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Comparative Study of the Thermal and Mechanical Properties of Foamed Concrete with Local Materials

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Abstract

Living in a habitat with comfort is requested by all. Cinder block bricks have poor thermal properties, leading people to use fan heaters and air conditioners to regain comfort. To overcome this problem of thermal discomfort in buildings, we used lightweight concrete such as foamed concrete which is a material that has improved thermal properties for thermal comfort. In addition, this material was compared with local materials used for the construction of buildings such as BTC, adobe and BLT mixed with binders. The results showed that foamed concrete is a material that has good thermal and mechanical properties compared to local materials mixed with binders. The foamed concrete having acceptable thermo-mechanical properties was that having a density of 930 kg/m^3. It has a thermal resistance of 0.4 m^2·K/W for a thickness of 20 cm. The foamed concrete having acceptable thermo-mechanical properties was that having a density of 930 kg/m^3. It has a thermal resistance of 0.4 m^2·K/W for a thickness of 20 cm. For sunshine on a daily cycle equal to 12 hours, the characteristic thickness achieved by this material is 7.29 cm. It also has a shallow depth of heat diffusion having a lower thickness than other materials. This shows that foamed concrete is a promising material for the construction of buildings.

Keywords

Foamed Concrete, Thermo-Mechanical Properties, Comparison, Local Materials

1. Introduction

The materials used by humans in the construction of buildings require energy to be produced or extracted. The availability of affordable and functional housing is one of the basic human needs that is vital for the well-being of every human being. The quality of housing reflects a person's standard of living and socio-economic status in society. Concrete is a composite material made up of hard aggregates of various sizes bonded together by a binder. It is one of the most popular building materials in the world. It has a wide application range of constructions such as residential houses, high-rise buildings, sidewalks, water storage tanks [1] [2] [3] [4]. It is made up of aggregates (sand, gravel, pebbles, stone grains), cement and water. Nowadays, the cement block being essential in masonry, is one of the most used materials in construction compared to compressed earth bricks (CEB), cut laterite blocks (CLB), and adobe. In Burkina Faso, this material is also the most used and this is due to its high mechanical properties, yet it struggles to guarantee thermal comfort. The hollow block and the solid block having densities of 1250 and 2100 kg/m^3 respectively have thermal conductivities of 0.67 and 1.1 W/m.K [5]. Following a survey on the choice of materials for the construction of the future habitat of the population, more than two thirds of the thousand people responded by indicating in the first place, the cement block, followed by the CLB in the second position at 18%, then the CEB at 13% and the earth at 4% [6]. Users focus only on the mechanical properties of materials without taking into account their thermal properties. This costs them even more when using cooling devices. Burkina Faso being a hot and dry country requires a lot of energy in buildings where it is essential to always look for other materials other than local materials for thermal comfort. Thus, a reflection is necessary on the reduction of the thermal properties of the breeze block. We thought of lightweight concrete such as foamed concrete. Foamed concrete is a light and strong material in which air bubbles are trapped in a binding matrix. With the innovation of concrete, certain building components can be replaced with lightweight foamed concrete to achieve benefits such as reduced environmental impact and lower appliance costs [7]. Foamed concrete is a new material for the African continent, this is justified through the work of Oginni and al 2015 [8]. Previous work has shown the insulating character of foamed concrete. Foamed concretes like all other earth-based materials are porous materials with a majority of capillaries. Then, the properties of the local materials were improved by the addition of other components by the researchers. Adding fibers to stabilized soils improves both the thermal and static properties of materials. In addition, the addition of cement increases the compressive strength and thermal conductivity of these materials [9] [10] [11] [12]. This work will consist in making a comparative study of foamed concrete with local materials (with the addition of binders) which have been studied to find optimal thermal and mechanical properties for the construction of buildings. The methodology of making this material has been described for further understanding.

We used the results of the thermal and mechanical properties of foam concrete by Adelaide Lareba OUEDRAOGO *et al.* which allowed us to make the comparison [13]. The interest of this study is to verify and know the materials that have good thermo-mechanical properties in an optimal way for users in order to minimize the excessive use of appliances (air conditioners, fans, etc.) in buildings that require a lot of energy due to heat.

2. Materials and Methods

2.1. Preparation of Foamed Concrete

For the formulation used, the density of each sample is 600, 650, 730, 830 and 930 kg/m^3 having respectively the ratio of foam to cement (F/C) 0.048, 0.0432, 0.036, 0.03 and 0.024. The composition of foamed concrete such as cement on cement (C/C = 1), sand on cement (S/C = 0.4) and water on cement (W/C = 0.6) [13].

