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Research Article

Thermophysical characterization of concrete reinforced with baobab trunk fibers (Adansonia digitata L.) for thermal insulation of buildings

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ABSTRACT

This work deals with characterizing concrete based on baobab trunk fibers for thermal insulation in buildings. The aim is to study the effect of the fiber content and the type of fiber treatment on the hygroscopic and thermo-physical properties of the concrete. Therefore, two types of treatment were carried out: an alkaline treatment and a thermo-alkaline treatment. Hygroscopic test results (34.25% to 54.92% for fiber content ranging from 14% to 28%) show that adding fibers to concrete makes them more sensitive to water. However, thermochemical treatment of the fibers reduces this water sensitivity. The thermal conductivities of concrete range from 0.202 to 0.086 W/m.K for the same fiber content. These results show that these biomaterials can be used in construction to improve building insulation.

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1. INTRODUCTION

The residential building sector consumes large quantities of energy for heating in cooler periods and air conditioning or ventilation in hot periods. In Senegal, the energy consumption of buildings is estimated at 49% of final national consumption [1]. This is explained by the fact that in Senegal, concrete (a conductive material) is the primary building material. With this material, air conditioning and artificial ventilation are always used to achieve minimum thermal comfort. In addition, manufacturing and recycling this material requires large amounts of energy and poses a real problem of environmental pollution and greenhouse gas emissions.

Faced with this problem, developing new alternative materials to concrete is becoming necessary. One of the solutions proposed to mitigate the environmental impact of concrete is the incorporation of vegetable fibers in the manufacture of construction materials. Vegetable fibers are local, available materials with low thermal conductivity. Thus, their use in building materials can be an alternative to reduce heat transfer.

Several researchers have been interested in determining bio-composite materials physical and thermal properties based on cement and plant fibers.

Benmansour et al. [2] studied the effect of fiber content on the water absorption, density, and thermal conductivity of a date palm fibers reinforced mortar. They noted a decrease in density, thermal conductivity, and an increase in water absorption as the amount of fibers in the mortar increased. Abdullah et al. [3] studied the physical and hygroscopic behavior of a cement mortar reinforced with coconut fibers. The authors concluded that the concretes' moisture content and water absorption increase as the fiber content

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increases. However, the density of the concrete decreases. Potiron et al. [4] worked on determining the thermal conductivity and density of concrete based on sugarcane bagasse. The fibers were treated with boiling and alkaline solution. The authors concluded that thermal conductivity and density decreased with increasing fiber content in the composite concrete. Taoukil et al. [5] studied the influence of water content on the thermal properties of a cement-sand composite reinforced with wood chips. The results showed that as the percentage of wood chips increased, the concrete's thermal conductivity and thermal diffusivity decreased. However, these values increase as the moisture content of the concrete increases. Chakraborty et al. [6] worked on the effect of adding jute fibers treated with an alkaline solution and another solution of Sika latex polymer (carboxylated Styrene Butadiene) on the density of cement mortar. The results show that treating the fibers with 5% Sika latex polymer increases the density of the composite concrete. Panesar et al. [7] studied the influence of cork waste fiber content on a cement mortar's density and thermal conductivity. They found that the density and thermal conductivity of the mortar decreased with increasing fiber content.

Osseni et al. [8] worked on the influence of the percentage of coir fibers on the thermal properties of a mortar. The results show that the thermal effusivity and thermal conductivity decrease by about 10% as the amount of coir fibers increases. Ashraf et al. [9] determined concrete's thermal conductivity and density containing date palm fibers. The authors noted a decrease in the thermal conductivity and density of the concrete as the fiber content increased. Similarly, Diaw et al. [10] manufactured and determined the thermo-physical properties of concrete incorporating typha australis aggregates. The authors concluded that these materials can be used in buildings to improve energy efficiency.

