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THERMAL PERFORMANCE OF CEMENT-BASED COMPOSITE TILES REINFORCED WITH SELECTED NATURAL FIBRES

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Abstract:
This study was designed to investigate the thermal performance of cement-based composite tiles reinforced with suitably processed sawdust of Gmelina arborea, pineapple leaves and corn husks. Standard procedures were followed in the production and testing of the tiles. The properties evaluated include thermal conductivity, resistivity and diffusivity. These properties were compared with conventional and commercially available roofing sheets. Insulating properties and hence thermal comfort improved with increase in fibre contents in the composites. Tiles reinforced with sawdust performed best followed by corn husks and pineapple leaves, in that order. Fibre reinforced cement-based composite tiles presented better thermal performance than conventional and commercially available roofing materials. The results obtained were similar to those of ceramics and asbestos roofing tiles. However, the use of asbestos tiles had been banned in advanced countries for health reasons. The selected natural fibre composite tiles are therefore considered as suitable building materials for housing in terms of thermal comfort when compared with the conventional roofing materials for the tropics.

Key words: *thermal properties; building materials; natural fibres; cement composite; thermal comfort.*

INTRODUCTION

Tropical climate is noted for high temperature, rainfall and relative humidity. The impacts of sunlight radiation falls directly on the roof and the heat absorbed by the roof is transmitted to the ceiling, which does little in insulating it from getting to the inhabitants. One of the essential parameters in the tropics is the thermal mass. For instance in the hot and dry regions, there remain clear evidences of fluctuations in temperature within a day thereby resulting into intermittent heating and cooling of the building during the day-light and at night respectively. Therefore, thermal properties of a building's cover, envelope or roof must be critically considered in the point of view of material choice for structures (Petrov, 1997). As a result, the need arises to research into materials that could enhance thermal insulation of such buildings. Thermal insulation provided by asbestos-cement corrugated sheets used to be considered appropriate; but for health concerns, it has been banned in most advanced countries (Baghban *et al.* 2018). Alternative building materials have, however, been found in fibre reinforced cement composites (Omoniyi 2019). The use of natural-fibre reinforced cement composite is gaining attention as a low-cost housing material in many developing countries. Natural fibres are residues obtained from harvested plants. They are available in abundance, renewable and cheap in most developing countries. The production process of roofing tiles involved the use of local technology and readily available materials.

OBJECTIVES

The objective of the study is to examine the thermal parameters of cement composite roofing tiles reinforced with selected natural fibres (corn husk, pineapple leaves, and sawdust) and compared the thermal parameters with conventional roofing materials.

MATERIALS AND METHODS

Materials used in the production of the composite tiles were corn husk fibres; Pineapple leaf fibres, sawdust from *Gmelina arborea*, limestone cement, aggregates (stone-dust) and potable water. Matured, Freshly harvested corn husks (*Zea mays* ssp. L.) and pineapple leaves were collected from local farmers while sawdust (*Gmelina arborea*) was obtained from a plank processing market, all in Ibadan metropolis, Oyo State. Corn husks and pineapple leaves were sliced using a knife and their moisture contents were determined in three replicates using moisture analyser at the Multidisciplinary Central Research Laboratory (MCRL), University of Ibadan. The expurgated samples were sun dried to a moisture content ranging from

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7% at the research field behind the Department of Agricultural and Environmental Engineering, Faculty of Technology, University of Ibadan. The dried samples of corn husks and pineapple leaves were further pulverized with a grinding machine at Adegbayi area and the samples were sieved. The sawdust was soaked in fresh water for 24 hours, filtered and properly sun dried; as a pre-treatment method. The processed corn husks, pineapple leaves and sawdust are as shown in Figs 1a, 1b and 1c respectively. A 50kg bag of Ordinary Portland Cement with a 42.5 grade, the cement meets the specifications of the British Standards for Ordinary Portland Cement BS 12 (1996), was purchased from a cement depot at Bodija, Ibadan, Oyo State. It was stored in air-tight containers and used up as soon as possible to avoid strength deterioration. The potable water source was from a bore-hole water supply at the Department of Civil Engineering, Faculty of Technology, University of Ibadan. Stone-dust was obtained from a construction site at Moniya, Ibadan. The sand was also properly sundried to reduce its moisture content.