The mixing is done mechanically by introducing water then sand, cement and foam into a mixer. The foam is first made with water and foaming agent using an air compressor connected to a foam generator and a water pump. This very stable foam is put in place using flexible hoses. The mortar is prepared by mixing in well-defined proportions quantities of the different constituents for a few minutes until the mixture is homogeneous. Then the foam obtained is added to the fresh mortar mixture, while continuing to mix so that it is homogeneous. The mixing time of the foamed concrete is about 5 to 10 min. After mixing, the paste is poured into aluminum molds having dimensions of 50 × 20 × 15 cm^3 and 50 × 20 × 12.5 cm^3. The molds are left in the ambient air for 24 hours covered with plastic material before being unmolded. Once unmoulded, the samples are left in the open air (at room temperature) still covered with plastic material for 28 days. They are watered until the cement has set. The mold is also self-leveling, which makes it possible to manufacture blocks of simple or complex shape.

We made several series of mixes corresponding to the different densities of the foamed concrete, by varying the amount of foam. The foamed concrete manufacturing process is shown in (**Figure 1**). **Figure 2** shows a photo of the foamed concrete specimens.

2.2. Compressive Strength (European Standard NF EN 13791)

The compressive strength characterizes the performance of the hardened material which often depends on certain parameters such as the nature of the constituents used and their proportions in the mixture. It is determined on cubic specimens of dimension 10 × 10 × 10 cm^3 using a hydraulic press. The cubic samples have been shown in (**Figure 3**).

- **Measurement of compressive strength**

Tests were made to determine the compressive strength of the test specimens developed. For carrying out the compression test, a computer-controlled static

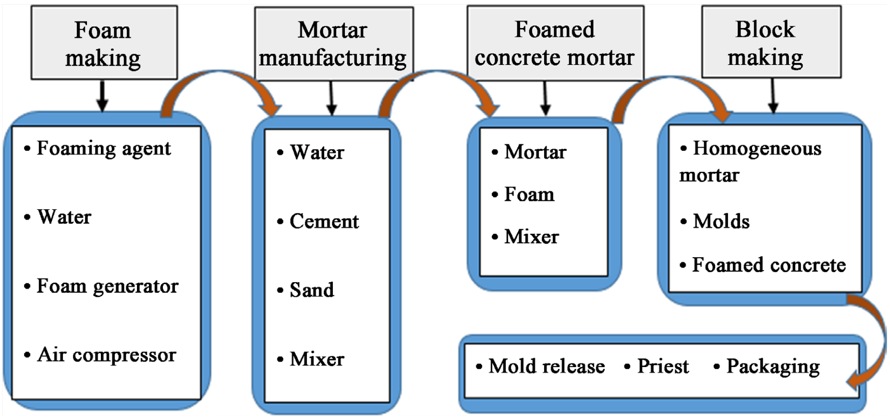

Figure 1. Procedure for making foamed concrete.

Figure 2. Specimens of foamed concrete.

Figure 3. Cubic samples of foamed concrete.

multi-test hydraulic press is used for crushing the foamed concrete block specimens. The experimental device for the compression test of the specimen is presented in (**Figure 4**).

This test consists of applying a load to the sample using a hydraulic press. A simple compressive load is applied until the complete failure of the sample and the value of the load is read on a computer screen. The value of the compressive strength is obtained by taking the ratio of the maximum force on the surface of the section of the specimen. The compressive strength is given by Equation (1).

