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Characterization of Clay and Granite Dust Blends as Novel Materials for Energy Storage and Diffuser in Constructing Flat-plate Solar Collector

Tajudeen Kolawole Ajiboye*, Mustapha Olawale Fabiyi, Ndagi Mustapha and Sulaiman Abdulkareem

Department of Mechanical Engineering, Faculty of Engineering & Technology, University of Ilorin, P.M.B. 1515, Ilorin, Nigeria

* *Corresponding author, e-mail: ajitek@unilorin.edu.ng*

Co-authors' e-mail addresses: fabiomustee@gmail.com; mxtykal2009@googlemail.com; sulkarm@yahoo.com

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Abstract

Sun is the main source of solar energy, and the energy it releases to the Earth's surface in one hour is more than what the whole planet consumes in a year. This present work is about characterizing novel material that can be used as energy storage and diffuser in constructing flat plate solar collector. Materials used are clay and granite dust obtained from Okelele and Kulende Quarry sites, both in Ilorin, Kwara State, Nigeria. The materials were sun-dried; the clay crushed before the two materials were sieved into different particle sizes. They were thereafter blended into different ratios and then characterized for thermal, physical and mechanical properties. Results showed that the highest thermal conductivity, thermal diffusivity and compressive strength were obtained from sample of particle size 0.075 mm and clay: granite ratio 50:50 (0.268176 W/mK, 3.58514 $\times 10^{-4}$ m^2/sec and 3.571 N/m^2, respectively). This same blend has a density of 0.91 g/cm^3 and specific heat capacity of 824 J/kgK. This sample, having the optimal thermal, physical and mechanical properties will be a good replacement for conventional insulating materials currently being used for solar flat-plate collector construction as it will serve as both energy storage and diffuser.

Keywords: Solar energy, solar collector, insulating material, clay, granite dust, thermal conductivity, thermal diffusivity.

Introduction

All living things depend on energy for survival, and as such there is need to explore every available source of energy and make it readily available for use. There are two main categories of energy sources; renewable and non-renewable sources. While the former can be naturally replenished, the latter cannot. Unfortunately the non-renewable energy source is the current popularly used one and there are challenges being encountered in its use, the prominent ones being its environmental hazardous nature and its possible inadequacy in the near future (Abubakar and Egbo 2014, Alghoul et al. 2014, Narbel 2014). It was estimated that by 2050, the demand for energy could double or even triple as a result of global population growth coupled with expansion of economies in the developing nations (Ziemelis et al. 2009, Foster et al. 2009 and Ayugi et al. 2011). Sun is the main source of solar energy and the energy released to the Earth's surface in one hour is more than what the whole planet consumes in a year. Furthermore, what the planet Earth receives from sun alone as energy is almost ten times more than the sum of all other energy sources put together

(Foster et al. 2009, Chen et al. 2012 and Chilambarasan et al. 2018). However, most of this energy released is not efficiently harnessed or stored for use. The upper atmosphere of the earth surface receives about 174 PW (174 $\times$ 10^{15} W) of solar radiation and about 30% of this is reflected back into the space while out of the remaining 70%, approximately 124 PW is absorbed by the land masses, clouds and oceans (Gond et al. 2016, Stutz et al. 2017). However, only an insignificant amount of this huge value is only harnessed for effective uses. For instance, as at 2018, the world solar photovoltaic installed capacity just reached 398 GW (398 $\times$ 10^{9} W), a mere 0.3% of solar energy utilization from the sun. The wide gap has been mainly attributed to lack of technology (Struckmann 2008, Bakari et al. 2014 and Karuppu et al. 2019).

Recent developments in some countries like Germany, China, Italy and USA have shown that solar energy will play prominent roles in global energy need in the near future. The global cumulative installed capacity of solar power increased rapidly from 1400 MW in 2000 to approximately 102,156 MW in 2012 with the four countries mentioned above taking the lead (Dara et al. 2013, Ohunakin et al. 2014, Chen et al. 2012 and Adelaja 2020).

It was no longer news that the use of fossil fuels causes the emission of carbon dioxide which is detrimental to human beings and the environment (Mehar and Kumari 2015, Meegoda et al. 2019. Solar energy is abundant and environmentally friendly but intermittent in supply. It is therefore imperative to devise a means of storing solar thermal energy when solar radiation is available and release such energy on demand (Chen 2011, Ge et al. 2014, Stanciu and Stanciu 2014).

