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Thermal and Mechanical Properties of Two Sensible Energy Storage Materials (Firebrick)

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ABSTRACT: The thermal and mechanical properties of two sensible energy storage materials (Firebrick) were investigated. The properties examined were compressive strength, bulk density, porosity and thermal conductivity. The compressive strength results of the two sensible thermal storage materials (STSM) A and B were 8.82 and 9.79 MPa, respectively. The bulk density values for the STSM A and B were 1740 and 1920 kg/m^3, respectively. Also, the obtained porosity values for the STSM A and B were 77.2 and 71.5%, respectively. The STSM A and B thermal conductivity values were 1.27 and 1.76 W/m.K, respectively. The study revealed that both the STSM A and B are suitable for sensible thermal energy storage purposes.

KEYWORDS: Thermophysical properties; Mechanical properties; firebrick; thermal storage materials; soil samples

1.0 INTRODUCTION

There is an increase in global energy demand due to the fast-growing population. Over the years, dependence on nonrenewable energy sources (fossil fuels) has become uneconomical. Additionally, the associated challenges of carbon emissions remain unresolved. Therefore, the adoption of renewable energy sources such as solar, hydro, wind, biomass, geothermal energy, etc., has played a major role in solving the energy crisis, and they could be adopted to reduce the world’s reliance on fossil fuels[1]. Among these renewable energy sources, solar energy is the most widely utilized in various applications, including drying, building energy efficiency, domestic water heating, and power generation. However, there are limitations to the operation of solar energy systems due to the associated problems of intermittency and weather dependency[2]. Hence, increasing the operation period of solar energy systems necessitates the introduction of thermal energy storage materials. Thermal energy storage materials can be classified as sensible, latent heat, thermophysical, or a combination of these[2-5]. The selection of the energy storage method depends on the source of energy, the energy requirement for the specific application, the budget, and the infrastructural feasibility of the system[6]. For sensible thermal storage, the amount of energy that can be stored within a specific medium depends mainly on the material’s specific heat capacity, energy density, thermal diffusivity, mass, thermal conductivity, specific volume, mechanical stability, operating temperature range, vapour pressure, and cost effectiveness[7]. Generally, the viability of materials as a storage medium in practical thermal storage systems is assessed based on their thermophysical, chemical, mechanical, environmental, and economic characteristics.[6]. Materials for thermal energy storage are anticipated to possess a large volumetric heat capacity, a compressive strength greater than 1 MPa, and the capacity to tolerate thermal cycling [8]. Also, for brick, compressive strength is important for determining the brick's load bearing capacity. The second method of thermal energy storage is latent heat storage, wherein the thermal energy is stored or released by the storage medium, called a phase change material (PCM), during a phase change. The amount of energy that can be stored or released depends mainly on either the latent heat of fusion or the latent heat of vaporization, depending on whether the phase change is between solid and liquid or liquid and vapor, respectively[6]. In a thermochemical thermal storage system, the solar energy to be stored is used to produce a certain endothermic chemical reaction and the products of the reaction are stored.

Researchers have documented the determination of thermophysical and mechanical properties of thermal storage materials for various applications. These include indigenous clay mixed with Gmelina seed shells particulates[8], fired clay bricks made by using grapevine shoots as pore forming agent[9], Sand, Clay and Coal Bottom Ash[10], fired clay bricks incorporated with cigarette butts[11], lightweight aggregate mortar incorporated with phase change material[12]. However, it should be noted that a report on the determination of thermal and mechanical properties of firebricks made from the termite mound and riverbank clay for heating purposes seems to be unavailable. The objective of the study is to determine the thermal and mechanical properties of the two firebrick materials made from the termite mound and riverbank clay to store thermal energy.

2.0 Materials and Methods

2.1 Preparation process of the firebrick samples

The soil samples (Figures 1 and 2) used for molding the STSMF A and STSMF B were collected from a termite mound and river bank clay soil (for local pot making) in Omu Aran, Nigeria. The two sites are a few meters from each other.

