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*Research Article*

# Coefficient of Thermal Diffusivity of Insulation Brick Developed from Sawdust and Clays

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This paper presents an experimental result on the effect of particle size of a mixture of ball clay, kaolin, and sawdust on thermal diffusivity of ceramic bricks. A mixture of dry powders of ball clay, kaolin of the same particle size, and sawdust of different particle sizes was mixed in different proportions and then compacted to high pressures before being fired to 950°C. The thermal diffusivity was then determined by an indirect method involving measurement of thermal conductivity, density, and specific heat capacity. The study reveals that coefficient of thermal diffusivity increases with decrease in particle size of kaolin and ball clay but decreases with increase in particle size of sawdust.

## 1. Introduction

In a recent study by Manukaji [1], thermal diffusivity is very important in all nonequilibrium heat conduction problems in solid objects. The time rate of change of temperature depends on the numerical value of thermal diffusivity. The physical significance of thermal diffusivity is associated with the diffusion of heat into the medium during changes of temperature with time. Nonequilibrium heat transfer is important because of the large number of heating and cooling problems occurring industrially [2]. In metallurgical processes it is necessary to predict cooling and heating rates for various geometries of conductors in order to predict the time required to reach certain temperatures. Materials with high thermal mass will take longer for heat to travel from the hot face of the brick to the cold face and will also take long to release their heat once the heat source is removed [3, 4]. A paper by Aramide, [5], points out that when brick samples made with sawdust are fired, the sawdust admixture burns off between 450–550°C, [6] leaving pores (air voids) in the brick, which retards heat flow.

One of the problems facing the building industry in Uganda 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, [7, 8]. Nevertheless, there are no classified thermal insulators produced in Uganda. The country depends on imported insulation materials which are very expensive and are not easily accessed by the local industry and yet there are abundant mineral deposits in different parts of the country, which can provide potential raw materials for the production of different ceramic products like thermal insulating bricks. Thus, this paper presents the results of an experimental study of the effect of particle size on thermal diffusivity of clay bricks of composition as shown in Table 1, which have been fabricated from a combination of kaolin, ball clay, and wood sawdust of different particle sizes.

## 2. Experimental Procedures

*2.1. Materials Processing.* The raw materials used in this study were kaolin, ball clay, and hard wood sawdust. The sawdust was obtained from mahogany. The hard wood was preferred because when incorporated in clay bricks, it forms uniform pores, has high calorific values, and does not cause bloating, [9]. The kaolin was collected from Mutaka in South Western Uganda while ball clay was collected from Ntawo (Mukono), 25 km east of the capital city, Kampala. The ball clay and

kaolin were separately soaked in water for seven days to allow them to dissolve completely in order to separate the colloids from heavy particles like stones, sand, and roots. The clay was then dried and milled into powder form in electric ball mill. The powders were sieved through test sieves stuck together on a mechanical test sieve shaker. The particle size ranges 0–45 $\mu$m, 45–53 $\mu$m, 53–63 $\mu$m, 63–90 $\mu$m, 90–125 $\mu$m, and 125–154 $\mu$m were obtained separately for kaolin and ball clay. Similarly, powders of sawdust of particle size ranges 0–125 $\mu$m, 125–154 $\mu$m, 154–180 $\mu$m, 180–355 $\mu$m, and 355–425 $\mu$m were also prepared.

The study was carried out using two sets of batch formulations. In the first part, the batch formulations $A_1$–$A_5$ had compositions of kaolin and ball clay of the same particle size ranges, which were mixed with equal masses of sawdust of three different particle size ranges in the ratios 9 : 7 : 4 by weight as shown in Table 1. The mixture of these powders was first sun dried and then compacted to pressure of 50 MPa into rectangular specimens with dimensions of 10.51 cm × 5.25 cm × 1.98 cm. The test samples were fired to 950°C in an electric furnace in two stages. In the first stage they were dried at a heating rate of 2.33°C min$^{-1}$ to 110°C and this temperature was maintained for four hours in order to remove any water in the sample. In the second stage, the samples were fired at a rate of 6°C min$^{-1}$ to 950°C. At this temperature, the holding time was one hour before the furnace was switched off to allow the samples to cool naturally to room temperature.

