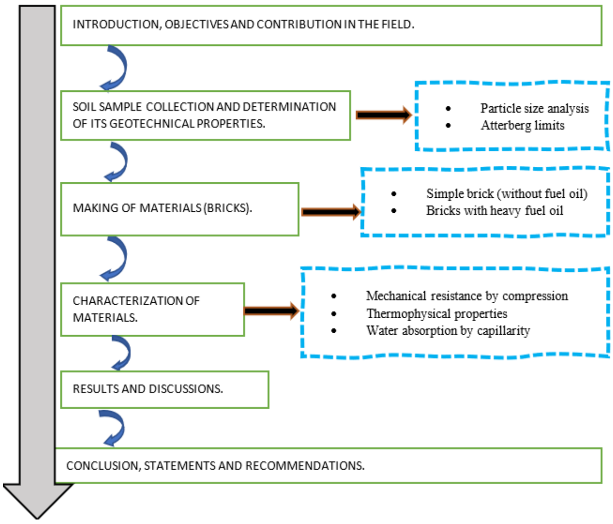

Fig. 1 Flowchart of the study process.

2.1 Descriptions of the Technique

This construction technique practiced by the populations consists of mixing soil and heavy fuel oil, of course by adding water to use the mixture obtained as a coating to reinforce the walls of their various constructions in raw ground. It should be remembered that fuel oil is a liquid fuel at room temperature, black in color, and of high calorific value, produced by refineries. It is a mixture of hydrocarbons of mineral or synthetic origin intended to produce heat in installations by its combustion [6]. The first reason for fuel oil importation in Burkina Faso is for supplying the large generators of the National Electricity Company of Burkina (called SONABEL).

The image in Fig. 5 presents a description of the technique for using fuel oil on Adobe constructions in several unplanned districts.

2.2 Protocol for Making the Material

In this phase of making the materials (bricks), to minimize the disproportion of the pressure exerted on the walls of the bricks during their making as well as the quantity of water in each brick, we thought it best to use a manual press equipped with two juxtaposed rectangular molds of the same dimensions, 5 cm high; width 11 cm and length 21 cm.

Fig. 2 Automatic hydraulic press with 3,000 kN of capacity.

Fig. 3 Measurement of thermal properties with KD2-Pro.

Fig. 4 Device for the test of water absorption by capillarity.

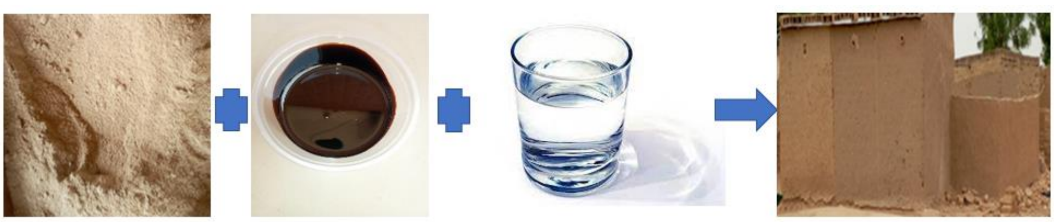

Fig. 5 Technique for using heavy fuel oil.

Fig. 6 Stages of the materials making.

For the confection, we first sift the soil through a sieve whose pores have a diameter of 1 mm. Then the sieved earth is poured into a mechanized mixer. For about 2 kg of soil, the quantity of 200 mL water is added then follows the mixing phase to make the mixture (soil + water) homogeneous.

Initially, it was a question of using approximately 2.2 kg of the mixture obtained after mixing to make simple bricks (without fuel oil). In the manufacturing process, there is the molding phase where a quantity of the mixture is simultaneously poured into the molds of the press. Pressure is then exerted on the molds using the lever of the press and we obtain the bricks which will finally be removed from the molds (Fig. 6).

To determine the effects of heavy fuel oil on the soil after the experimental tests that we carried out in the laboratory on the different types of bricks, we have designed other types of bricks. But this time a certain amount of heavy fuel oil was added to the mix.