$$R_c = \frac{F}{S} \tag{1}$$

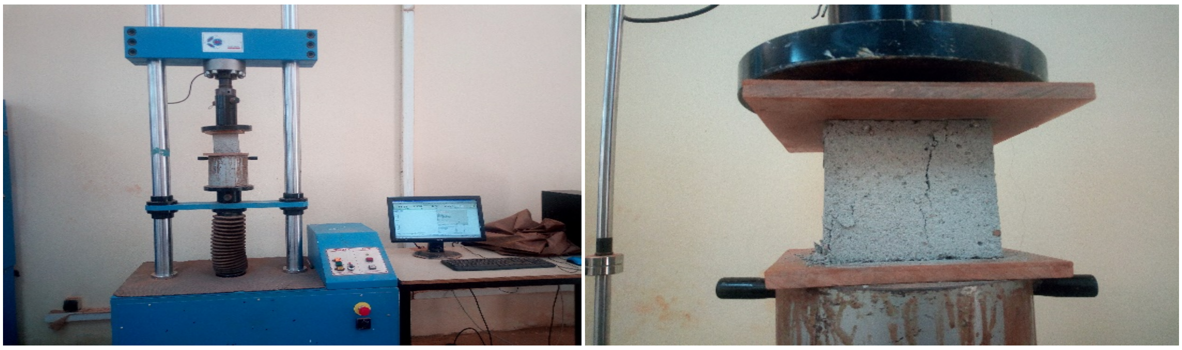

Figure 4. Experimental compression test device.

With R_c the compressive strength (MPa), F the maximum value of the force applied (N) at break and S the surface of the specimen in (mm^2).

2.3. Thermal Conductivity

For the measurement of thermal conductivity, we used the DesProTherm device. It is a device that makes it possible to estimate thermal properties using the hot plane method. It was developed to allow rapid and reliable characterization. Thus, the thermal conductivity was determined using the Equation (2).

$$\lambda = \frac{E^2}{\rho C_P} \tag{2}$$

With λ the thermal conductivity of the material (W·m^{-1}·K^{-1}), ρ the density of the material (kg·m^{-3}), C_P the specific heat capacity of the material (J·kg^{-1}·K^{-1}), E thermal effusivity (J·K^{-1}·m^{-2}·S$^{-1/2}$).

2.4. Thermal Resistance

Thermal resistance is the material's ability to withstand variations in heat. It makes it possible to quantify the insulating properties of materials for a given thickness. Thermal resistance is determined by the relationship (3).

$$R_{th} = \frac{e}{\lambda} \tag{3}$$

With R_{th}, the thermal resistance in (m^2·K/W), e the thickness of the material in (m).

2.5. Thermo-Physical and Mechanical Properties of Materials

We have identified some thermo-physical and mechanical properties of the different materials in the literature found by other researchers. These values presented in (Table 1) will allow a comparison to be made following the work.

2.6. Heat Diffusion Time

Thermal diffusivity determines the rate at which heat travels through the material. It is high when the thermal conductivity of the material is high.

The relationship between the requested thickness and the heat diffusion time

Table 1. Values of some thermo-physical and mechanical properties of the foamed concrete studied with other local materials with a mixture of binders.

Properties Autors	Materials	Thermal conductivity (W/m·K)	Thermal resistance (MPa)	Young's dynamic modulus (GPa)	Density (kg/m³)
She Wei and al [14]	FC-1700	0.423			1700
	FC -1900	0.5			1900
Ashfaque Ahmed Jhatial and al [1]	FC-1600		9.87	7.945	1600
	FC-1800		13.93	10.643	1800
Cheick Soré and al [15]	CEB + 15% G CEB	0.71	6.67	6.2 2.9 (without addition)	1730
Philbert Nshimiyimana and al [16]	CEB + 25% CCR	0.69	4.5		1477
	CEB + 15% CCR	0.79	4.6		1573
E. Ouédraogo and al [17]	Earth-paper Earth-paper-cement Earth	0.49 0.588	3.33 7.572	2.478 4.443 2.548 (without addition)	1745.34 1820.47
Elena Olacia [18]	Adobe + 3% fiber	0.62 0.55	2.012 1.803		1858 1825
Kossi B. IMBGA [19]	LaG 4%	0.603	2.169		1796.223
	LaC 4%	0.611	2.420		1671.874
Fati ZOMA [20]	mat + 1% fibre	0.72	3.51		1789.48
E. OUEDRAOGO 2018 [21]	CLB	0.444			1813
		0.469			1853
		0.577			1892
Lawane Gana 2014 [22]	CLB	0.415	2.08	4.66	1700
		0.471	2.17	3.76	1830
		0.507	3.29	3.87	1880

G = Geopolymer; CCR = calcium carbide residue; LaG 4%: Laterite plus 4% néré pod; LaC 4%: Laterite plus 4% cement; La + 1% fiber: material (laterite) plus 1% fiber.

inside a building construction material is obtained by calculating the product of the heat capacity by the thermal resistance of this material [23]. The diffusion of heat in the material depends on its thermal diffusivity, thermal conductivity, specific heat and density. The scattering depth is given by the relation (4).

$$e = \left(t \cdot \alpha\right)^{1/2} \tag{4}$$

The thermal diffusivity expressed as a function of thermal conductivity, specific heat and density is given by the relation (5).

$$\alpha = \lambda / \rho C_P \tag{5}$$

With t, the time in (h) et λ thermal conductivity (W/m·K).