Al-Mohamadawi et al. [11] investigated the influence of increasing flax shives treated with paraffin wax on cement concrete's thermal conductivity and density. The results showed that adding raw or treated fibers decreases cement concrete's density and thermal conductivity (<0.3 W/mK). However, the density and thermal conductivity of the treated fibers concrete increased compared to that of the raw fibers concrete. Khazma et al. [12] worked on determining the thermal conductivity and density of concrete reinforced with flax shives treated by coating with a pectin + polyethylene (pp) mixture. The authors noted increased treated concrete's density and thermal conductivity compared to raw concrete. Abderraouf [13] studied the influence of the percentage of Diss and Doum fibers treated with a sodium hydroxide solution on the thermal conductivity of cement concretes. The results show that, for fiber content of 4% by mass, the thermal conductivity of Diss and Doum treated fibers mortars decreases by 40% and 33%, respectively, compared to the control mortar. Becchio et al. [14] studied the influence of the percentage of wood aggregates on the thermal conductivity of cement concrete. Their results showed a decrease in the thermal conductivity of composite concrete compared to control concrete.

This literature review shows that many vegetable fibers manufacture thermal insulation or filling materials in housing construction. No studies have been conducted to determine the hygroscopic and thermo-physical properties of concrete made from baobab (Adansonia digitata L.) trunk fibers. The baobab is a gigantic tree of the Bombacaceae family that grows in the southern, western, and southeastern regions of Senegal [15]. This tree has long been exploited for food (leaves and fruits) and traditional medicine (leaves and bark). Baobab trunk and branches are very fibrous and are used for rope making and mat weaving. Extracting fibers from these parts does not affect the tree's health, as these parts regenerate every six months after exploitation [16].

This work aims to develop and determine cement concrete's hygroscopic and thermo-physical properties based on baobab trunk fibers. The properties studied are water absorption, moisture content, density, and thermal conductivity. Compared to the work mentioned above, the originality of this work is the use of baobab trunk fibers in producing bio-sourced concrete to manufacture insulating cementitious concrete with low environmental impact.

2. MATERIALS AND CHARACTERIZATION METHODS

2.1. Baobab Trunk Fibers

In this study, the fibers used were extracted from the trunk of a local tree, the Baobab (Adansonia digitata L.). The baobab is a gigantic tree generally found in Africa's south-eastern and south-western regions, i.e., in the Sahelian and Sudano-Sahelian zones. In Senegal, the baobab is widespread in areas such as Thiès, Kaolack, Tambacounda, and in the southern regions, the Casamance. After extraction, the fibers were cleanly washed and air-dried for a week before being cut by hand into 1 cm lengths. [16, 17].

Two treatments were applied to the fibers:

- The alkaline treatment consisted of immersing the fibers for 4 hours in a sodium hydroxide (NaOH) solution of 5% concentration by mass at room temperature. They were washed thoroughly with distilled water and soaked again in a 1% sulphuric acid solution for 2 hours. Finally, the fibers were washed clean with distilled water and dried at room temperature for 72h. This fiber is noted as F.T.NaOH.
- Thermochemical treatment involves boiling the fibers for at least four hours and rinsing them thoroughly with distilled water to remove organic substances (waxes, peptides, impurities). The exact process then treats the boiled fibers with the same sodium hydroxide solution. This fibThis fiber F.B.T.

Several studies on the characterization of bio-based composites have already shown that heat treatment and alkali treatment of plant fibers can reduce large quantities of lignin, hemicellulose, and water-soluble substances. These compounds are the primary agents responsible for the delayed setting of the cementitious matrix and poor adhesion at the fiber/cement interface [4, 18].

Table 1. The fibers hygroscopic, physical, and thermal properties [17]

Types de fibres	ω (%)	ρ ($kg.m^{-1}$)	λ ($Wm^{-1}.K^{-1}$)
F.T.N_aOH	230.62	225	0.041
F.B.T.	226.08	220	0.043

Table 2. Composition chimique du ciment CEM II/ B-M 32.5 R

Composition	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	SO_3	Cl-
Weight (%)	55.8	19.7	6.2	3.9	2.2	0.33	0.70	2.6	0.07

Table 3. Mass percentages of cement and fibers

Components			CFTNaOH/C.F.B.T.			
Fibers content (%)	14	16	20	22	26	28
Cement content (%)	86	84	80	78	74	72

2.2. Sample preparation

This work uses both treated fibers (F.T.NaOH) and (F.B.T.). Their properties are listed in Table 1.