The heavy fuel oil we used has very low sulfur content with a density of approximately 0.97 g/cm^3. Thus, for the same quantity of the mixture (soil + water) used to design a simple brick (without fuel oil) rated “BS”, we added 50 mL respectively, 100 mL and 150 mL of heavy fuel oil to obtain three other types of bricks rated “BS + 50 mL”; “BS + 100 mL” and “BS + 150 mL”. These volumes of fuel oil added correspond respectively to 2.2%, 4.4% and 6.6% by mass of the mixture (soil + water). The bricks are dried in the sun in the open air for at least two months before the experimental tests. The image in Fig. 5 shows the different bricks, the bricks without the white dots represent the bricks without fuel oil; those with a single dot represent the bricks with 50 mL of fuel oil; the bricks with two dots represent those with 100 mL of fuel oil and finally those with three dots represent the bricks with 150 mL of fuel oil added to the raw material.

3. Results and Discussions

3.1 Particle Size Analysis

The purpose of particle size analysis is to determine the proportions of grain sizes in a material. It is carried out by sieving (square-mesh sieve) for grains with a diameter greater than 80 μm, and by sedimentation analysis for the finest grains. So, the particle size distributions analyzed by sieving and by sedimentation analysis were carried out according to standards NF P18-560 and NF P94-093&057 respectively. They made it possible to obtain the complete particle size distribution of our sample in Fig. 7.

3.2 Atterberg Limits

It makes it possible to assess the quantity and type of clays present in a sample. In accordance with standard NF P 94-051, the test is carried out in two phases, the first phase of which consists of finding the LL (liquid limit) using the Casagrande apparatus. The second phase is the search of the PL (plastic limit) by forming rolls approximately 3 mm in diameter [2]. A liquidity limit curve (Fig. 8) is then obtained, which will subsequently make it possible to determine the value of LL. The PI (plasticity index) determined by the difference between the liquid limit and the plastic limit (IP = LL - PL), defines the extent of the plastic domain.

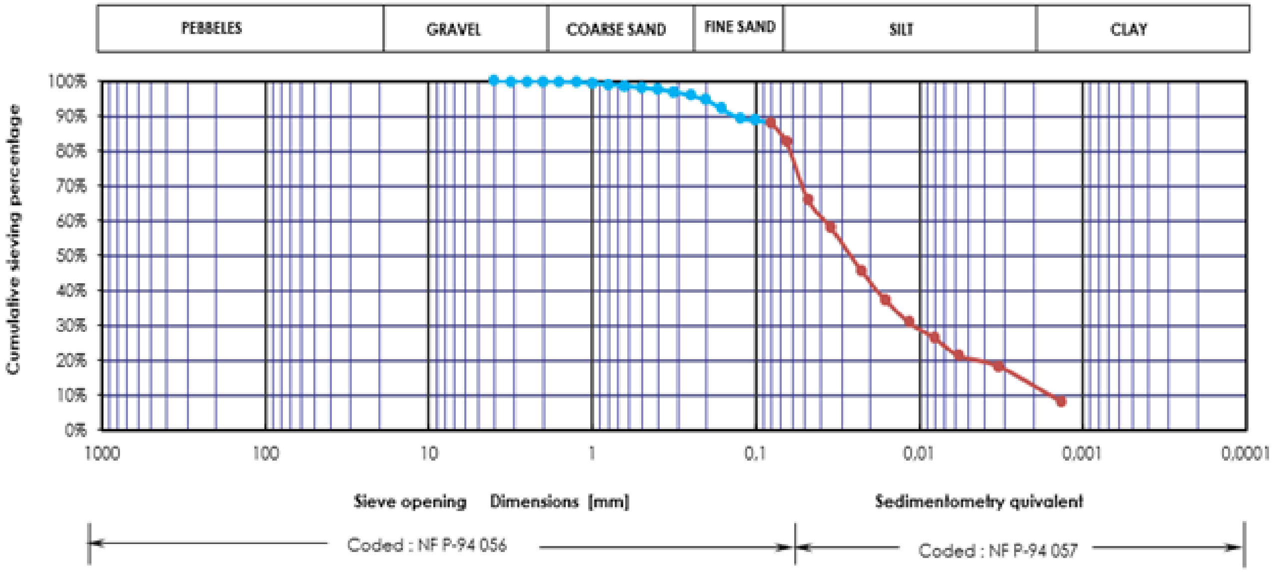

Fig. 7 Curve of the complete grain size of the sample.