Many researchers have worked on solar energy harnessing and storage especially on solar flat plate collector, but there are still much more to be done. A lot have been done on how best to improve on the efficiency of flat plate solar collectors by investigating the effects which modifications of different materials or mechanisms involved in constructing the collector will have (Hamdan and Sarsour 2018, Ibrahim et al. 2015, Jithinraj et al. 2014, Ihaddadene et al. 2018). Till to date, most emphases have been laid on how to improve on solar irradiance onto the glass, increased absorptivity, decreased emissivity and best tilt angle. However, not much has been done on how to store energy on the collector itself (Lavinia 2012, Kalogirou 2014, Jayakumar et al. 2018, Kanimozhi 2019). This aspect of energy storage has been done more on storage tank as back up for the collector. The significance of this work is to characterize and investigate the effects of clay/granite dust blend on energy storage capability of a flat plate solar collector when energy is available and how best the stored energy is released during energy off period.

Materials and Methods

The materials used for this research were clay and granite dust mixed in different particle sizes and ratios. These materials were obtained from Ilorin, Kwara State, Nigeria.

Materials processing

The procured clay was sun dried for a week to remove moisture (Plate 1). The dried clay was crushed and sieved using a set of sieves mounted on a mechanical shaker to obtain 0.075, 0.150, 0.300, 0.600, 1.00 and 1.40 mm particle sizes.

Plate 1: Samples of clay and granite dust being sun dried.

The granite dust was also sun dried and sieved into different particle sizes as those of clay, that is, 0.075, 0.150, 0.300, 0.600, 1.00 and 1.40 mm, using the same equipment and method as for the clay. After obtaining the different particle sizes, each of the samples for the two materials was tested for thermal and physical properties, as regards, thermal conductivity (W/mK), thermal diffusivity (m^2/sec), specific heat capacity (J/gK) and density (g/cm^3) (Plate 2)

Plate 2: Blended samples prepared for thermal property tests.

Thermal conductivity test

Thermal conductivity test was conducted according to ASTM E 192.11 2015 using Conductivity Meter SLS 3000 at Spectral Laboratory Services, Kaduna. The equipment has a probe which consists of a single heater wire and thermocouple. When the heater receives constant energy (electric power), its temperature rises in exponential progression. A graph of temperature rise against time axis is scaled in logarithm. The slope of this line increases if the sample has less thermal conductivity and vice versa. Thermal conductivity is determined from the slope of the rising temperature using the equation below (Chen et al. 2016, Naik and Palatel 2014);

$$k = \frac{q \cdot \ln\left(t_2 / t_1 \right)}{4\pi \left(T_2 - T_1 \right)} \quad (1)$$

where:
k = thermal conductivity of sample (W/mK);
q = generated heat per unit length of sample /time (W/m);
t_1, t_2, are the measured time length (sec);
T_1 and T_2 are temperatures at t_1 and t_2 [K] (Laboratory report).

Thermal diffusivity

Having obtained the results for thermal conductivities of the samples, their densities were obtained by measuring the volume of a known mass that has passed through a sieve into a cylinder and the specific heat capacities were also measured using Differential Scanning Calorimetry which is a thermal analysis technique in which the heat flow into or out of a sample is measured as a function of temperature or time, while the sample is exposed to a controlled temperature program. Thermal diffusivity, α, was then calculated using the relationship given below (Lasode and Ajimotokan 2011, Chen et al. 2016);

$$\alpha = \frac{k}{\rho C_p} \quad (2)$$

where:
α = Thermal diffusivity (m^2/sec);
ρ = Density (g/cm^3);
C_p = Specific heat capacity (J/gK).

Water absorption capacity test

For every five blends, each of 0.075, 0.150, 0.300, 0.6 and 1.00 mm particle sizes, 25 grams of material was mixed in the clay: granite dust ratio 50:50, 60:40, 70:30, 80:20 and 90:10 using a cylindrical metal mold made of mild steel (Plate 3). The mould is 50 mm diameter and 5 mm high.

Water absorption capacity was carried out in accordance with ASTM D570-98(2018) 50 mm diameter x 10 mm thick samples. The samples were prepared and allowed to dry for 24 hours in a drying oven (attached to the Testometric Universal Tensile Testing Machine). The oven temperature was set at 120 °C. After drying, they were weighed and immersed completely in water.

