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CHARACTERIZATION OF CLAY AND GRANITE DUST BLEND AS NOVEL MATERIAL FOR SOLAR FLAT–PLATE COLLECTOR

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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 work is about developing a novel material to use as both energy storage and diffuser in constructing flat plate solar collector. Materials used are clay and granite dust obtained from Okelele and Kulende Quarry site, both in Ilorin, Nigeria. The materials were sundried; 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 0.075mm and clay: granite ratio 50:50 (0.268176 W/mK , 3.58514×10^{-4} m^2/sec and 3.571 N/m^2 respectively). This same blend has a density of 0.91 g/cm^3, 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

1. 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 being environmentally hazardous and its possible inadequacy in the near future. 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 [1–3] 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 [4–6]. 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 (174×10^{15} W) of solar radiation, about 30% of this is reflected back into the space while the remaining 70%, approximately 124 PW is absorbed by the land masses, clouds and oceans. However, only an insignificant amount of this huge value is only harnessed for effective use. For instance, as at 2018, the world solar Photovoltaic installed capacity just reached 398 GW (398×10^9W), a mere 0.3% of solar energy utilization from the sun. The wide gap has been mainly attributed to lack of technology [8–10].

Recent development in some countries like Germany, China, Italy and U.S.A has shown that solar energy will play a very important role 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 [11,12].

2. PROBLEM STATEMENT

Use of fossil fuels causes the emission of carbon (iv) oxide which is detrimental to human and the environment. Solar energy is abundant and environmental 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.

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. Till date most emphasis 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. 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 effect 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.

Investigation of the effect of bottom reflector as an efficiency booster on a flat plate solar collector was established [12–15]. A highly reflective rectangular mirror was attached to the collector from the bottom (lower) edge. This enable direct, diffused and reflected radiation from the sun to be transmitted onto the glass cover of the collector and this was transmitted as heat energy onto the absorber increasing the solar radiation. From the study, it was discovered when the setup was compared with the conventional solar thermal collector, the average daily solar radiation absorbed was increased by about 20% when the ratio of the reflector length to collector length was 1:0.5, 27% when the ratio was 1:1 and 33% when the ratio was 2:1. These conditions were true if and only if the length and width of the collector are equal in all cases. Also, the daily solar radiation absorbed on the collector per unit effective glass cover area decreased with an increase in the ratio of collector length to width and increased with an increase in the ratio of reflector length to collector length.

3. METHODS

— Materials Procurement

The materials used for this research were clay and granite dust mixed in different particle sizes and ratios. The clay was obtained from Okelele area of Ilorin while the granite dust was from Kulende Quarry site in Ilorin.

— Materials Processing

The procured clay was sun dried for a week to remove moisture (Figure 1). The dried clay was crushed manually after which it was 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.

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 mechanical sieve shaker.

Figure 1: Samples of clay and granite dust being sun dried

— Equipment, tools and other materials

Equipment, tools and other materials used for this work included k–type thermocouple, set of sieves with shaker, weighing scale, drying oven (attached to the Universal Tensile testing Machine FS50AT; manufacturer; Testometric), metal moulds for molding samples for compressive strength and water absorption capacity tests, conductivity meter SLS–3000, beakers, 50kN Testometric Universal Testing Machine(FS50AT), plain glass of dimension (330x300x4)(length x width x thickness) mm as glazing cover, 2–mm thick galvanized steel sheet (coated black as absorber plate), wooden frame.