In the second part of the study, batch formulations $B_1$–$B_5$ had each of the particle size ranges 0–125 $\mu$m, 125–154 $\mu$m, 154–180 $\mu$m, 180–355 $\mu$m, and 355–425 $\mu$m of sawdust mixed with kaolin and ball clay of the same particle size ranges in the ratio 4 : 9 : 7 as shown in (Table 1) before compacting them at a pressure of 50 MPa into rectangular specimens of dimensions 10.51 cm × 5.25 cm × 1.98 cm. A similar firing process as for the first batch formulation was followed. Each of the sample formulations had a total mass of 200 g (90 g of kaolin, 70 g of ball clay, and 40 g of sawdust).

*2.2. Determination of the Coefficient of Thermal Diffusivity.* The coefficient of thermal diffusivity was determined from measured values of the specific heat capacity, thermal conductivity, and density using the following equation derived from Fourier's law of heat conduction through solid:

$$\alpha = \frac{k}{\ell c_p}, \tag{1}$$

where $\alpha$ is the thermal diffusivity, $k$ is the thermal conductivity, $\ell$ is density, and $c_p$ is specific heat capacity [10].

The thermal conductivity was measured by the Quick Thermal Conductivity Meter (QTM-500) with sensor probe (PD-11) which uses transient technique (nonsteady state) to study the heat conduction of the samples [11, 12]. Specific heat capacity was determined by method of mixtures [13] and the density was determined by measuring the dimensions and mass of the sample. Measurements of thermal conductivity, density, and specific heat capacity were performed at room temperature.

Table 1: Formulation of the brick samples.

| Sample | Particle size ($\mu$m) | | | |
|---|---|---|---|---|
| | Kaolin (90 g) + ball clay (70 g) | Sawdust addition (40 g) | | |
| $A_1$ | 90–125 | 0–125 | 125–154 | 154–180 |
| $A_2$ | 63–90 | 0–125 | 125–154 | 154–180 |
| $A_3$ | 53–63 | 0–125 | 125–154 | 154–180 |
| $A_4$ | 45–53 | 0–125 | 125–154 | 154–180 |
| $A_5$ | 0–45 | 0–125 | 125–154 | 154–180 |
| Sample | Particle size ($\mu$m) | | | |
| | Sawdust (40 g) | Kaolin (90 g) + ball clay (70 g) addition | | |
| $B_1$ | 0–125 | 63–90 | 90–125 | 125–154 |
| $B_2$ | 125–154 | 63–90 | 90–125 | 125–154 |
| $B_3$ | 154–180 | 63–90 | 90–125 | 125–154 |
| $B_4$ | 180–355 | 63–90 | 90–125 | 125–154 |
| $B_5$ | 355–425 | 63–90 | 90–125 | 125–154 |

*2.3. Chemical Composition.* The chemical composition of the fired samples was determined by the X-ray fluorescence (XRF), spectrometer, model X′ Unique ll [14], to establish the chemical composition of major compounds that influence the thermal properties of insulation clay bricks Table 2.

## 3. Results and Discussions

*3.1. Effect of Particle Size on the Coefficient of Thermal Diffusivity.* The coefficient of thermal diffusivity was determined by an indirect method involving the measurement of thermal conductivity, specific heat capacity, and density of fired samples [2, 10]. The effect of particle size on thermal conductivity, density, and specific heat capacity and thermal diffusivity is discussed below.