Composite production parameters were: cement: sand: water ratio of 1:3:0.6 by mass. The ratios were kept constant for the entire production. However fibre contents (corn, sawdust and pineapple leaves) were varied from 1,2,3,4, to 5% of the mass of cement. The purpose was to determine the effect of fibre mass fractions on the thermal properties of composite tiles produced. Production processes involved batching and mixing sand, water, cement and fibres. The materials were well blended to ensure uniformity and consistency of composite components before casting was done. The constituents were batched according to the experimental design of 3 × 5 × 3 Factorial design ANOVA with three replicates as shown in Table 1.

The measured amounts of cement and sand were first of all mixed dry until high level of uniformity was attained; then, water was added very slowly while mixing continued for four minutes until a homogenous mixture was achieved. Fibres were then added and gently mixed for even distribution. This was to minimize possible damage to the fibres. Interface sheets were spread on the vibrating table as the paste was poured onto the profile mould assembled with the vibration table (Fig. 2). The slurry (paste) was vibrated for 20 seconds to remove void spaces and trapped air for proper compaction and consolidation. The compacted slurry was then smoothened with a hand trowel. The formed flat mould was covered with polyethylene sheet and placed in a cool dry place to cure for 24 hours after which it was de-moulded. The composites tiles produced were then cured in fresh water for 28days in accordance with (Omoniyi and Akinyemi 2012).

a. *b.* *c.*

Fig. 1.
Processed fibres: a - Corn husk; b - Pineapple leaves; c - Gmelina arborea.

Fig. 2.
Composite Tiles Production.

Table 1

Mix-Design for the Production of the Composite Tiles

Fibres	Fibre content (%) by cement weight
Corn	1
Sawdust	2
Pineapple leaves	3
	4
	5

The cement: sand: water ratios were kept constant at 1:3:0.6.

Density of Tiles

An electronic digital weighing balance was used to measure the mass of the wood fibre reinforced cement based composite produced during this study. The average masses of each of the design mix were taken and recorded. The volume of each of the samples with dimensions 300mm (length) by 300mm (breadth) by 6mm (thickness) was calculated. The average density was determined using equation (1)

$$\text{Density} = \frac{Mass\ (kg)}{Volume\ (m^3)} \quad (1)$$

Thermal Conductivity

Thermal conductivity is defined as the quantity of heat (Q) transmitted through a unit of thickness (L) in a direction normal to a surface of unit area (A) due to unit temperature gradient (ΔT) under steady state conditions and when the heat transfer is dependent only on the temperature gradient (Kabre 2010). According to ASTM C-518, the condition of steady state temperature must be reached before the value is recorded. The thermal conductivity of the composite tiles was tested using a device called KD2 Pro at the Department of Geology, Faculty of Science, University of Ibadan. Fig. 3 shows the experimental set-up for thermal properties test. Small hole was bored on the tested specimen to allow the needle to stand erect on the specimen very tightly before the equipment was operated. The specimen size used for this assessment was 150mmx150mmx6.0mm. Each sample reading was completed between 10 to 11 minutes and the needle was allowed to cool for 15 minutes before another specimen was tested. The measured values were recorded.

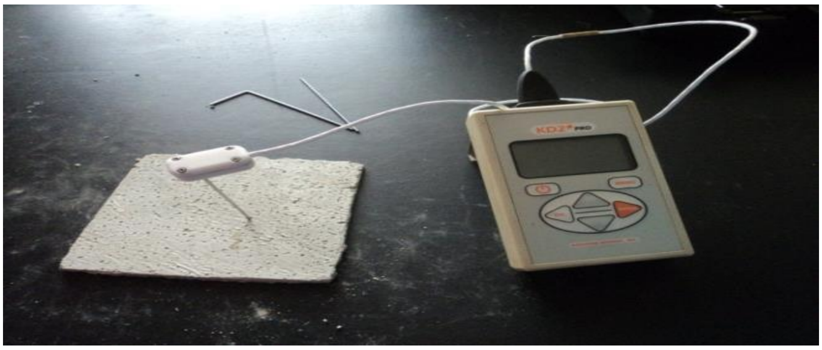

Fig. 3.
Experimental set-up for thermal test.

Heat conduction

This is the ability of a material to allow heat passage through it. Heat transfer may be through conduction, convection or radiation.
The equation for heat conduction through a solid medium is given by (Mijinyawa 2014):

$$q = \frac{k}{l} \times \Delta t \text{, for unit area} \quad (2)$$

where:

q = rate of heat transfer
k = thermal conductivity of the medium (W/m·K)
l = thickness of the medium
Δt = temperature difference between the two sides of the composite.