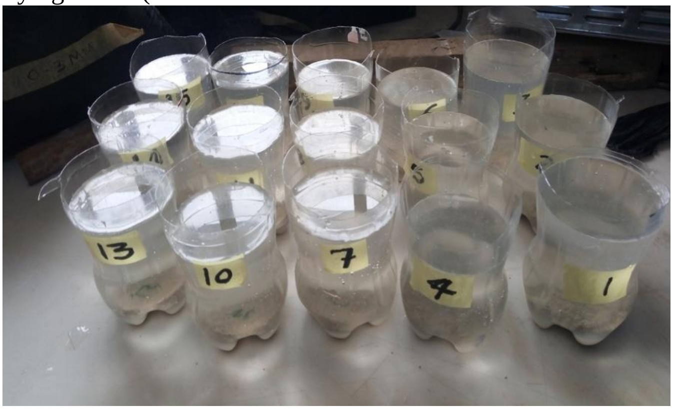

Plate 3: Samples being tested for water absorption capacity.

Compression strength test

The compression test was carried out in accordance with ASTM standard D- 3039 2014. 60 mm (ø) x 20 mm (thickness) samples were prepared for different particle size constituents and mix ratios. The samples were dried in a drying oven (set at 120 °C) for 24 hours. They were then tested for compression strength. The test was carried out using the 50 kN Testometric Universal Testing Machine FS50AT (Plate 4). Samples were mounted one at a time based on their respective sieve sizes and test speed of 2 mm per minute was applied until samples failed. The test was repeated for the various particle sizes and constituent ratios.

Plate 4: Compression strength samples under test.

Results and Discussion

Thermal conductivity of initial dusts

Thermal conductivity test of both clay and granite dust, separately conducted for particle sizes of 0.075, 0.150, 0.300, 0.600, 1.00 and 1.40 mm are shown in Figure 1.

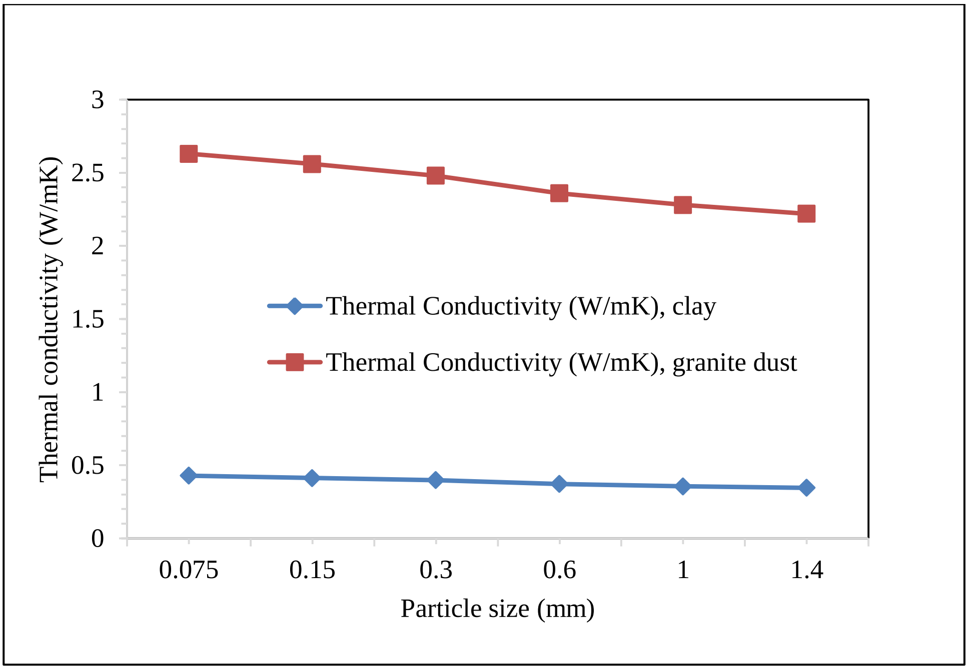

Figure 1: Thermal conductivities of clay and granite dust for different particle sizes.

For clay and granite dust, it was discovered that particle size 0.075 mm has the highest thermal conductivity, while 1.40 mm has the lowest thermal conductivity, although for corresponding particle sizes, granite dust has higher values. Clay of particle size 0.075 mm has the highest thermal conductivity (0.429 W/mK) and particle size 1.40 mm has the lowest thermal conductivity (0.346 W/mK). Granite dust of particle size 0.075 mm has the highest thermal conductivity of 2.63 W/mK, while its particle size 1.40 mm has the lowest thermal conductivity (2.20 W/mK).

