IJISET - International Journal of Innovative Science, Engineering & Technology, Vol. 8 Issue 10, October 2021
ISSN (Online) 2348 – 7968 | Impact Factor (2020) – 6.72
www.ijiset.com

Determination of Thermal Conductivity, Thermal Diffusivity and Thermal Effusivity in Fired Clay Bricks

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Abstract

Thermal diffusivity, thermal phase lag, conductance, thermal resisivty, thermal conductivity and thermal effusivity were determined for two pieces of brick a new made sample and an old one. Samples were then coated with cement and measurements were repeated. Thermal diffusivity of the samples were found to range from $6.8\times10^{-7}m^2s^{-1}$to $18\times10^{-7}m^2s^{-1}$, thermal phase lag ranged between 5.6 h^{-1} and 29 h^{-1} while conductance ranged from 1.2 $Wm^{-2}K^{-1}$ to 1.7 $Wm^{-2}K^{-1}$ thermal resistivity ranged between $0.83m^2K.W^{-1}$ and 0.58 $m^2K.W^{-1}$ thermal conductivity was found to range from 1.6 $Wm^{-1}K^{-1}$to 2.02 $Wm^{-1}K^{-1}$ whereas thermal effusivity was found to range from $12.28\times10^2 Ws^{1/2}/m^2K$ to $23\times10^2\ Ws^{1/2}/m^2K$. All results were compared with previous studies.

Key words: thermal effusivity, phase lag, diffusivity.

1.**Introduction**

Clays have a wide range of applications mainly in the refractory and ceramic industries. Accordingly, in the last few decades many studies have been made on clays and their applications [1], [2] and [3].

One of the problems facing school building industry is the high consumption of electric energy caused by poor ventilation and air conditioning systems. This is mainly due to lack of thermal insulation techniques in buildings. Most of the time the country depends on imported insulation materials which are very expensive and are not easily accessed by the local industry, thus there is potential need for the production of thermal insulating bricks.

Clay brick is used in building houses, schools and so on. The clay brick production varies in composition from one place to another. Silica (grains of sand), alumina, lime, iron, manganese, sulphur and phosphates, with different proportions are composing mainly in the clays. Grinding or crushing the clay in mills and mixing it with water to make it plastic are the steps to manufactured bricks. Then, the plastic clay is moulded, textured, dried and fired. Bricks are manufactured with variety of colours, such as dark red, brown and gray base on the firing temperature of the clay during manufacturing. The firing temperature for brick manufacturing varies from 900°C-1200°C. Clay bricks have an average density of 2 mg/m^3[4]. Clay was used as a mortar in brick chimneys and stone walls where protected from water [5]. Most studies target at the ageing process, durability, physical and chemical deterioration process of clay bricks.

1.1 The benefits of clay bricks keep stacking up

When planning to build a sustainable home for acomfortable life, you have a lot to consider. With theircomplete range of cost, comfort and style benefits, clay bricks are the one and only choice.

i) Clay brick is secure, an investment for life:

As one of the world's most sought after and trustworthy sources of sustainable building materials, clay bricks are renowned for their strength and secure investment potential. The quality construction, quiet calm and ageless appeal of a solid clay brick home will protect your family for generations to come

ii) Clay brick is energy efficient

for energy efficient warmth in winter and cool in summer, clay brick combines perfectly with passive building design to harness natural sources of energy. The natural density and thermal insulating qualities of clay moderate building temperature and reduce energy consumption rates, to provide year-round comfortand savings.

iii) Clay brick is low maintenance:

The most endearing quality of a clay brick home is its ability to withstand the test of time, even under the harshest environmental conditions. Clay bricks don't need paint or other treatments to maintain aesthetics and durability. They are strong, reliable and relatively maintenance free, saving you on the cost and time required to upkeep your home, compared to lighter weight materials.

iv) Style and design:

Clay bricks add distinct style to any type of home. Their natural colors and textures enable you to create striking contrasts or more traditional neutral color tones. Clay bricks are producedwith a variety of surface finishes, exciting colors and different sizes. The result is a wonderful range of clay bricks for you to build a stylish, contemporary home.

v) Clay brick is sustainable:

Made from organic minerals found in shale and local, naturally abundant sources of clay; clay brick's long-lasting life cycle offers ongoing environmental and health benefits. Durable, re-usable, free from contaminants and naturally resistant to pests or fire, claybrick is safe to live in, making it the ultimate material in responsible and economical home building design.

vi) Clay bricks are fully reusable:

they are one of the very few materials that can be reused (not just recycled) with all their original qualities intact. And if they are consigned to landfill, clay bricks are chemically inert and can't pollute groundwater or contaminate soil

In a previous work the chemical composition of the samples [6] was performed also the specific heat capacity and absorption of water. It was found that the specific heat capacity did not differmarkedly with age but it increased due to coating with cement only. The water absorption decreased after coating with cement but was kept within accepted range, both old and new samples are of the first-class clay bricks.

