World Academics Journal of Engineering Sciences
Vol.9, Issue.3, pp.07-14, September (2022)
Research Paper
E-ISSN: 2348-635X

Production and Characterization of Rice Husk Ash-Based Thermal Insulators for Heat Energy Saving Applications

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Available online at: www.isroset.org

Received: 05/Jul/2022, Accepted: 15/Aug/2022, Online: 30/Sept/2022

Abstract-Insulating refractories are usually produced and used for different applications to reduce energy losses and save energy. In this research, thermal insulators are made using the nanosilica-based ash generated from chemically treated rice husks. Typically, the rice husks were sieved and washed with deionized water. The husks were boiled in hydrochloric acid (HCl) and then soaked in Phosphoric acid (H_3PO_4) to further remove mineral impurities. The thermal insulators were formed by the pressing method and were fired at temperatures between 1000-1400 ^oC. The generated ash contains high silica content. The low thermal conductivity and enhanced mechanical and physical properties of the thermal insulators indicate that the insulators are suitable for heat energy-saving applications especially, in furnaces and other similar devices.

Keywords- Thermal Insulator, Rice Husk Ash, thermal conductivity, Porosity, Pressing method

I. INTRODUCTION

One major interest of any industry is the conservation of energy. Thermal insulation is one method used to reduce energy losses [1]. For industrial furnaces, and other similar equipment energy losses are lessened and thermal efficiency enhance by using well-functioning and high-efficiency thermal insulation materials applied to the lining of the interior of the equipment [2]. Recently, research demand has shifted to utilizing waste materials in industrial products with many benefits viz: preserving natural resources and energy. The application of waste into industrial products also replaces open field burning and landfilling as methods of waste disposal [3]. One major biowaste that has received much research attention and application is rice husk [4, 5, 6].

The global rice production estimates in 2015 and 2016 as reported by Food and Agricultural Organization were 494.6 and 490.6 million tons respectively. The production rose to approximately 758 metric tons in 2017 [7]. A natural covering called rice husk (RH) forms and envelops the rice grain [8]. The husk is made up of lignin and opaline silica, two hard substances. During the milling of rice, it separates from its grain. [8]. Rice husk adds around 20-25 % by weight of the total dry mass of paddy [9]. Rice husk ash (RHA) contains incompletely burned organic components and a mixture of crystalline and about 85-90% amorphous silica [10, 11, 12]. The ashes' make-up naturally made them opposed to chemical etching (acid slag) and thermal shock (temperature change greater than 600 $^{\circ}$C) and the thermal conductivity is low as well as mechanical characteristics. The ashes are appropriate for use as raw materials in industrial ceramic processes like thermal insulation because of these characteristics. [7, 13, 14]. The environmental threat posed by rice husk or its ash calls for urgent attention. So far, the best method of doing away with the husk or its ash is processing for valuable applications such as heat resistance applications.

Thermal insulation (heat resistance) is the reduction of heat transfer between objects in thermal contact or the range of radiative effects [15]. Heat transfer is the movement of thermal energy between objects of varying temperatures. Thermal insulation gives a way of sustaining the gradient of temperature, by providing a region of resistance in which heat flow is reduced or thermal radiation is reflected rather than absorbed [16]. It reduces energy consumption by resisting energy gain and losses. Thermal conductivity is the primary product feature that influences insulating efficiency in thermal engineering of insulating systems for ovens, reactors, furnaces, and building construction, among other applications. [17]. Rice husk ash, based on its aforementioned properties is a promising candidate to produce thermal insulators for efficient thermal insulation applications.

The demand for sustainable and green thermal insulators keeps increasing every day because they are cheaper and more affordable as the raw materials are inexpensive. In addition, the thermal insulators resulting from green materials are efficient and reliable. The enhanced properties of the green thermal insulators are dependent on the particles of the raw material used. The emergence of nanoscience and nanotechnology has provided different methods to produce materials at the nanoscale, which proved to have better properties than conventional materials. Motivated by the enhanced properties of green thermal insulators to save energy and reduce losses and the need to find an efficient means of utilizing rice husk, therefore, this research used rice husk as the basic raw material to make thermal insulators. The raw rice husk has been processed to produce nanosilica- based- rice husk ash, which is used for thermal insulator fabrication. The insulators are characterized for heat energy-saving applications in some mechanical devices such as dryers, Ovens, Kilns, furnaces, and building construction among other Applications. Finding an effective use for rice husk is crucial from an economic and environmental standpoint.