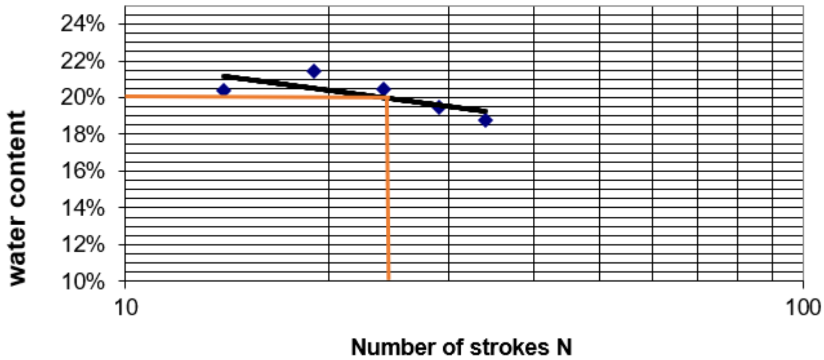

Fig. 8 Curve of the water content as a function of the number of strokes *N*.

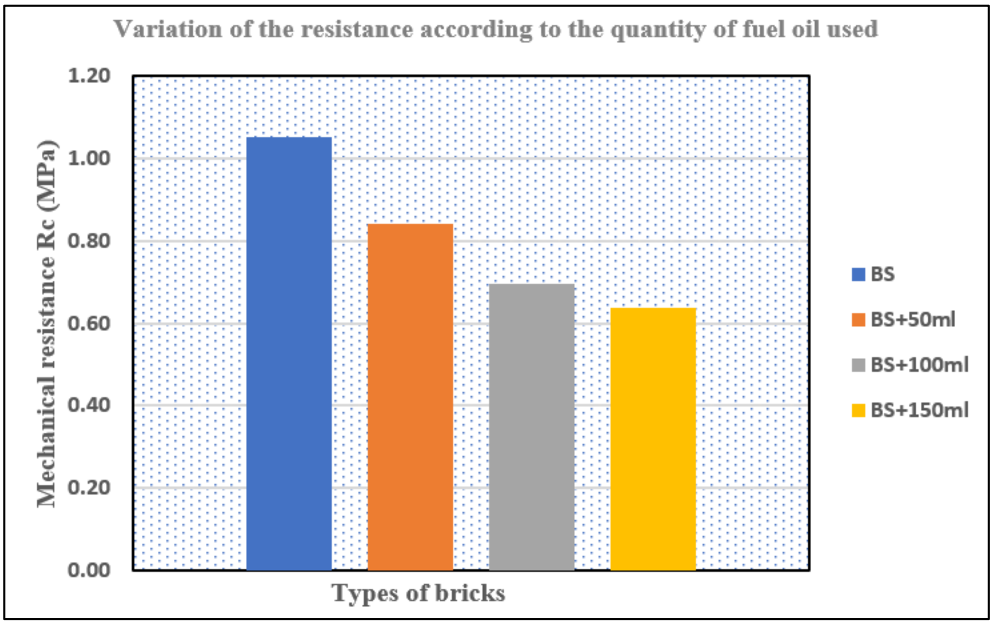

Fig. 9 Representation of the mechanical resistance of each brick.

Table 1 Values of the thermophysical characteristics of different types of bricks.

Property	BS	BS + 50 mL	BS + 100 mL	BS + 150 mL
λ (W/m K)	0.617	0.624	0.677	0.901
C (MJ/m^{3}K)	2.412	2.312	2.402	2.156
ρ (kg/m^3)	1,772.439	1,884.026	1,775.564	1,788.629
C_P (kJ/kg K)	1.361	1.227	1.353	1.205
α (mm^2/s)	0.256	0.270	0.282	0.418

Thus, by reading the LL corresponding to the number of strokes equal to 25 in Fig. 8, the following consistency limit results are then obtained: LL = 20%; PL = 16.6% and IP = 3.4%.

3.3 Mechanical Resistance of Materials by Compression

Monoaxial compressive strength tests were carried out on stacked pieces of brick measuring 5 × 10.5 × 11 cm using a press equipped with a hydraulic cylinder with a capacity force of 3,000 kN (Fig. 2). The maximum strength of compression is determined by the following equation:

$$Rc = F/S$$

With, Rc (MPa): the mechanical resistance which means the compressive strength of the material; F (N): the force applied to break the brick; S (mm^2): the surface where the force is applied. The results obtained are used to make the following diagram in Fig. 9.