Thermal Resistivity

Thermal resistivity of a building can be defined as the heat resistance ability of the building envelope/cover. It is a heat property and a measure of temperature difference by which a material resists the flow of heat. It is the reciprocal of thermal conductivity, i.e R = $\frac{1}{k}$ (Engineering Toolbox, 2020). Thermal resistivity can be categorised in three distinct ways, which are:

(i) Absolute thermal resistance *R* (k/W),
(ii) Specific thermal resistance or specific thermal resistivity R_λ (k·m/W), a material constant,
(iii) Thermal insulance (m^2k/W), the thermal resistance of unit area of material.

Thermal resistivity can be expressed as:

$$R = l / k \qquad (3)$$

where: R = thermal resistance per unit area of the piece of material (m^2k/W),
l = thickness of the material (m) and
k = thermal conductivity of the material (W/m·K).

Thermal Diffusivity

The heat loss through the building envelope is the function of the heat transfer coefficient and the capability of the envelope to store heat. The time lag, decrement factor and the overall heat transfer coefficients of different surfaces of the building's orientation can be used to calculate the "heat loss". This is dependence on the thermal diffusivity of the opaque components (Al-Obaidi *et al.* 2014). The thermal diffusivity of the opaque material is used to describe the heat storage capacity of a building envelope. The thermal properties of some selected common roofing materials are given in Table 2. The thermal diffusivity is determined from eqn. (4) used by (Gulten and Zerrin 2008, Radmanovic 2014):

$$\alpha = \frac{k}{\rho . c} \qquad (4)$$

where:
α = thermal diffusivity, m^2/s
k = thermal conductivity, W/m-K
ρ = density, kg/m^3
c = specific heat, J/Kg K.

The k-value, ρ-value and c-value for the different roofing materials as presented in Table 2 where all as recorded by the International Organization for Standardization (ISO/FDIS 10456: 2007E).

Table 2

Thermal Parameters for the Conventional Roofing Materials

Roofing Materials	*Thermal Conductivity, k, (W/m.k)	*S.H.C, C_p, (J/kg.k)	*Density (ρ) (Kg/m^3)	**Thermal Resistivity, R (m.k/W)	**Thermal Diffusivity, α, (10^{-7} m^2/s)
Steel Sheet	50	480	7800	0.02	130
Aluminium Sheet	160	896	2800	0.0063	640
Asbestos-Cement Sheet	0.360	1050	1500	2.78	2.3
Clay Tiles	0.840	800	1900	1.19	5.5

*Source: ISO/FDIS 10456 (2007E). SHC= Specific Heat Capacity, ** = Estimated value

RESULTS AND DISCUSSION

Selected natural fibres are ligno-cellulose materials and are poor conductors of heat. Table 3 shows the thermal properties of natural fibres cement-composite tiles reinforced with sawdust of *Gmelina arborea*, corn and pineapple fibres. The density (ρ), specific heat capacity (c_p), thermal conductivity (k), thermal resistivity (R), and thermal diffusivity, α, of the various composite tiles produced.

A comparison of the thermal performance on the basis of thermal parameters values presented in Table 3 with those of conventional roofing materials as presented in Table 2 is given in Table 4 at 3% of the selected fibres content.

Specific Heat Capacity (SHC) and Density

The SHC and density are two important parameters required for the determination of the value of the thermal diffusivity of the composite tiles. The change in the specific heat capacity tends to be constant for all the design mix. This may be due to the relative closeness of the SHC values reported for sawdust and non-wood fibres. The density decrease with the increase in the fibre content, this is due to the increase porosity created in the composites by the increased wood fibre contents as expected. The parameters were used mainly to estimate the value of the thermal diffusivity of the composites in accordance with Idicula *et al.* (2006).

Table 3

Thermal Parameters of the Fibre Reinforced Cement Composite Tiles

Fibre Type	Fibre Content (%)	T. C, k, (W/m.k)	S.H.C, C_p, (J/Kg.k)	Density ρ, (Kg/m^3)	Resistivity R, (m.k/W)	T. D, α, (10^{-7} m^2/s)
Sawdust	1	0.234	919.8	1765	4.27	1.44
	2	0.228	919.6	1760	4.39	1.41
	3	0.210	919.4	1755	4.76	1.30
	4	0.195	919.2	1747	5.13	1.21
	5	0.186	919.0	1741	5.38	1.16
Corn Husk	1	0.243	919.8	1913	4.12	1.38
	2	0.231	919.6	1900	4.33	1.32
	3	0.201	919.4	1888	4.98	1.16
	4	0.186	919.2	1876	5.38	1.08
	5	0.159	919.0	1864	6.29	0.92
Pineapple Leaves	1	0.309	919.8	1803	3.24	1.86
	2	0.291	919.6	1787	3.44	1.77
	3	0.270	919.4	1783	3.70	1.65
	4	0.258	919.2	1773	3.88	1.58
	5	0.240	919.0	1765	4.17	1.48

