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Improving The Mechanical and Thermal Behavior of a Compressed Earth Block Using Fibers

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Abstract

Fibers are widely used in construction because they have mechanical and thermal properties that improve the properties of structures added to them. This paper addresses the improvements made to the compressed earth block (CEB) when palm fibers and glass are added. This block is made up of soil and cement. The fiber ratio varies between 0% and 0.4%, and a compressive force of 2.5 MPa is applied to the samples. The physical, mechanical, and thermal properties of the CEB are studied according to systematic criteria using a numerical simulation program to find out how heat is transferred inside the samples. Preliminary results showed that the addition of fibers reduces the bulk density value between 1.88% and 11%, increases the compressive strength between 14.28% and 28.85%, decreases the thermal conductivity value between 1.38% and 22.22%, and decreases specific heat observed by 19.34% and 25.77%. These results give a clear view of the changes in the CEB when fibers are added and how to improve some properties.

Keywords: Bulk density; Compressed earth block; Compressive strength; Glass fibers; Palm fibers; Specific heat thermal conductivity

1. Introduction

Because cement building materials contribute to carbon dioxide emission by 7% globally [1], [2], it has become popular to pay attention to traditional buildings or environmentally friendly houses [3]; these buildings use environmentally friendly materials, such as clay in their installation, because they reduce energy consumption and are considered an excellent thermal insulator and they are also low cost of production and use [4]. In the south of Algeria, the population suffers from overheating, and residents in rural areas use local materials in construction to cope with high temperatures [5]. In ancient times, adobe bricks were used in several regions, such as New Zealand, India, and Australia [6]-[9]. However, researchers note this brick has several disadvantages, such as wear over time. It is not resistant to climatic factors and significantly absorbs water. Therefore, the researchers turned to the use of compressed earth technology. It is made by compacting the soil in a particular area. This results in increased brick hardness and reduced water absorption. Elavarasan used this technique in his work [10].

Moreover, Han, and others used fibers in their work [11]. Fibers are added to the soil to increase its firmness. In previous studies, palm fibers, straw [12], [13], bamboo, cork, and coconut [14]-[16] were used. Stabilizers such as lime can be added to improve thermal properties [17] or cement to reduce soil shrinkage [18].

In this paper, the improvements that occur on the compressed earth block when adding palm fiber and glass are studied from the physical, mechanical, and thermal points of view. Samples of soil and cement are made, and the fiber ratio is changed to 0% ‹0.1% ‹0.2‹%, 0.3 %, and 0.4% after drying the samples for 28 days. Physical properties such as the change in bulk density are studied. It studies mechanical properties by calculating the compressive strength needed to crush samples.

Experiments are limited to thermal properties such as thermal conductivity and specific heat. For comprehensive work, the COMSOL numerical simulation program performs numerical simulations of samples to understand the methods of heat propagation. Heat is considered a mechanical stress that affects the walls and the building. The work is divided into three teams: the first determines the change in the bulk density of the samples when adding fibers. The second group studied the change in the pressure force applied to the samples. The third group studied the thermal variables of the samples. Its objective is to compare the experimental and theoretical results to understand the thermal behavior of houses made of this brick. This paper aims to link the mechanical and thermal properties in the compressed earth block when adding fibers in terms of improvements (increased rigidity and thermal insulation).

2. Materials and Method

2.1. Materials

2.1.1. Soil

This paper used soil from the Bechar region in southern Algeria. It was analyzed granularly, the Atterberg limits studied, and the most appropriate water content determined. These characteristics show that this soil contains a little clay; the rest contains sand and silt. It is suitable for forming compressed earth blocks (CEB). Table 1 shows this soil's chemical composition and physical properties [19].

Table 1. Characteristics of the soil used[19].