3. Results and Discussion

3.1. Compressive Strength and Thermal Conductivity Values

Table 2 and Table 3 [13] show us the values obtained for the compressive strength and the thermal conductivity as a function of the density of the foamed concrete. We note that for the values obtained in the tables, the density with a value of 930 kg/m^3 has both good thermal and mechanical properties compared to the other values. This value represents a compromise between the density and the thermo-mechanical properties of the foamed concrete.

The density of the foamed concrete used for the comparison is that of 930 kg/m^3. This material has a thermal conductivity of 0.2 W/m.K, a resistance of 3.4 MPa and a Young's modulus of 3.1 Gpa [13].

To better illustrate the impact of density on thermal conductivity and compressive strength, we have made the graphic representation in **Figure 5**. It shows the evolution of the curves of compressive strength and thermal conductivity foamed concrete.

Table 2. Compressive strength values.

Samples	FC1	FC2	FC3	FC4	FC5
Density (kg/m^3)	600	650	730	830	930
Compressive strength (MPa)	1.2	1.6	2.2	2.8	3.4

Table 3. Thermal conductivity values.

Samples	FC-650	FC-730	FC-830	FC-930
Thermal conductivity (W/m·K)	0.05	0.09	0.16	0.2
Thermal diffusivity (m^2/s)	2.53×10^{-8}	5.4×10^{-8}	1.16×10^{-7}	1.23×10^{-7}

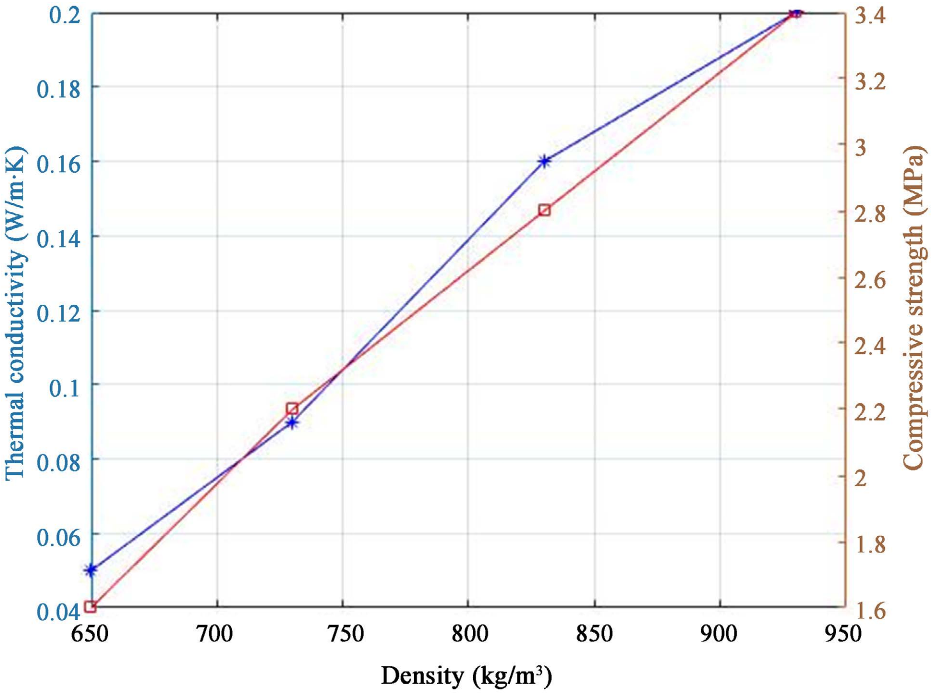

Figure 5. Evolution of thermal conductivity and compressive strength as a function of foamed concrete density.

We notice that the compressive strength and the thermal conductivity increase with the density. The physical, mechanical and thermal properties of foamed concrete increase when the amount of foam introduced into the mortar decreases. Indeed, for a density equal to 650 kg/m^3 to 930 kg/m^3 the compressive strength starts from 1.2 MPa to 3.4 MPa. Moreover, for a density equal to 650 kg/m^3 to 930 kg/m^3 the thermal conductivity of 0.05 W/m.K to 0.2 W/m.K. For the comparison of foamed concrete with other building materials, we chose foamed concrete with a density of 930 kg/m^3.

