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Experimental Investigation on the Thermal Properties of Gypsum Plaster-Rice Husk Ash Composite

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Abstract

This experimental investigation aims at evaluating the thermal properties of rice husk ash (RHA)—filled gypsum plaster composite for potential applications, as insulating materials. The thermal conductivities of composites of gypsum plaster reinforced with RHA at 0%, 10%, 20%, 30%, and 40% volume fractions were determined experimentally using Lee's disc method. The experimental results show that integrating RHA reduces the thermal conductivity of gypsum plaster and improves its insulation capacity. The results obtained from the experiments were compared with the Rule of Mixture Model, Maxwell Model, and Russell Model. It was observed that the thermal conductivities obtained from experiments and the theoretical models decreased with an increase in the volume fraction of RHA. The errors associated with the models with respect to experimental results are on the average of 28.7% for Mixture Rule, 31.6% for Russel Model, and 18.8% for the Maxwell Model. An agricultural waste like RHA can be beneficially used for the preparation of composites and, due to improved insulation capability, these composites can be used for applications such as insulation boards and sheathing, hardboard, ceilings of roofs, decorations, etc.

Keywords

Rice Husk Ash, Thermal Conductivity, Gypsum Plaster, Lee's Disc Method, Agricultural Waste

1. Introduction

An increase in population and urbanization has led to an increase in amount of agricultural waste. The quest to preserve the ecosystem as well as minimize environmental waste is a concern for the sustainable utilization and effective management of agricultural wastes. Rice is one of the most consumed staples in Nigeria, with a consumption per capita of 32 kg. Consumption has increased to 4.7% in the past four decades, amounting for up to 20% of Africa's consumption [1]. A huge amount of solid waste such as rice husk is being produced during the processing of rice. Despite the abundance of these wastes, their optimal utilization is still inadequate; leading to their disposal in landfills and open fields.

In recent years, the use of agricultural waste as a reinforcing material for polymer matrices has gained a lot of attention from researchers. This is because agricultural wastes, being abundantly available in Nigeria, have the impending prospect of serving as an alternative for artificial fibre composite. The widespread utilization of these agricultural wastes is because of their availability, low cost, low densities, nonabrasive nature, high filler loading, low energy consumption, high specific properties, biodegradability, and safe working environment [2] [3]. These properties make agricultural wastes attractive as an alternative composition in polymer production. As engineers are faced with the task of developing new material with the aforementioned properties, the use of rice husk ash (RHA) as a filler in gypsum plaster—RHA composite provides an opportunity to explore other additional engineering options.

Many researchers have studied the use of agricultural waste in composites from different perspectives and environments. Broad studies on the mechanical and thermal properties of composites filled with agricultural waste such as bagasse [4], pineapple leaf [5], rice husk [3], oil palm press fibre [6], jute-coir fibre [7] and coconut fibre [8] have been carried out. Investigations show that the alignment of these natural fibres has a significant effect on the thermal conductivity of composites. Mbimda [9] investigated the thermal properties of a hybrid composite consisting of rice husk, bagasse, and saw dust. The criteria they used for the evaluation include the experimental determination of thermal conductivities and specific heat capacities for composite samples and other dependable properties. The results from the study identify sample with 0.231 $W \cdot m^{-1} \cdot K^{-1}$ and 22.114 m^{-1} as the best mixed with more rice husk and a considerable percentage of bagasse compared to a lesser percentage of sawdust. Raju and Kumarappa [2] conducted a study with the objective of preparing a polymer-based composite material using agricultural waste as reinforcing material and analysing some mechanical and thermal properties. They chemically modified groundnut shell particles and combined them with epoxy to form novel bio-based composites. They observed that the thermal conductivity of composite specimens ranges from 0.07638 to 0.3487 $W \cdot m^{-1} \cdot K^{-1}$ and linear thermal expansion varies from 0.725×10^{-6} to $1.296 \times 10^{-6}/^{\circ}C$. The results showed that groundnut shell particles could be used successfully to develop a beneficial composite that would be a substitute for wood-based panels in many applications. Samsul *et al.* [10] conducted a study to determine the influence of the oil palm boiler ash (OPBA) reinforcement on the thermal properties of epoxy polymer composites. They reported that the thermal stability and the percentage of char residue of the composite increased with increasing filler loading. The findings of their study reveal that the OPBA has the potential to be used as reinforcement or filler as well as an alternative to silica-based inorganic fillers used in the enhancement of mechanical, physical, and thermal properties of the epoxy polymer composite.