II. RELATED WORKS

Goncalves and Bergmann [18] fabricated thermal insulators using rice husk ashes. The correlation of properties and microstructures of the produced insulators was studied. Haryati et al [14] studied insulation materials using rice husk granules. The low thermal conductivity makes the insulators suitable for use as insulating materials. Babaso and Sharanagouda [19] reviewed the applications of rice husk. The use of rice husk ash for making insulating refractories was also studied. Hossain et al [20] also reviewed the use of rice husk/rice husk ash as an alternative source of silica in ceramics with an emphasis on the manufacture of traditional and advanced ceramics. In a similar paper, Hossain and Roy [1] also developed a new route to utilize rice husk ash for insulation refractory. Loy et al [21] studied Malaysian rice husks and used the husk to generate ash to produce silica-based ceramics. The effect of sintering temperature on properties such as crystalline phase formation, density, microstructure, and thermal diffusivity was investigated. Selvaranjan et al [22] developed a cheaper thermal insulation wall plaster using rice husk ash as the major raw material. The properties of the insulation material were also investigated.

III. MATERIALS AND METHOD

Materials and Chemicals

The major raw material in this research is rice husk (RH). The same sample of rice known as Osi (Nerica-I) variety of rice reported in our previous research [4] is used for the preparation of nanosilica-based- RHA. Typically, RH was collected from a rice milling station in Makurdi, Benue State Nigeria. Hydrochloric acid (37 wt %), and phosphoric acid (85 wt %) were all purchased from Sigma Aldrich. All of the chemicals were of analytical grade and were utilized directly. Besides, plasticizer additives and binders including Bentonite, modified starch, and sodium silicate were also purchased from Sigma Aldrich. Wood sawdust was used as a porosity-maker agent. A little amount of wood sawdust was added to prevent laminating effect during forming and sintering.

Method

Rice Husk Ash Production

Raw RH was sieved to remove dirt and other unwanted particles or contaminants. Washing was done using deionized water and the water content was drained in an open shield. The RH was thereafter first washed in 10-wt% hydrochloric acid (HCl) and then in phosphoric acid (H_3PO_4) for further purification. The double acid–washed samples of RH were dried in an oven at 100 °C for 24 h. The samples were then calcined in a box furnace at 550 °C for 6 h. The procedure was repeated to produce more of the samples known as rice husk ash (RHA).

Specific Gravity and Loss on Ignition Tests of ash

The specific gravity of the RHA was determined using equation 1.

$$Specific\,Gravity = \frac{(m_2 - m_1)}{(m_4 - m_1) - (m_3 - m_2)} \quad 1$$

Where

$m_3(g) = mass\ of\ Jar,\ plate, RHA, and\ water$

$m_2(g) = mass\ of\ Jar,\ plate, and\ RHA$

$m_4(g) = mass\ of\ Jar,\ plate, and\ water$

$m_1(g) = mass\ of\ Jar, and\ plate$

$m_2 - m_1 = mass\ of\ RHA$

$m_4 - m_1 = mass\ of\ water$

$m_3 - m_2 = mass\ of\ water$

The loss on ignition was determined using equation 2.

$$\%\,loss\,on\,ignition = \frac{Loss\,on\,ignition}{Mass\,before\,heating} \times 100 \quad 2$$

Sieve Analysis

The rice husk ash and wood sawdust grain size were found by sieve analysis. Typically, sieves of different diameters were used for a total of 500 g RHA and 500 g of Wood sawdust. The mass retained and mass passing with respective percentages were recorded for each sieve.

Chemical Composition, Structure, and Morphology of RHA

Energy Dispersive X-ray Fluorescence (ED-XRF) Spectrometry determined the chemical composition of the acid-treated ashes. The structure of the major component of the ash so produced was determined using X-ray Diffraction (XRD) analysis while the morphology was determined using Scanning Electron Microscope (SEM), and Transmission Electron Microscope (TEM).