Chemical properties		Physical properties	
Carbonates (Co_3^{-2})	6.8%	Absolute density (g/cm^3)	2.7
Sulfates (SO_4^{-2})	Traces	Apparent density (g/ cm^3)	1.3
Chlorides (CL^-)	0.39%	Sand equivalent ES (%)	11.58
Insoluble (SiO_2,MGO,CAO,AL_2O_3+ Fe_2O_3)	92.81%	Liquidity limit (%)	19.45
VBS	1.2%	Limit of plasticity (%)	11.36
Activity coefficient Ca	0.87%	Consistency index (%)	0.92
		Plasticity index (%)	8.09

The test demonstrates the Atterberg limit. This soil's plasticity index is 8.09%, which means that it is moderately plastic and contains little clay. Fig. 1 represents the granular analysis of the soil used in the experiments.

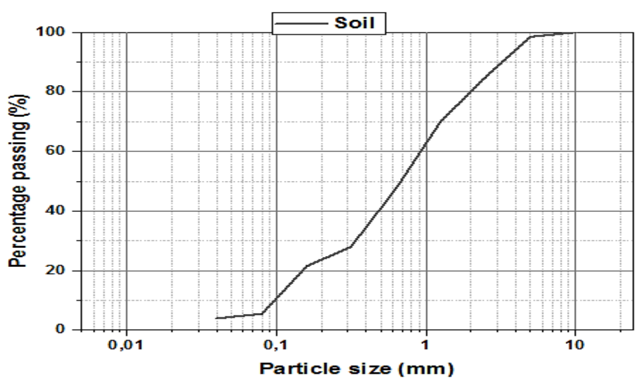

Figure 1. Soil particle analysis.

2.1.2. Cement

Portland cement CEM II/B class 42.5 was used. This cement is widely spread in northern Algeria and is characterized by a high percentage of calcium oxide (CaO), 61.43%. The chemical composition of this cement is presented in Table 2 [18].

2.1.3. Palm Fibers (PF)

Palm fibers are vegetable fibers sourced from the palm tree. This fiber is characterized by its natural fiber. It does not cost to extract or use. In addition, it is environmentally friendly [20]. It contains chemical elements such as cellulose, hemicellulose, lignin, and lipids. In addition to its mechanical properties, it can increase durability in Earth samples. The properties of palm fiber are shown in Table 3 [21].

Table 2. Chemical composition of cement used [18].

SiO_2(%)	Al_2O(%)	Fe_2O(%)	CaO(%)	MgO(%)	$SO(\%)_3$	Cl(%)	K_2(%)O	Na_2O(%)
21.45	4.31	4.56	61.43	1.24	2.28	0.01	0.61	0.39

Table 3. Properties of palm fibers [21].

Chemical Properties		Mechanical Properties	
Cellulose	27%	Tensile strength	170-275 MPa
Hemicellulose	37%	Young's modulus	5 – 12 MPa
Lignin	28%	Elongation	5 -10 %
Fats	7%		

2.1.4. Glass Fibers (GF)

Glass fibers are synthetic fibers characterized by great shear strength and thermal stability. This makes them the best product in composite material applications. Class E was used, which is used in the manufacture of internet threads that contain silica, silicon, and aluminum oxides. Table 4 shows the characteristics of these fibers [20].

Table 4. Properties of glass fibers [22].

Density (g/cm^3)	Filament diameter (mm)	Diameter (μm)	Tensile strength (MPa)	Lengthen at break (%)	Modulus of elasticity (Mpa)	Density (g/cm^3)
2.57	12	19	3500	4.8	73500	2.57

2.2. Method

In these experiments, the following devices were used:
1. A sieve is used for sifting the soil with a diameter of 5 mm.
2. Scissors are used to cut palm fiber and glass with a length of 2 cm.
3. An electric mixer is used to mix the soil with cement and water well.
4. Laboratory funnel for determining the percentage of water and measuring volume.
5. Hydraulic pressure machine with a screen to control the pressure force on the samples.

