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Assessment of Thermophysical properties for Partially Insulated Roofing Materials in Ibadan.

J. B. Taiwo[1], B. I. O. Dahunsi[2]
[1]Architecture, University of Ibadan; [2]Civil Engineering, University of Ibadan

Abstract
Tropical regions of the world particular those in Africa face intense thermal radiation and attracted different roofing materials and patterns as coping mechanism. But, there is a paucity of studies that establish thermal properties of the roofing materials to minimize the incidence radiation as reported in this study. Two different kinds of Stone-coated roofing sheets (ST-A & ST-B) and plywood-lined aluminum sheets (PLAS) were evaluated in the laboratory to ascertain the thermal conductivities of the chosen roofing materials, an examination was conducted utilizing the ASTM standard of ice and steam apparatus, under a constant heat source. The result revealed that ST-A, ST-B and PLAS have thermal conductivities of 97.068, 83.680 and 150.62 (W/mK), respectively, the results demonstrated that PLAS had good conductivity qualities, followed by ST-A and ST-B. This implied that PLAS is likely to conduct heat away quickly from the roof than the other samples. The corresponding Thermal Resistivities of each are 0.0103, 0.0120, and 0.0066 (mK/W) indicated that ST-A & ST-B are better insulator than PLAS. The Thermal Diffusivities of 3.095, 1.390 and 1.570 x 10^{-7}(m^2/s) respectively implies that the sample materials possess high diffusivity rate, which help in cooling and regulating the indoor heat movement. Also, Specific Heat Capacity of 8.887, 3.164 and 3.726 x 10^3 (J/kg/K) respectively is an indication that the samples have relative high density with storage capacity for heat infiltration. Therefore, PLAS is suitable and good roofing material in tropical climates since it outperforms stone-coated materials in comparison.
Stone coated; Plywood-lined Aluminium; Tropics; Partially-insulated.

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I. Introduction

The primary purpose of the roofing materials is to provide heat resistance. Consequently, the building's materials' thermophysical characteristics determine how much heat enters the building through the roofs (Medina *et al.,* 2021). On the other hand, one important surface characteristic that influences how much energy a building uses for heating and cooling is its thermal emissivity (Akbari and Konopacki 2015). But a good roofing sheet's strength is its resistance to outside influences (Elewa *et al*., 2019). Because of these characteristics, the roof is a crucial part of a building that shields its residents from outside threats (Ariyadasa *et al*., 2015). While the building's roof has several functions, one of the most important is to prevent incident radiation from entering the structure and creating a cooling effect. Cooling is a necessary prerequisite for achieving optimal interior thermal comfortability in buildings, especially in tropical climates like Nigeria (Dominkovic *et al*., 2018 & Ferrucci *et al*., 2017). This is brought on by both the actuality of climate change and the high frequency of heat radiation. Historically, various methods have been employed to improve a building's thermal comfort. The conventional method involves designing buildings to optimize air circulation by strategically placing openings. Another mechanical method is the use of air conditioning, which is estimated to be responsible for between 30% and 75% of a home's energy usage (Elewa et al., 2019 & Onyenokporo et al., 2019). Currently, the building architect and engineer are searching for a potential roofing material and design combination that will result in interior thermal comfort.

1. Impact of Roofs on the Building Internal Comfort

In Nigeria, many house owners rarely take architecture and energy efficiency that foster internal thermal comfort into consideration because of ignorance, poverty, lack of awareness, and/or improper policy on building regulations by the Government (Usman, 2022). It was recommended that a country like Nigeria needs a climate-responsive sustainable building and roofing material to achieve a more comfortable indoor environment (Cakir, 2006) as against the mechanical means which produce greenhouse gases, air, and noise pollution amongst others (Nwofe, 2014).

However, some schools of thought consider the colour and texture as vital to a building's roof thermal performance. The cool roofs are manufactured specially to redirect a huge amount of incident solar radiation (Barozzi *et al*., 2017). This is because high albedo roofing material possesses high reflective properties (Akbari and Konopacki 2015). Hence, the increase in the overall albedo of roofs is an attractive way to reduce the net radiative heat gains through the roof (Akbari and Konopacki 2015). It is an assumption in this study that if the thermal properties of different roofing materials are assessed and reported, citizens will make an informed choice on the possible combination of roofing materials that will produce thermal comfort.