Thermal Insulator Paste Formulation

Five samples of the thermal insulators were produced from the same mixture of RHA as the major raw material, plasticizer (Bentonite), binders (starch and sodium silicate), Wood sawdust) and water. The mixture was done manually and the quantity of the constituents of the ceramic paste was calculated based on mass. The amount of water added was based on the mass of the solid. The cylindrically formed thermal insulators were formed by the pressing method. Thereafter, the samples were dried in an oven at 100 °C for 24 hours and were fired at different temperatures of 1000, 1100, 1200, 1300, and 1400 °C for 2 hours in a muffle furnace with a heating and cooling rate of 5 °C/min. The samples were set for characterization.

Characterization

The produced thermal insulators were characterized based on porosity, density, compressive strength, and thermal conductivity.

The porosity of the fired thermal insulators was done based on the recommendations of ASTM C20-00. A sample of the fired thermal insulators was weighed and the result was written as W_O. It was then submerged in water at ambient temperature, removed and the weight was recorded as W_1. Thereafter, the sample was re-immersed in the water and allowed to absorb water until saturation, and the weight was recorded as W_2. The density of water is 1 gcm^{-3}.

$$Apparent\ Porosity\ (\%) = \frac{W_2 - W_o}{W_2 - W_1} \times 100 \quad 3$$

The bulk density was determined following ASTM C693. It was measured using equation 4.

$$Bulk\ Density = \frac{W_o}{W_2 - W_1} \quad 4$$

A compressive Strength testing machine under ASTM 773 /88 measured the maximum compressive load the thermal insulator can bear before fracturing.

Thermal conductivity test was done under standard laboratory test and ASTM E 1225/87. The electrical method of Lee's conductivity apparatus L44-590 was employed to determine the thermal conductivity.

IV. RESULT AND DISCUSSION

Properties of RHA

Physical and chemical properties of RHA

The physical characteristics of rice husk ash (RHA) considered in this research are specific gravity, loss of ignition, and grain size (Particle size) distribution. The mean value of specific gravity as determined using equation 1 is 2.17. The value of specific gravity of 2.17 indicates that the density of RHA is 2170 kg/m^3. The value is the same as that obtained by Oyekan et al. [23] and it is less than 2.36, and 2.21 reported by Cook et al. [24], and Amin and Bassam [25] respectively. The specific gravity value obtained here is also very close to the 2.15 obtained by Sampaio et al. [26]. The difference in the value of the specific gravity of RHA is indicative of its dependence on location and harvest time [23].

Loss of ignition (LOI) is primarily because of the presence of moisture, unburned residues, and unstable mineral phases at high temperatures [27]. The result of loss on ignition of 3.90 %wt is less than the 4.13 value obtained by le Tuan and Nguyen [27]. Table 1 displays the result of sieve analysis conducted on rice husk ash obtained in this research.

Table 1. Grain size distribution of rice husk ash (500 g)

BS Diameter X 10^{-1} mm	Mass Retained (g)	% Retained	Mass Passing (g)	% passing
23.60	0	0.00	500	100
17.00	0	0.00	500	100
11.80	4	0.80	496	99.2
8.50	9	1.80	487	97.4
6.00	20	4.00	467	93.4
4.25	25	5.00	442	88.4
3.00	36	7.20	406	81.2
1.50	81	16.2	325	65.0
0.75	145	29.0	180	36.0
pan	180	36.0	-	

The sieve analysis was done beginning with a total mass of 500 g of rice husk ash derived from the calcination of acid–pretreated rice husk. From the result in Table 1, it can be observed that RHA used in this research have finer grain sizes. The result shows that the smaller the sieve size the greater the percentage of the RHA grains retained on it and the smaller the percentage of the grains passing through it. The pan retained the highest percentage of the RHA grains indicating the finest nature of the grains.

Table 2 shows the grain size distribution of wood sawdust used as a load or porosity-maker agent in this research. The result from table 2 indicates that sieves of sizes 0.3 mm and 0.15 mm having 29 and 35.2 % respectively retain most of the wood sawdust. This indicates that most grains of the wood sawdust have sizes of 0.3 and 0.15 mm.