Here we aim to study more physical properties namely thermal conductivity, thermal diffusivity and thermal effusivity of clay bricks. The determination of thermal properties, such as thermal conductivity, thermal diffusivity, thermal effusivity, is of great importance during constructing buildings where heat transfer takes place.

This article is composed of three parts beside the introduction. The second part of this work presents an experimental study conducted to investigate the thermal conductivity, thermal diffusivity, thermal phase lag, conductance, thermal resistivity and thermal effusivity of fired clay bricks. Results and Discussion compose the third part and finally the conclusion.

2. Methodology

The thermal conductivity of the two samples was measured using Lee's Disc experiment also the coefficient of thermal diffusivity, thermal phase lag, conductance, resistivity and the coefficient of thermal effusivity were calculated in order to determine which sample is to be chosen in a certain building to keep the temperature lower inside the building.The measurements were repeated after covering the samples with a thin layer of cement.

2.1 Determination of thermal conductivity

An element that characterizes the thermal properties of materials is the thermal conductivity. It is a measure of the heat flow through a sample of material of a known thickness, when a known temperature difference is applied across two surfaces. Thermal conductivity measures the ease with which heat can travel through a material. It is measured in units of W/m.K .

The thermal conductivity of the two samples was measured using Lee's Disc experiment. Lee's disc apparatus consists of [7] a metallic disc resting on a 5 cm deep hollow cylinder (steam chamber) of same diameter. It has inlet and outlet tubes for steam. In addition, it has radial holes to insert thermometers, Figure1.

Figure1: Lee's disc apparatus

When steam is passed through the cylindrical vessel a steady state is reached soon. At the steady state, heat conducted through the bad conductor is equal to heat radiated from the Lees disc. The Lee's Disc experiment determines an approximate value for the thermal conductivity k of a poor conductor like clay. The procedure is to place a disc made of clay, radius r and thickness x, between a steam chamber and two good conductivity metal discs (of the same metal) and allow the setup to come to equilibrium, so that the heat lost by the lower disc by convection is the same as the heat flow through the poorly conducting disc.

The upper disc temperature Θ_2 and the lower disc temperature Θ_1 are recorded. The clayis removed and the lower metal disc is allowed to heat up to the upper disc temperature Θ_2. Finally, the steam chamber and upper discs are removed and replaced by a disc made of clay.

The metal disc is then allowed to cool through $\Theta_1 < \Theta_2$ and toward room temperature.The temperature of the metal disc is recorded as it cools so a cooling curve can be plotted. Then the slope $S_1 = d\Theta/dt$ of the cooling curve is calculated where the curve passes through temperature Θ_1 .Its value was used in the following relationship:

$$k = \frac{4dMC}{\pi D^2(\theta_1 - \theta_2)} \times \frac{d\theta}{dt} \qquad (1)$$

where D is the diameter of brick clay, d is the thickness of brick clay, M is the mass of aluminum disc, C is the specific heat capacity of aluminum disc.

2.2 Determination of the Coefficient of Thermal Diffusivity, Thermal Phase Lag, Conductance and Resistivity

Thermal diffusivity is the property that defines the speed of heat propagation by conduction during changes of temperature. The higher the thermal diffusivity, the faster the heat propagation. It measures the ability of a material to conduct thermal energy relative to its ability to store thermal energy. The ratio of thermal conductivity (k) to the product of density (ρ) and specific heat capacity (c_p) of a material is known as thermal diffusivity (α) of the material. It is given in m^2/s. Methods, known as the flash methods [8] and [9] to determine the thermal diffusivity exist. In this case the coefficient of thermal diffusivity was determined from measured values of the specific heat capacity, thermal conductivity, and density and applying the following equation derived from Fourier's law of heat conduction through solid:

$$\alpha = k/\rho \qquad (2)$$

Specific heat capacity was determined by method of mixtures [10] and the density was determined by measuring the mass of the sample and the dimensions to get the volume. Measurements of thermal conductivity, density, and specific heat capacity were performed at room temperature.