Moreover, the use of roof insulation is not popular in Nigeria, and the significance of different forms of roof insulation materials on internal thermal comfort has not been well-researched in Nigeria (Adaji *et al*., 2019 & Kwag *et al*., 2019). Moreover, (BEEC, 2018) the National Building Energy Efficiency Code (BEEC) suggested a minimum R-value of 1.25 m^2 K/W for roof insulation (Federal Ministry of Power Works and Housing, 2017) but the appropriate thermophysical properties were not stated. Also, much research has been carried out to recommend a suitable condition for internal thermal comfort for instance, (Akande, 2010) researched the effect of building orientation, materials, and natural ventilation on occupant comfort, (Morakinyo *et al*., 2016) explored the influence of tree shading but the no known research has been conducted on the thermophysical properties of the partially insulated roofing materials. Therefore, this research compared the thermophysical properties of some partially insulated roofing sheets in Ibadan, Nigeria.

2. Materials and Method

2.1 Materials: Ice and Steam apparatus was predominantly used to carry out the conductivity test. The selected samples are presented in Table 1. The test applied the principle of steady-state longitudinal heat and steam flow to the specimen. The rationale behind the selection of the stone coated roofing materials (ST-A and ST-B), and the plywood-lined aluminium roofing sheet PLAR, was due to the fact that ST-A and ST-B are majorly use in Nigeria. They are also associated as the roofing materials of the rich due to their market price. Meanwhile, PLAR is a new innovation introduced by this research to evaluate its thermal efficiency in comparison with ST-A and ST-B within this tropical region. PLAR is a composite of two (2) different materials, which include aluminium (a conductor) and plywood (an insulator) jointly lined together to form a single roofing sheet. Plate 2 and 3 show the samples of the stone coated roofing sheets. While Plate 4 revealed the plywood-lined aluminium roofing sheet.

Table 1: Material specifications for the selected roofing Sheets

Sampled materials	Thickness (mm)	Mass (g)	Area (m^2)
Stone coated (ST-A)	1.30	37.40	0.00936
Stone coated (ST-B)	1.45	38.10	0.00936
Plywood-lined Aluminium C	9.29	85.60	0.00936

2.2 Method: The samples were obtained from the builders' market in Ibadan, Oyo State, Nigeria. The samples were cut into 128 x 128 mm, sizes, based on the configuration of the test apparatus. Using mass balance for the mass (mg), micrometer screw gauge for the height (m), and steel ruler for the length (m), respectively of the samples were obtained and related parameters calculated and presented in Table 1. The setup was arranged as shown in Plate 1, Figure 6 and the result was tabulated as shown in Table 2 and 3. The ice and steam apparatus test were carried out according to the following procedures (stipulated by the UNE EN standard):

i. The ice mold was filled with water and froze. I ensured the water did not freeze with the lid on the jar (Also, a few drops of a non-subsing detergent were added to the water before freezing to help the water flow more freely as it melted, which did not significantly affect the results.).
ii. The jar was run under warm water to loosen the ice in the mold.
iii. Then the thickness of the sample material was measured and recorded as h.
iv. The sample material was mounted onto the steam chamber as shown in Figure 6. However, the following conditions were strictly adhered to:

a. I ensure I did not attempt to "pry" the ice out of the mold.
b. I also ensured the sampled material was flushed against the water channel so that water did not leak by tightening the thumbscrews. A bit of grease between the channel and the sample was added to help create a good seal.

v. Afterwards, the diameter of the ice block was measured. This was recorded as a value of d_1. The ice was then placed on top of the sample, as shown in Figure 6
vi. The ice was allowed to sit for several minutes, so it began to melt and came into full contact with the sample.
vii. Subsequently, data for determining the ambient melting rate of the ice was obtained as follows:
viii. The mass of a small container used for collecting the melted ice was determined and recorded.
ix. The melting ice was then collected in the container for a measured time ta (approximately, 7 minutes).
x. Then, the mass of the container and the water was determined and recorded.
xi. The first measured mass was subtracted from the second to determine m_{wa}, the mass of the melted ice.
xii. The steam was run into the steam chamber. This took place for several minutes until temperature stabilised and the heat flow was steady (A container was placed under the drain spout of the steam chamber, where the water that escapes from the chamber was collected.)
xiii. The cup used for collecting the melted ice was then emptied. Step 7 was repeated with the steam running into the steam chamber. The mass of the melted ice and t, the time during which the ice melted (5 minutes), were measured and recorded as m_w.
xiv. The diameter of the ice block was remeasured and recorded as d_2.
xv. The test result was calculated to determine the Thermal Conductivity (TC) and Thermal Resistivity (TR).

