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Experimental Study of Thermal Conductivity of Some Selected Ceiling Materials Used in Building Design in Sokoto

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Abstract **Original Research Article**

The hot-dry climate of Sokoto Metropolis demands building materials that can minimize indoor heat gain. This study assessed the thermal conductivity of four commonly used ceiling materials: Plywood, plaster of Paris (POP), suspended mineral fiber ceiling and Asbestos cement board. Samples were obtained from major markets in Sokoto and tested under standard Laboratory conditions to determine their thermal conductivity, density and thickness. Results revealed that plywood had the lowest thermal conductivity followed by suspended ceiling, POP and asbestos cement board with the highest value. The finding indicate plywood and suspended ceiling boards offer better thermal insulation and are more suitable for reducing indoor temperatures and cooling energy demand in Sokoto. It is recommended that these materials be prioritized in building design, while the use of asbestos should be discouraged due to high conductivity and health risk. Enhancing POP ceiling with insulation is also advised for improved thermal performance.

Keywords: Thermal conductivity, ceiling materials, indoor comfort, Sokoto, Energy efficiency.

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1. INTRODUCTION

In our homes, indoor thermal discomfort has been challenging and it depends on one or more of the materials used either as ceiling board, rock used as walling materials, wood used in making doors, wood materials, wood used in making doors, wood sample used in making roofing support and the roofing sheet or combination of all of them. The most important concerns of the trained builders is to design a building that the indoor environmental condition is thermally tolerable and conducive to the occupant of the building (1). Besides the wall, the ceiling, the door and the roofing materials used for flooring and carpeting also generate heat therefore contributing to the thermal discomfort of a building (1). The comfort of the building depends largely on the materials that constitute them, such as ceiling, roofing, walling etc and the way they are used. Despite the important progress experienced by the construction industry there is no clear methodology to implement a suitable selection of these materials (2).

Most building materials, particularly roofing and walling materials are good conductors of heat. Materials like zinc and aluminium are commonly used in the form of sheet materials for roofing and walling in building construction, but these materials are known to have a high ability to

conduct heat due to solar radiation into the interior space of a building, a situation that causes discomfort in indoor spaces in tropical (3). The knowledge of thermal properties of different walling materials is very important in the choice of the type of materials to be used in the construction of a self-cooling or passively cooled building design. Heat flow through building material is depended on the thermal properties of the material(4).

In this study emphasis is on the comparision of the thermal insulation efficiency of the different commonly used ceiling materials based on their properties. The ceiling materials are made from different materials with different thermal conductivities, thermal absorptivities, and thermal resistivities (4). Depending on how large or small the value of these thermal may be more efficient in terms of thermal insulation than another. Study have shown that people that are economically favoured usually go for the most costly and fancy ceiling materials without any consideration for the thermal insulation efficiency. (1).

Thermal conductivity is the intrinsic property of a materials which relates its ability to conduct heat. Heat transfer by conduction involved transfer of energy within a material without any motion of the materials as a whole. Conduction takes place when a temperature gradient exists in a solid medium. Conductive heat flow occurs in the direction of decreasing temperature because higher temperature equates higher molecular energy or more molecular movement. (4). Energy is transferred from the more energetic to less energetic molecules when neighbouring molecules collide. Thermal conductivity is therefore defined as the quantity of heat transmitted through a unit thickness in a direction normal to a surface of unit area due to a unit temperature gradient under steady state conditions and when the heat transfer is dependent only on the temperature gradient. (4).

The term thermal insulation can be referred to as materials used to reduce the rate of heat transfer. Heat energy can be transferred by conduction, convection or radiation a thermal insulation prevents heat from entering a container. In order words thermal insulation can keep an enclosed area such as a building warm or it can keep the inside of a container cool. Insulators are used to minimize that transfer of energy. In home insulation, the R-value is an indication of how well a materials insulates. Insulator is a materials that provides a high resistance to heat flow, examples plastic, glass fibres, cork, etc. (5). Ceiling boards are installed beneath the roof to act as a thermal barrier. They reduce heat transfer into rooms, improve comfort and reduce energy used for cooling. The effectiveness of ceiling board depends largely on its thermal conductivity. (5).