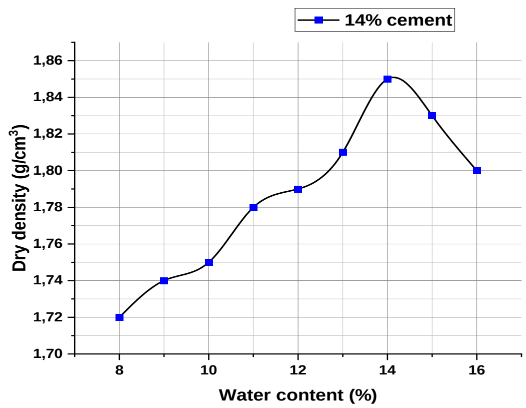

Figure 2. Optimum water content at 14% of cement.

2.2.1. Preparation of Laboratory Samples

The proctor pressure test was used [23] to determine the optimal water content for sample pressure. This test correlates the purity density with the water content. The optimal water percentage is determined by changing it each time, and the bulk density value is calculated. By plotting a curve, a clear relationship between the water percentage and the bulk density value has been demonstrated, a key finding in the paper. The best water ratio corresponds to the highest value of bulk density. This test is referenced according to ASTM D1557. The percentage of water used in mixing is changed as the ratio of soil and cement. The samples with the highest density will correspond to the optimal water content. Fig. 2 shows the optimal water content for mixing cement with the used soil. Based on the analysis of Fig. 2, the best water percentage is 14%, which corresponds to a cement content of 14%. Samples are prepared according to the following:

Weight 2000 grams (total mass) 14% Water, 14% cement, 72% soil. The optimal cement ratio is calculated similarly to the water rate. The cement percentage is changed from 10 % to 18 %. Mix the contents with an electric mixer for 3 minutes to obtain a homogeneous mixture. Glass fibers and palm are added. Table 5 shows how to prepare samples. The wet mass is pressed into a metal mold with dimensions of 20×10×5 cm^3. They are using a hydraulic press machine. A compression force of 2.5 MPa is used. Three samples are made from each fiber ratio. The samples are left to dry for 28 days.

Table 5. Sample preparation.

Soil (%)	Cement (%)	Water (%)	Glass fibers (%)	Palm fibers (%)	Samples
72	14	14	0	0	SF0
			0.1	0	SG1
			0.2	0	SG2
			0.3	0	SG3
			0.4	0	SG4
			0	0.1	SP1
			0	0.2	SP2
			0	0.3	SP3
			0	0.4	SP4

2.2.2. Change in Density

The bulk density was measured by weighing the samples and measuring their volume by applying Equation (1):

$$\rho = \frac{m}{v} \tag{1}$$

The bulk density is related to the number of pores in the soil and expresses the extent of water and air movement. The results of the bulk density measurement are shown in Fig. 3.

2.2.3. Change in Compressive Strength

The pressure force was measured using the type 3000 KN headlock pressure. A vertical pressure was applied to an area of 20×10 cm^2 at a speed of 0.3 N/s. Power supply: 230V 50Hz 750W.The stresses law was applied, as described in Equation (2):

$$\sigma = \frac{F}{A} \quad (2)$$

The machine adjusts when the samples break. The values were taken from the machine screen. The results of measuring the pressure value are shown in Fig. 4.

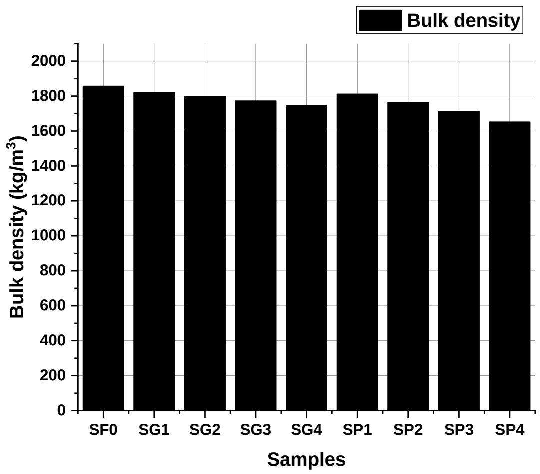

Figure 3. The change in bulk density when adding fibers.