Each sample of the particle sizes for the two materials was tested for the following thermal and physical properties;

a. Thermal Conductivity (W/mK)
b. Thermal Diffusivity (m^2/sec)
c. Specific Heat Capacity (J/gK) and
d. Density (g/cm^3)

— Thermal Properties of blended Samples

Table1: Blended samples for thermal property tests

Particle Size (mm)	Sample Code	Clay (%)	G.dust (%)	Sample code	Clay (%)	G.dust (%)
0.075	1	50	50			
	2	60	40	6	40	60
	3	70	30	7	30	70
	4	80	20	8	20	80
	5	90	10	9	10	90
0.150	10	50	50			
	11	60	40	15	40	60
	12	70	30	16	30	70
	13	80	20	17	20	80
	14	90	10	18	10	90
0.300	19	50	50			
	20	60	40	24	40	60
	21	70	30	25	30	70
	22	80	20	26	20	80
	23	90	10	27	10	90

From the results obtained above, samples of three particle sizes have optimal thermal properties required for the material under investigation. These are 0.075, 0.0150 and 0.300 mm particle sizes. Clay and granite dust of corresponding particle sizes were weighed using an electronic weighing balance (HX–T) with 300 g maximum capacity and sensitivity of 0.01g. Nine samples of each particle size were mixed in different ratios of (clay: granite dust) 10:90, 20:80, 30:70, 40:60,50:50, 60:40, 70:30, 80:20 and 90:10 (Table 1). The blended samples (Figure 2) were tested for the same properties as before, that is specific heat capacity, density, thermal conductivity and thermal diffusivity.

Figure 2: Blended samples prepared for Thermal property tests

— Thermal Conductivity Test

Thermal conductivity test was done 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 rising against time axis is scaled in logarithm. The angle of this line increases if the sample has less thermal conductivity and vice versa. Thermal conductivity is determined from the angle of the rising temperature graphic line using the equation below;

Thermal Conductivity, k is then given by;

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

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. T_2 are Temperatures at t_1, t_2 [K] (Laboratory report)

— Thermal Diffusivity

Having obtained the results for thermal conductivities of the samples, their densities were also obtained as well as their specific heat capacities which was constant. Thermal diffusivity, α, was then calculated using the equation;

$$\alpha = \frac{k}{\rho C_p} \tag{2}$$

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

— Other properties of the blended samples

Other properties of the samples tested for are physical (water absorption capacity) and mechanical (Compressive strength) tests as detailed below.

— Water Absorption Capacity test

For every five blends each of 0.075, 0.150 and 0.300mm 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. The mould is 50 mm diameter and 5 mm high.

Water absorption capacity was carried out in accordance with ASTM D570–98(2018) 50mm diameter x 10 mm thick samples. The samples were prepared and allowed to dry for 24 hours in a drying oven (attached to the Universal Tensile Testing Machine; Manufacturer; Testometric). The oven temperature was set at 120°C. After drying, they were weighed and immersed in $50cm^3$ of water.

— Compression Strength test

The compression test was done 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 50KN Testometric Universal Testing Machine FS50AT (Manufacturer: Testometric). Samples were mounted one at a time based on their respective sieve sizes and test speed of 2mm per minute was applied until samples failed. The test was repeated for the various particle sizes and constituent ratios

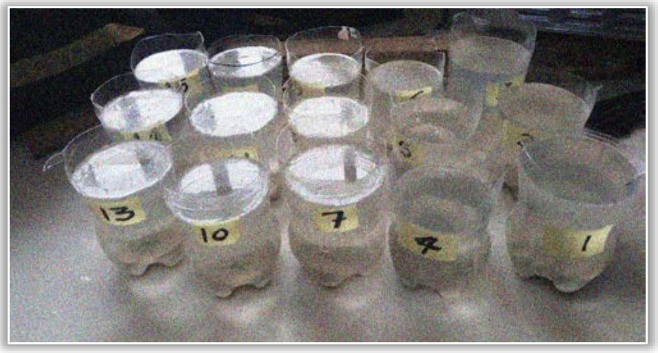

Figure 3: Samples being tested for water absorption capacity

Figure 4: Compression strength samples under test

4. RESULTS AND DISCUSSION

— Thermal Conductivity

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 was shown in Figure 5 below.