Table 2: Grain Size Distribution of Wood Saw Dust (500 g)

BS Diameter X 10^{-1} mm	Mass Retained (g)	% Retained	Mass Passing (g)	% passing
23.60	0	0	500	100
17.00	0	0	500	100
11.80	19	3.8	481	96.2
8.50	21	4.2	460	92.0
6.00	27	5.4	433	86.6
4.25	74	14.8	359	71.8
3.00	145	29.0	214	42.8
1.50	176	35.2	38	7.6
0.75	30	6	8	1.6
pan	8	1.6	-	

Table 3 presents the X-ray fluorescence (XRF) result of the RHA. The result indicates the presence of SiO_2 as the major compound and some other impurities. The sum of the percentages of SiO_2, Fe_2O_3, CaO, and K_2O is more than the minimum of 70 % required for the ash to be used as a pozzolan according to ASTM C618, 1978 [18]. The high yield of silica (99.20 %) obtained in this result is due to acid pre-treatment of the raw rice husk.

Table 3: Chemical Analysis of RHA by XRF

Compound	Percentage (%)
SiO_2	99.240
Fe_2O	0.231
P_2O_5	0.008
MnO	0.031
K_2O	0.096
CaO	0.198
RuO_2	0.143
TiO_2	0.005
ZnO	0.001
CuO	0.023
Re_2O_7	0.014
Cr_2O_3	0.010

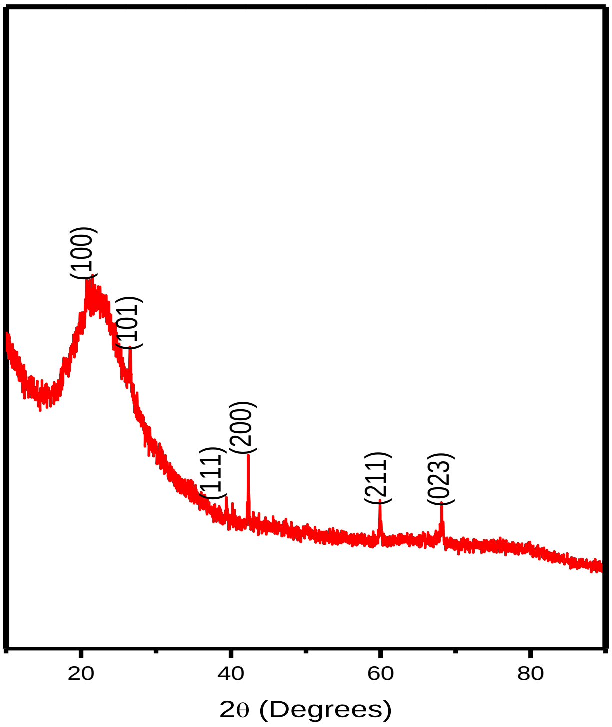

Fig.1. XRD patterns of RHA

Structure and morphology of RHA

Figure 1 presents the XRD patterns of rice husk ash (RHA) used for the production of thermal insulators in this research. The XRD pattern in Figure 1 shows a single broad peak from 15 to 30° with a maximum at 2θ ~22.19°, which suggests amorphous silica [4, 28, 29]]. There is also a crystalline peak at about 2θ ~26.58° which is assigned to the (101) plane and belongs to the silica phase. The XRD pattern of the RHA also shows several small peaks at about 2θ= 39.46, 42.45, 59.97, and 68.21° which are assigned to the (111), (200), (211), and (023) Planes respectively.

Fig. 2 (a) presents the SEM image of rice husk ash (RHA) derived from rice husk (RH). The image shows the formation of agglomerates of nano-sized irregular-shaped particles. Fig.2 (b) shows the TEM image of the RHA. The TEM micrograph shows dispersed nano-sized spherical-shaped particles. The average particle size of the particles as determined using the TEM micrograph gives the value of approximately 47.6 nm indicating nanosilica-based RHA.