Common ceiling materials used in Sokoto metropolis include asbestos sheets, plywood, plaster of Parris (POP) and suspended ceiling boards. Asbestos was widely used in the past due to availability, but health concerns have reduced its use. Plywood and POP are now popular for homes while suspended ceilings are common in offices, banks and schools. Despite wide use, there is little local data comparing how these materials perform thermally under Sokoto's climate. Builders and home owners often select materials based on cost and appearance, not thermal performance, hence this study seeks to fill that gap.

2. Theoretical Frame Work

In term of thermal requirement for materials such as ceilings and roofing materials for the house to ensure thermal comfort for the occupants. Hence, the following theoretical consideration have to be put in place.

2.1 Thermal Conductivity K.

Given a thin slab of material of thickness $\delta\lambda$ and uniform cross-sectional area A between whose faces a small temperature difference $\delta\theta$ is maintained as seen below. If a quantity of δQ passes through the slab by conduction on time δt, the thermal conductivity K of the material is defined by equation.

$$\frac{\delta Q}{\delta t} = -\frac{KA\delta Q}{\delta x} - - - - - - - - (1)$$

$$K = -\frac{\delta Q/\delta t}{A\frac{\delta\theta}{\delta x}} - - - - - - - (2)$$

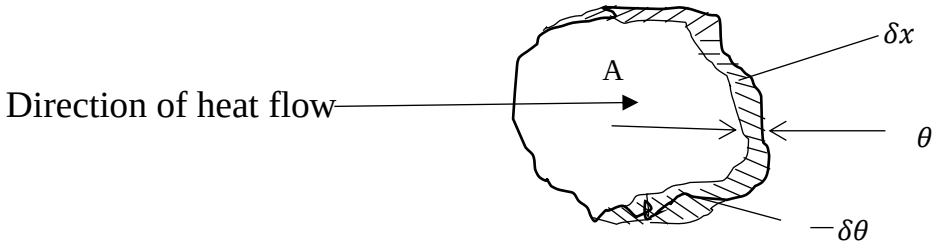


Fig. 1: direction of heat flow in the slab

The negative sign indicates that heat flows towards the lower temperature that is as x increases θ decreases, making $\frac{\delta\theta}{\delta x}$ called the temperature gradient. Hence the thermal conductivity can be defined as the rate of flow of heat through a material per unit area per unit temperature gradient (5)

2.2 THERMAL CONDUCTION

Thermal conduction is the process of heat transfer through a material such that the average position of the particle of the material remains the same. Heat energy moves through a material due to collisions between free electrons, irons atoms and molecules of the materials. Conduction requires temperature difference between materials in thermal contact, so that those atoms with higher energy in the substance transfer energy to atoms with lower-energy in the cooler substance when atomic collision occurs. (5).

2.3 TEMPERATURE GRADIENT

Temperature gradient is a physical quantity that describes the direction and the rate at which the temperature changes the most, rapidly around a particular location. The temperature gradient is a dimensional quantity expressed in units of degree per unit length as Kelvin per metre (Km^{-1}). If the temperature at point A is T_A, the temperature at point B is T_B and the distance between the two points is Dx, then $T_B - TA$ is called DT, hence the thermal gradient is given by (5)

$$\frac{T_B - T_A}{D_x} = \frac{DT}{Dx} \quad ------ (3)$$

2.4 U – VALUE

In practice, heating engineers find the U-value of materials to be a more convenient quantity to work with than thermal conductivity, K, Thus U-value describes the rate of flow of energy through a conductor per square metre for a temperature difference of 1K between its two surfaces. It is measured in $Wm^{-2}K^{-1}$ (5).

$$\text{U – Value} = \frac{rate\ of\ loss\ of\ energy}{surface\ area\ x\ temperature\ difference} \quad ----- (4)$$