It is important to mention here that unlike in the conventional flat-plate solar collector where a material with low thermal conductivity is chosen as insulator, this work is a different case because the material to be used to replace insulator should be able to store enough energy and should be able to release such energy when required.

For this reason, all the samples to be considered in this work must have relatively higher thermal conductivity and thermal diffusivity than the conventional insulating materials used in a typical flat-plate solar collector. This will enhance storage of appreciable amount of energy and diffuse such on demand. The material can be further insulated from the surrounding by a stronger insulting material. For this work, the wooden housing serves as one.

Thermal diffusivity

It was also discovered that the thermal diffusivities of both clay and granite dust decreased with increase in their particle sizes. Clay of particle size 0.075 and 1.40 mm had thermal diffusivities of 8.68 $\times 10^{-4}$ and 4.94 $\times$ 10^{-4} m^2/sec, respectively. As for granite dust, its highest thermal diffusivity, 3.658 $\times$ 10^{-3} m^2/sec was recorded with the particle size of 0.075 mm, while the lowest, 2.579 $\times$ 10^{-3} m^2/sec was recorded with the particle size 1.40 mm. Just like thermal conductivity, the corresponding particle sizes of granite dust had higher thermal diffusivity values than that of clay as shown in Figure 2.

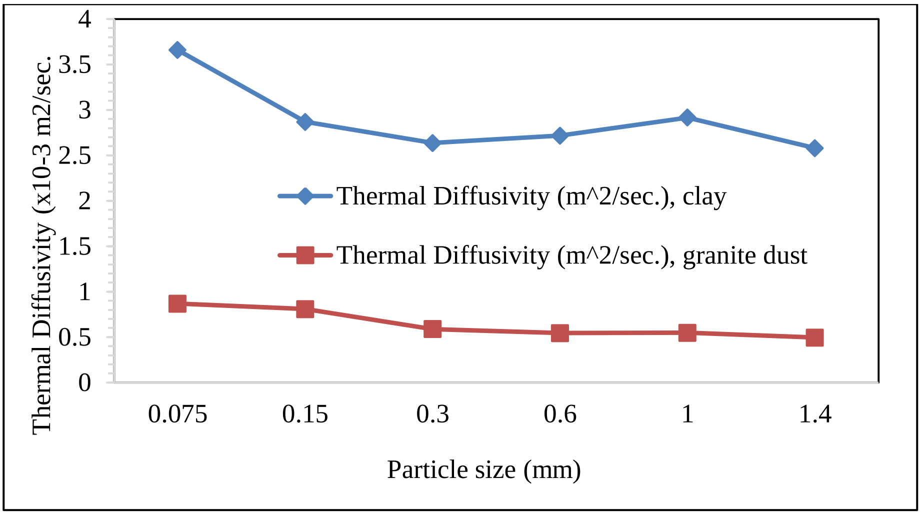

Figure 2: Thermal diffusivities of clay and granite dust for different particle sizes.

Density

Figure 3 shows the densities of corresponding particle sizes of both clay and granite dust. For clay, the density values increased gradually with increase in particle sizes. At 1.00 mm particle size, the density value dropped to 0.79 Kg/cm^3. This might be adduced to the factors influencing density of materials such as: such as shape of the particle; concentration; distribution; and pore size (Fruhstorfer and Aneziris 2017, Nayak and Rao 2016). Ordinarily, it is expected that the density should be increasing with increase in particle size but if due to particle shape, the pores increase, then the density will decrease. A similar trend was observed for the granite dust.