3.2. Thermal Resistance

Figure 6 and **Figure 7** respectively show the thermal resistance of foamed concrete and those of foamed concrete with other materials as a function of density.

Thermal resistance is used to quantify the insulating performance of materials. A wall is all the more insulating as its thermal resistance is high.

Figure 6 shows an evolution of the curves of the thermal resistance of the foamed concrete according to the density. These results also vary for each chosen thickness. For thicknesses of 20 cm, the thermal resistances of 650 kg/m^3, 730 kg/m^3, 830 kg/m^3 and 930 kg/m^3 are respectively equal to 4 m^2·K/W, 2.22 m^2·K/W, 1.25 m^2·K/W and 1 m^2·K/W.

Figure 7 shows an evolution of the thermal resistance of foamed concrete with other materials, for a thickness of 20 cm for all materials. Analysis of the results in **Figure 7** show that foamed concrete has a higher thermal resistance than other materials for a density equal to 930 kg/m^3. These results show the foamed concrete considerably loses their thermal resistance from a higher density

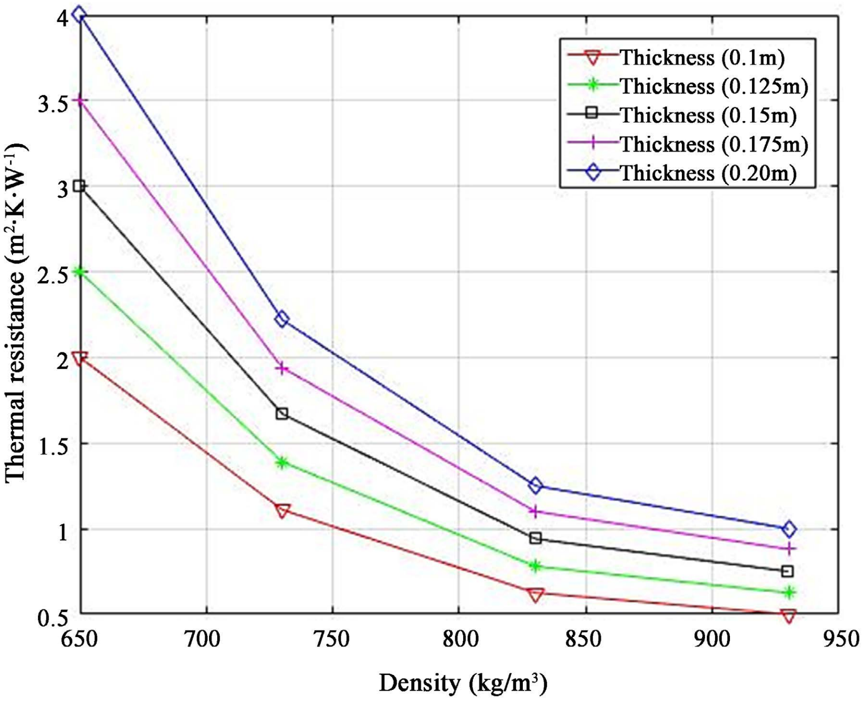

Figure 6. Thermal resistance of foamed concrete as a function of density.

of 930 kg/m^3.

In view of the results obtained and those of the literature, we can say that our material is insulating [24]. This confirms the low thermal conductivity of foamed concrete, as these two parameters are inversely proportional [25].

3.3. Comparison of Foamed Concrete and Materials with Added Binders

Figures 8-10 obtained are comparisons made with foamed concrete and materials such as CEB and adobe with the addition of binders (geopolymer, calcium carbide residues, paper, cement, fiber, néré pod) and the CLB.