3.4 Thermophysical Properties

The thermophysical properties of materials are quantities that characterize the behavior of materials. Some of these properties represent the capacities of a body to propagate or store heat. The thermophysical characteristics such as thermal conductivity (λ), thermal diffusivity (α) and volumetric heat capacity (C) of our materials were measured using KD2-Pro (Fig. 3), equipped with a double-needle probe [7]. The measurements allowed us to have the results of Table 1.

3.5 Heat Diffusion Time

The propagation of heat in a material depends on its thermal diffusivity α, which is the ratio of the thermal conductivity λ in W/(m K) on the volumetric heat capacity ($C = \rho C_P$) expressed in J/ (m^3 K) [8]:

$$\alpha = \frac{\lambda}{\rho C_P}$$

With ρ the density in kg/m^3 and C_P the specific heat capacity in J/(kg K.). The thermal diffusivity α (m^2/s) determines the speed with which heat goes through the material.

The higher the material's conductivity becomes and with low heat capacity, the higher the diffusivity is. The relationship between the requested thickness $e(t)$ (cm) and the heat diffusion time t inside a homogeneous building material is formulated by taking the product of the surface heat capacity value (Q) by the thermal resistance (R) of this material [8]:

$$t = Q.R = (e\rho C_P)\left(\frac{e}{\lambda}\right)$$

where $e(t) = \sqrt{\alpha t}$.

For example, assuming a sunshine duration on a daily cycle equal to 12 h, the variations of the diffusion thicknesses for each material are observed in Fig. 10.

3.6 Water Absorption by Capillarity

Absorption is a physical phenomenon by which a liquid migrates from the outside to the inside of a porous body thanks to capillary rise. It leads to a gain in mass of the material. The water absorption test is intended to determine the amount of water absorbed by capillarity by the samples. In this case of absorption, the material is not immersed. The tests were carried out on our different bricks based on the AFPC-AFREM 2004 protocol and according to the standard XP-P13-901 [9], shown in Fig. 4.

For each type of brick, we carried out three tests on different bricks over a period of 24 h and calculated the average absorption, rated i(t) (g cm^{-2}) which represents the quantity of water absorbed per unit of surface at each time step. The results obtained allowed us to represent the variations of the absorption of the bricks according to the square root of time (Fig. 11).

3.7 Discussions and Interpretations

The particle size distribution results (Fig. 7) reveal that our soil sample is composed of approximately 77% silt, 12% clay, 8% fine sand and 3% coarse sand. In view of these elements, we can consider our soil sample as being silty-clayey soil.

As regards the Atterberg limits (Fig. 8), the PI obtained, which is a value of 3.4%, is less than 12%. We can allow from this result that the soil is less plastic because of weakly clayey, and this supports the result obtained by the grain size distribution.