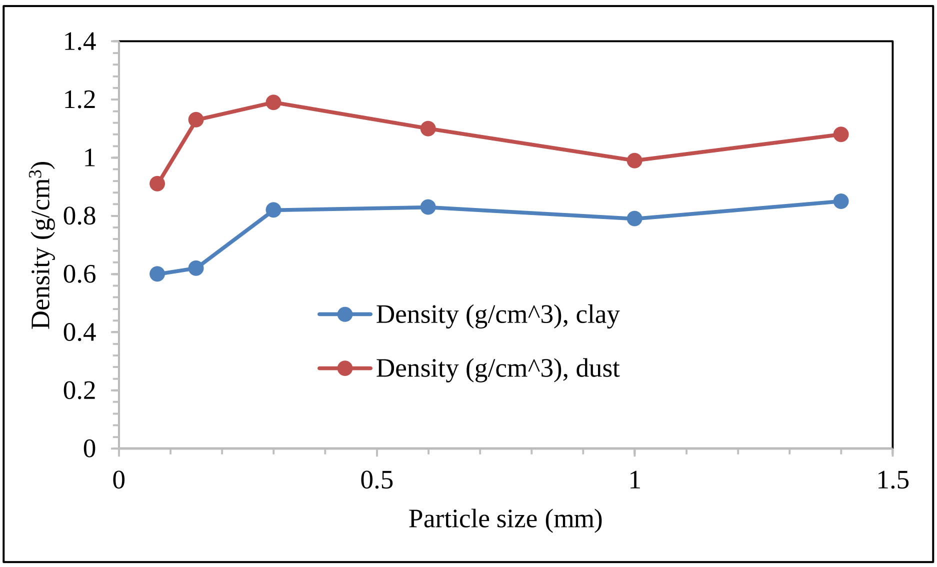

Figure 3: Densities of clay and granite dust for different particle sizes.

Blended materials property analyses

The results of the property analysis of the blended materials of the selected particle sizes are shown and discussed below.

Thermal conductivity

Figure 4 shows the thermal conductivities of the blends of different particle sizes. It was discovered that material blend of particle size 0.075 mm and blend ratio 50:50 has the highest thermal conductivity (0.268176 W/mK) compared to others. Similarly, for every blend with higher clay content, materials of particle size 0.075 mm has the highest thermal conductivity. This could be attributed to the fact that the particle size and porosity of materials like clay, quartz and silts have influence on their thermal conductivity. The finer the grain size, the lower the porosity and the higher the thermal conductivity, which compared favourably with the findings of Akinyele et al. (2019).

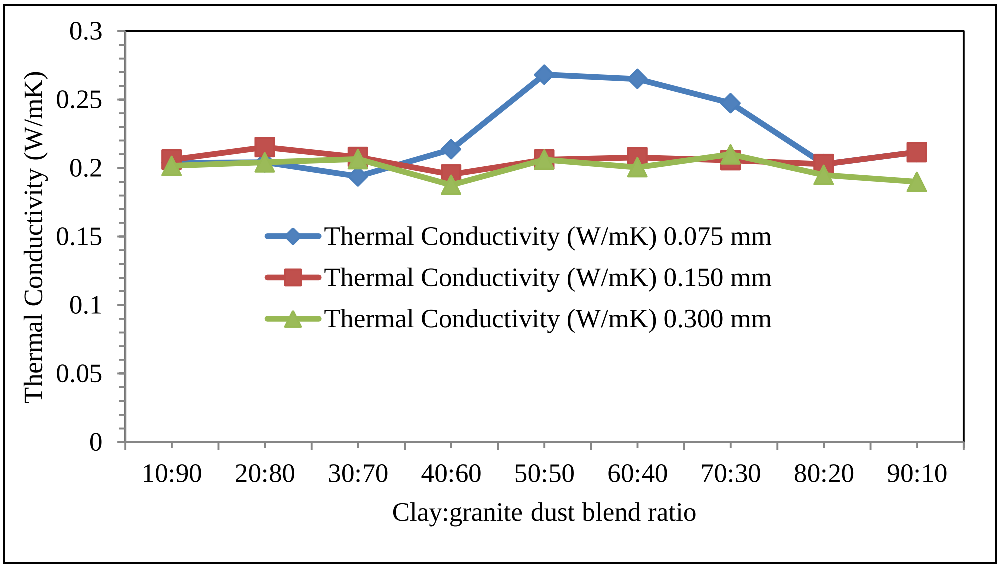

Figure 4: Thermal conductivities of the blends of different particle sizes.

Thermal diffusivity

Figure 5 shows the thermal diffusivities of the blends of different particle sizes. It was shown that sample of particle size 0.075 mm with clay: granite dust ratio 50:50 has the highest value (3.58514 × 10^{-4} m^2/sec), while sample of particle size 0.300 mm with the same blend ratio has the lowest value (2.84918 × 10^{-4} m^2/sec.). The reason for this could be attributed to the same fact that finer particle size has lower porosity and higher thermal conductivity. Since thermal conductivity varies directly with its diffusivity, it then follows that samples with higher thermal conductivity will equally have higher diffusivity (Oluyamo and Bello 2014, Tanaka 2015, Yılmaz 2018).