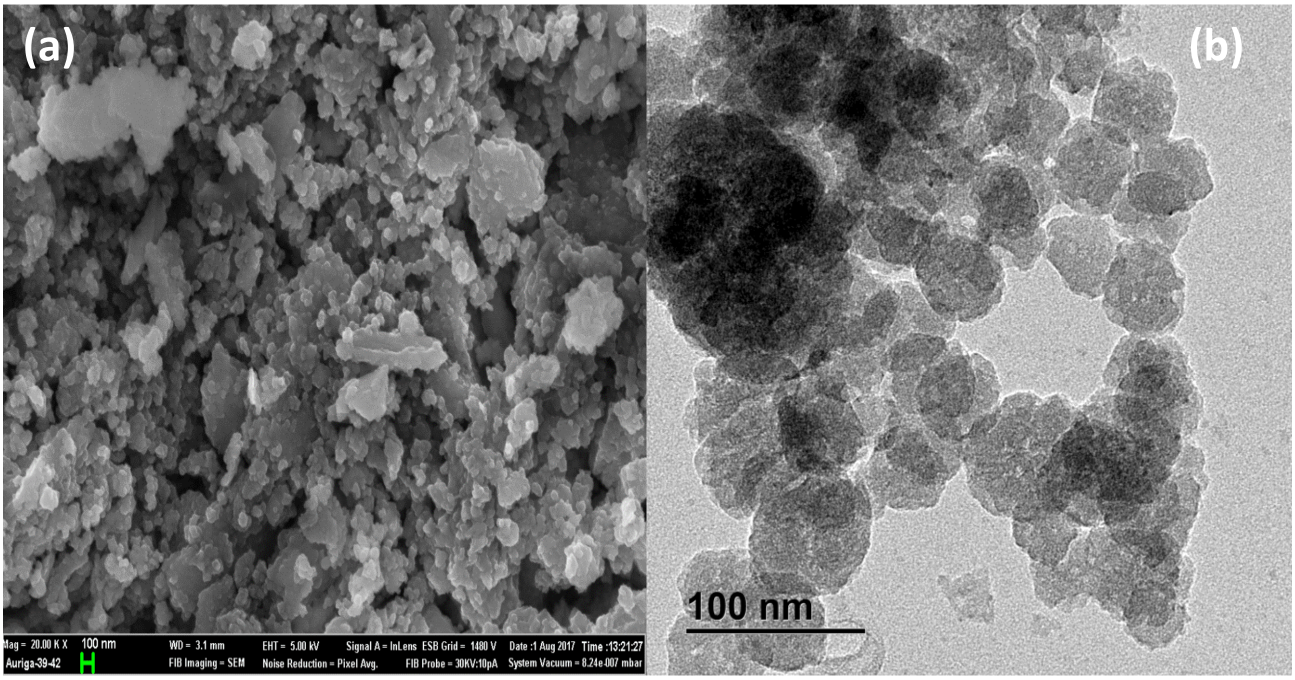

Fig 2: (a) SEM image and (b) TEM image of RHA

Physical, Mechanical, and Thermal properties of RHA Thermal Insulators (RHA-TI)

Table 4 shows the physical, mechanical, and thermal properties of RHA thermal insulators.

Table 4: Physical, mechanical, and thermal properties of (RHA-TI)

Sample/Temperature (^{o}C)	Apparent Porosity (%)	Bulk Density (g/cm^{3})	Compressive Strength (MPa)	Thermal Conductivity (Wm^{-1}K^{-1})
RHA-TI 1000	68	0.64	3.50	0.130
RHA-TI 1100	63	0.69	9.00	0.133
RHA-TI 1200	60	0.73	15.0	0.138
RHA-TI 1300	58	0.81	23.5	0.143
RHA-TI 1400	55	0.84	29.0	0.152

The efficient performance of a thermal insulator is most affected by its porous nature [30]. Figure 3 represents the apparent porosity of the RHA-TI. The apparent porosity is observed to decrease with an increase in temperature. Hossain et al. [7] attribute this behavior to enhanced change in the sintering kinetics at higher temperatures and reduction in pores/pore size due to the nanoscale size of the insulator forming rice husk ash particles. The decrease in porosity is shown in Figure 3. The behavior was also observed in the insulation bricks prepared from the utilization of the plant's waste [31].