The chemical composition of the fibers was not given because no laboratory was available to carry out the chemical characterization.

The chemical composition of the cement used in this study is given in Table 2.

The concretes manufactured are composed of Portland cement CEMII/B-M 32.5 R supplied by the cement company Sococim Industries of Senegal and fibers from the baobab's trunk (Adansonia digitata L.). The ratio of water mass to cement mass is taken as 0.3. Table 3 shows each composite type's mass percentages of fibers and cement.

The fibers and cement were manually mixed in a 5 L capacity beater to achieve a homogeneous distribution of the fibers, and then the beater was inserted into an E095-type mixer. Mixing was maintained for 5 minutes, gradually adding the water necessary to hydrate the cement. The homogenized paste is then poured into 10 cm x 10 cm x 2 cm heat test molds. A Time-Tronic shaking machine was used to compact a total of 60 shakes. After 24 hours, the samples were removed from the molds, placed in plastic bags to even out the distribution of water, and kept under laboratory conditions for 28 days. Before conducting the thermo-physical measurements, the samples were dried in an oven at 105 °C for 24 hours.

An example of the concrete used for hygroscopic, physical and thermal characterization is presented in Figure 1.

Figure 1. Baobab trunk fibers concretes.

2.3. Characterization Methods

2.3.1. Water Absorption

First, the concretes were dried in an oven for 24 hours, and then their masses were weighed. Then, they were introduced into distilled water at room temperature.

By carrying out successive weighings, It is noted that, after 24 hours of immersion, the concretes reached their water saturation point (Δm≤0.01g). Finally, the masses at saturation were weighed.

The expression of the water absorption is:

$$\omega = \frac{m_h - m_o}{m_o} \; x \; 100 \qquad (1)$$

m_h: Mass of concrete saturated with water.
m_o: Mass of concrete in a dry state.

2.3.2. Moisture Content

The concretes were kept in the atmospheric conductions of the laboratory for 24 h before being weighed (m_a) and placed in an oven at a temperature of 105 °C. 24 hours later, the drying was stopped when the last two measurements were very similar (Δm≤0.01g). The expression calculates the moisture content= $\frac{m_a - m_s}{m_a} \times 100$ (2)

m_s: Mass of concrete in a dry state.
m_a: Mass of the concrete in the ambient state.

2.3.3. Apparent Density and Porosity

- The bulk density is the ratio of the mass (m_o) to the bulk volume of the sample. The mass of the sample was weighed with a 0.01 g precision balance. The dimensions of the sample were measured with a caliper to calculate the apparent volume. The equation obtains the bulk density:

