Improvement of the energy efficiency of buildings: Thermal characterization of an ecological building material based on industrial cotton waste

Abdou Raimi Alakouko[1,*], *Clarence* Semassou[1], *Roger* Ahouansou[1], *Armel* Amadji[1], *Chakirou* Toukourou[2], *Gratien* Kiki[3]

[1]University of Abomey-Calavi, Laboratory of energetics and applied mechanics, Abomey-Calavi, Benin

[2]University of Abomey-Calavi, Pôle Technologique de Promotion des Matériaux Locaux, Abomey-Calavi, Benin

[3]University of Liege, Building Energy Monitoring and Simulation, Arlon, Belgium

Abstract. The aim of this work is to study the thermal characteristics of a concrete reinforced with cotton waste fiber for building construction. The concrete used was formulated with the Dreux-Gorisse method and has a compressive strength of 14.13 MPa. The fiber-reinforced concrete contains 0.1% to 0.8% of fibers by mass. The thermal properties were determined by the asymmetric hot plane method used with a DesProTherm device. Other properties were also computed. The results show that the density of the concretes decreases with the percentage of fibers, from 2.205 t/m^3 for the concrete without fiber to 2.001 t/m^3 for the concrete containing 0.8% of fibers. The thermal conductivity and thermal diffusivity also decrease with the percentage of fibers, they range respectively from 1.021 W/m.K to 0.448 W/m.K and from 5.64 10^{-7} m²/s to 2.19 10^{-7} m²/s. As for the thermal capacity, it is almost constant with 0.1% of fibers (1810 to 1800 kJ/m^3.K) then increases progressively up to 2046 kJ/m^3.K for 0.8% of fiber. These results show that the incorporation of fibres improves the thermal characteristics of concrete. The use of this material would provide better thermal conditions inside the buildings, and consequently the reduction of energy consumption.

1 Introduction

Buildings consume the third of the world's energy production and are responsible for more than 30% of global greenhouse gas (GHG) emissions [1, 2]. The development of industrial activities and population growth will increase this consumption to more than 53% in the next decades [1] and will increase by 104% in 2040 in Africa [2]. All this leads to a high emission of GHGs which has negative consequences on the environment, society and rural economic activities [3].

Indeed, building envelope is the essential element that promotes or limits energy consumption in the building. This is by its orientation, its mass, the materials used and other factors [4-6]. For example, according to Sadineni et al. building envelope is the element separating the indoor and outdoor environments of a building, then it is the key factor that determines the quality and controls the indoor conditions independently of the transient outdoor conditions [6]. Other researchers like Zwanzig also concluded that the energy consumption of buildings can be significantly reduced by using thermally massive building materials [7]. Therefore, it is important to work on local thermally insulating materials to limit this energy consumption of buildings.

In Benin, cotton production that is a pillar of the agricultural economy has been increasing since 2016. It has doubled in 2021 compared to the one in 2016 [8, 9]. This high production generates a large quantity of waste that remains unused. They are burned and/or thrown away, and remain a threat to the environment (Fig. 1) [10]. The study of the characteristics of these wastes shows that the ginning clods, cotton ginning wastes, are available in significant quantities and have physical and chemical characteristics necessary to be used in the production of materials of durable construction [11].

Fig. 1. Discarded and burned textile mill waste [10].

In addition to the above, several scientific works have shown that materials based on vegetable fibers are

---

[*] Corresponding author: abdou.alakouko@gmail.com

alternatives for the production of thermal insulation materials for buildings. These materials have thermal characteristics that promote good indoor comfort in buildings [12-15]. For example, according to Binici, textile wastes can be used as raw materials for the production of thermal insulation materials for buildings [15].

In order to contribute to the achievement of the objectives of sustainable development related to the reduction of GHG emissions, the fight against global warming, the protection of the environment, the construction of sustainable habitats, the goal of this work is to develop and determine the thermal characteristics of a building construction material (concrete) based on cotton ginning waste. Specifically, it will involve the formulation of a concrete reinforced with cotton waste fiber, the experimental determination of the thermal capacity and thermal effusivity of the samples, the analytical determination of the other thermal characteristics (thermal conductivity and thermal diffusivity) and finally the selection of the best samples that can be used in the construction of less energy consuming buildings.