Fig1: Sensible thermal storage material A

Fig. 2: Sensible thermal storage material B

Before the molding of the soil samples into bricks, particle size analyses were carried out using the hydrometer method (Bieganowski and Rayzak,7). The two analyses revealed that the proportions of sand, silt, and clay were 52, 6 and 42% in soil sample A (termite mound) and 26, 33 and 42% for soil sample B (river bank clay soil), respectively. The dried soil samples were finely crushed and sieved (Komolafe, 2020). They were then mixed into thick pastes with water and then molded into bricks of size 90 × 80 × 40 mm as shown in Figures 3 and 4.

Fig.3: Moulded STSM A

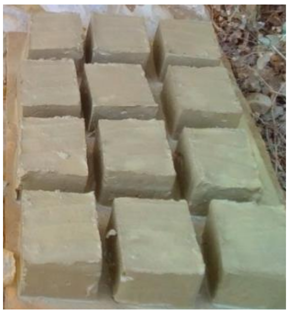

Fig.4: Moulded STSM B

The moulded bricks (STSM A and STSM B) were initially air dried at room temperature for 24 hours and then in an electric laboratory oven (Control testing equipment Ltd., Italy. Serial No. 10-D1398) at 200 °C as depicted in Figure 5. After heating to 200 °C, the bricks lost most of the water added to the samples during the preparation phase. Drying was carried out when the moisture content of the molded bricks was high to prevent the swelling or bloating of the samples, which occurs at high temperatures[13]. The firing operation for the two types of fired bricks was carried out following the procedure mentioned[13]. Firing operations were conducted as shown in Figure 6 in a box type muffle resistance electric furnace (Item No: Sx2-2.5-10, Shanghai Guagdi Instrument/equipment Company Ltd., China. Serial No: 2011-4) at 700 °C- 1100 °C in steps of 100 °C increments for 2 hours. That is, each of the five firing temperatures was maintained at 700C, 800C, 900C, 1000C, and 1100 °C. After the firing operation, the furnaces were turned off and the samples were allowed to cool down and then removed from the furnace[2, 14].

Fig. 5: Drying of STSM A and B at 200 °C

Fig. 6: Firing of STSM A and B at 700 -1100 °C

Fig. 7: Fired STSM A

Fig. 8: Fired STSM B

2.2 Mechanical Properties

2.2.1 Bulk Density

The bulk density is the weight per unit volume of the firebrick materials and it was determined following the ASTM C373-88 2006 standard[8] . After drying the firebrick samples, their dry weights were measured in a suspended condition in the air and recorded. They were allowed to cool and then immersed in a beaker of water. Bubbles were observed as the pores in the specimens were filled with water. Their soaked weights were measured in the suspended condition, both in the air and water and recorded. The bulk density of the firebrick was calculated using equation (1)

$$B_k = \frac{\rho_w \times m_{da}}{m_{sa} \times m_{sw}} \quad (1)$$

where B_k is the bulk density, ρ_w is the density of water, and m_{da}, m_{sa} *and* m_{sw} represent the dry weight of the sample in air, the soaked weight of the sample in air and the soaked weight of the sample in water, respectively.

2.2.2 Porosity

Porosity is the percentage change in volume of voids over the total volume of the sample. It can be calculated using equations (2)

$$P_{rs} = \frac{m_{sa} - m_{da}}{m_{sa} - m_{sw}} \times 100 \quad (2)$$

where P_{rs} is the porosity

2.2.3 Compression strength

Compressive strength is the ratio of the maximum load (or load until failure) to the material cross sectional area resisting the load. It was calculated using equation 3 following ASTM C133-97(2008) E1.

$$\text{Compressive strength} = \frac{Maximum\ load}{Cross\ sectinal\ area} \quad (3)$$

Compression tests were performed on samples of the two types of firedbrick using a universal Material tester (testometric M500 – 50AT) as shown in Figure 9.

Three randomly selected samples of the two brick types were used for the tests. Each firebrick STMS was placed between the testometer. The brick samples were compressed at a constant deformation rate of 1.5 mm/min (Adejumo, 2006). The applied forces and their corresponding deflection for each brick were read directly from the force-deflection curve. The mechanical behaviour of the firebricks was expressed in terms of the force required to deform the sample to initial rupture and its specific deformation.