Sawdust = Sawdust fibre Reinforced Composite Tiles, Corn husk = Corn Husks Fibre Reinforced Composite Tiles, Pineapple leaves = Pineapple Leaves Fibre Reinforced Composite Tiles, T.C = Thermal Conductivity, S.H.C = Specific Heat Capacity, T.D = Thermal Diffusivity.

Table 4

Thermal Parameters for the Conventional and Experimental Roofing Materials

Roofing Types	Roofing Materials	Thermal Conductivity, k, (W/m.k)	S.H.C, C_p, (J/kg.k)	Density, ρ, (Kg/m3)	Thermal Resistivity, R (m.k/W)	Thermal Diffusivity, α, (10-7 m2/s)
Conventional	Steel Sheet	50	480	7800	0.02	130
	Aluminium Sheet	160	896	2800	0.0063	640
	Asbestos-Cement Sheet	0.36	1050	1500	2.78	2.3
	Clay Tiles	0.84	800	1900	1.19	5.5
Experimental (@ 3% fibre contents by mass of cement)	Sawdust cement tiles	0.21	919	1755	4.76	1.3
	Corn fibre cement tiles	0.2	919	1888	4.98	1.16
	Pineapple leaves cement tiles	0.27	919	1783	3.7	1.65

Source: Extracts from Table 2 and Table 3

Thermal Conductivity

The thermal conductivities obtained for the composites at different composition are presented in Fig. 4. Generally the thermal conductivity decreases with increasing fibre contents, so also does the density, this is because the fibre components tend to trap air into the tile microstructure, thus decreasing the density and improving the thermal performance in comparison to convectional roofing materials. This is expected as the fibre materials are insulating materials. The values decreased for sawdust from 0.234 to 0.186 W/m.k, corn husk from 0.243 to 0.159W/m.k, and pineapple leaves from 0.309 to 0.240W/m.k. The values depicted that pineapple leaves' fibres have less effect on the Cement-based composite tiles, while sawdust fibre performed best, as the lower the lower the thermal conductivity the better and more comfortable application provided by the material. The values compared well with those reported for ceramics and asbestos-cement sheet (Tonoli *et al* 2011) and far better than those of steel and aluminium sheets used as roofing materials. This follows the pattern described by (Perera and Modasia 2004, Gulten and Zerrin 2008 and Madhumathi *et al*. 2014) for thermal comfort and sustainability in the interior part of the building.