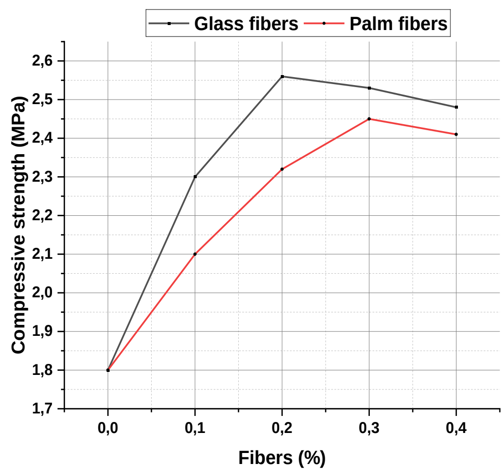

Figure 4. Compressive strength of samples.

2.2.4. Change in Thermal Conductivity

The thermal conductivity is measured with a Huxseflux device equipped with a thermal needle, which is also used to measure the heat resistance in the soil.

The measurement is carried out according to ASTM d5334 standards. A hole is drilled in the samples, and the carrier is measured with a needle inside the brick. The device gives direct numerical values. The results of measuring thermal conductivity are shown in Fig. 5.

2.2.5. Calculation of Specific Heat

A calorimeter, a device used to measure the amount and exchanges of heat, was used to measure the specific heat [24]. The calorimeter acts as an isolated system of substances contained inside it. It prevents the loss or gain of energy or matter with the external medium [25]. Three samples weighing 50 g were made from each ratio of palm fibers and glass.

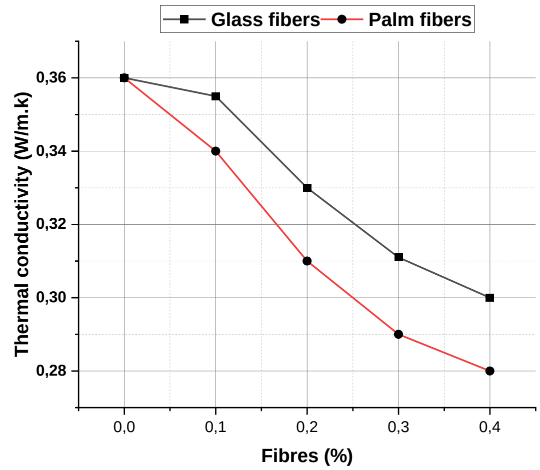

Figure 5. Change in thermal conductivity.

After being dry for 28 days, the samples were covered with aluminum strips and placed in a 50 C^0 oven for 6 hours. Each sample is placed in a calorimeter, and the temperature change is measured. Specific heat was calculated using Equation (3):

$$CP = \frac{Q}{m.\Delta T} \quad (3)$$

Q is heat (J),m is mass (g), ΔT is Temperature change (C^0). When samples are placed inside the calorimeter, a heat exchange occurs between the heat of the masses and the water.

To obtain accurate results, initial and final water temperatures were calculated (after placing the samples in the calorimeter). The calculation stops when the state of thermal equilibrium is reached, which means that the water temperature is equal to the temperature of the samples. Equation (4), Equation (5), and Equation (6) are used to calculate the heat.

$$Q_{water} = Q_{sample} \quad (4)$$

$$Cp_{water} \times m_{water} \times (T_2 - T_1) \quad (5)$$

$$Cp_{sample} \times m_{sample} \times (T_2 - T_1) \quad (6)$$

The amount of water heat is calculated:

- Water weight 0.25 kg= 250 CL. The specific heat of water is 4180 J/kg.k. The initial temperature is T_1=20C^0.
- The final temperature is T_2 water. The results are shown in Fig. 4.