In addition, thermal diffusivity can be used to calculate the thermal phase lag ϕ which determines how long it takes for heat to go through a given thickness $d$of a material It is also the elapsed time between a thermal variation in a medium and its manifestation on the surface opposite to a constructive component subjected to a periodic regime of heat transfer. Thermal phase lag is equal to the thickness squared divided by the thermal diffusivity [11] ,its unit is in hours. Hence

$$\varphi = d^2/\alpha \qquad (3)$$

Thermal conductance λ is defined as the quantity of heat that passes in unit time through a plate of particular area $A$and thickness d when its faces differ in temperature by one kelvin, its unit is W/m^2K. The conductance is given by

$$\lambda = kA/d \qquad (4)$$

The reciprocal of the thermal conductance is the thermal resistivity *R* of the material. Thermal Resistance measures the material's resistance to heat flow. Its units is in m²K/W. Hence

$$R=1/\lambda \quad (5)$$

2.3. Determination of Thermal Effusivity

Thermal effusivity *e* also known as heat penetration coefficient of a material is a measure of its ability to exchange thermal energy with its surroundings. Thermal effusivity explains, for example, why at touch some bodies seem colder than other bodies at the same temperature. It describes the ability of a material to exchange heat with its surroundings. It is given by the following equation([12]:

$$e = (k\rho c_p)^{1/2} \quad (6)$$

where abbreviations are the same as above. Its units are $Ws^{1/2}/m^2K$ or $J/s^{1/2}m^2K$. Thermal effusivity was calculated from measured quantities and applied in the above relation. It can be directly measured by thermal effusivity sensors [13].

3. Results and Discussion

3.1 Results of thermal conductivity

The results of thermal conductivity, conductance, thermal resistivity for the old and the new samples are shown in table1.

	d/m	$k/Wm^{-1}K^{-1}$	λ /$Wm^{-2}K^{-1}$	R/m^2KW^{-1}
old	0.32×10^{-2}	1.95	1.70	0.58
new	0.33×10^{-2}	1.6	1.35	0.74
old cem	0.47×10^{-2}	2.02	1.20	0.83
new cem	0.4×10^{-2}	1.87	1.31	0.76

Table1: Thermal conductivity, conductance and thermal resistivity of the old and new samples before and after coating with cement for a brick of area of 28×10^{-4} m^2, a length of 17×10^{-2}m and diameter of 11.39×10^{-2}m.

Results of thermal conductivity were found to be in good agreement with [14]. Thermal conductivity increased after coating with cement for both samples. As good bricks should have low thermal conductivity so that buildings are kept cool in summer and warm in winter, thus the best kind of brick is the new sample before coating with cement as its thermal conductivity is the lowest.Thermal conductivity was also found to decrease with thickness for the two samples after coating with cement in agreement with [15] whereas this was not the case for the samples before coating with cement as the new sample was thicker than the old sample but its thermal conductivity was lower.The conductance of both samples decreased after coating with cement, the decrement in the old sample was much clearer. Comparisons between thermal conductivities and conductance for old and new samples with and without cement are given in Figure2.

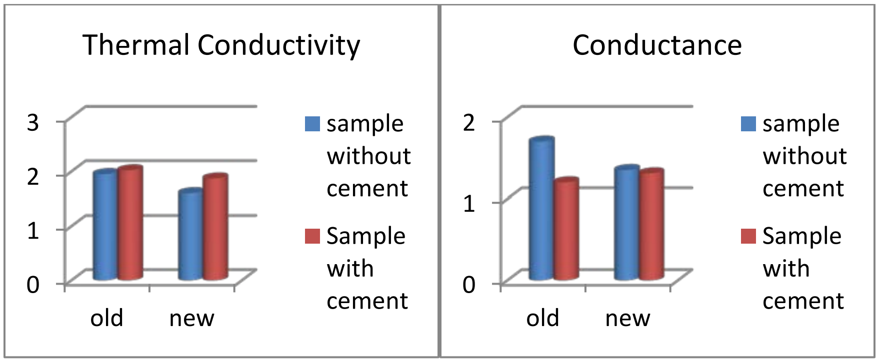

Figure2: Comparison between thermal conductivities of the two samples shows that it increases in both samples after coating with a thin layer of cement, whereas comparison between conductance of the two samples shows that it decreases in both samples after coating with a thin layer of cement.