This study aims at evaluating the thermal properties of rice husk ash-filled gypsum plaster composite for potential applications as an engineering material. Thus, it provides an innovative approach to transform this residue into a valuable end product to minimize rice production costs as well as reduce the negative impact on the environment.

2. Materials and Methods

2.1. Materials

The matrix used was gypsum plaster with a density of 2.76 g/cm^3 and a molecular mass of 290.3 g/mol. Rice husk ash was used as the filler material. The rice husk is first screened for dirt by washing to remove impurities. It was air dried for 48 hours and burnt in a furnace at 550˚C for approximately 6 hours in order to produce the ash used in the experiment. Horse hair fibre, chosen because of its reliability, availability, and cost effectiveness, was used as the reinforcement material.

2.2. Methods

2.2.1. Preparation of Composite Moulds

A circular disc-shaped mould of 110 mm in diameter and 10 mm thick was prepared for the experiment. Initially, a layer of soapy mixture of groundnut oil was applied to the mould so that the specimen can be easily taken out of the mould. Proper measured quantities of RHA and gypsum plaster according to Equations (1) and (2) [11] were taken in a plastic container and stirred thoroughly to get a homogeneous mixture.

$$V_F = 100 - V_M \tag{1}$$

$$V_C = V_F + V_M \tag{2}$$

where V_C, V_F and V_M are the weight of the composite material, RHA and gypsum plaster, respectively, as **Table 1** shows..

The mixture was poured into the mould to a level half the volume of the mould, and the set up was kept for 24 hours. After curing, the composite board was taken out of the mould. Specimen A was cast neat gypsum plaster and was used as the control.

2.2.2. Experimental Set up

The experimental set up was adopted from a technique presented by Ramesh, *et al.* [12]. The Lee's disc method shown in **Figure 1** consists of two parts: the lower part is circular metal disc (Nickel). The experimental specimens (A - E) are placed on it. The diameter of the specimens is equal to that of the nickel disc,

Table 1. Composition of the composite materials.

Sample	% V_F	% V_M
A	0	100
B	10	90
C	20	80
D	30	70
E	40	60

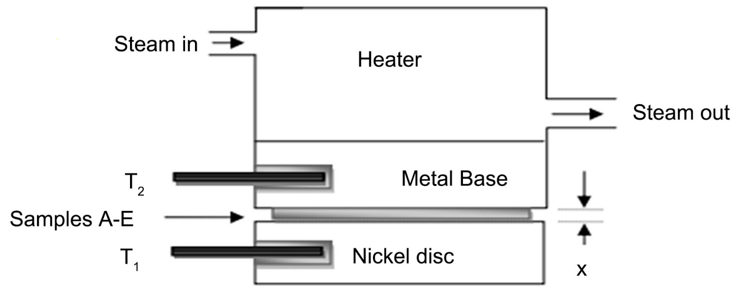

Figure 1. Experimental set up of Lee' disc method.

and the thickness is uniform throughout. A steam chamber was placed on the nickel. The lower part of the steam chamber was made of a thick metal plate of the same diameter as that of nickel disc. The upper part is a hollow chamber in which two side tubes are provided for the inflow and outflow of steam. Two thermometers, T_1 and T_2, were inserted into two holes in the nickel disc and the metal base, respectively. There were three hooks attached to the nickel disc. The complete setup was suspended from a clap stand by attaching threads to these hooks.

The rate of heat conducted through the specimens is given by:

$$\dot{Q} = kA\frac{T_1 - T_2}{L}. \tag{3}$$

where, L is the thickness of the samples A-E, A is the area of cross section of the samples, k is the thermal conductivity, and T_1-T_2 is the temperature difference.