2 Materials and Methods

2.1 Concrete composition and production

The material of this study is a fiber reinforced concrete. It is composed of dune sand, crushed 0/5, cement, water and cotton ginning waste. It is an eco-material, without additives. The aggregates that make it up have been collected in compliance with the environmental protection rules. The dune sand comes from a site located in the city of Lokossa in the South of Benin (6°42'24"N 1°40'26"E), the crushed 0/5 is a by-product of a crushing industry (COLAS AFRIQUE) located in the town of Djidja in the South of Benin (6°27'36"N 2°14'48"E). The ginning waste comes from the cotton ginning factories of the SODECO Company in Benin. The cement is CEMII 32.5 R. This is the cement usually used in building construction in Benin. The different raw materials are presented in Fig. 2.

Fig. 2. Raw material (a) Dune sand (b) crushed 0/5 (c) cotton ginning waste (d) cement.

The base concrete (without fiber) was formulated by the Dreux-Gorisse method [16, 17], with a compressive strength of 14.13 MPa. The fiber-reinforced concrete was obtained by incorporating fiber into the starting concrete. They were formulated for mass percentages of fiber of 0.1%, 0.2%, 0.4%, 0.6% and 0.8%. The composition of each sample (concrete) is detailed in Table 1. The main materials used for the realization of the samples are an electronic balance and the mixer of Fig. 3.

Fig. 3. Concrete mixer.

Table 1. Composition for 1 m^3 of concrete

Sample	Fiber rate	Component mass (kg)				
		Fiber	Cement	Water	Crush 0/5	Dune sand
BF-00	0%	0.00	350.00	230.00	433.20	1193.80
BF-01	0.1%	2.21	350.00	230.00	428.67	1181.28
BF-02	0.2%	4.42	350.00	230.00	424.13	1168.76
BF-04	0.4%	8.86	350.00	230.00	415.01	1143.64
BF-06	0.6%	13.32	350.00	230.00	405.86	1118.43
BF-08	0.8%	17.80	350.00	230.00	396.67	1093.10

2.2 Thermal characterization

The thermal characteristics were determined by the asymmetric hot plane method with the DesProTherm device (Fig. 4) under controlled ambient conditions (20 C ± 2 °C and 50% ± 5% relative humidity). The principle of the asymmetric hot plane method is presented in Fig. 5, which allows the determination of the thermal effusivity *E* and the volumetric heat capacity *C* of the samples. The thermal effusivity was determined with samples of dimensions 6x4x3 cm^3 and the heat capacity with samples of 6x4x1 cm^3 (Fig. 6.). These dimensions allowed to completely cover the measuring cell and on the one hand to prevent the heat flow from passing through the sample (for the measurement of the thermal effusivity) and on the other hand to completely pass through the sample (for the measurement of the thermal capacity). All these conditions are absolutely essential in this experiment. [18].

Fig.4. DesProTherm thermal characteristics measurement device.

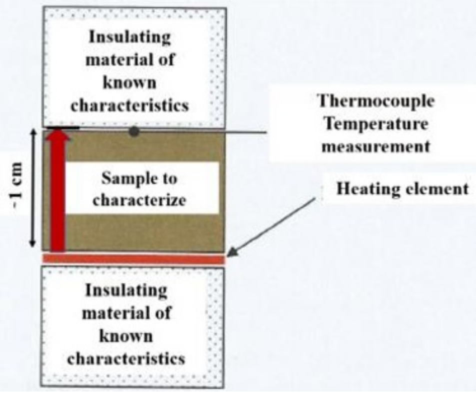

Fig. 5. Functional principle of the asymmetric hot plane method [18].

Fig. 6. Photo of the thermal test samples.

2.3 Computing other thermal characteristics

To further investigate this study, other thermal characteristics were determined by calculation. The thermal conductivity λ and thermal diffusivity a were determined by expressions (1) and (2), respectively [18].

$$\lambda = \frac{E^2}{\rho.C} \tag{1}$$

$$a = \left(\frac{E}{\rho.C}\right)^2 \tag{2}$$

ρ is the density of the material.

The associated errors in the calculations of λ and *a* were calculated with expressions (3) and (4), respectively. These expressions were obtained by uncertainty propagation [19].

$$\frac{\Delta\lambda}{\lambda} = \left(2\frac{\Delta E}{E} + \frac{\Delta\rho}{\rho} + \frac{\Delta C}{C}\right) \tag{3}$$

$$\frac{\Delta a}{a} = 2\left(\frac{\Delta E}{E} + \frac{\Delta\rho}{\rho} + \frac{\Delta C}{C}\right) \tag{4}$$

To carry out these calculations, the densities of the concretes were determined according to the standard NF EN 12390-7 [20].