Figure 8 and **Figure 9** show the evolution of the thermal conductivity and

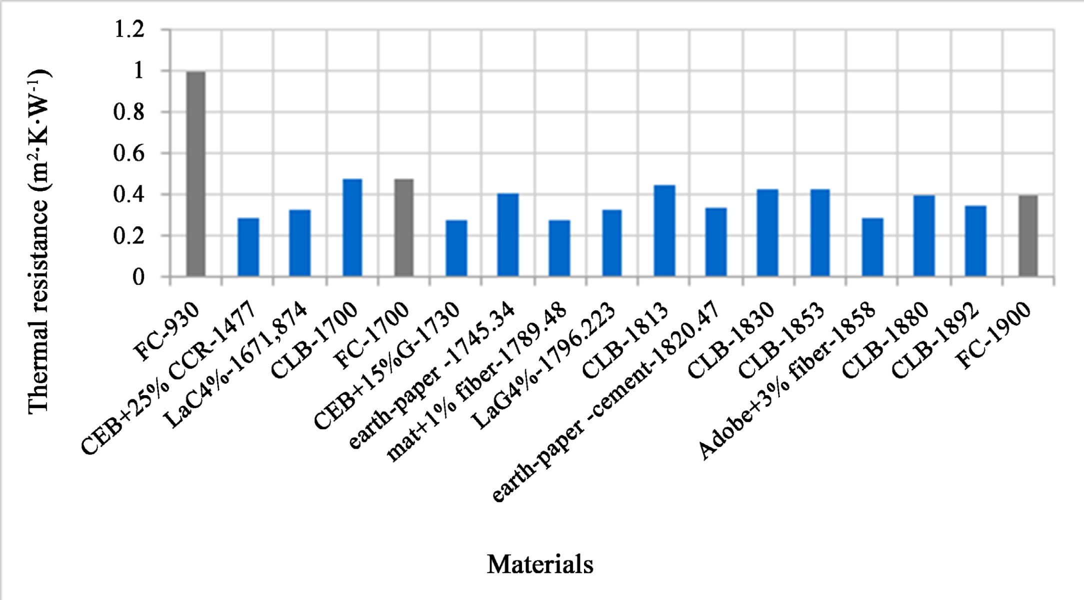

Figure 7. Thermal resistance of foamed concrete with other materials.

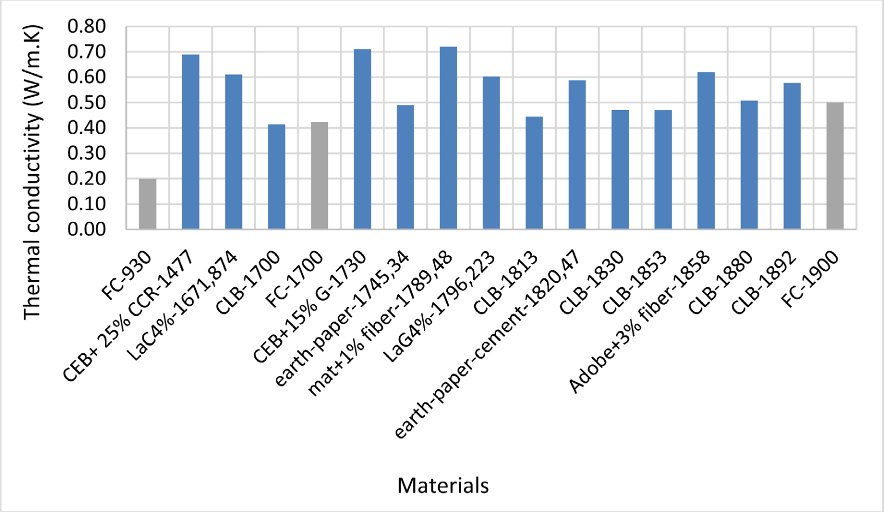

Figure 8. Comparison of thermal conductivity of foamed concrete and materials (CEB, adobe, CLB) containing binders as a function of density.

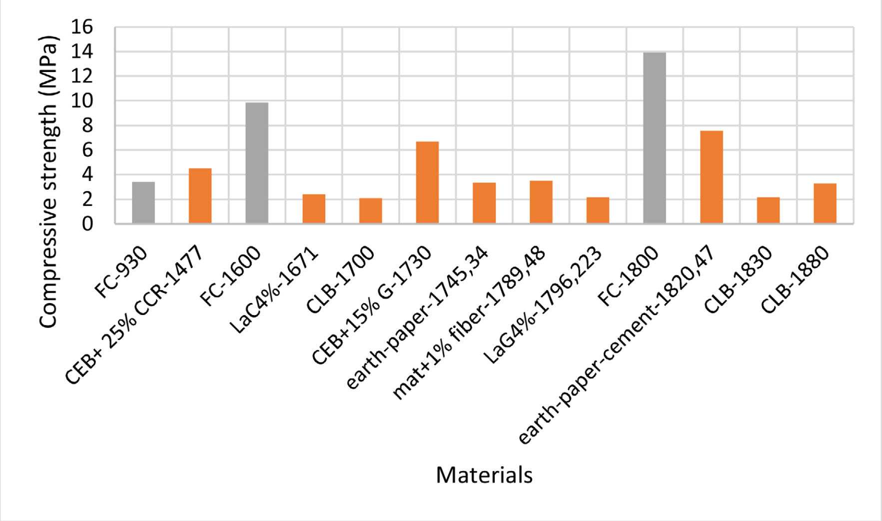

Figure 9. Comparison of the compressive strength of foamed concrete and materials (BTC, adobe, BLT) containing admixtures as a function of density.