*3.1.1. Effect of Particle Size on Thermal Conductivity.* The results (Figure 1) show that thermal conductivity increases with decrease in particle size of kaolin and ball clay for fixed particle size of sawdust. This is because larger particles create large pores due to poor filling of the voids that contain air after firing compared to small particle sizes [15, 16]. Thermal conduction of a ceramic material depends on thermal conductive pathways which are affected by the microstructure, particle size distribution, and the amount of air space or voids created during the firing of a body [17]. Figure 2 shows that thermal conductivity decreases when the particle size of sawdust incorporated into the clay mix increases. This is because particle size of combustible organic waste determines the amount of air spaces that are created in the insulation clay brick [18–20]. In addition, thermal conductivity decreases further when particle size of the mixture of kaolin and ball clay increases due to less contact between particles [21]. Interlocking of clay particles depends on particle size distribution and particle size range of small

Table 2: Chemical composition of fired samples.

| Compound | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | $TiO_2$ | $Na_2O$ | MgO | $K_2O$ | $MnO_2$ | $P_2O_5$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Weight (%) | 68.98 | 22.29 | 1.87 | 1.15 | 0.48 | 2.04 | 1.04 | 2.54 | 0.05 | 0.57 |

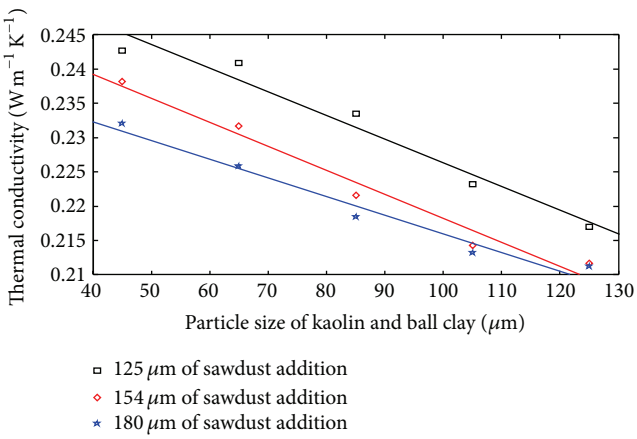


Figure 1: Effect of particle size of kaolin and ball clay on thermal conductivity with different particle size of sawdust.

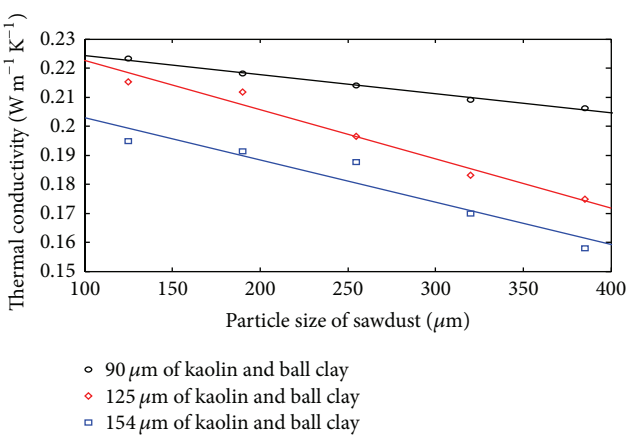


Figure 2: Effect of particle size of sawdust on thermal conductivity at different particle size of a mixture of kaolin and ball clay.

and large particles and also on whether the body is made of monosized particles or multiple size particles.

*3.1.2. Effect of Particle Size on Density.* The density of the samples increases with decreasing particle size of the mixture of kaolin and ball clay at fixed particle size of sawdust (Figure 3). Smaller particle sizes have more contact points that allow for more cohesion and lubrication of kaolin by ball clays. Multiple particle sizes in a ceramic body increase packing of particles and produce high density body because finer grains go into the interparticle voids of the coarser particles and thus increase the packing density. This study also shows that there is further decrease in density with increase in particle size of sawdust at fixed particle size of kaolin and ball clay [20].