3 Results and discussions

3.1 Thermal Effusivity and Heat Capacity

The results obtained after the experiments are summarized in Table 2. Fig. 7 and 8 show respectively the evolution of thermal effusivity and heat capacity as a function of the fiber percentage. The thermal effusivity *E* decreases when the quantity of fibers in the samples increases. This decrease is gradually reduced from 11.4% (between 0 and 0.1% of fibers content) to 5% (between 0.6% and 0.8% of fibers content). Its evolution is approximately linear with a correlation coefficient $R^2=0.90$. In addition, the heat capacity *C* increases with the fiber rate from 0.1%. Its variation is almost linear with a correlation coefficient $R^2 = 0.96$. The volumetric heat capacity being the heat necessary to raise by 1°C the temperature of a cubic meter of a material and the thermal effusivity being the capacity of a material to exchange heat with its environment, the increase of *C* and the decrease of *E* with the percentage of fiber shows that the fiber reinforced concretes would be less sensitive to heat exchanges.

Table 2. Thermal characteristics of concretes

Materials	**Mass percentage of fibers**	**Thermal Effusivity ($J/m^2.K.s^{1/2}$)**	**Volumetric heat capacity ($kJ/m^3.K$)**
BF 00	--	1360 ± 13	1810 ± 1
BF 01	0.1%	1205 ± 33	1800 ± 13
BF 02	0.2%	1144 ± 18	1875 ± 26
BF 04	0.4%	1038 ± 12	1918 ± 72
BF 06	0.6%	1009 ± 18	2010 ± 12
BF 08	0.8%	958 ± 4	2046 ± 62

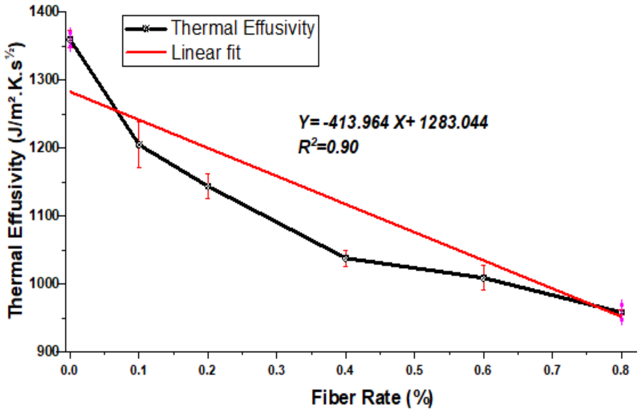

Fig. 7. Thermal effusivity evolution

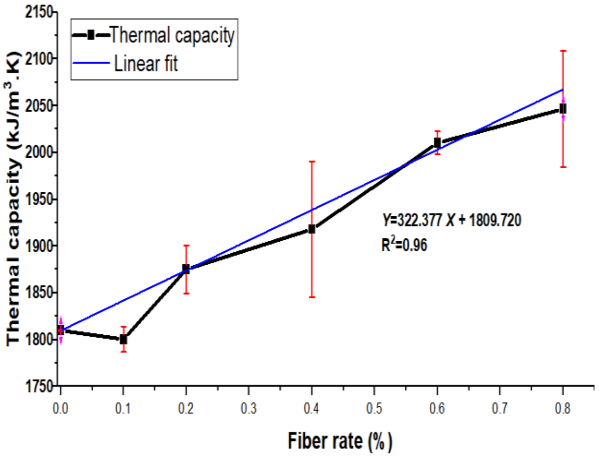

Fig. 8. Evolution of thermal/heat capacity

3.2 Density

In order to find the other thermal characteristics, the densities were determined. Fig. 9 shows the evolution of the density as a function of the fiber ratio. The density decreases with the increase of the fiber rate. It varies from 2.205 t/m^3 to 2.001 t/m^3. This is not surprising, since the fibers are lighter than the aggregates, and therefore make the concrete lighter [21]. Moreover, an approximation shows that the evolution of the density follows a linear law with a correlation coefficient $R^2 = 0.99$. The value of the correlation coefficient shows that this approximation is very good.