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

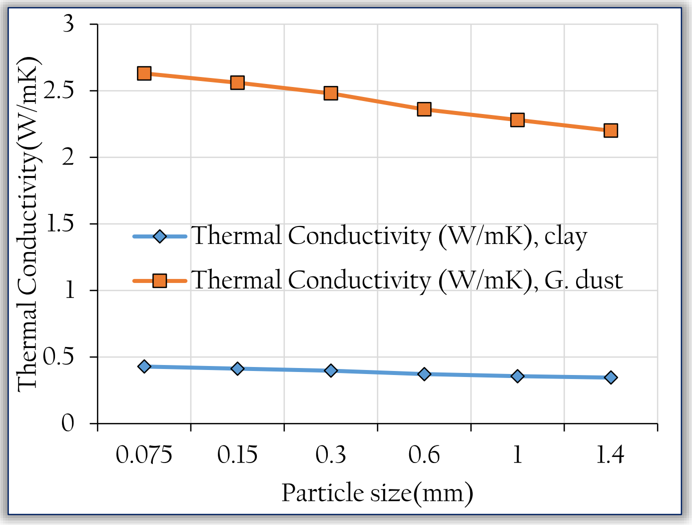

Figure 5: Thermal Conductivities of clay and granite dust for different particle sizes

It is important to mention here that unlike in the conventional flat–plate solar collector where 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 on demand.

For this reason, all the sample(s) 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 have thermal diffusivities of 8.68×10^{-4} and 4.94×10^{-4} m^2/sec. respectively. As for granite dust, its highest thermal diffusivity, 3.658×10^{-3} m^2/sec is recorded with the particle size of 0.075 mm while the lowest, 2.579×10^{-3} m^2/sec. is recorded with the particle size 1.40 mm. Just like thermal conductivity, the corresponding particle sizes of granite dust have higher thermal diffusivity values than that of clay as shown in Figure 7.

— Density

Figure 7 shows the densities of corresponding particle sizes of both clay and granite dust. For clay, the density value increased gradually with increase in particle size .At 1.00 mm particle size, the density value dropped to 0.79 Kg/cm^3. This may due to many factors that influence the density of a material such as shape of the particle, concentration, distribution and pore size [16–18]. 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.

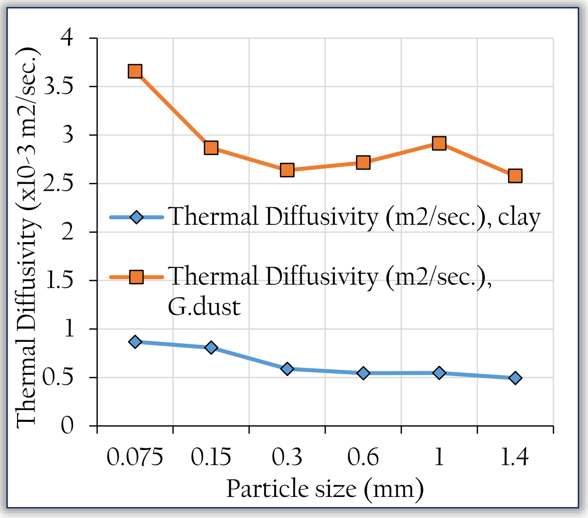

Figure 6: Thermal Diffusivities of clay and granite dust for different particle sizes