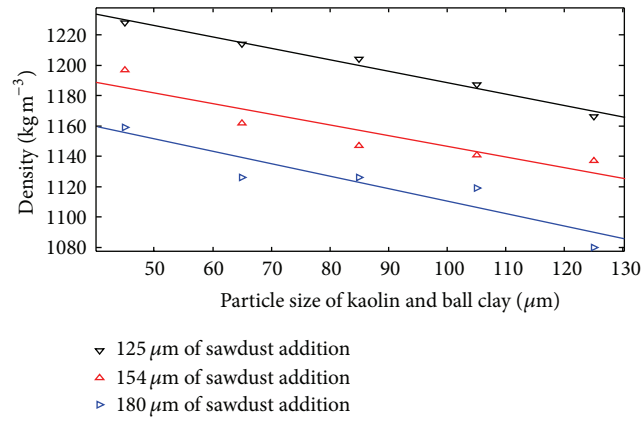


Figure 3: Variation of density with particle size of kaolin and ball clay for different particle size of sawdust.

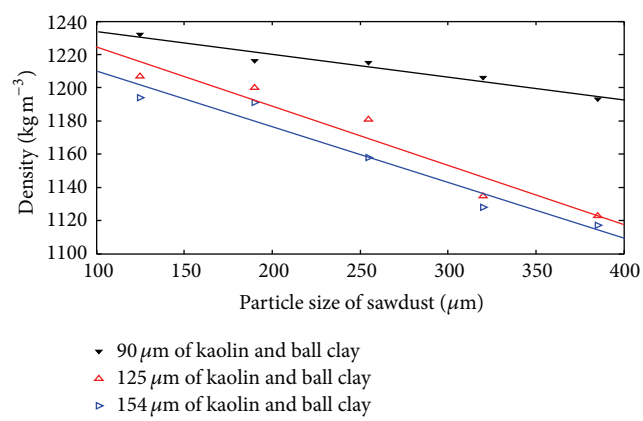


Figure 4: Variation of density with particle size of sawdust at different particle size of kaolin and ball clay.

In Figure 4, density of the samples decreases with increase in particle size of sawdust for fixed particle size of kaolin and ball clay. Small pores that are created by small particle size of sawdust tend to be closed during densification as a result of formation of intergranular contact areas, while large pores will remain in the clay matrix during firing and maturing [18]. This is attributed to the sufficient length of sawdust that improves the bond at the sawdust-clay interface to oppose the deformation and clay contraction during drying and firing [9].

*3.1.3. Variation of Specific Heat Capacity with Particle Size.* The specific heat capacities for samples $A_1$ to $A_5$ are generally lower than those of $B_1$ to $B_5$ (Figures 5 and 6). This implies that lower thermal diffusivity can be achieved by use of bigger particle sizes of sawdust [9]. The specific heat capacity increases with increase in particle size of clay materials

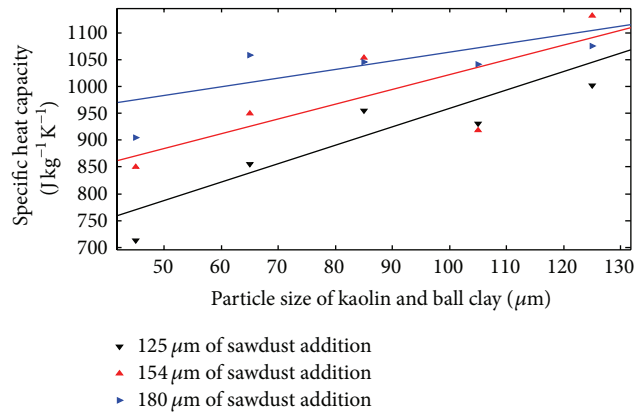


Figure 5: Effect of particle size of a mixture of kaolin and ball clay of specific heat capacity at different particle sizes of sawdust addition.