Fig. 9: Compressive test on dried STSM using Universal testometric

2.3 Thermal conductivity

The thermal conductivity of the firebrick samples was determined using equation (4)[15]

$$K_T = \frac{2.303 M_w C\delta\left[log\left(\frac{T_{st-}T_i}{T_{st-}T_f}\right)\right]}{A \times t} \quad (4)$$

where K_T is the thermal conductivity of the firebrick sample (W/m °C); T_{st} represents the steam temperature (°C); T_i represent the initial temperature of water (°C); A represents the area of the firebrick sample (m^s), M_w is the mass of water (kg); C is the specific heat capacity of water (J/kg °C); δ represents the thickness of the firebrick sample (m)

3.0 RESULTS AND DISCUSSION

3.1Mechanical properties of sensible thermal storage materials

3.1.1 Determination of Compressive force and deflection

Figure 10 shows the mechanical behaviour of the sensible thermal storage material (STSM) from the termite mound under compression loading. The figure showed that the compression loading increased with the increase in the deflection. From the figure, the maximum compressive force and the corresponding deflection for the three samples tested were 164.18, 169.53 and 170.82 N; and 4.62, 4.90 and 8.07 mm respectively. The maximum compressive force obtained from the three samples was very close. However, the third sample showed the highest maximum compressive force and deflection.

Figure 11 shows the mechanical behaviour of the sensible heat storage firebrick (SHSF) from the riverbank clay under compression loading. The figure revealed that as compression loading increased, the deflection also increased. It can be seen that the tested samples exhibited three phases. During the first phase, the compressive force and the corresponding deflection for the three samples (1, 2 and 3) were 174.62, 236.47 and 164.1 N; and 6.53, 7.15 and 2.53. During the second phase, the compressive force fluctuated between 174.62 and 195.49 N; 236.47 and 203.94 N; and, 164.1 and 170.93 N; while their corresponding deflections were between 6.53 and 7.68; 7.03 and 9.31; and, 2.53 and 5.66 respectively. The third phase showed decay in compressive force.