The highest obtained value concerning resistivity was for the old sample after coating with cement followed by the new sample after coating with cement followed by the new sample followed by the old sample. The obtained values range from $0.83 m^2K.W^{-1}$ to $0.58 m^2K.W^{-1}$ which are quite acceptable compared with the results of [16], where thermal resistivity ranged from $0.249 m^2K.W^{-1}$ to $0.763 m^2K.W^{-1}$ for clay and was $0.40 m^2K.W^{-1}$ for concrete. The cooling curves for the old sample before and after coating with cement are given in Figure3.

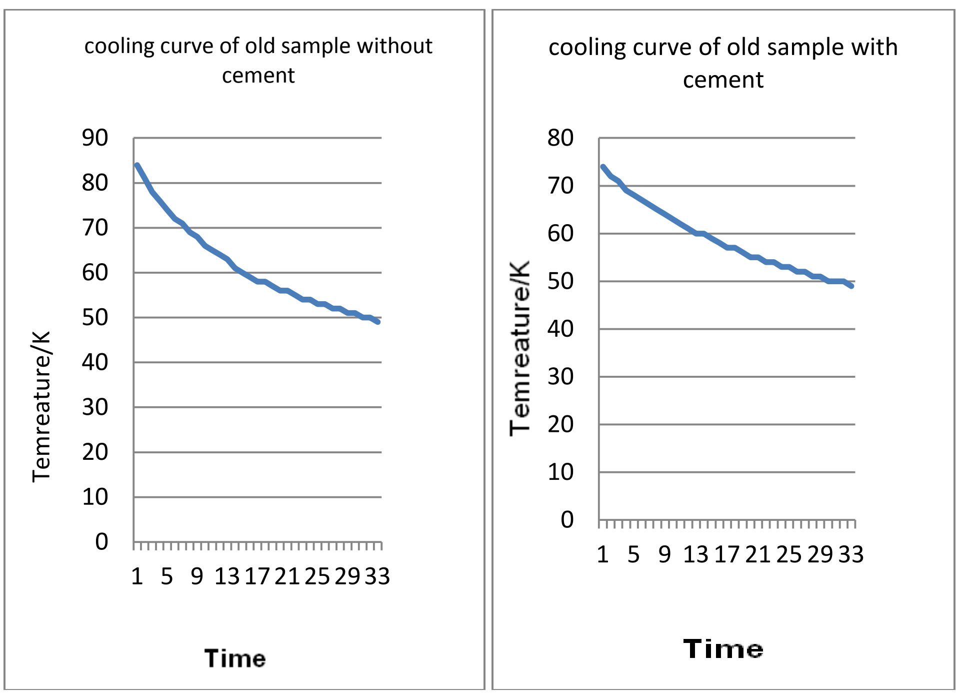

Figure3: Cooling curves of old sample with and without cement

The cooling curves for the new sample before and after coating with cement are given in Figure4.