2.5 THERMAL RESISTANCE COEFFICIENT

Thermal resistance coefficient (X) of a material is the thermal resistance of unit area and is related to the thermal resistance Re by the equation. $X = R_e A$ ––––– (5) It is measured in $m^2 Kw^{-1}$

From the analogy between energy flow and electric charge flow. Energy flow rate = $\frac{temperature\ difference}{resistance\ to\ flow}$ ––––– 6)

$\emptyset = \frac{\Delta\theta}{Re}$ ––––––(7) where $\Delta\theta$ is temperature difference in Kelvin $\emptyset$ is the energy flow rate in W. Re is the thermal resistance of the sample in kw^{-1}. Comparing this with thermal conductivity equation (1) above. $\frac{DQ}{Dt} = KA\frac{\Delta\theta}{\Delta x}$ –––––– (8)

$$\emptyset = K.A\ \frac{\Delta\theta}{\Delta x} - - - - - (9)$$

2.6 REVIEW OF CEILING MATERIALS

2.6.1 ASBESTOS CEILING BOARD.

Asbestos is a naturally occurring fibrous silicate mineral. It was widely used for roofing and ceiling due to fire resistance and low cost. Reported thermal conductivity ranges from 0.15 to 0.25 W/mk. However, inhalation of asbestos fibers causes asbestosis, lung concern and mesothelioma. Due to health hazards, many countries including Nigeria have restricted its uses. Despite this, it is still found in old building in Northern Nigeria. (6) and (7).

2.6.2 PLYWOOD

Plywood is an engineered wood product made by gluing veneers together. It is commonly used for ceiling in residential building because it is cheap and easy to install. Thermal conductivity of plywood ranges from 0.12 ro 0.17 W/mk depending on density and moisture. Studies by Olotuah (2006) showed that wood-based materials perform moderately in hot but degrade faster under high temperature and termite attack. Plywood has no air pockets, so insulation is limited compared to fibrous materials (8).

2.6.3 PLASTER OF PARRIS (POP) CEILING.

POP is calcium sulphate hemihydrate. When mixed with water it sets into gypsum. POP ceiling are popular in Nigeria for decorative purposes. Thermal conductivity ranges from 0.25 to 0.50W/mk. The porosity of POP creates tiny air pockets that slightly improve insulation. Adeyemi and Adetomowo (2017) reported that POP ceilings in Ilorin reduced indoor temperature by 2 – 3^0C compared to buildings without ceilings. However, POP is brittle and affected by moisture (9).

2.6.4 SUSPENDED CEILING BOARDS

Suspended ceiling boards consists of tiles on a metal grid with an air gap of 15 – 30cm above. Tiles are made of minerals fiber, gypsum or calcium silicate the air gap acts as an additional insulating layer. Thermal conductivity of mineral fiber tiles is about 0.05 – 0.10 W/mk. Nwofe (2017) found that suspended ceiling reduced roof heat gain by up to 45% in Lagos office buildings. They are widely used in banks, schools and hospital in Sokoto due to aesthetics and acoustics. (10).

2.7 CLIMATE OF SOKOTO AND THERMAL COMFORT REQUIREMENTS.

Sokoto lies in the Sudan–Sahelian zone. Means annual temperature is 28.3^{0}C with maximum of 45^{0}C in April. High solar radiation of 5.5 – 6.5 Kwh/M^2/day makes roof the major source of heat gain. (11) and (12).

ASHARE recommends indoor operative temperature of 23 – 26^{0}C for comfort. To achieve this in Sokoto, building envelops must have low heat gain. Balarabe and Ibitoye (Pg. 9) stated that ceiling materials with K < 0.2 W/mk are ideal for Northern Nigeria. (13).