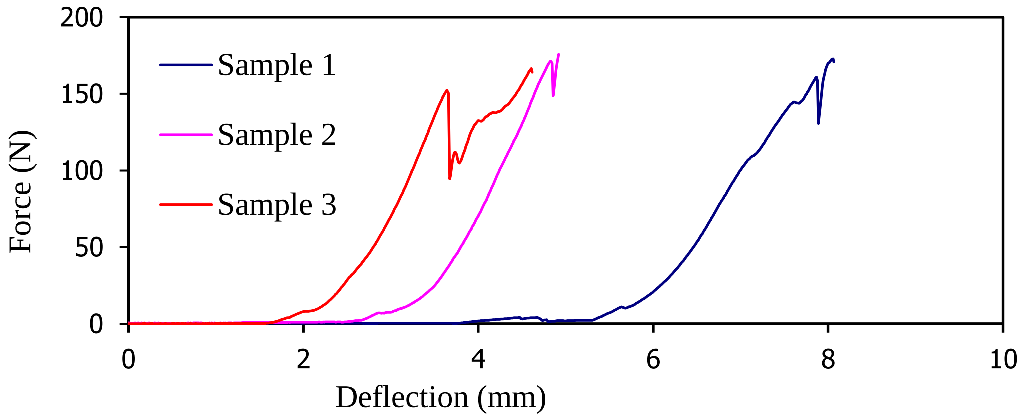

Fig. 10: Plot of force versus deflection for STSM A

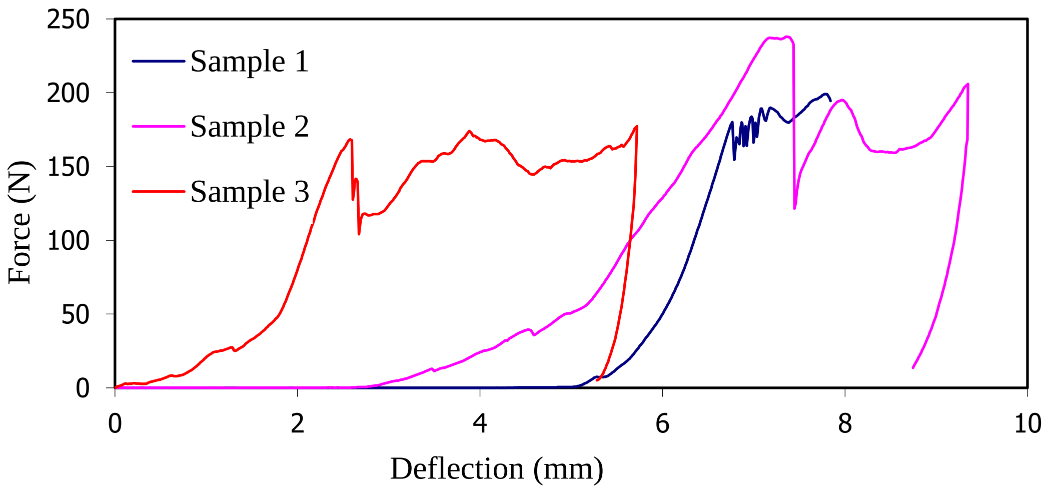

Fig. 10: Plot of force versus deflection for STSM B

Table 1 shows the average values of compressive strength, bulk density, porosity and thermal conductivity for the STSM A and B

Table 1: Average value of thermal and mechanical properties of STSM A and STSM B

Sample	Compressive strength (Mpa)	Bulk density (kg/m^3)	Porosity (%)	Thermal conductivity (W/m.K)
STSM A	8.82	1740	77.2	1.27
STSM B	9.79	1920	71.5	1.76

3.1.2 Compressive strength

The compressive strength is important for the determination of the load bearing capacity. From Table 1, the compressive strength results of the two sensible thermal storage materials A and B were 8.82 and 9.79 MPa respectively. These values are higher than the common minimum recommended values of 3 – 5 MPa and 5 – 10 MPa for non load and load bearing fired clay bricks respectively[11, 16]. The values are also greater than the range of 1-4 MPa reported for lightweight aggregate mortar[12]. Nevertheless, following the report [17] which states that thermal energy storage material should have a compressive strength higher than 1 MPa, the ability to withstand thermal cycling and high volumetric heat capacity. The obtained compressive strength values showed that the two STSM (A and B) are good sensible thermal storage materials.

3.1.3 Bulk density

From Table 1, the bulk density values obtained for the STSM A and B were 1740 and 1920 kg/m^3. These values are within the range of 1730 – 2050 kg/m^3 [10], 1800 – 2000 kg/m^3 according to AS 3700 [11]reported for (sand, clay and coal bottom ash) and (standard clay) respectively. The obtained bulk densities were also very close to 1700 kg/m^3 reported for the fired clay bricks[9]

3.1.4 Porosity

As shown in Table 1, the obtained porosity values for the STSM A and B were 77.2 and 71.5%, respectively. These values are within 70 - 82.4% considered acceptable standard values[8]

3.2 Thermal conductivity

In Table 1, the STSM A and B thermal conductivity values were 1.27 and 1.76 W/m.K, respectively. These values are higher than the thermal conductivity values of different specimens range from 0.331 to 1.014 W/m.K reported for sand, clay and coal bottom ash[10]. In general, the thermal conductivity values obtained are higher than the required value for a thermal energy storage material ($\geq 1\frac{W}{m}.K$). The obtained values are also higher than 0.28 – 0.12 W/m.K reported for refractory bricks[8]. Applications and thermal performance of the STSM A and B during solar drying of cocoa beans have been reported [2, 4, 14, 18]

CONCLUSION

In this study, the thermal and Mechanical properties of two sensible energy storage materials (Firebrick) were determined. The two sensible thermal storage materials (raw termite mound and riverbank clay) were moulded into bricks, dried and fired following the recommended standard. From the results obtained in this study, the following conclusions could be drawn:

(i) The compressive strength results of the two sensible thermal storage materials A and B were 8.82 and 9.79 MPa, respectively.

(ii) The bulk density values obtained for the STSM A and B were 1740 and 1920 kg/m^3, respectively.

(iii) The obtained porosity values for the STSM A and B were 77.2 and 71.5%, respectively.

(iv) The STSM A and B thermal conductivity values were 1.27 and 1.76 W/m.K, respectively.

The results of the thermal and mechanical properties from the two STSM indicate that they are suitable for storing heat. An analysis of the microstructural characteristics of the two STSMs is recommended for further study.

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