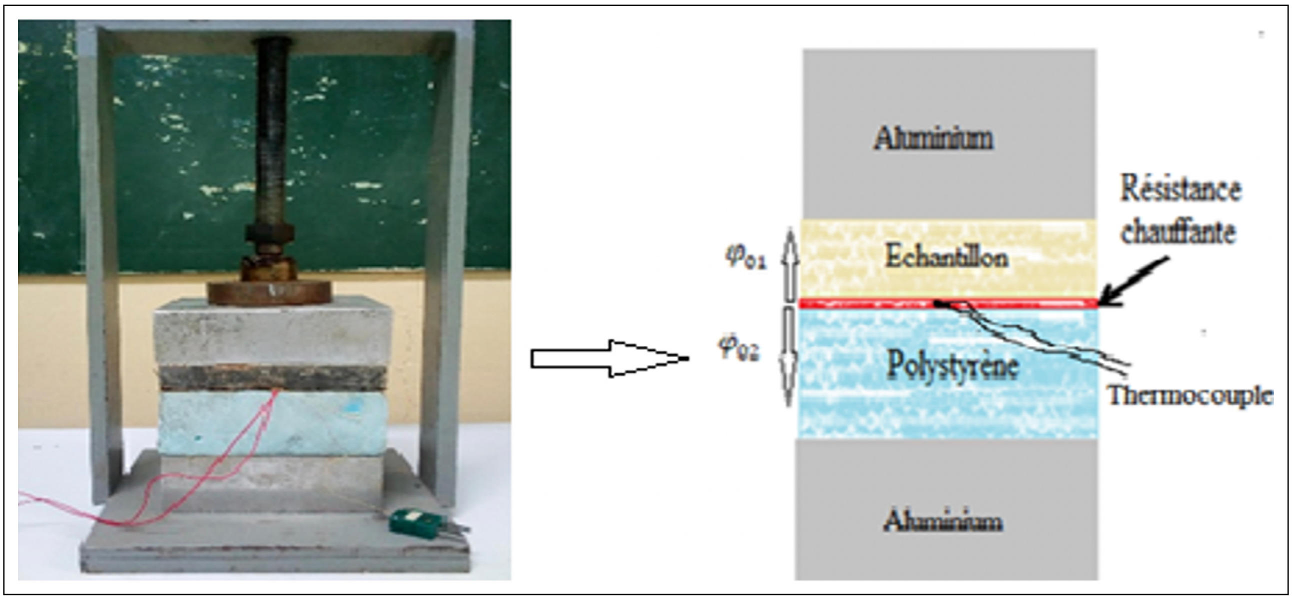

Figure 2. Asymmetrical hot-plane device.

Table 4. Thermal properties of polystyrene

e (m)	λ (Wm^{-1}.K^{-1})	E (J.K^{-1} .m^{-1} .s$^{-1/2}$)
0,015	0,035	43,226

$$\rho = \frac{m_0}{V} \tag{3}$$

- The water-accessible porosity is the ratio of the pore volume to the volume of the concrete. The pore volume is the difference between the mass of the water-saturated concrete (m_h) and the concrete in the dry state (m_o). The equation gives the porosity:

$$\eta = \frac{m_h - m_0}{\rho_e V} x100 \tag{4}$$

η: concrete porosity
V: Volume of the sample
ρ_e: Water density

2.3.4. Thermal Characterization

The thermal characterization consisted of the simultaneous determination of thermal conductivity and thermal effusivity using the asymmetric hot plane method at a constant sample backside temperature (Fig. 2).

The principle of this method and the modeling have been described in detail by Diéye et al. [19]. System modeling is based on two hypotheses: the heat transfer at the center of the sample is unidirectional (1D), and the temperature at the back of the sample is maintained constant. During measurement, the heating element applies a constant heat flow to one side of the 10 cm x 10 cm x 2 cm sample. A thermocouple placed in the center of the heating element records the evolution of the temperature Ts(t). The principle is to determine the values of the sample's thermal conductivity and thermal effusivity that minimize the squared deviation between the experimental and theoretical curves. The expression for the square deviation is:

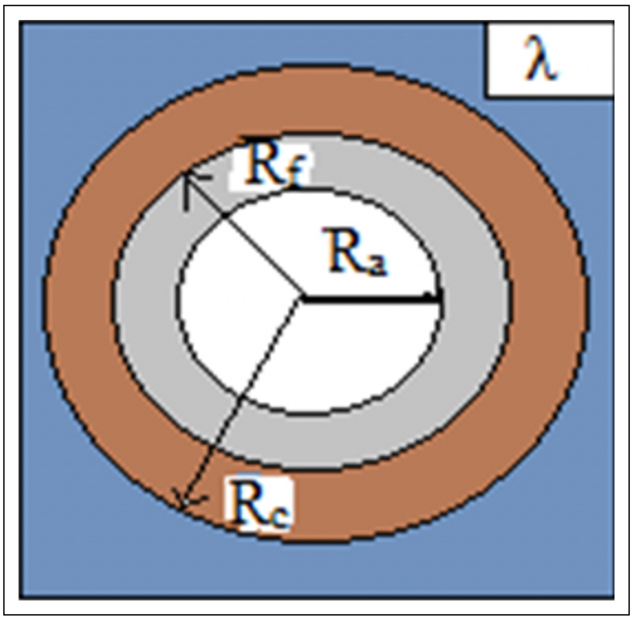

Figure 3. Three-phase homogenized medium.

$$\psi = \sum_i^n [T_{exp}(t_i) - T_{mod}(t_i)]^2$$

With:
ψ: The quadratic error between the experimental and theoretical values.
T_{exp}: Experimental temperature.
T_{mod}: Theoretical model temperature.