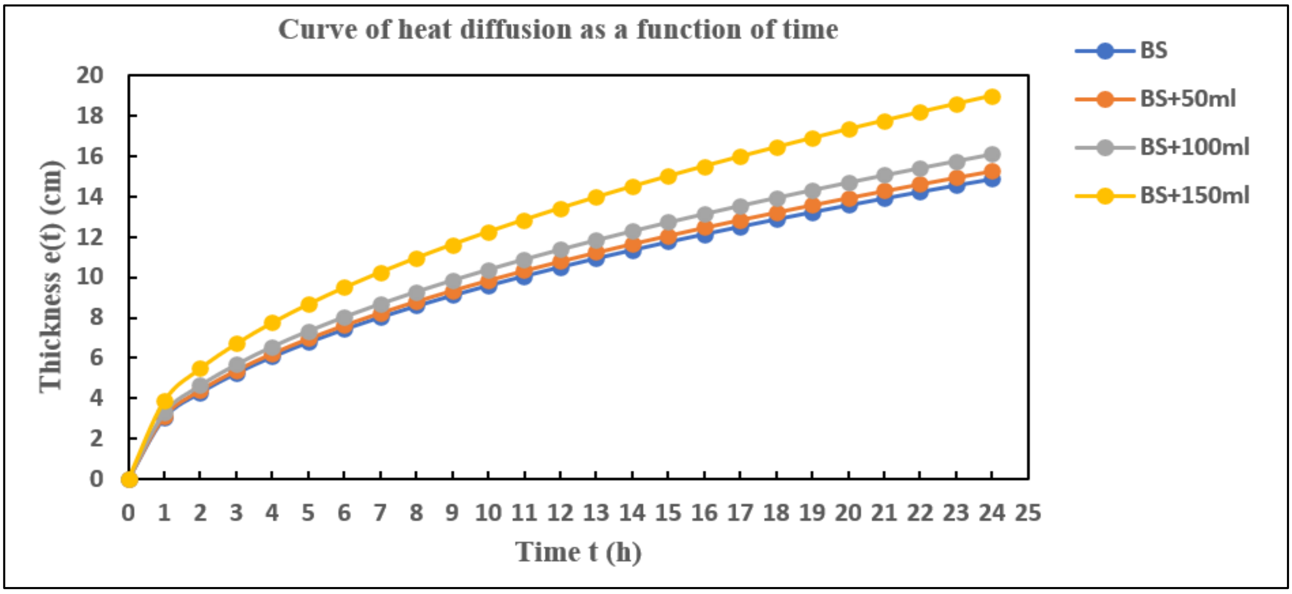

Fig. 10 Heat propagation for different materials as a function of diffusion time.

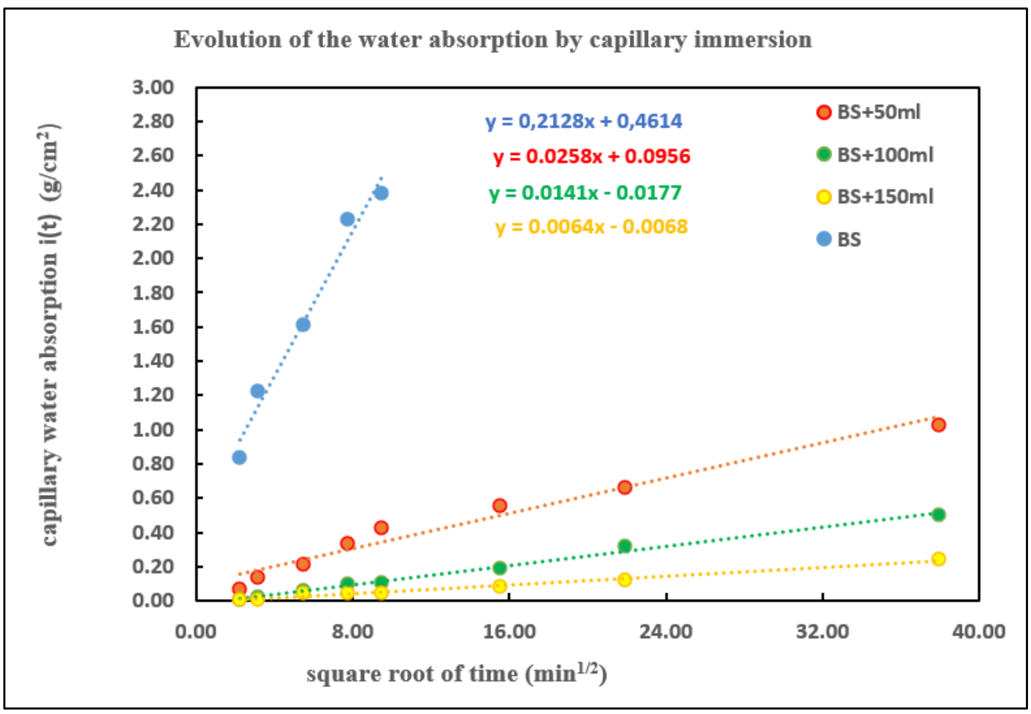

Fig. 11 Curve of water absorption by capillarity as a function of time.

For the results of the mechanical resistance by compression of the materials (Fig. 9) we have a resistance of the order of 1.05 MPa for the materials (BS) without binder. This strength gradually decreases with the addition of the binder. We notice a decrease in resistance of around 40% with the materials “BS + 150 mL” containing 150 mL of the binder (heavy fuel oil). This is explained by the contribution of a low water content in the fuel oil used as a binder.