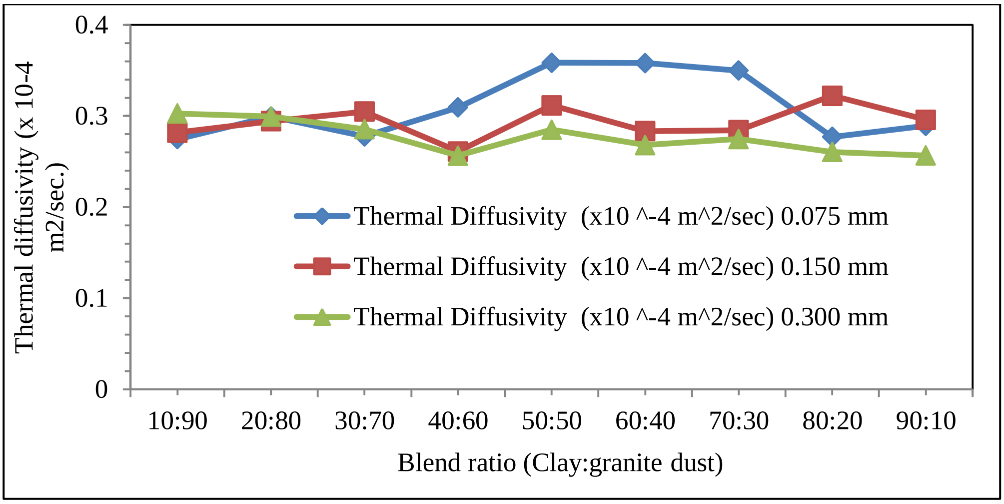

Figure 5: Thermal diffusivities of the blends of different particle sizes.

The density

Figure 6 shows the densities of the blends of different particle sizes. Analysis of the density of each of the samples was carried out and it was discovered that the sample of the blend with 0.300 mm particle size and 70:30 clay: granite dust ratio had the highest density (0.93 g/cm^3) and lowest density (0.79 g/cm^3) was recorded for particle size 0.150 mm and blend ratio 80:20 (clay:granite dust). The highest density of 0.91 g/cm^3 for 0.075 mm particle size and mix ratio of 50:50 clay: granite dust was recorded, 0.91 g/cm^3 was also the highest density recorded for particle size of 0.150 mm under a mix ratio of 40:60 clay: granite dust. However, the lowest densities for 0.075, 0.150 and 0.300 mm are 0.83 g/cm^3 at 20:80, 0.79 g/cm^3 at 80:20 and 0.81 g/cm^3 at 10:90, respectively. It was also discovered that the density values with respect to the blending ratio increased initially for the 0.150 mm and 0.300 mm before a gradual decrease was observed, while the density for the 0.075 mm particle size decreased initially before a gradual increase was observed. This trend is traceable to the fact that density of a material can be influenced by particle size of the material, concentration, distribution and shapes of the particles (Fruhstorfer and Aneziris 2017).

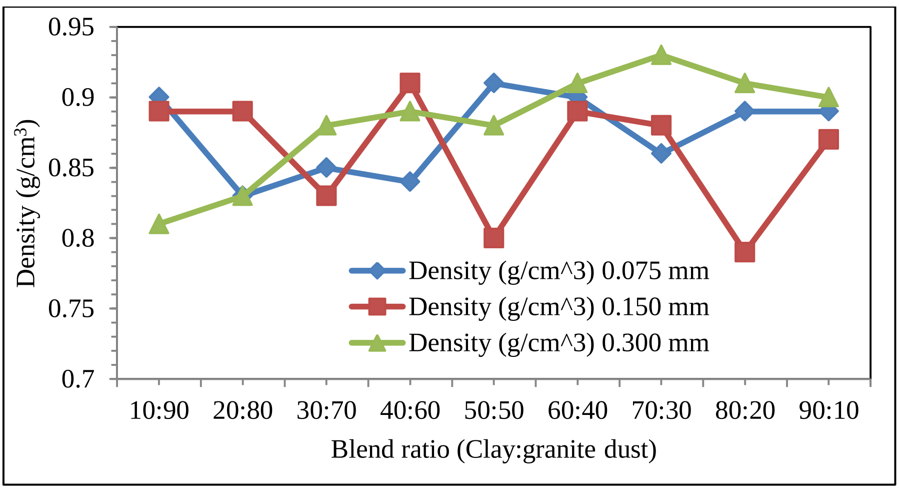

Figure 6: Densities of the blends of different particle sizes.