To test the validity of this method, an extruded polystyrene sample of known dimensions and thermal parameters was tested, and the results are presented in Table 4.

2.4. Thermal Conductivity Estimation by the Self-Consistent Method

This work used the three-phase model [20, 21] to determine the homogeneous medium's equivalent thermal con-

Table 5. Water absorption of composites

Fibers content (%)	14	16	20	22	26	28
Water absorption-CFBT (%)	34,25	35,56	35,82	36,57	43,84	50,79
Water absorption-CFTNaOH (%)	37,46	37,63	39,44	41,73	51,84	54,92

Table 6. Moisture content of concretes

Fibers content (%)	14	16	20	22	26	28
Moisture content - C.F.B.T. (%)	4,04	4,21	4,33	4,58	4,67	4,9
Moisture content - CFTNaOH (%)	4,28	4,37	4,48	4,66	4,7	4,95

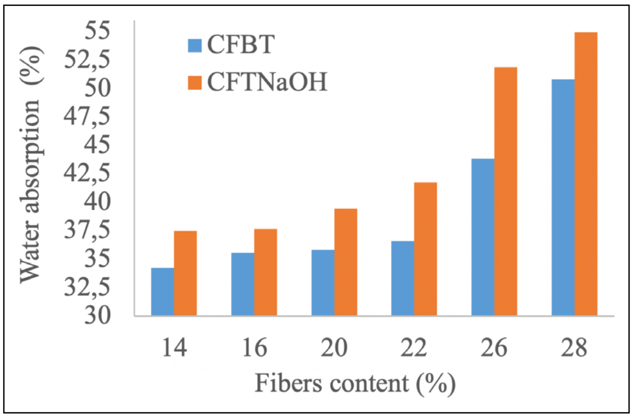

Figure 4. Water absorption as a function of fiber content.

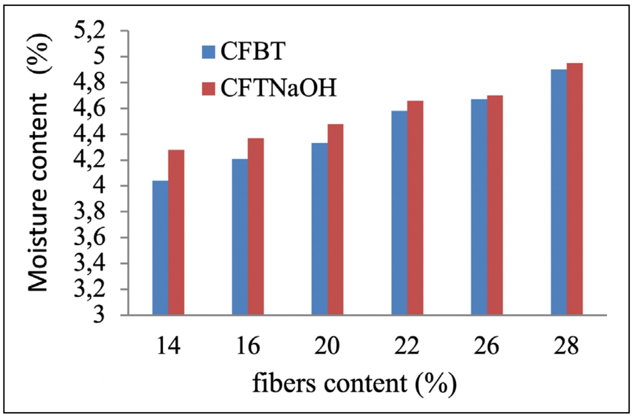

Figure 5. Moisture content as a function of fibers content.

ductivity (λ). The principle of the method is to assimilate a heterogeneous material to a homogeneous medium whose equivalent thermal conductivity is determined. The sample has assimilated an assembly of centrally located spherical air bubbles (Ra, λa), covered by a concentric spherical layer of fibers particles (Rf, λf), and the whole is covered by a cementitious matrix (Rc, λc) as illustrated in Figure 3.

3. EXPERIMENTAL RESULTS AND ANALYSIS

3.1. Hygroscopic Characterization

3.1.1. Influence of Fibers Content and Treatment on Water Absorption

The results of water absorption at saturation of the concretes are given in Table 5.

Figure 4 shows the evolution of water absorption as a function of fiber content and type of treatment. It shows that the water absorption of concrete increases as the amount of fibers increases. Baobab trunk fibers have a high water absorption coefficient [17]. Incorporating these fibers in the cementitious matrix explains the increase in water absorption of concretes when the fiber content increases. A similar behavior was observed by Xie et al. [22] on concretes based on rice straw and bamboo fibers and Benmansour et al. [2] on date palm fiber concretes. It can also be seen that the type of treatment affects the water absorption. The water absorption of C.F.B.T. concretes is slightly higher than that of CFTNaOH concretes.