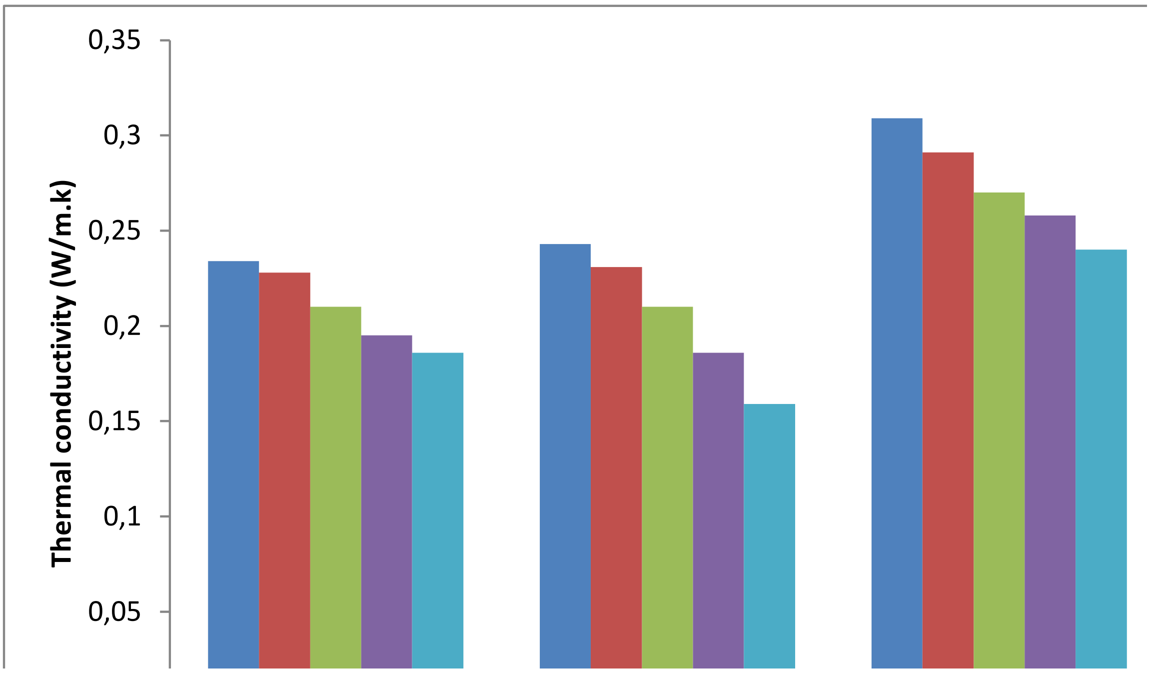

Fig. 4.

Influence of fibre contents and types on thermal conductivity of fibre-reinforced cement composite.

Thermal Resistivity

The thermal resistivity R, of a substance depends largely on the thermal conductivity k, of such substance, as it is its reciprocal value. This is to say, the lower the thermal conductivity of a material the higher the insulating capability of that material. Figure 5 presents the thermal resistivity of the different composite tiles produced. The resistivity values for sawdust ranged from 4.27 to 5.38mk/W, corn husk from 4.12 to 6.29mk/W and pineapple leaves from 3.24 to 4.17mk/W. The higher the resistivity value the better the materials' thermal performance (Melo and Lamberts 2012, Tong *et al* 2014, Jeong *et al* 2017), judging from this, the design mix corn husk at Fibre content of 5% by mass of cement give the best result of 6.29mk/W. generally the composite performed better with increase in fibre contents and compared favourably with literatures values (Pavilik *et al* 2014).

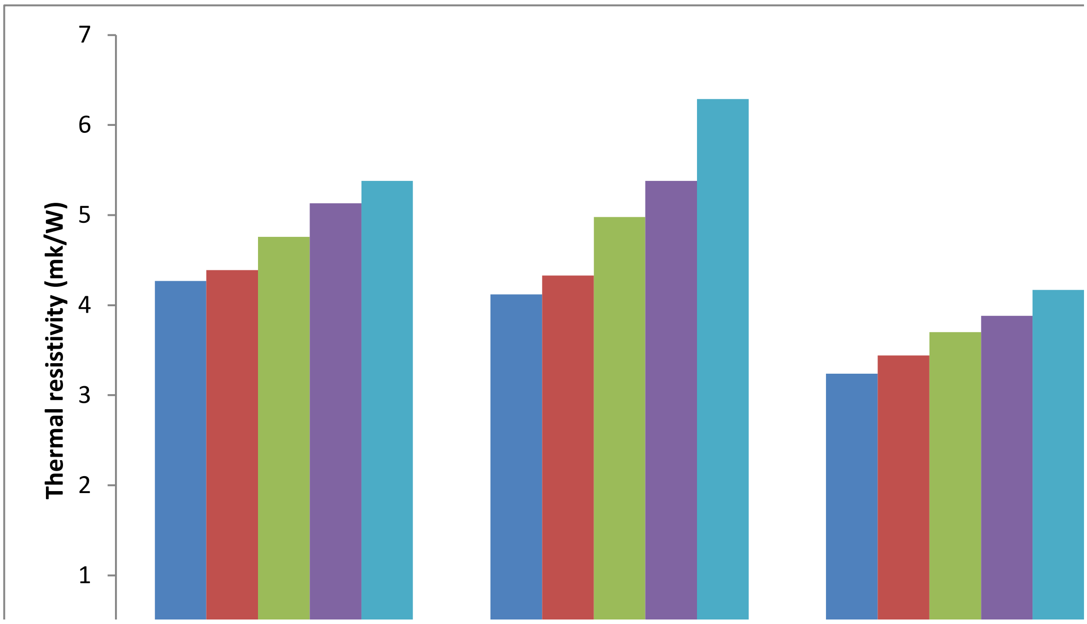

Fig. 5.
Influence of fibre contents and types on thermal resistivity of fibre-reinforced cement composite.