2.8 PREVIOUS STUDIES ON THERMAL CONDUCTIVITY OF CEILING MATERIALS.

Agbo et-al (2018)(14), measured thermal conductivity of laterite, cement and POP in mankind, POP had the lowest K- value among them. (17). Akinyemi and Famuyiwa (2015)(15), compared thermal properties of plywood, Hard board and particles board, plywood was found to have K-value of 0.14 W/mk. Sambo (2016) (16) studied roof cooling techniques in Kano and found that ceiling reduced indoor temperature by 4^{0}C. Nwofe (2014) and Iweaka et.,al(2019) evaluated thermal properties of local building materials in Ebonyi and recommended gypsum-based boards for hot climate. (17) and (18).

Most of these studies were carried out in Southern Nigeria. Hence, there is no documented study comparing asbestos, plywood, POP and suspended boards specifically in Sokoto Metropolis.

3.0 MATERIAL AND METHODS.

3.1 MATERIALS

3.1.1 STUDY AREA

Sokoto metropolis, in Sokoto State Nigeria is located on latitude 13^0O'N, longitude 5^0 14'E. Sokoto lies in the Sudan-Sahelian zone, it is characterised by high solar radiation and low humidity ranges from 52 –56%, the minimum and maximum temperature are within the range of 19^0C and 38^0C respectively. Interestingly, Sokoto is one of the hottest cities in the world. The mean annual rainfall ranges from 500mm to 1300mm which is unevenly distributed (12).

3.1.2 SAMPLE COLLECTION

The materials used for this study are four different samples of commonly used material for ceiling in the study area, they are POP, plywood, Asbestos and Suspended ceiling tile. The plywood asbestos, and suspended ceiling tile were obtained from building materials market at Kofar Gabas in Sokoto, while the POP board was obtained from the building site along Unguwar Rogo road in Sokoto.

The samples of materials were coded as shown in the table 1.

Table 1: Materials and code for selected ceiling samples.

S/N	Material	Sample
1.	POP	A
2.	Plywood	B
3.	Asbestos	C
4.	Suspended tile	D

3.1.3 MATERIALS AND APPARATUS.

The materials and apparatus used for this study are stated thus:

1. Samples A, B, C and D
2. Lee's Disc Apparatus
3. Burner (4) weight balance
5. Thermometer, (6) vernier caliper, (7) stop watch

3.2 EXPERIMENTAL DETAIL.

The samples A, B, C, and D were shaped to have the same cross-sectional area and thickness, using vernier caliper and micrometre screw gauge, while the mass was taken with the aid of weighing balance. Then the measured parameters were calculated and presented in table 2.

Table 2: Specification for the Samples.

S/N	Sample	Thickness (m)	Mass (Kg)	SHC $kj^{-1}K^{-1}$	Diameter(d) (m)	Mean(m^2) Surface are
1.	A	0.03	0.250	1.09	0.11	0.0095
2.	B	0.03	0.0168	1.21	0.11	0.0095
3.	C	0.03	0.4330	0.84	0.11	0.0095
4.	D	0.03	0.0150	1.00	0.11	0.0095

Thermal conductivity were determined for each of the ceiling samples using the steady state method. Lee's and Charlton's disc apparatus were used as shown in the figure 2. The specific heat capacity determined for each sample by method of cooling correction as described by Tyler (1971) which takes care of heat that might be lost due to radiation. The densities were calculated for each sample by weighing and measurement of the dimensions. Hence thermal diffusivity, λ absorptivity $\propto$, resistivity, r, were evaluated for each sample using the equations (10) - (12) as shown below and presented in Table 3.



Figure 2: Lee's Disc Apparatus

$$\lambda = \frac{K}{PC} - - - - - - (10)$$

$$\propto = \left(\frac{\omega}{\emptyset\lambda}\right)^{1/2} - - - - - (11)$$

$$R = \frac{1}{K} - - - - - - - (12)$$

where $\omega = \frac{2\pi}{period}, \lambda = thermal\ diffusivity, \propto =$ thermal absorptivity, C = specific heat capacity = density and r = thermal resistivity.

4.0 RESULTS AND DISCUSSION.

Table3: Characteristics of thermal Properties of different ceiling samples.