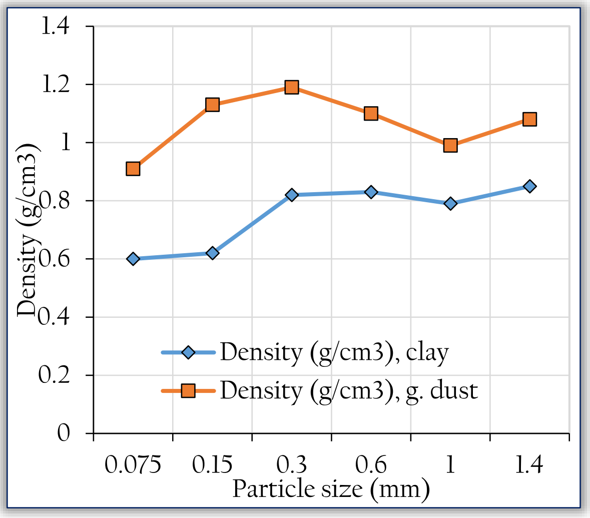

Figure 7: Densities of clay and granite dust for different particle sizes

5. BLENDED MATERIALS PROPERTY ANALYSES

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

— Thermal Conductivity

Figure 8 shows the thermal conductivities of the blends of different particle sizes. It was discovered that material blend of particle size size 0.075mm and blend ratio 50:50 has the highest thermal conductivity(0.268176W/mK) compared to others (Figure 8). 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.

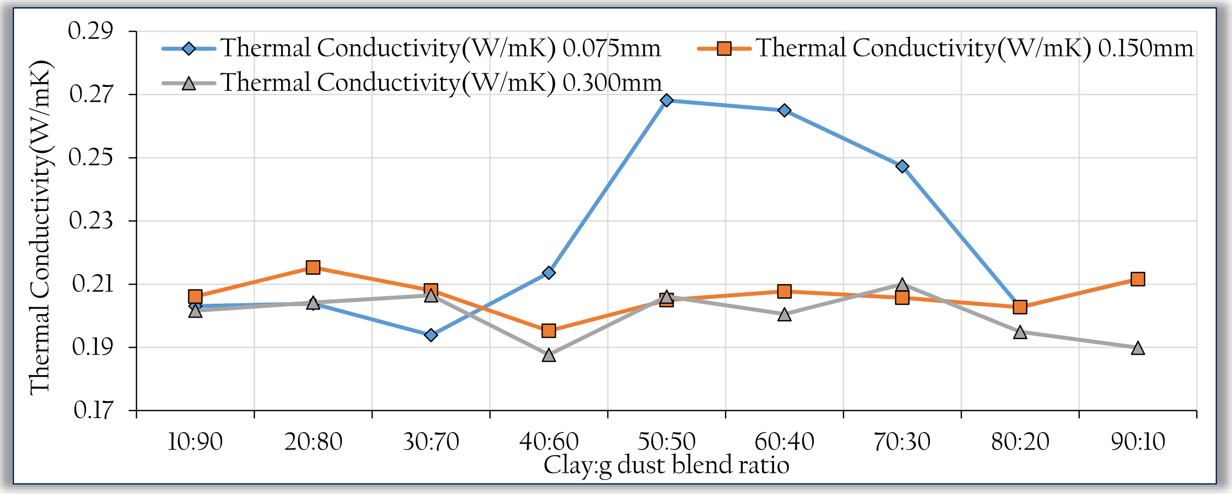

Figure 8: Thermal Conductivities of the blends of different particle sizes

— Thermal Diffusivity

Figure 9 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 (3.58514x10^{-4} m^2/sec) while sample of particle size 0.300 mm with the same blend ratio has the lowest value (2.84918x10^{-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.

— The Density

Figure 10 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 sample of the blend with 0.300 mm particle size and 70:30 clay: granite dust ratio has the highest density (0.93g/cm^3) and lowest density(0.79g/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 density for 0.075, 0.150 and 0.300 mm are 0.83g/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 [6].