Thermal Diffusivity

Thermal diffusivity, α, is a quantity that governs the speed of heat propagation in transient problems or during change in temperature overtime (Salazar 2003). The lower the value the better it is for the thermal performance. Thermal diffusivity decreases with increase in fibre content. Figure 6 presented the estimated thermal diffusivity values of the produced composite tiles. The results showed that the thermal diffusivity of the composite produced ranged from 1.16-1.44 x $10^{-7}m^2/s$, 0.92-1.38 x $10^{-7}m^2/s$ and 1.48-1.86 x $10^{-7}m^2/s$ respectively for sawdust, corn husk and pineapple fibre-cement composites. These showed that the corn husk reinforced-cement composite performed best thermally with the lowest thermal diffusivity of 0.92 x $10^{-7}m^2/s$ at 5% fibre contents, while the least performed composite is that made from pineapple leaves reinforced cement composites at 1% fibre content with a thermal diffusivity of 1.86 x $10^{-7}m^2/s$. The observation indicated that cornhusk reinforced cement composite has the best insulating properties.

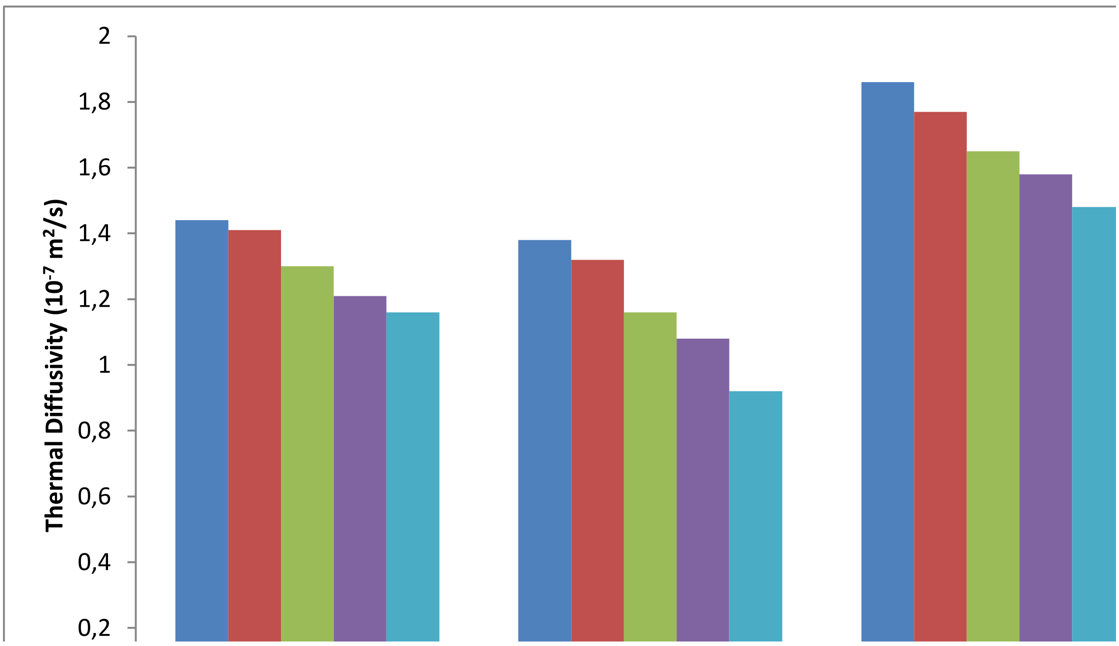

Fig. 6.
Influence of fibre contents and types on thermal diffusivity of fibre-reinforced cement composite.

CONCLUSION AND RECOMMENDATION

Natural fibre reinforced composite tiles were produced from sawdust, corn husks, and pineapple leaves. The composites were tested for their thermal performance. The results obtained showed that:

1. As the percentage of the fibre content increased from 1% to 5% the thermal performance also improved, and all the three fibres reinforced composite tiles as described by the their parameter values performed better than conventional materials such as steel and aluminium sheets. Asbestos cement tiles compared favourably with natural fibre reinforced cement composite, however, the use is prohibited for health reasons.
2. The 5% fibre composition of corn husk fibre composition has the best combination of values from a thermal conductivity of 0.159W/m.k, to a resistivity of 6.29m.k/W, to a diffusivity of 0.92m^2/s for an optimum thermal performance.
3. The materials can be considered more suitable than steel and aluminium for tropics in terms of their comfort since they show lower thermal conductivity and higher specific heat capacity, hence lower thermal diffusivity.

Further study should be carried out on the thermal mass, the use of interfacial thermal resistance similar to Kapitza thermal contact resistance concept to examine the effective thermal conductivity of composites tiles for roofing and the application of model, such as *FEM* analysis.

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