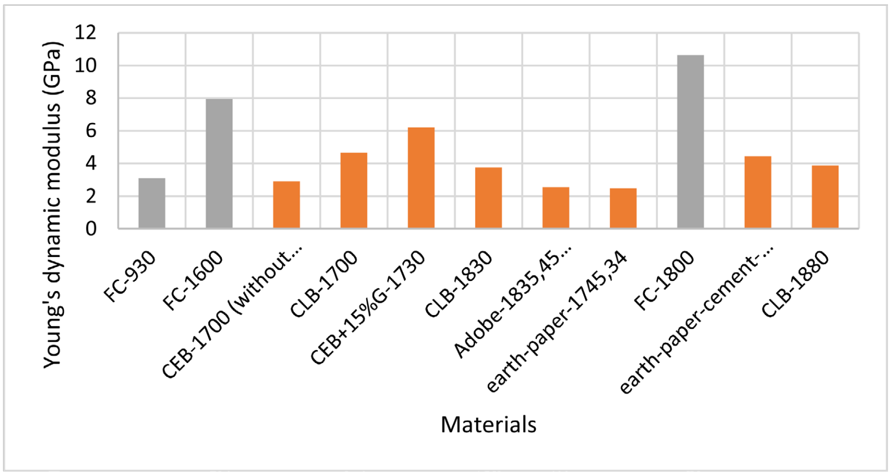

Figure 10. Comparison of the dynamic Young's modulus of foamed concrete and materials (BTC, adobe, BLT) containing binders.

compressive strength curves as a function of foamed concrete, CEB, adobe and CLB. We notice that the values of the thermal conductivity of foamed concrete (FC-930, FC-1700 and FC-1900) are almost lower than those of other materials mixed with binders whatever the density used. This confirms the insulating nature of foamed concrete.

Despite the low density of FC-930, we observe that it has a higher compressive strength than other materials except those of CEB containing 25% CCR, CEB containing 15% G and earth-paper-cement. On the other hand, the materials FC-1700 and FC-1900 having approximately the same densities as adobe, CEB and CLB have higher compressive strengths. Moreover, if we refer to the results of Kalifala Dao *et al.* [26], we find that the FC-930 having a low thermal conductivity of 0.2 W/m·K has a compressive strength of 3.4 MPa which is superior by compared to those obtained by Kalifala Dao *et al.* Thus, the foamed concrete has good thermal conductivities and sufficient compressive strengths.

Figure 10 also shows an evolution of Young's dynamic modulus curve as a function of foamed concrete, CEB, adobe and CLB. Depending on the evolution of the density, the values of the Young's dynamic modulus of the foamed concrete are higher than those of the other materials. It is noted that the value of Young's dynamic modulus (3.1 GPa) of foamed concrete is higher than those of CEB and adobe without the addition of binders as well as that of the earth-paper material. But we also find that the value of FC-930 is lower than that of CEB + 15% G and that of earth-paper-cement. The density of the foamed concrete FC-930 used for the comparison is lower than those of the other materials. But the samples of foamed concrete FC-1600 and FC-1900 have higher values than those of other materials regardless of their density. Foamed concrete also has acceptable mechanical properties for the construction of buildings.

3.4. Heat Diffusion Time

Figure 11 shows us the evolution of the curves of the characteristic thickness of the materials as a function of time.

Figure 11 gives the characteristic thickness of the different samples studied. Heat penetrates more and more into the material having higher thermal diffusivity during a given period t (h). For sunshine on a daily cycle equal to 12 hours, the characteristic thickness reached is 3.29 cm for the FC-650; 4.83 cm for the FC-730; 7.08 cm for the FC-830 and 7.29 cm for the FC-930. We notice that the more the density increases, the more the characteristic thickness increases. For a possible use of foamed concrete in the construction of buildings, the density could be a significant factor to guarantee thermal comfort among many