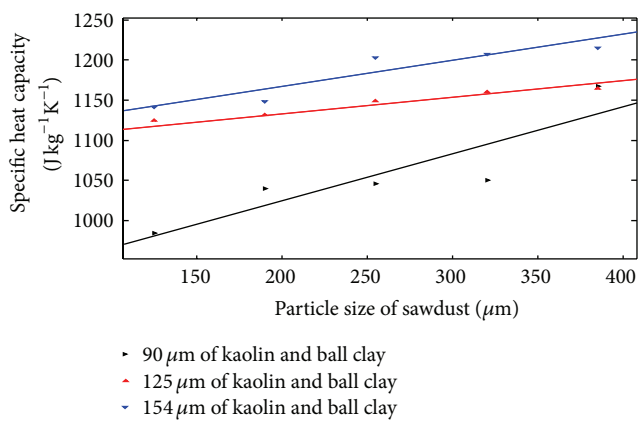


Figure 6: Effect of particle size of sawdust on specific heat capacity at different particle size of a mixture of kaolin and ball clay.

(Figure 5) used and increase in particle size of sawdust addition (Figure 6).

*3.1.4. Coefficient of Thermal Diffusivity.* The coefficient of thermal diffusivity increases as the particle size of the mixture of kaolin and ball clay decreases at fixed particle size of sawdust addition (Figure 7). The principal effect of particle size on the thermal diffusivity of the solid material is related to the amount of solid and air space which the heat has to transverse in passing through the material. This is attributed to large particle size which results in high porosity levels due to poor filling of voids between large size particles compared to small sizes thus creating large air spaces [21]. The large proportion of air produces low value of the coefficient of thermal diffusivity because of its low thermal conductivity. The decrease in particle size increases particle content per unit volume which decreases the average interparticle distance of the clay matrix. This results in close packing of particles that leads to densification of clay bricks which increases thermal diffusivity [16, 20]. Hence, a fine-grained, closed-textured material (small particle size) has a much greater thermal diffusivity than one with a coarser open texture

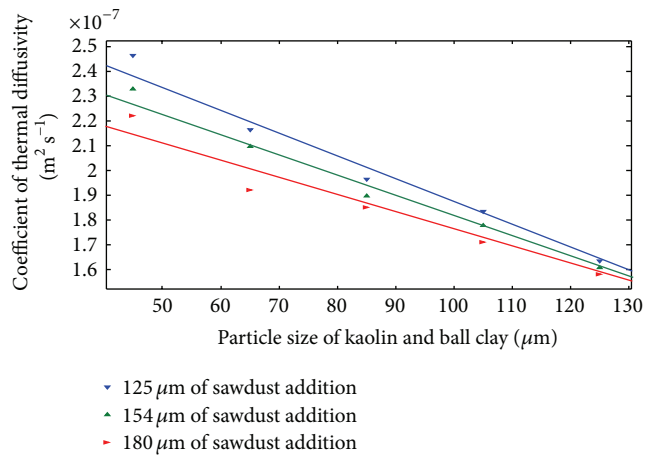


Figure 7: Effect of particle size of a mixture of kaolin and ball clay on thermal diffusivity at fixed particle size of sawdust.

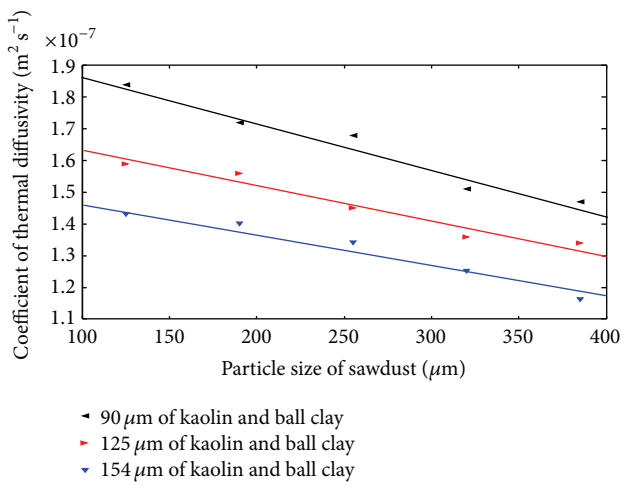


Figure 8: Variation of thermal diffusivity with particle size of sawdust at different particle size of a mixture of kaolin and ball clay.