Indeed, it has been shown that the thermochemical treatment of fibers contributes better to reducing the water-soluble components responsible for the hydrophilic character of fibers [17]. This reduces the water absorption capacity of the fibers. This same behavior was observed by Abderraouf [4].

3.1.2. Influence of Fibers Content and Treatment on Moisture Content

The moisture content values of C.F.B.T. and CFTNaOH concretes are shown in Table 6.

Figure 5 shows that the concretes' moisture content increases when the fibers' mass fraction increases. This is because fibers comprise molecules with large amounts of free hydroxyl groups (-O.H.) and can bind water vapor [23]. It can be seen that the type of treatment also influences the moisture content. We noted that the C.F.B.T. concretes showed lower moisture contents than the CFTNaOH concretes (Fig. 5). This phenomenon can be explained by the fact that the thermochemical treatment leads better to the dissolution of lignin and hemicellulose. This makes the fibers less hydrophilic. This same behavior was also found by Sawsen et al. [24].

Although the water absorption and moisture content of the fibers have been reduced, it has to be recognized that the concretes studied are still highly sensitive to water. Therefore, for their use in buildings, they are either used for internal insulation in the form of panels or by applying a layer of waterproof plaster to the outside face when the concretes are used to fill the walls.

Table 7. Apparent densities and water-accessible porosity of concretes

Fibers content (%)	14	16	20	22	26	28
C.F.B.T.						
ρ (kg.m-3)	1122,50	1118,15	1107,40	1018,55	945,05	861,10
Porosity (%)	38,11	38,85	39,20	39,72	41,53	45,69
CFTNaOH						
ρ (kg.m-3)	1111,07	1090,50	1084,25	1027,95	920,00	859,50
Porosity (%)	39,69	40,00	41,53	42,32	46,40	47,79

Table 8. Thermal conductivity of C.F.B.T. concretes

Fibers content (%)	0	14	16	20	22	26	28
Thermal conductivity - C.F.B.T. (W/mK)	0,691	0,202	0,117	0.104	0,096	0,089	0,086
Thermal conductivity - CFTNaOH (W/mK)	0,691	0,188	0,112	0,105	0,091	0,085	0,083

3.2. Thermo-Physical Characterization

3.2.1. Influence of the Fiber Content on the Density

The values of the apparent densities and water-accessible porosity of the concrete (C.F.B.T. and CFTNaOH) are given in Table 7.

Figure 6 shows the density variation as a function of fiber content and type of fiber treatment. It is noted that the bulk density decreases as the fiber content increases. Adding plant fibers in a cementitious matrix increases the porosity of the fiber-reinforced concrete (Table 7). However, as the porosity of the concrete increases, the density decreases. This justifies the decrease in the density of concrete fibers. Potiron et al. [4] also observed the same behavior.

Figure 6 also shows that the treatment influences the bulk density of the concrete. It can be seen that the densities of C.F.B.T. concretes are slightly higher than those of CFTNaOH concretes. Some authors have shown that the treatment increases the density of the fibers Ghabo et al. [17], Asasutjarit et al. [25]. This justifies the importance of the density of C.F.B.T. concretes compared to CFTNaOH concretes.

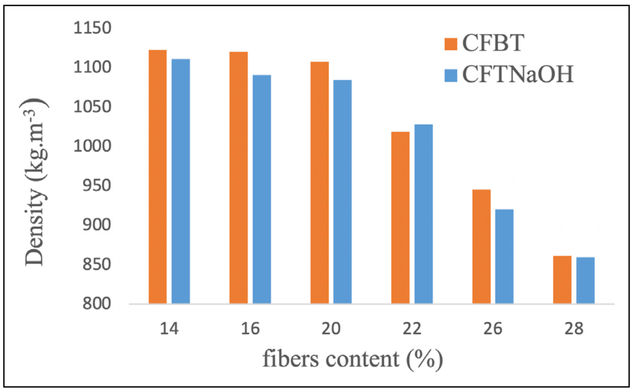

Figure 6. Density of concrete as a function of fiber content.