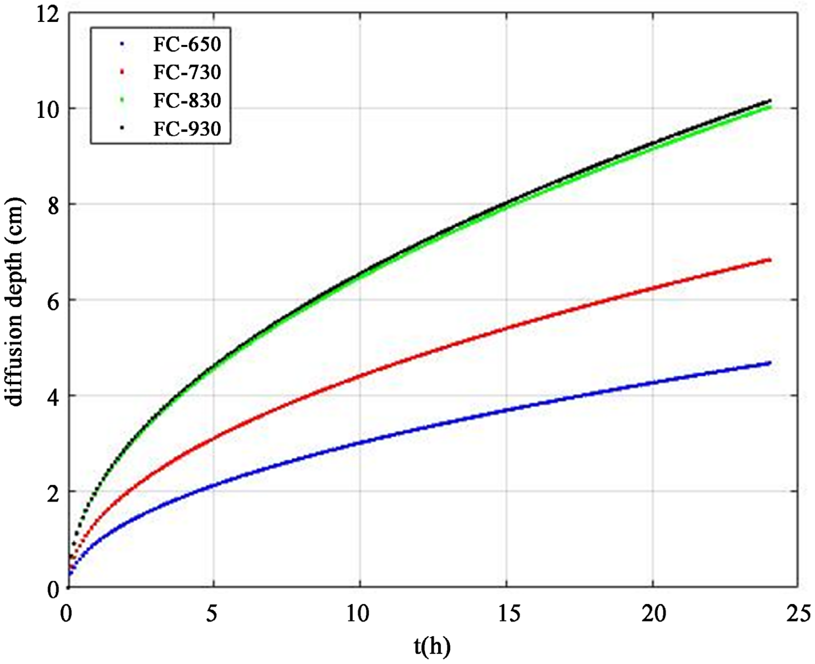

Figure 11. Propagation of heat as a function of time in foamed concrete.

others. Assuming sunshine on a daily cycle equal to 12 hours, the characteristic thickness is 18 cm for heavy concrete (material with a higher density than conventional concrete), 6.7 cm for heavy wood and 21.6 cm for granite [23]. In addition, E. OUEDRAOGO *et al.*, 2015 [17] also worked on the heat diffusion time of these materials. They noted that the characteristic thickness reached is 9.88 cm for the earth-cement block, 9.78 cm for the earth block, 8.74 cm for the paper earth block and 9.70 cm for the earth-cement-paper block. Boro Drissa *et al.* 2017 [27] found that plain mud bricks have a characteristic thickness of 7.70 cm and those stabilized with 8% sawdust is 6.16 cm.

In our case, we find that the characteristic thickness is less than 8 cm over a daily cycle of 12 hours of sunshine. We also noticed that, whatever the material, the diffusion depth is less than the wall thickness. In addition, foamed concrete is a material that has a lower thermal diffusivity than other materials. This shows that the heat penetrates less and less into the foamed concrete. Thus, we can say that the foamed concrete studied is an insulating material from a certain density.

4. Conclusions

At the end of this work, the thermo-mechanical properties of materials such as thermal conductivity, thermal diffusivity, compressive strength and Young's dynamic modulus were compared. In addition, the manufacturing procedure of foamed concrete (new material in Burkina Faso) was described.

Material comparison showed that the thermal conductivity, compressive strength and Young's dynamic modulus of foamed concrete (FC-930) are sometimes higher or lower than other materials with higher density, despite its low density. Foamed concretes (FC-1700, BM-1900) having a density of 1700 kg/m^3 and 1900 kg/m^3 have a thermal conductivity of (0.423 W/m.K and 0.5 W/m.K) which are lower than those of CEB, Adobe and the CLB. In addition, those (FC-1600, FC-1800) with a density of 1600 kg/m^3 and 1800 kg/m^3 have a compressive strength of (9.87 MPa and 13.93 MPa) which are higher than those compared materials. We can say that foamed concrete is a material that has good thermal and mechanical properties acceptable for the construction of buildings. This shows that foamed concrete is an advantageous or even promising material. Ultimately, this study allowed us to compare the thermo-mechanical properties of foamed concrete with other materials that can enter the construction process in Burkina Faso. Investigations can always be carried out to improve the properties of materials and make users aware of the importance of using these materials, namely:

- Improve the mechanical properties while decreasing the thermal properties of foamed concrete while adding local binders.
- Educate users on the importance of using insulating construction materials for their well-being (for thermal comfort).
- Design a typical building (control building) with the local climate to determine the average internal temperature.

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Conflicts of Interest

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

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