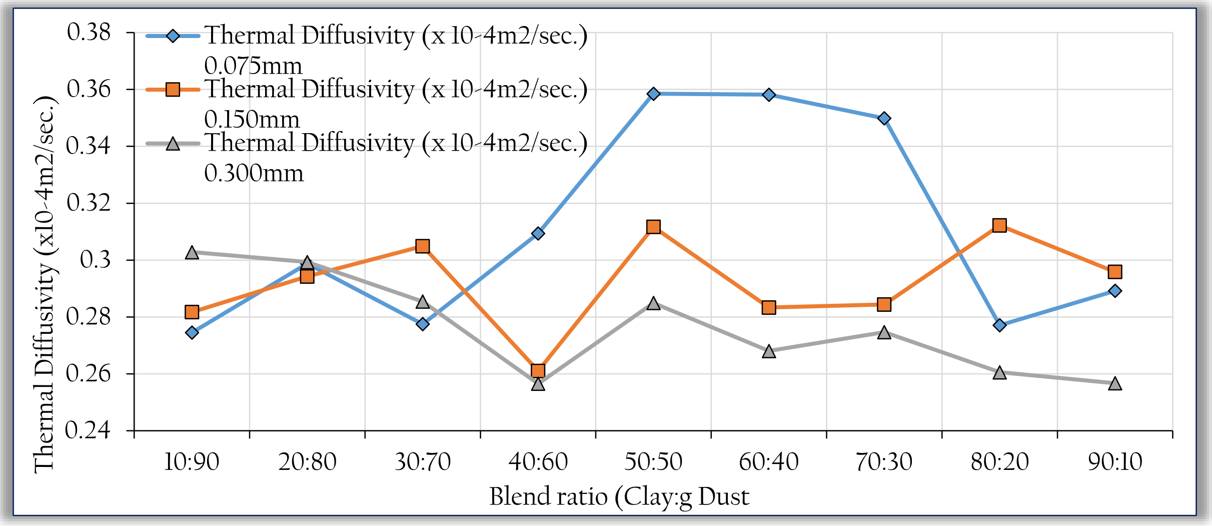

Figure 9: Thermal Diffusivities of the blends of different particle sizes

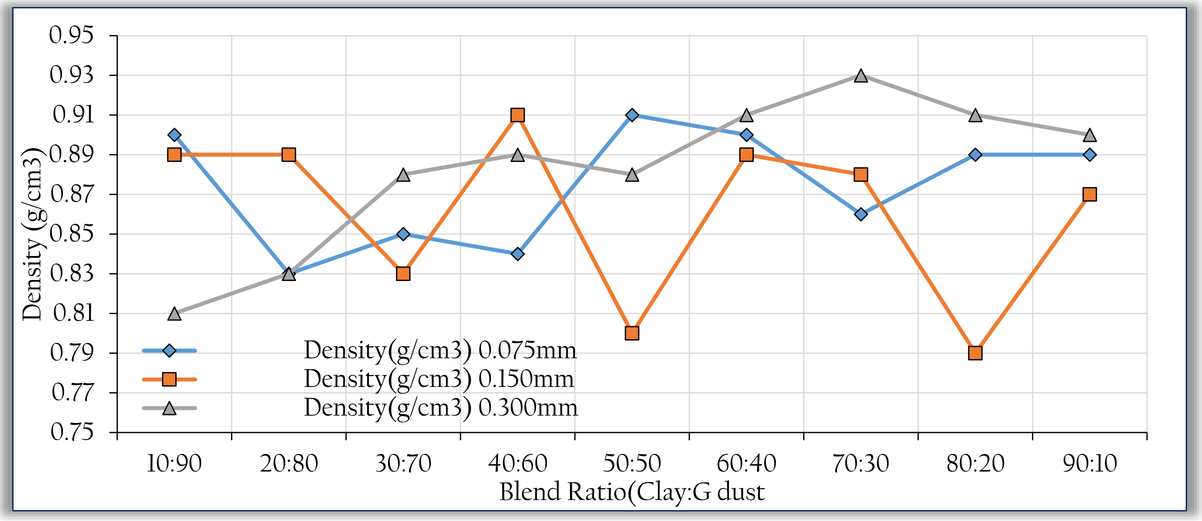

Figure 10: Densities of the blends of different particle sizes

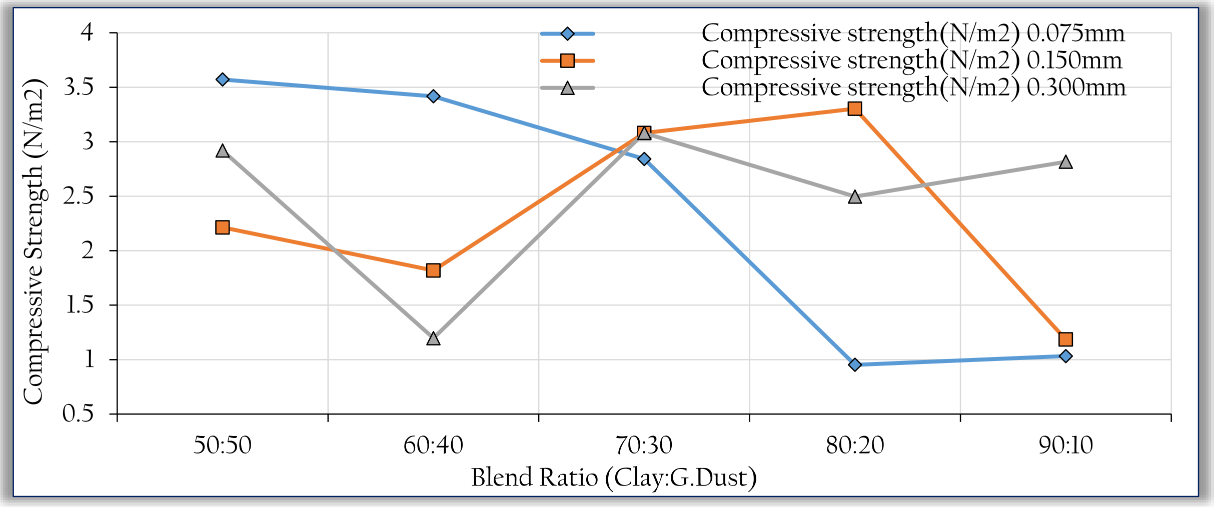

Figure 11: Compression Strengths of blends of different particle sizes.

— Compression Strength Test

Figure 11 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 3.571N/m^2 while the lowest is sample with the same grain size of 0.075mm and blend ratio 80:20 (clay: granite dust) which has 0.952N/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.

— Water absorption capacity

After 12 hours of immersion in cold tap water, 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 [19] during their water resistance test carried out on corncob and rice husk briquette.

6. CONCLUSIONS

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

- The materials for the study were pre–processed and blended in different particle sizes and ratios.
- 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 (0.268176W/mK) and highest thermal Diffusivity(3.5851x$10^{-4}$$m^2$/sec). This same blend ratio and particle size also has the highest compressive strength of 3.571N/m^2. Sample of material with particle size 0.300 mm and blend ratio 70:30 (clay:granite dust) has the highest density of 0.93g/cm3. All the samples are permeable, as they dissolved in water after twelve hours.
- Analysis of the samples showed that the 50:50 clay/granite dust blend of 0.075 mm particle size, having the optimal thermal and mechanical properties was considered to have the potentials to serve both as energy storage material as well as energy diffuser and should be prepared and use as replacement for conventional insulating material in a solar flat–plate collector.

LIST OF ABBREVIATIONS AND SYMBOLS

W	Watts	CO_2	Carbon–dioxide	α	Thermal diffusivity
m	Meters	CSP	Concentrated Solar Power	ρ	Density
K	Kelvin	MJ	Mega Joules (Jx10^6)	C_p	Specific heat capacity
sec.	Seconds	Pv	Photovoltaic (cell)	kN	kilo Newton
N	Newton	Wh	Watthour	GMT	Greenwich Mean Time
g	grams	ASTM	American Society of Testing and Materials	Q	(Solar) heat energy input
cm	centimeters	k	Thermal conductivity	I	Solar radiation intensity
kg	kilograms	q	Generated heat per unit length	A	(Glazing) Area of collector aperture
J	Joules	t_1, t_2	Measured time length (sec.)	τ_δ	Effective transmittance–absorptance coefficient
EJ	Exa Joules (Jx10^{20})	T_1, T_2	Temperatures at t_1, t_2 [K]		

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