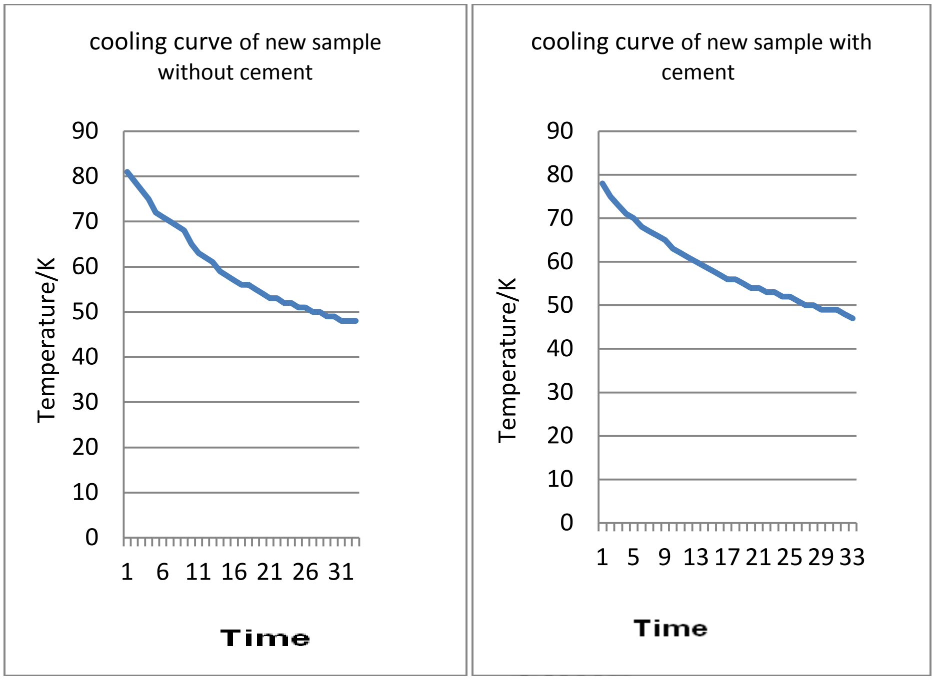

Figure4: Cooling curves of new sample with and without cement

Comparisons between thermal resistivity for old and new samples with and without cement are given in Figure5.

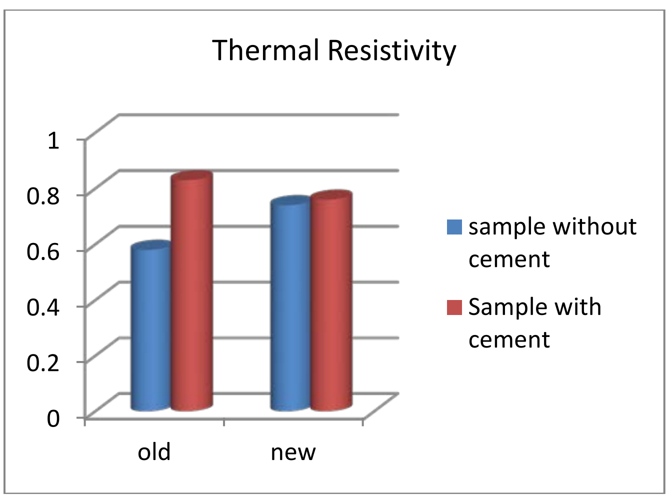

Figure5: Comparison between thermal resistivity of the two samples shows that it increased in both samples after coating with a thin layer of cement.

3.2 Results of Thermal Diffusivity and Thermal Phase Lag

Results of thermal diffusivity and thermal phase lag are shown in table2. Diffusivity of the samples were found to range from $6.8\times10^{-7} m^2s^{-1}$to 18×10^{-7} m^2s^{-1}. As materials having higher thermal diffusivity conduct heat quickly through them thus the new sample coated with cement is the best sample as it has the lowest diffusivity then the old sample coated with cement then the bare new sample and the worst is the bare old sample as it has the highest diffusivity. Thermal phase lag ranged from 5.6s for the old sample to 29s for the old sample after coating with cement. The percentage increment of thermal phase lag equals 19.31% for the old sample whereas it equals 27.82% for the new sample. Also, it was found that there was a direct proportional relation between thickness and thermal phase lag. All the obtained values are quite high compared with [17] where the thermal phase lag for clay was 3.6s and for concrete it ranged between 3.1s and 3.3s.

Table2: Density, specific heat capacity, thermal diffusivity, thermal phase lag and thermal effusivity of the old and new samples before and after coating with cement.

	ρ /kgm^{-3}	c_p/ Jkg^{-1}k^{-1}	α / m^{2}s^{-1}	Φ /s	e/Ws$^{1/2}$m^{-2}K^{-1}
Old	1.5×10^3	710.6±14.23	1.8×10^{-6}	5.6	14.41×10^2
New	1.3×10^3	726.63±220.49	1.7×10^{-6}	6.4	12.28×10^2
old with cement	3.25×10^3	810.6 ± 23.695	7.6×10^{-7}	29	23×10^2
new with cement	2.95×10^3	930.26±150.54	6.8×10^{-7}	23	22×10^2

A comparison between thermal diffusivity and thermal phase lag of old and new samples before and after coating with cement are shown in Figure6.