Sample	Density (Kg/m^{3-})	Specific heat capacity (C)($Jk^{-1}K^{-1}$)	Thermal Conductivity (K)$Wg^{-1}K^{-1}$)	Thermal Diffusivity(λ)	Thermal resistivity (r)($w^{-1}mk$)	Thermal absorptivity ($\propto$)
A	87.72	1090	0.3171	1.446	3.154	15.86
B	58.95	1210	0.0925	4.021	10.810	30.07
C	1.519.30	842	0.2261	1.390	4.423	16.17
D	52.63	1000	0.0858	1.510	11.655	15.52

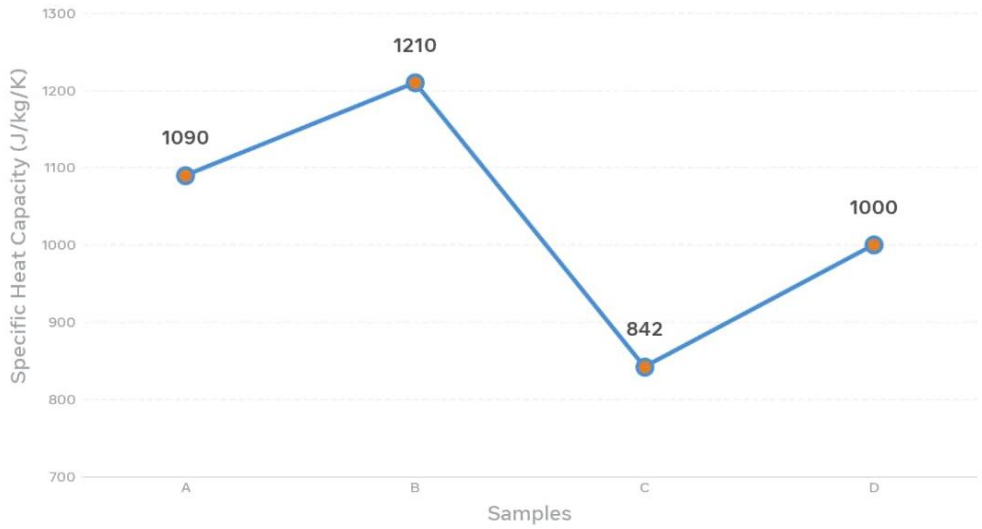


Fig.3: A graph of specific Heat Capacity against Sample A, B, C, D

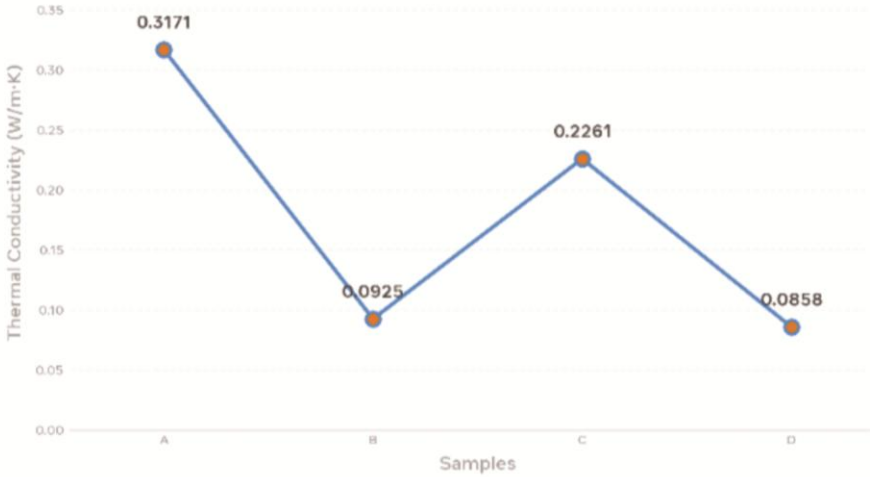


Fig.4: A graph of thermal Conductivity against Sample A, B, C, D

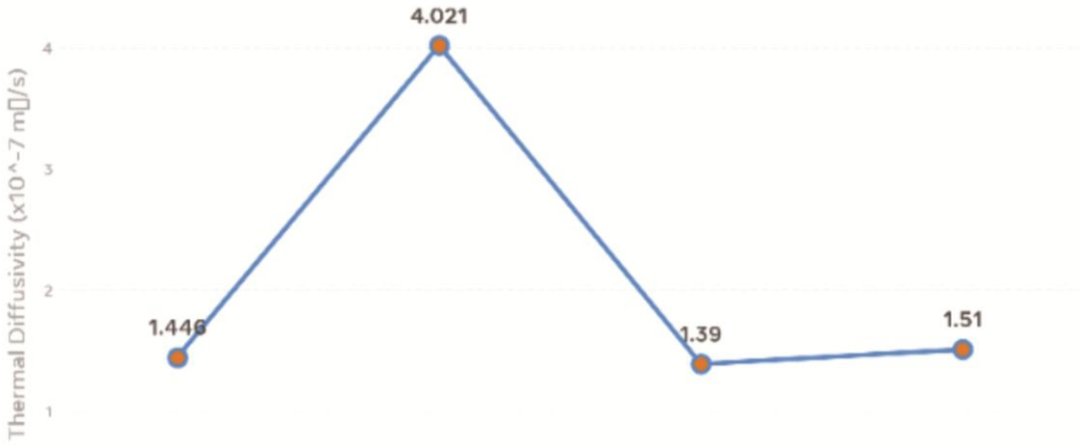


Fig.5: A graph of thermal Diffusivity against Sample A, B, C, D

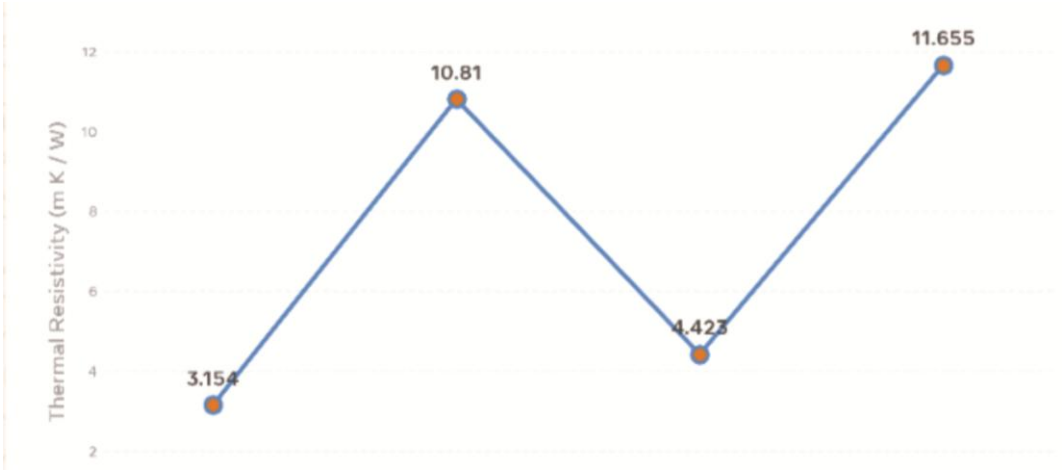


Fig.6: A graph of thermal Resistivity against Sample A, B, C, D

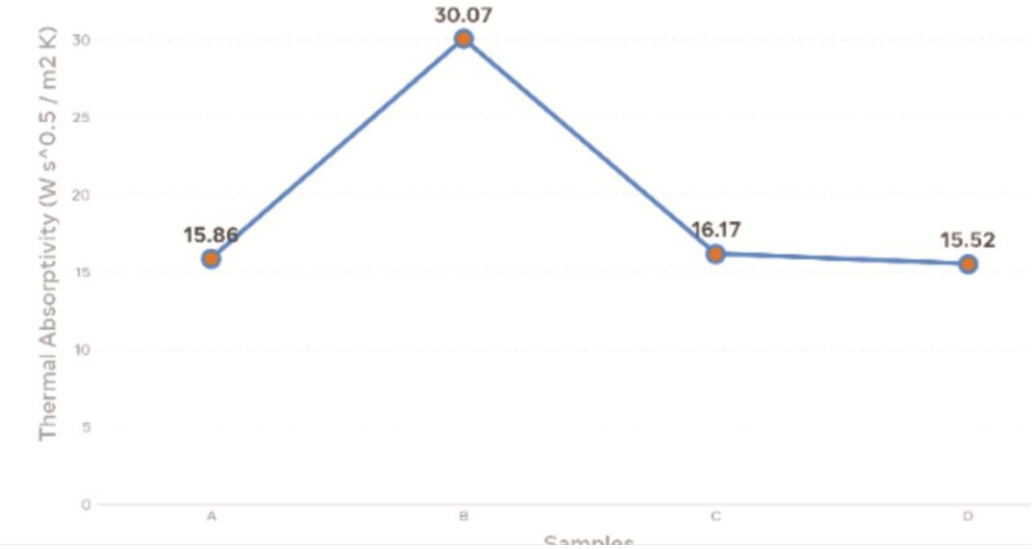


Fig.7: A graph of thermal Absorptivity against Sample A, B, C, D

The table 3 above shows the experimental results for the thermal conductivity, specific heat capacity, thermal absorptivity, thermal diffusivity and thermal resistivity for the four different materials studied. From the table the values of thermal conductivity range from 0.0925 to 0.3171 w/mk for plywood and POP respectively. In all the ranges of the thermal conductivities of the ceiling materials