3.2.2. Influence of Fiber Content and Treatment on Thermal Conductivity

The values of the thermal conductivities of the studied concrete are given in Table 8.

The variation in thermal conductivity as a function of fiber content and type of treatment is shown in Figure 7.

Firstly, It can be noted that the thermal conductivity of the concrete decreases as the fiber content increases. Indeed, adding fibers to a cement matrix increases the porosity of the concrete. This contributes to the decrease of the thermal conductivity of the concrete when the fiber content increases. Other authors have observed similar behavior, Osseni et al. [8] and Benmansour et al. [2].

Secondly, it can be seen that the thermal conductivities of C.F.B.T. concretes are slightly higher than those of CFTNaOH concretes. The thermochemical treatment decreased the porosity of the fibers more than the chemical treatment Ghabo, et al. [17]. Thus, the incorporation of chemically

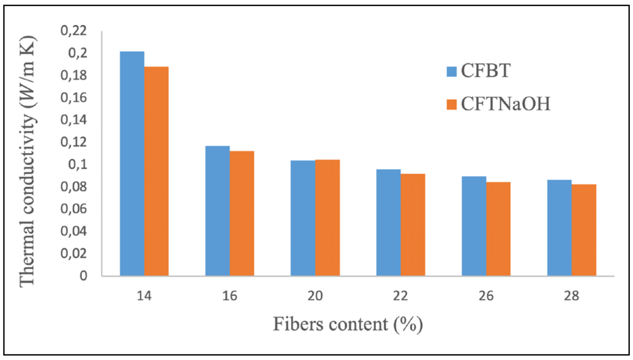

Figure 7. Thermal conductivity of C.F.B.T. and CFTNaOH as a function of fibers content type of treatment.

treated fibers reduces the thermal conductivity of the concrete more. This justifies the superior thermal conductivity of C.F.B.T. concretes. Potiron et al. [4] have observed similar behavior in concretes based on sugarcane bagasse fibers.

3.2.4. Influence of Bulk Density on Thermal Conductivity

Figure 8 and 9 show the evolution of the thermal conductivity as a function of the density of the concrete. It is noted that the thermal conductivity of concrete decreases as the density decreases. The addition of the fibers contributes,

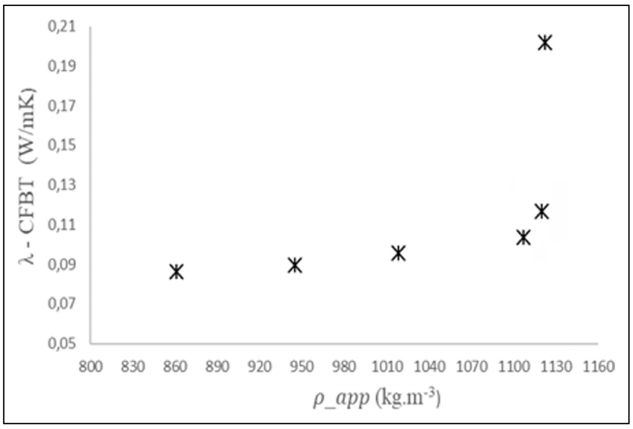

Figure 8. Thermal conductivity of CFBT concrete as a function of density.

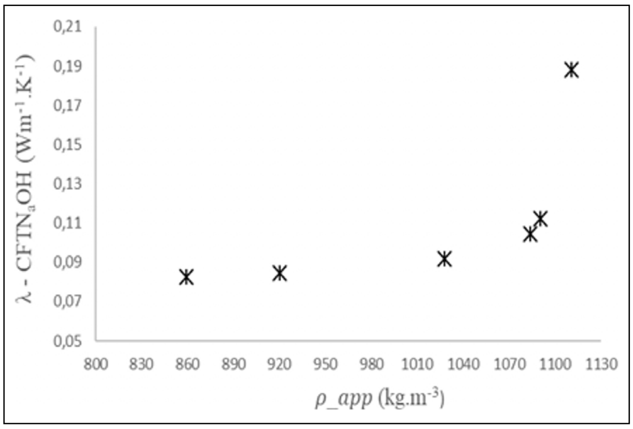

Figure 9. Thermal conductivity of CFTNaOH concrete as a function of density.