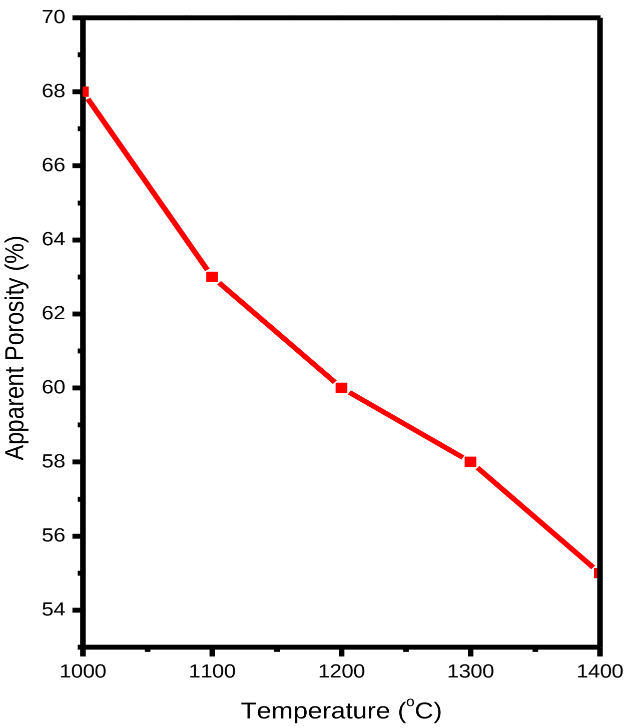

Fig. 3. Porosity versus Temperature

Table 4 and Fig. 4 presents the result of the Bulk density of the rice husk ash thermal insulators. As predicted, the density of the RHA-TI increases as the temperature increases. The density is less than 1 following the specified standard of IS: 2042.

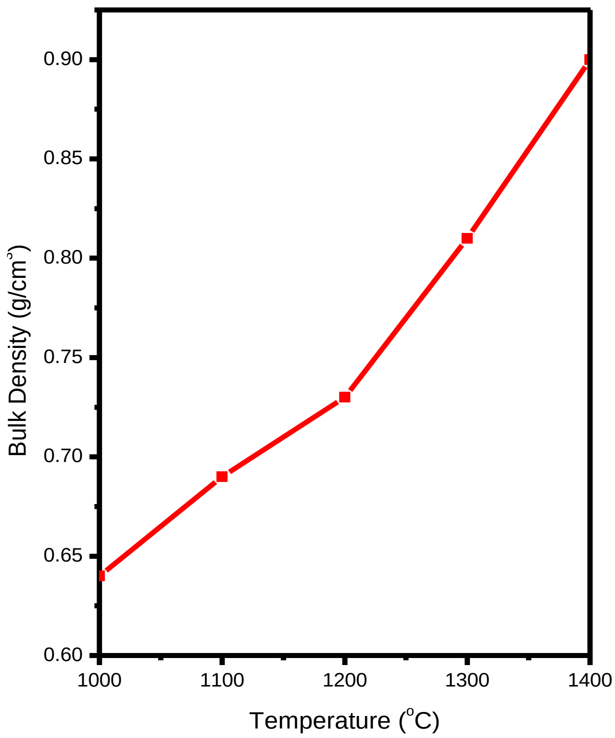

Fig. 4. Bulk density Vs Temperature

The low density of rice husk ash is responsible for the low density of the RHA-TI [7]. The increase in density at the higher temperature of firing is a confirmation of the reduced porosity observed at higher temperatures.

The variation of temperature with compressive strength of the insulators (RHA-TI) is displayed in Fig.5 (a) and shown in Table 4. From Fig.5 (a) and Table 4, it is clear that the compressive strength of the samples increases as the firing temperature increases. In addition, from Fig 5 (b) and Table 4, the compressive strength has shown a relationship with the porosity of the samples. The higher the values of porosity the lower the value of compressive strength for all the samples. Hossain and Roy [1] reported a similar result where the compressive strength increases as the porosity decreases. Besides, the compressive strength is also observed to vary with the density of the samples (See Fig. 5 (b)). The strength of the RHA-TI increases as the density of the insulators increases. The compressive strength of samples is therefore dependent on the porosity, pore size, and density of the material [1, 32]. The use of wood Sawdust also contributed to the good mechanical properties of the RHA-TI as it enhances the mechanical reinforcing effect due to the high interaction of the fibers and the binder [33].