Heat lost by the nickel disc to the surrounding under steady state is:

$$\dot{Q} = mc\left(\frac{\partial T}{\partial t}\right)_{T_2}. \tag{4}$$

where m is the mass of nickel disc, c is the specific heat of the metal base and $\frac{\partial T}{\partial t}$ is its rate of cooling at T_2. Also, from Equations (3) and (4), k is given as:

$$k = \frac{mc\left(\frac{\partial T}{\partial t}\right)_{T2}}{A\frac{T_1 - T_2}{L}}. \tag{5}$$

The thermal resistivity (r) is given as the reciprocal of the thermal conductivity.

$$r = \frac{1}{k} \tag{6}$$

2.2.3. Theoretical and Empirical Models

The thermal conductivity results obtained from the experiments are compared with three theoretical and empirical models proposed to predict the effective thermal conductivity of materials. These models are the rule of mixture model, the Russel model, and the Maxwell model.

The Rule of Mixture [12] assumes that:

$$\frac{1}{k_c} = \frac{1-\phi}{k_m} + \frac{\phi}{k_f}. \tag{7}$$

where, ϕ is volume fraction of filler and subscripts c, m and f are composite, matrix and filler, respectively.

The Russel Model [13] assumes that the discrete phase is isolated cubes of the same size dispersed in the matrix material and that the isothermal lines are planes, an equation for the thermal conductivity of the composite was derived using a series parallel network is given by:

$$k_c = k_m \left[\frac{\phi^{\frac{2}{3}} + \left(\frac{k_m}{k_f}\right)\left(1-\phi^{\frac{2}{3}}\right)}{\phi^{\frac{2}{3}} - \phi + \frac{k_m}{k_f}\left(1+\phi-\phi^{\frac{2}{3}}\right)} \right]. \tag{8}$$

Maxwell developed effective thermal conductivity of composite is derived by considering spherical fillers dispersed in a continuous matrix randomly [14]. He assumed that these fillers are distributed into the matrix having no thermal interaction with each other. His model is governed by Equation (9).

$$k_c = k_m \left[\frac{k_f + 2k_m + 2\phi\left(k_f - k_m\right)}{k_f + 2k_m - \phi\left(k_f - k_m\right)} \right] \tag{9}$$

Equations (7), (8) and (9) apply to only two-phase mixtures.

3. Results and Discussion

The cooling rate of the gypsum plaster and RHA mixture in terms of time – temperature curve is shown in **Figure 2**. The thermal conductivity of the samples obtained from the experiment is shown in **Figure 3**. The result shows that the incorporation of RHA results in an increase of thermal conductivity from 0.186 W/mK to 0.195 W/mK at 10% composition of RHA and then a reduction of thermal conductivity of the subsequent mixtures with increased composition of RHA. Therefore, increasing the percentage of RHA (**Table 1**) decreases the thermal conductivity of the composite, thereby increasing its insulation capability.

With the addition of 20%, 30%, and 40% of RHA, the thermal conductivity of the gypsum plaster, as shown in **Table 2**, dropped by 23.1%, 21.5%, and 40.3%, respectively. The thermal conductivity of the different specimens obtained from the experiment was compared with several thermal conductivity models as shown in **Figure 4**. It is observed that the thermal conductivities obtained from experiments and the three theoretical models used in this study decrease with an increase in the volume fraction of RHA (except for specimen B). It is additionally observed that the thermal conductivities obtained from the three models are overestimated compared to the experimental results.

In comparison, it was found that the errors associated with all the three models with respect to experimental results are on average 28.7% for the Mixture Rule, 31.6% for Russel Model, and 18.8% for the Maxwell Model. Based on this, the Maxwell (Max.) Model is the most accurate among the three models used in this study. The values of thermal conductivities for all the models are given in **Table 3**.

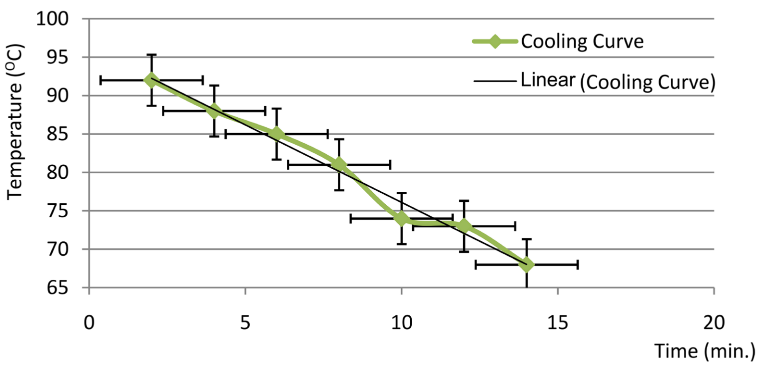

Figure 2. Cooling rate for composite (Time-Temperature curve).