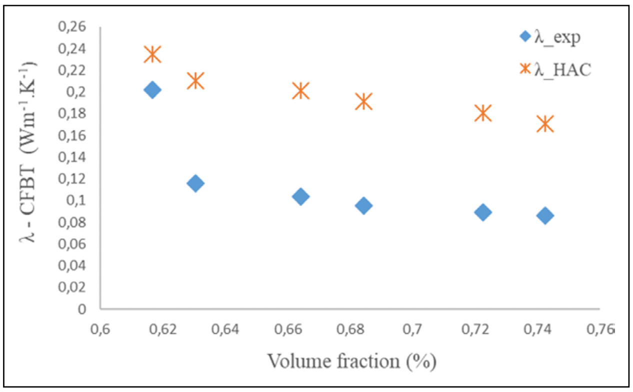

Figure 10. Thermal conductivity of C.F.B.T. concrete as a function of volume fraction.

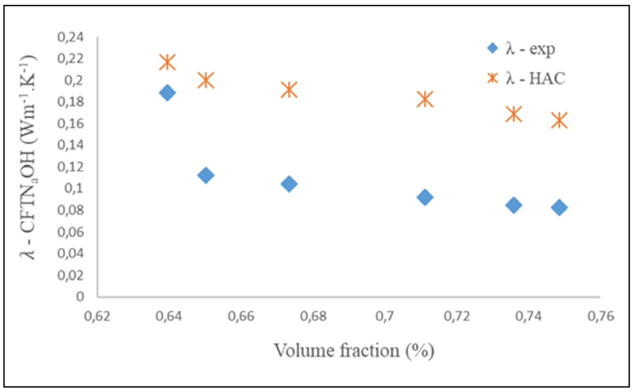

Figure 10. Thermal conductivity of CFTNaOH concretes as a function of volume fraction.

in one sense, to increase the porosity and, in the other sense, to reduce the density of the concrete. However, the increase in porosity leads to a decrease in density, which explains the reduction in thermal conductivity as a function of density.

3.2.5. Comparison of Theoretical and Experimental Results

The variations of the experimental and theoretical thermal conductivity as a function of the fibers' volume fraction are shown in Figure 10 and 11. It can be seen that as the volume fraction of the fibers increases, the difference between the experimental and theoretical values increases. The deviations obtained between the theoretical and experimental values are between 3.3% and 8.5% for C.B.T.F. concretes and 2.9% and 8% for C.F.T.NaOH concretes. This difference can be justified by several factors: the generic pattern of the tri-composite structure for which the three phases are arranged as concentric and continuous spheres and the shape of the inclusions, which should be spherical. In addition, the experimental measurements of the thermal conductivities of the fibers and the cementitious matrix would have measurement errors. Therefore, using these values to calculate the equivalent thermal conductivity could explain this difference. The self-consistent homogenization model has also been used by Cerezo [21] and Benazzouk et al. [26] to estimate the thermal conductivity of bio-based concretes.

4. CONCLUSION

This work focused on the effect of incorporating baobab trunk fibers on the thermo-physical and hygroscopic properties of concrete. The fibers were chemically and thermochemically treated to study the impact of their incorporation on the properties of concrete.

- The results obtained for the hygroscopic characterization showed that the thermo-physical treatment of the fibers contributes to reducing the moisture content and water absorption of the concretes studied.
- From a thermophysical point of view, it was noted that the incorporation of fibers resulted in a significant decrease in the thermal conductivity and density of the composites. For a fiber content of 20%, the thermal conductivity decreased by 58.64% and 58.72%, respectively, for the C.F.B.T. and C.F.T.NaOH composites compared to the control concrete.
- The theoretical results of the self-consistent method are similar to the experimental results with acceptable deviations.
- Regarding the thermal insulation of the building, both types of concrete studied showed good thermal insulation properties.
- Therefore, we propose the use of this material in construction to reduce energy consumption in the building sector.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

PEER-REVIEW

Externally peer-reviewed.

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