Compression strength test

Figure 7 shows the compression strengths of blends of different particle sizes. It was discovered that sample with grain size 0.075 mm and blend ratio 50:50 (clay:granite dust) has the highest compressive strength of 3.571 N/m^2, while the lowest is sample with the same grain size of 0.075 mm and blend ratio 80:20 (clay:granite dust) which has 0.952 N/m^2. The high strength recorded for the 0.075 mm particle size may be attributed to the fact that finer particle will have lesser pores and can be more compacted to have high strength that coarse (large) particle size.

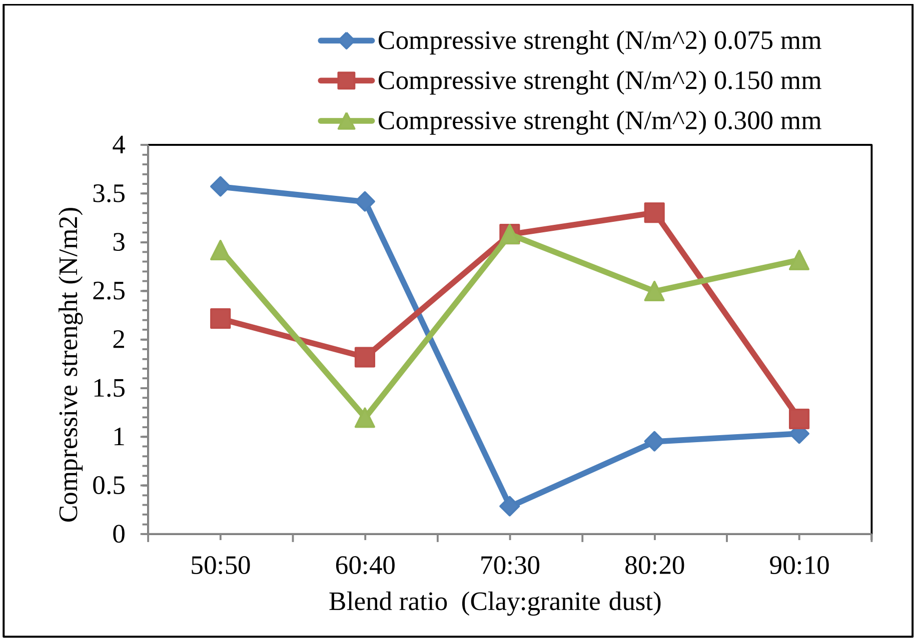

Figure 7: Compression strengths of blends of different particle sizes.

Water absorption capacity

After 12 hours of immersion in water at room temperature, the samples dissolved in water. This is because clay served as binder in the sample mix and no polymeric binder was used. This result is similar to the findings of Ajao et al. 2013, Vettrivel and Mathiazhagan 2017) during their water resistance test carried out on corncob and rice husk briquette.

Conclusions

Based on the findings from this study, the following conclusions were drawn:

1. The materials for the study were pre-processed and blended in different particle sizes and ratios.
2. The blended samples were characterized based on thermal, physical and mechanical properties. It was discovered that material sample of particle size 0.075 mm and blend ratio 50:50 (caly:granite dust) has the highest thermal conductivity (0.268176 W/mK) and highest thermal diffusivity (3.5851 $\times 10^{-4}$ m^2/sec). This same blend ratio and particle size also has the highest compressive strength of 3.571 N/m^2. Sample material with particle size 0.300 mm and blend ratio 70:30 (clay:granite dust) has the highest density of 0.93 g/cm^3. All the samples are permeable, as they dissolved in water after twelve hours.
3. The material, clay:granite dust (50:50) composite of 0.075 mm particle showed high potential of storing solar thermal energy during the day from 9:30 am to 18:30 at sunset. The energy stored was then gradually released over four hours (from 18:30 to 22:30). Highest temperature of 56.8 °C was recorded on

the fifth day. It was observed that temperature of the material does not fall to ambient overnight**.**

4. The developed material, clay and granite dust blend of 50:50 ratio from 0.075 mm particle size is a good material to replace conventional synthetic insulating material for the construction of solar flat–plate collector. It also has ecofriendly properties and its degradability over the conventional synthetic insulation materials being used for flat–plate solar collection construction.

Conflict of Interest: No conflict of interest, financial or other, exists.

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