(large particle size). Small particle sizes enhance low thermal resistance because the contact points for thermal conduction are very closely packed. Large grain size of kaolin and ball clay produces bricks that are more porous and thus more resistant to sudden temperature changes across the specimen [1, 22]. The low thermal diffusivity values are suitable for minimizing heat conduction. It is observed (Figure 7) that increasing particle size of sawdust addition further decreases the thermal diffusivity.

Thermal diffusivity decreases with increase in particle size of sawdust at fixed particle size of a combination of kaolin and ball clay (Figure 8). This is because particles of sawdust burn out between 450-550°C, [6] leaving pores or voids in the samples. During drying and firing, densification takes place and small pores created by small particle size of sawdust tend to be closed by clay minerals as a result of formation of intergranular contact areas, while large pores will persist in the clay matrix [18].

Incorporation of sawdust into the ceramic body which is removed during the firing step leaves pores whose sizes are related to the organic particle sizes. Finer sawdust forms smaller pores most of which may be eliminated during densification while large particle sizes form large pores. Sawdust of large particle size improves the bond at the sawdust-clay interface that opposes the deformation and clay contraction. This yields high porosity, low density, low thermal conductivity, and low rate of change of temperature across the specimen. Hence thermal diffusivity decreases as particle size of sawdust increases. Generally, the values of thermal diffusivity of $B_1$ to $B_5$ are lower than those of $A_1$ to $A_5$. This is a result of the multiplicative porosity created by clay and sawdust addition.

*3.2. Chemical Composition.* The percentage composition of $SiO_2$ is 68.0% while that of $Al_2O_3$ is 22.0%. According to the Bureau of Energy Efficiency [23] report on fireclay refractories, low density fireclay refractories consist of aluminum silicates with varying silica content between 67 and 77% and $Al_2O_3$ content between 23 and 33%. The chemical composition of alumina in the developed samples can be improved either by beneficiating the raw materials (kaolin and ball clay) or by increasing the percentage composition of kaolin in the samples. The clay samples contain less than 9.0% of the fluxing components ($K_2O$, $Na_2O$, and CaO).

*3.3. Implications.* The physical significance of low values of thermal diffusivity is associated with the low rate of change of temperature through the material during the heating process. The samples, therefore, have low values of the coefficient of thermal diffusivity and are suitable for use as thermal insulators. The suitable thermal insulator is the sample containing a combination of kaolin and ball clay of particle size range of 125–154 $\mu$m with sawdust of particle size range of 355–425 $\mu$m. This combination was characterized by the lowest value thermal diffusivity of $1.16 \times 10^{-7}$ $m^2$ $s^{-1}$ and can easily be prepared for commercial production of thermal insulation bricks.

## 4. Conclusions

The results of the study show that all the samples analyzed are good thermal insulators and the coefficient of thermal diffusivity is directly affected by particle size of a combination of kaolin and ball clay minerals as well as particle size of sawdust addition. Thus from the overall experimental analysis carried out, the following was observed.

(1) The coefficient of thermal diffusivity increases with decrease in particle size of a mixture of kaolin and ball clay at fixed particle size of sawdust addition. Sawdust addition of larger particle size decreases thermal diffusivity even at very small particle size of kaolin and ball clay.

(2) The coefficient of thermal diffusivity decreases with increase in particle size of sawdust addition to a fixed particle size of kaolin and ball clay. Incorporation of kaolin and ball clay of a much higher particle size further decreases the coefficient of thermal diffusivity due to the multiplicative effect of higher porosity produced by sawdust and clay minerals.

(3) The samples contain suitable compositions of silica and alumina which are suitable for lightweight high temperature insulation bricks.

(4) The samples, therefore, have low values of the coefficient of thermal diffusivity and are suitable for use as thermal insulators.

## Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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