In the calorimeter, energy is conserved. This means that the amount of heat the water gains equals the heat lost by the samples. The value of each sample's thermal energy and weight is substituted, and the specific heat of each sample is calculated.

3. Results

Table 6 represents the results of measuring the bulk density, compressive strength, thermal conductivity, and specific heat.

Table 6. Measurement results in experiments.

Samples	Bulk density(kg/m^3)	Compressive strength (MPa)	Thermal conductivity(W/m.k)	Specific heat(J/kg.k)
SF0	1857	1,8	0,36	913
SG1	1822	2,3	0,355	1173
SG2	1798	2,56	0,33	1167
SG3	1773	2,53	0,311	1156
SG4	1745	2,48	0,3	1132
SP1	1812	2,1	0,34	1230
SP2	1764	2,32	0,31	1211
SP3	1713	2,45	0,29	1190
SP4	1652	2,41	0,28	1181

3.1. Bulk Density

Fig. 3 represents the change in bulk density values when adding palm fibers and glass, showing that the density decreases when the percentage of fibers increases. Compared with the fiber-free sample (SF0), a decrease in density between 1.88% and 6.03% was observed with the addition of glass fibers and a reduction between 2.42% and 11.04% with palm fibers. This is explained by adding fibers in the CEB, increasing the number of pores inside the samples, called high porosity [26].

The decrease in density is more significant with samples containing palm fiber. This is explained by the fact that the palm fibers absorb part of the water used for mixing. This makes the samples dry faster. This is consistent with previous work [27]. At the same time, glass fibers do not absorb water and keep the moisture of the material. In addition, the diameter of the glass fiber is smaller than the diameter of the palm fibers. This shows that the pore size is smaller in bricks that contain these fibers [28].

3.2. Compressive Strength

When analyzing Fig. 4, it appears that the compressive strength value increases with the increase in the fiber's ratio. When comparing the increase in the pressure force, it was observed that it increased by 21.7% and 29.7% with glass fibers and increased by 14.3% and 26.53% with palm fibers.

The compressive strength increases to within 0.2% of the glass fibers and then decreases, as the same observation is in palm fibers at 0.3%, where the compressive strength decreases after this percentage. Adding fibers to the CEB increases the hardness of bricks [29]. The fibers increase the cohesion between the soil grains, which increases the compressive strength necessary to break the samples [30].

In terms of increased durability, glass fiber is better than palm fibers, and this is explained by the fact that glass fibers have greater tensile strength than palm fibers (3500>275), as shown in Tables 3 and 4. Fibers' effect is limited in specific proportions, and it becomes negative when added in large proportions [31].

3.3. Thermal Conductivity

Thermal conductivity is important in determining the degree of thermal insulation of objects. Heat is transmitted through several ways (convection - radiation-conduction.) [30]. Fig. 5 represents the change in thermal conductivity values when adding palm fibers and glass. It was observed that the thermal conductivity decreases when adding fibers. The convection decreases between 1.38% and 16.66% when adding the glass fibers and drops between 5.55% and 22.2%. This decrease is explained by the fact that the fibers create gaps inside the bricks, thus impeding heat transfer. This is consistent with previous work [33]. A direct relationship between thermal conductivity and bulk density. The lower the density, the lower the thermal conductivity [34].

The decrease in thermal conductivity is more significant with samples containing palm fibers. This is explained by the fact that palm fibers are plant-derived and insulate heat better than glass fibers [35].