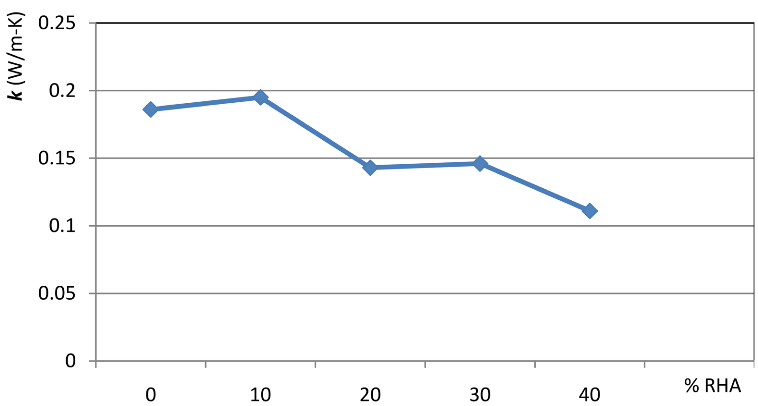

Figure 3. Effects of percentage RHA on the composition thermal conductivity.

Table 2. Thermal conductivity and resistivity of the composites for varied % RHA.

Samples	RHA % Conc.	Experimental *k* (W/m K)	% Reduction of *k* with respect to sample A	*r* (mK/W)
A	0	0.186	0.186	5.38
B	10	0.195	−4.8	5.19
C	20	0.143	23.1	7.00
D	30	0.146	21.5	6.85
E	40	0.111	40.3	9.00

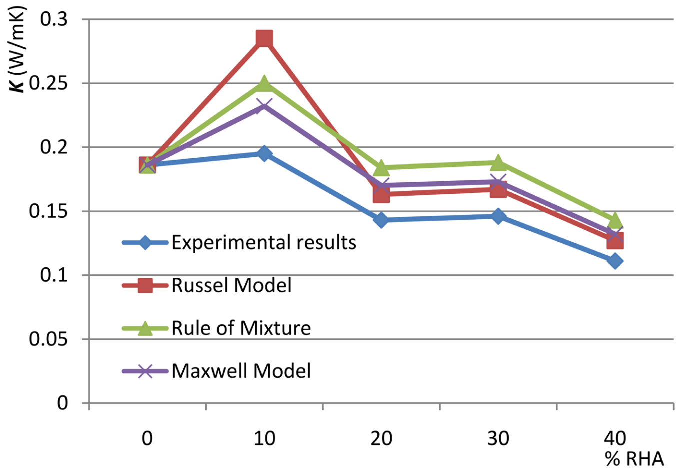

Figure 4. Comparison of experimental thermal conductivity with the model values for varied filler content.

Table 3. The composites thermal conductivity obtained from different methods.

Sample	% RHA Content	Experimental k (W/m-K)	Mixture Rule (W/m-K)	Russel Model (W/m-K)	Max. Model (W/m-K)
A	0	0.186	0.186	0.186	0.186
B	10	0.195	0.250	0.285	0.232
C	20	0.143	0.184	0.163	0.170
D	30	0.146	0.188	0.167	0.174
E	40	0.111	0.143	0.127	0.132

4. Conclusion

The investigation determined the influence of RHA on the thermal properties of an RHA-reinforced gypsum plaster composite. It shows that the thermal conductivity of the RHA filled composite reduces with increased content of RHA. The analysis also revealed that at 40% RHA, 60% gypsum plaster, the thermal conductivity obtained was 0.111 W/mK. It is concluded from the above analysis that agricultural waste like RHA, can be beneficially used for the preparation of composites, which is due to improved insulation capability. These composites can be used for applications such as insulation boards and sheathing, hardboard, ceilings of roofs, decorations, etc.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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