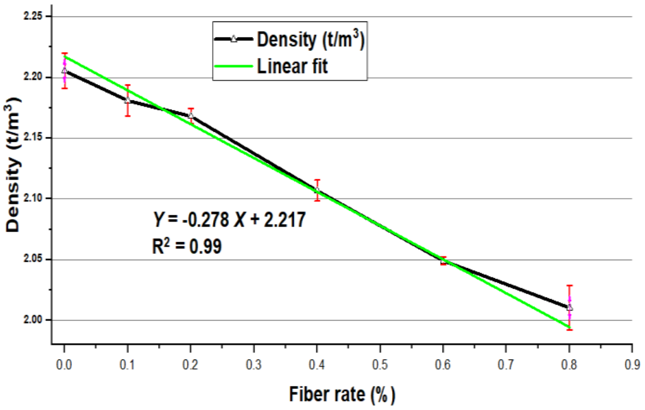

Fig. 9. Density evolution with fiber content

3.3 Thermal conductivity and thermal diffusivity

The thermal conductivity and thermal diffusivity of the concretes were calculated as described in Section 2.3. The results are summarized in Table 3. Fig. 10 and 11 show respectively the evolution of thermal conductivity and thermal diffusivity as a function of the percentage of fiber in the concrete. These figures show that the two characteristics decrease when the quantity of fibers in the samples increases. The evolution of each of the two characteristics is comparable to an asymptotic exponential function, with correlation coefficients of $R^2 = 0.99$. Being boundary formulations (percentage below 1%), the thermal conductivity and thermal diffusivity would follow an exponential law [22].

Table 3. Thermal characteristics of concretes (continued)

Materials	**Mass percentage of fibers**	**Thermal conductivity (W/m.K)**	**Thermal Diffusivity ($10^7.m^2.s$)**
BF 00	--	1.022±0.020	5.647±0.328
BF 01	0.1%	0.806±0.050	4.479±0.804
BF 02	0.2%	0.698±0.032	3.722±0.454
BF 04	0.4%	0.562±0.034	2.929±0.424
BF 06	0.6%	0.506±0.021	2.519±0.301
BF 08	0.8%	0.448±0.017	2.191±0.188

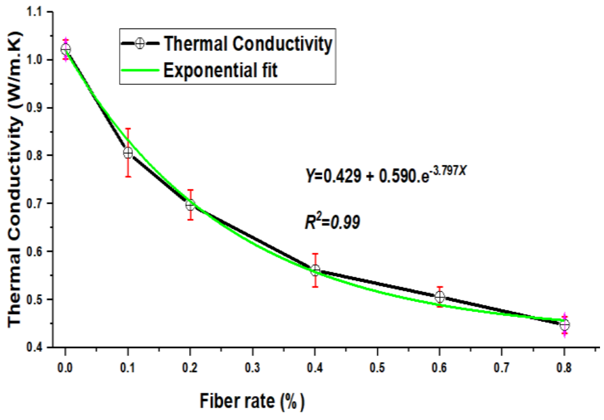

Fig. 10. Evolution of the thermal conductivity with the fiber rate

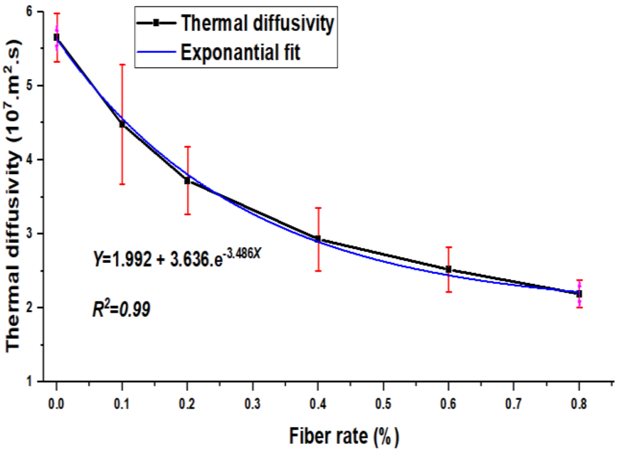

Fig. 11. Evolution of the thermal diffusivity with the fiber rate

The thermal conductivity is the main thermal characteristic of an insulating material, it defines its ability to conduct heat. It is used to determine the thermal resistance *R* of a wall (wall) by the formula (5). The lower λ is, the higher *R* is and the wall resists heat. The concretes containing these fibers would resist better to heat than conventional concretes.

$$R = \frac{e}{\lambda} \tag{5}$$

e is the thickness of the wall.

The graphs in Fig. 10 and 11 are exponential functions that each have a concavity in the interval [0.2%, 0.4%]. This concavity is a particular point. It is the point that would correspond to the best formulation to obtain the optimal thermal characteristics. The cotton ginning waste fiber concretes with the best thermal characteristics would contain 0.2% to 0.4% fibers.

4 Conclusion

This study explored the possibility of incorporating fibers in building materials and the evaluation of the thermal performance of these new materials. The evolution of the thermal characteristics with increasing fiber content was also studied. It is deduced that concretes containing fibers are lighter than ordinary concretes, and the density of concretes decreases linearly with the fiber content.