3.4. Specific Heat

Before adding fibers, the specific heat value is 913 j/kg.k.The particular heat value increases when the glass fibers are added between 22.16% and 19.34%. It also rises when palm fibers are added between 25.77% and 22.7% compared with the sample. At the same time, the specific heat decreases when the proportion of palm fibers and glass increases; when analyzing Fig. 6, it was noted that the particular heat decreases with the higher percentage of fibers [36]. This explains that the fibers increase in thermal insulation, thereby improving the samples' specific heat [37]. The decrease is more significant with palm fibers in proportion to 14%—compared with glass fibers. The specific heat of the CEB is related to the thermal conductivity. The particular heat decreases when the thermal conductivity value decreases [38]. When measuring the specific heat, the samples must be dry and moisture-free, affecting the accuracy of the results [39].

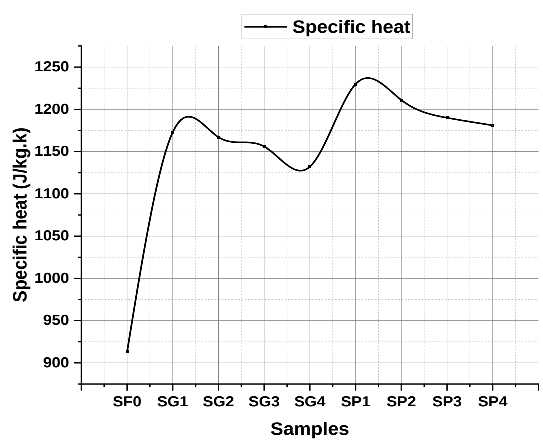

Figure 6. Change in specific heat value.

A heat transfer simulation was performed using the COMSOL program to understand the heat transfer inside the compressed brick. This program simulates designs and devices in various fields, such as manufacturing and engineering. It can define the properties of materials and identify phenomena, which gives accuracy in the results and calculation [40]. This program is used to understand how heat is transferred through compressed earth bricks exposed to an initial temperature of 50 C^0. The Heat-exposed area is 20×5 cm^2—sample thickness 10 cm. Fig.

7 represents a 90-minute heat transfer in a fiber-free sample. It turns out that the temperature is in a gradient and is related to the type of fiber, the kind of fixing material, the degree of humidity, and the duration of heat exposure [41].

The convergence in heat transfer is observed between Fig.7(A), where heat is transferred for 35 minutes, and Fig.7(B), where heat transfers for 40 minutes.

The difference in the distance the heat has moved is shown between Fig.7(C), where the heat is transferred for 60 Minutes, and Fig.7(D), where the heat has been transferred for 90 minutes.