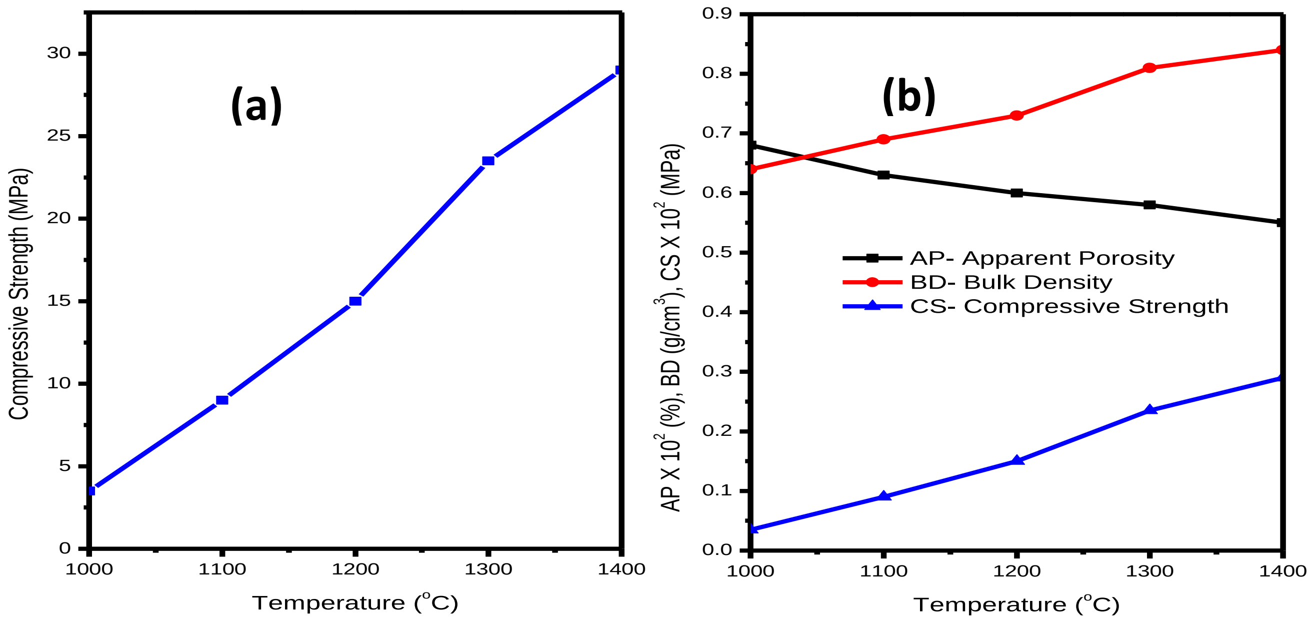

Fig. 5. (a) Compressive Strength Vs Temperature (b) Correlation between Apparent Porosity, Bulk Density, and Compressive Strength

The thermal conductivity of a material is the property of the material that shows the measure of the ability of the material to conduct heat [34, 35]. Fig. 6 (a) displays the thermal conductivity values of the RHA-TI (also see Table 4). The values of thermal conductivity increase as the temperature increases to higher values. Temperature, chemical and mineralogical composition, pores/pore size, and other defects affect the thermal conductivity of refractories [1]. The observed increase in thermal conductivity at higher temperatures may be due to a decrease in porosity and enhanced densification (see Fig 6 (b)). At low temperatures, the RHA-TI are with higher pores, which act as a barrier to the flow of heat, therefore, reducing thermal conductivity. The porosity is reduced at higher sintering temperatures. To explain this, consider that the transfer of heat through a solid material is mainly dependent on the transfer of energy among the vibrating atoms via phonons, photons, electrons, or ions. For refractories, phonons and photons are the likely candidates. The role of any of them is temperature dependent. At low temperatures up to 400 ^{o}C, energy transfer is majorly by lattice vibrations (phonons) at the speed of sound [36]. However, at higher temperatures, photon conductivity (radiation) becomes the major mechanism by which energy travels in the solid material. There is a rapid absorptions and emissions of photons, which travel at the speed of light [1, 36]. Obviously, at higher temperatures, photon conductivity (radiation) becomes the major mechanism by which energy travels in the solid material. It is the mechanism that controls how energy moves through materials at high temperatures [37]. It is the mechanism responsible for increasing thermal conductivity at higher temperatures in ceramic materials like our RHA-TI.