The incorporation of the fibers led to an increase in the heat capacity and a decrease in the thermal effusivity. This shows that fiber-reinforced concretes would be less sensitive to heat exchange. Moreover, the decrease in thermal diffusivity and thermal conductivity leads to the conclusion that these concretes diffuse less, conduct less and therefore resist heat more. The best compositions would contain 0.2% to 0.4% of cotton waste fibers. Therefore, concretes reinforced with industrial cotton waste fibers could allow the construction of buildings respecting the tropical climate and providing an interior comfort requiring less air conditioning and/or ventilation.

The thermal properties of these materials give them an autonomous capacity of temperature regulation by a good thermal resistance that limits the heat transfer, a low thermal diffusivity that limits the diffusion (loss of stored heat) and a high thermal capacity that allows to store a large quantity of heat. The use of these materials would have several advantages. It would limit the carbon footprint of buildings. It would also allow the keeping of clean cities by the valorisation of industrial and agricultural waste. The use of these materials would also lead to the construction of buildings that could be, from the comfort aspect, energetically intelligent and autonomous.

This incorporation is limited because it would have other consequences on the mechanical properties of the concrete. Future studies must address the limit of incorporation while maintaining the maximum of other properties of concrete.

Acknowledgements

The work was financed by the company COLAS AFRIQUE, within the framework of a collaboration with the Polytechnic School of Abomey-Calavi. The authors also thank the World Bank through its financing of the CoE-EIE center of the University of Abomey-Calavi.

References

1. Direction de la Stratégie Groupe Engie, *Un Monde d'Energie*, (2019).
2. Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC), *Réchauffement planétaire de 1,5 °C*, (2019).
3. T. H. Oh, S. C. Chua, Renew. Sustain. Energy Rev., **14**, 2095–2103, (2010).
4. Z. Fang, N. Li, B. Li, G. Luo, Y. Huang, Energy Build., **77**, 197–205, (2014)
5. S. Mirrahimi, M. F. Mohamed, L. C. Haw, N. L. N. Ibrahim, W. F. M. Yusoff, A. Aflaki, Renew. Sustain. Energy Rev., 53, 1508–1519, (2016).
6. S. B. Sadineni, S. Madala, R. F. Boehm. Sustain. Energy Rev., 15, no. 8, 3617–3631, (2011)
7. S. D. Zwanzig, Y. Lian, E. G. Brehob, Energy Convers. Manag., 69, 27–40, (2013)
8. Gouvernement de la Republique du Bénin, "Évolution de la production du coton ces 10 dernières années au Bénin," 2021.
9. FAO, *Cultures et produits animaux*, (2021). http://www.fao.org/faostat/fr/#data/QCL.
10. G. C. Semassou, A. R. O. I. Alakouko, and E. C. Vodounnou, Int. J. Adv. Res., **9**, 714–723, (2021).
11. A. R. Alakouko, G. C. Semassou, R. H. Ahouansou, and C. Guidi, Adv. Mater., **11**, 60–68, (2022)
12. N. Ranjbar and M. Zhang, Cem. Concr. Compos., **107**, (2020)
13. L. Aditya et al. Renew. Sustain. Energy Rev., **73**, 1352–1365, (2017)
14. A. Briga-Sá et al. Constr. Build. Mater., **38**, 155–160, (2013)

15. H. Binici, M. Eken, M. Dolaz, O. Aksogan, M. Kara, Constr. Build. Mater., **51**, 24–33, (2014).
16. J. Festa, G. Dreux, *Nouveau guide du béton et ses constituants*. Eyrolles. (1998).
17. C. Hamza, S. Bouchra, B. Mostapha, B. Mohamed, Procedia Struct. Integr., **28**, 430–439, (2020)
18. S. Omar Sore, A. Messan, E. Prud'homme, G. Escadeillas, F. Tsobnang, Constr. Build. Mater., **165**, 333–345, (2018).
19. D. Pelletier, *Les sources d'incertitude en gestion des pêcheries. Evaluation et propagation dans les modèles*, Institut National Agronomique, (1991).
20. CEN, NF EN 12390-7. (2019).
21. M. Saidani, D. Saraireh, M. Gerges, Eng. Struct., **113**, 328–334, (2016).
22. N. GHEBRID, *Etude des problèmes de conduction thermique dans un matériau composite à matrice polymère pigmenté de dioxyde de Tit*, Université Ferhat ABBAS, (2018).