studied fall within the conductivities of construction and heat – insulating materials given by Ibitoye (2020) (16) as 0.2 W/mk which is ideal for Northern Nigeria. This also in conformity with the report of the Akinyemi and Ademowo (2017) in which they compared the thermal properties of plywood, hardwood and particle board, in which plywood had a thermal conductivity K of 0.14 W/mk. Hence, this is more reasons why they are used as heat- Insulating materials.

The specific heat capacity value lie between $842JKg^{-1}K^{-1}$ for Asbestos and $1210JKg^{-1}K^{-1}$ for plywood. The thermal absorptivity value lie between $15.52m^{-1}$ for suspended tile and $30.07m^{-1}$ for plywood. While the values of thermal diffusivity lie between 1.390 (m^2/s) for Asbestos

and 4021(m^2/) for plywood. From the table 3 and the graphs shown in the figureS 3-7

5.0 CONCLUSION.

This study investigated the thermal conductivity of four selected ceiling materials commonly used in Sokoto metropolis: POP, Plywood, Asbestos Cement Board and Suspended mineral Fiber Ceiling Board.

1. Thermal Performance: - Among the four materials, Plywood exhibited the lowest thermal conductivity, followed by Suspended Mineral Fiber Ceiling, POP and Asbestos Cement Board having the highest. This indicates that Plywood and Suspended ceiling boards are better insulators and can reduce heat transfer into buildings more effectively than POP and asbestos.
2. Climate suitability for Sokoto: - Sokoto Metropolis experiences high solar radiation and ambient temperatures, especially from the Months March to May. Materials with lower thermal conductivity are more suitable for maintaining indoor thermal comfort and reducing cooling loads. Therefore, plywood and suspended ceiling boards are more thermally suitable for residential and office buildings in Sokoto.
3. Heat gain Reduction: - The use of low-conductivity ceiling materials can significantly reduce indoor heat gain, thereby lowering the dependence on mechanical cooling system such as air conditioners and fans.
4. Health and safety Condition: - While asbestos cement board is still found in some older buildings, its use poses serious health risks due to borne fibers. Its relatively high thermal conductivity further makes it less desirable for modern energy –efficient buildings.

In general, the choice of ceiling materials significantly influences the thermals performance of buildings in hot-dry climates like Sokoto. Selecting appropriate ceiling materials can contribute to energy conservation and improved indoor comfort.

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