About the results of the thermal tests (Fig. 10), we note that the depth of heat diffusion is less than 14 cm over a daily cycle of 12 h of sunshine. Over a given period, the heat penetrates more in the materials having more quantity of binder (heavy fuel oil). The addition of the binder increases the diffusivity of the materials. The increase in heat diffusion depth is about 2.7%, 8.2% and 27.6% when the material contains respectively 50 mL, 100 mL, and 150 mL of heavy fuel oil. This increase in diffusivity is due to the high calorific value of fuel oil.

The results of the water absorption test by capillarity of the different bricks (Fig. 11) show that the brick “BS” without binder has a very high-water absorption compared to those containing the binder. It should be noted that there is a strong reduction in water absorption by the addition of the binder. Over a 24-h period, there is a reduction in absorption of approximately 57%, 79% and 90% respectively for adding 50 mL; 100 mL and 150 mL of binder. The heavy fuel oil used has a very strong influence on the water properties of our materials, on its absorption of water by capillarity. This is because the heavy fuel oil globules stretch into very thin solid films which adhere to the soil particles and coat them.

4. Building Sustainable Cities and Communities

How can we build sustainable cities and communities in the country with populations of low financial incomes? Regarding the United Nations SDGs, not only will goal number 11 be achieved if this challenge is met, but also its effects on other areas will be observed.

Soil bricks absorb a lot of water by capillarity. This means that houses made from these bricks present a great risk of collapse in the event of flooding. However, bricks made from the mixture of raw soil and heavy fuel oil are more resistant to water. Indeed, water absorption is reduced by up to 90% depending on the fuel oil content added for its manufacture. Conversely, the mechanical resistance is progressively reduced up to 40% and a small increase in the depth of heat diffusion which can reach 28% is observed.

Heavy fuel oil has a very strong influence on the water properties of soil bricks. Chemically, the fuel oil globules stretch into very thin solid films, adhere to the particles of the material, and coat them to reduce the pores through which water infiltrates. This allows the mixture of silty-clayey soil and heavy fuel oil, used as a coating to protect the walls of raw earth constructions against rainwater and therefore habitats from collapsing during a flood, for example.

This technique, better mastered and supported, can help poor populations in urban areas, for example, to build habitats that are durable and able to withstand periods of high rainfall. This idea can be deepened and developed to allow people to make the best use of this material to build sustainable cities and communities.

5. Conclusions

Our observation is since people use heavy fuel oil in the construction of their mud houses, as a surface coating without fully understanding or mastering the effects of fuel oil on the material. The objective is to protect against any systematic destruction of their habitats in cases of flooding.

At the end of this study, we can retain that following the mechanical tests, heat and water on our manufactured materials, heavy fuel oil moderately reduces the mechanical resistance of materials, and slightly increases its thermal diffusion. Great satisfaction comes from the water properties where heavy fuel oil has a very good performance on water absorption by capillarity. Indeed, heavy fuel oil reduces to approximately 90% of water absorption when 150 mL of it is mixed with approximately 2 kg of silty clayey soil wetted with 200 mL of water. This performance could be very beneficial to people who follow this practice in the sense that the main objective of using fuel oil is to protect the walls of their construction in raw soil as material which are very vulnerable to water by preventing precipitation water from infiltrating during the rainy season. However, the situation remains better if this technique is used only to serve as plaster on the walls of dwellings and not as bricks for their construction. It is also necessary to avoid the use of fuel oil with a very high sulfur content which could cause risks in terms of public health.

It seems important that the populations understand that although the heavy fuel oil used in this way manages to reduce the infiltrability of water in the walls, it contributes to reducing the mechanical resistance of their house and increasing the heat inside the habitats, if its use concerns the making of bricks for construction of their habitats.

Because the lack of means is the main reason why people are interested in this method, asking them to use electrical devices to lower the temperature inside their house, or to add a little cement or another chemical binder, would simply be incongruous.

It is now clear that heavy fuel oil mixed with silty or clayey soil has a favorable water effect to protect habitats if this mixture is used as surface dressings, but not as a material for making bricks to be used in the construction of habitats, because its thermomechanical effect is unfavorable.

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