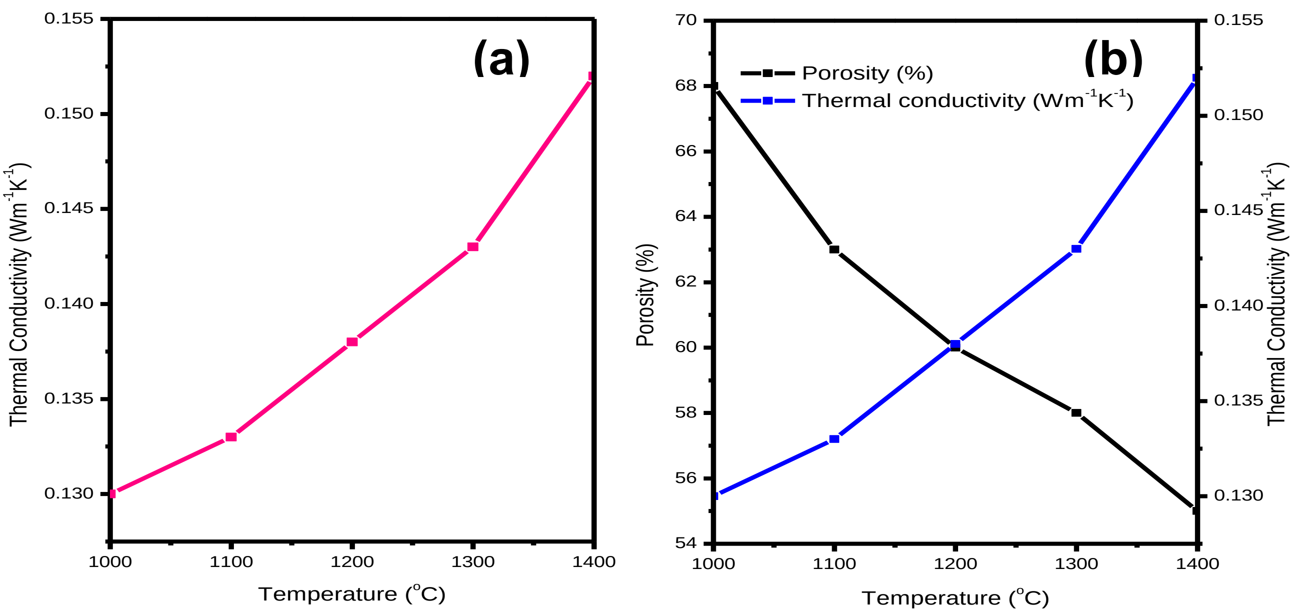

Fig. 6 (a) Thermal Conductivity Vs Temperature (b) Correlation between Temperature, Porosity, and Thermal Conductivity.

V. CONCLUSION AND FUTURE SCOPE

Rice husk ash thermal insulators have been produced by the pressing method using ash generated from the burning of chemically treated rice husk. The enhanced properties of the RHA-TI are due to the chemical treatment of rice husk, which produced nanosilica-based rice husk ash with improved chemical, morphological and structural properties. Typically, the thermal conductivity of the RHA-TI increases as porosity decreases at higher temperatures. Besides properties such as compressive strength and density have also increased at higher temperatures. The low thermal conductivity values in addition to the enhanced mechanical properties of the RHA-TI indicate that the insulators are potential insulating materials in the lining of furnaces and other applications. However, much improvement and more research are needed to fabricate nanosilica-based rice husk ash thermal insulators for applications requiring high temperatures above 2000 ^{o}C.

ACKNOWLEDGMENT

This research work has been sponsored by Tertiary Education Trust fund, Abuja, Nigeria.

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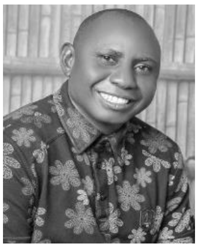

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