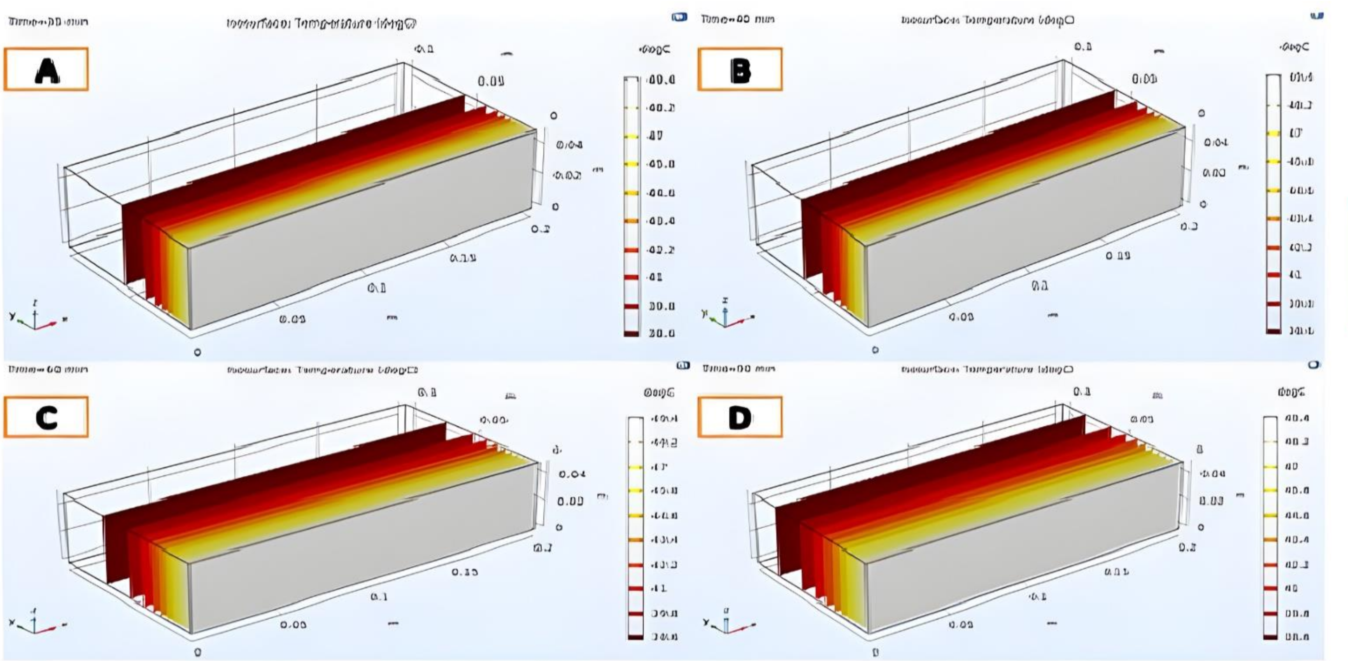

Figure 7. Heat transfer in the sample SF0.

4. Conclusions

In this paper, the effect of adding palm fibers and glass in proportions of 0% to 0.4% was studied on the mechanical and thermal properties of a compressed earthen block (CEB) consisting of 72% soil, 14% cement, 14% water, which was compressed with a pressure force of 2.5 MPa. The following results can be concluded:

The composition of the CEB affects the overall characteristics, and the addition of fibers reduces the bulk density by 1.88% - 11%, which improves the brick and makes it light. The addition of fibers, A specific percentage, significantly enhances the compressive strength of the brick, leading to a substantial improvement in its hardness. The effect of the fibers is limited to particular proportions (0.2% glass fibers, 0.3% palm fibers), and their impact becomes negative in high proportions. Glass fibers represent the best option for increased durability compared to palm fibers. Adding fibers increases thermal insulation and impedes heat transfer through the brick. This is evidenced by a decrease in thermal conductivity value between 1.38% and 22.22% and a decrease in specific heat between 19.34% and 24.6%, which is considered a positive thing in the field of thermal insulation.

The fibers and the applied compressive strength improve the compressed earth block's (CEB) properties. The results also showed that palm fiber has better thermal insulation than glass fibers. The sizeable compressive strength also increases the brick's cohesion and reduces its water permeability. Given these findings, this technology could be particularly beneficial in construction projects in regions with low rainfall and infrequent seismic activity.

Nomenclature

CEB Compressed earth block.

SF0 Traditional block without improvements

SG1 Improved block compressed under 2.5MP strength with 0.1% glass fibers.

SG2 Improved block compressed under 2.5MP strength with 0.2% glass fibers.

SG3 Improved block compressed under 2.5MP strength with 0.3% glass fibers.

SG4 Improved block compressed under 2.5MP strength with 0.4% glass fibers.

SP1 Improved block compressed under 2.5MP strength with 0.1% palmfibers.

SP2 Improved block compressed under 2.5MP strength with 0.2% palm fibers.

SP3 Improved block compressed under 2.5MP strength with 0.3% palm fibers.

SP4 Improved block compressed under 2.5MP strength with 0.4% palm fibers.

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Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Authors Contributions Statement

Fidjah Abdelkader: Proposed a business problem and supervised its results.

Rabehi Mohamed and Kezrane Cheikh verified the analytical methods and supervised the findings of this work.

Adda Hanifi Mohamed Amine: Provision of paper materials.

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