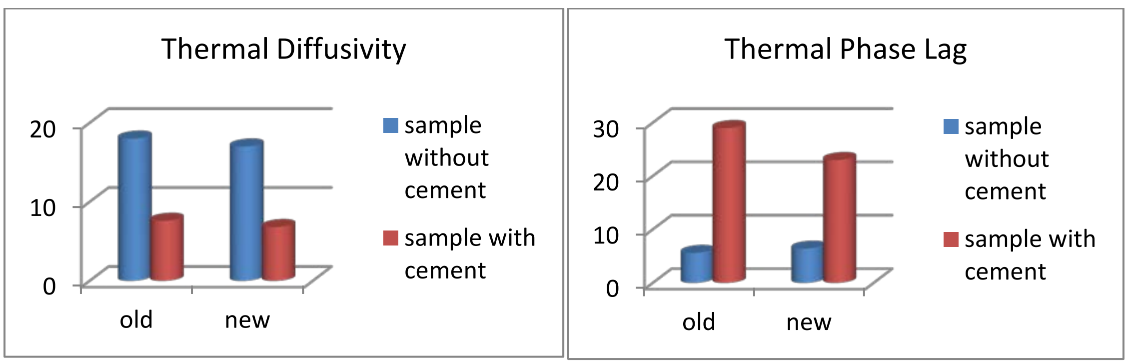

Figure6: Comparison between thermal diffusivities of the two samples shows that it decreases in both samples after coating with a thin layer of cement. The value of thermal diffusivity is multiplied by10^{-7}. Comparison between thermal phase lag of the two samples shows that it increasesin both samples after coating with a thin layer of cement.

3.3 Results of thermal effusivity

Results of thermal effusivity were shown in table2 above. The old sample coated with cement has the highest effusivity then the new sample coated with cement then the bare old sample and finally the bare new sample. The four samples have high effusivity compared with [18] where it ranged between 690 Ws$^{1/2}$m^{-2}K^{-1} and 720 Ws$^{1/2}$m^{-2}K^{-1} .A comparison between the samples is shown in Figure7 below. The best sample is the new sample as the thermal effusivity is the lowest followed by the old sample followed by the new coated sample and finally the old coated sample.

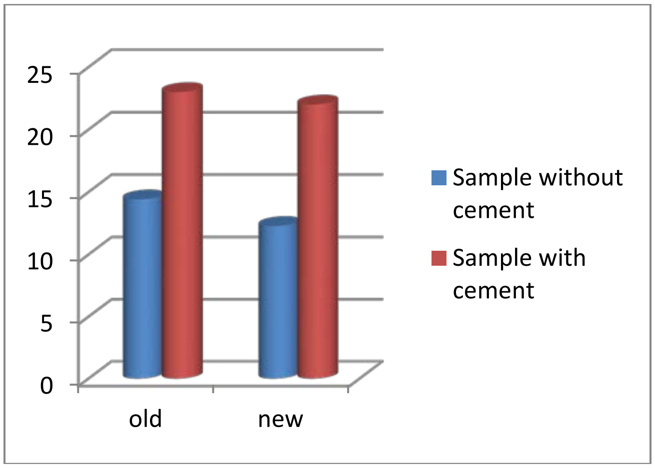

Figure7: Comparison between thermal effusivities of the two samples shows that it increases in both samples after coating with a thin layer of cement. The value of thermal diffusivity is multiplied by10^2.

4. Conclusion

The best kind of brick concerning thermal conductivity is the new sample before coating with cement as its thermal conductivity is the lowest then the old sample before coating then the new sample after coating and finally the old sample after coating with cement.

Concerning thermal diffusivity the new sample coated with cement is the best sample as it has the lowest diffusivity then the old sample coated with cement then the bare new sample and the worst is the bare old sample as it has the highest diffusivity, whereas concerning thermal phase lag a value of 10h-12h is sought [19], thus one can see that samples before coating have much lower values than desired whereas coated samples have much higher values than desired.

As the higher the value of thermal resistance, the more efficient the material is, this leads to the conclusion that the old sample coated with cement is the best sample followed by the new sample coated with cement followed by the new sample and the last sample is the old sample as it has the lowest resistance.

The best sample with regard to thermal effusivity is the new sample as the thermal effusivity is the lowest followed by the old sample followed by the new coated sample and finally the old coated sample.

All samples ought not be used for thermal insulation as their thermal conductivity is high, a material is considered a good insulator if its thermal conductivity is lower than 0.065 W/mk.

5. Acknowledgements
This work was funded by the Ministry of Higher Education, Sudan.

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