Note: Mc (mass of empty container) = 37.1g; d_1 = Diameter of ice block:
d_2 = Repeat Diameter of ice block; d_{avg} = Average of d_1 and d_2; h = Thickness of sample
Therefore,
R_a represents the rate at which the ice melted before the steam
R represents the rate at which the ice melted after the steam
R_o represents the rate at which ice melted due to temperature differential
M_{wa} represents mass of the container and water
M_w represents mass of the water
t_a represents initial time during which the ice melted
t represents the final time during which the ice melted

$$R_a = \frac{M_{wa}}{t_a} \quad (1)$$

$$R = \frac{M_w}{t} \quad (2)$$

$$R_0 = R_a - R \quad (3)$$

Calculate k, the conductivity of the sample: k (cal cm/cm^2 sec)
Note: The equation giving the amount of heat conducted through a material is:
Q represents the quantity of heat conducted
k represent constant
ΔT = Boiling point of water (100 □ at sea level) - 0□.
A represents the area of the sample material
ΔT represents change in temperature
h represents the thickness of the material

$$Q = k\,A\,\Delta T/h \quad (4)$$

Therefore, thermal conductivity was calculated by the equation

$$k = (\text{cal cm/cm2 sec}) = \frac{(\text{mass of melted ice})\,(80\ \text{cal/gm})\,(\text{thickness of material})}{(\text{area of ice})\,(\text{time during which ice melted})\,(\text{temp.differential})}$$

$$k = \frac{(m)(80\text{cal/gm})(h)}{(A)\Delta T} \quad (5)$$

The tabulated value of k is shown in Table 3. However, the conductivity k (calcm/cm2sec□) was converted to k (W/mK) in Table 4 by multiplying k-value with 418.673 for further evaluation of other thermophysical parameters.

These parameters include thermal resistivity and thermal diffusivity, which were calculated by the equations 6 and 7, and tabulated in Table 4.

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

where, r is the resistivity; k is the conductivity.

Diffusivity $$\alpha = \frac{k}{pc}$$ 7

where, α is the diffusivity; p is the density and c is the specific heat capacity.

Table 2: Mass of the ice before and after melted

Samples	h(cm)	d_1	d_2	Ta (mins)	M_{war}	t (mins)	M_w
A	0.178	7.42	7.12	7	0.0103	5	31.9
B	0.224	7.92	7.60	7	0.0120	5	28.4
C	0.936	7.91	7.73	7	0.0066	5	14.0

Table 3: Rate at which the ice melted due to temperature differential

Samples	h(cm)	R_a	R	M (kg)	R	A (m^2)	R_0	k (calcm/cm²sec°C)
A	0.178	38.81	106.30	2550	3.64	41.52	67.49	0.232
B	0.224	40.00	94.67	2272	3.88	47.30	54.67	0.200
C	0.936	23.57	46.67	1120	3.91	48.04	23.10	0.360

Table 4: Comparison of thermal properties of the Selected Partially Insulated Roofing Materials

Samples	h(m)	Density (kg/m^3) $\rho = \frac{m}{v}$	Conductivity (W/mk) K	Resistivity (mK/w) $r = \frac{1}{k}$	SHC (J/kgk) x 10^3 C	Diffusivity (m^2/s) x 10^{-7} $\alpha = \frac{k}{pc}$
A	0.00178	2369	97.068	0.0103	3.164	3.095
B	0.02240	1812	83.680	0.0120	8.887	1.390
C	0.09360	6412	150.62	0.0066	3.726	1.570

3. Results and discussion

Figure 1, revealed that sample C (PLAR) has the highest density of the three partially insulated materials, suggesting that it has a tendency to absorb and retain heat more effectively than ST-A and ST-B. This material's ability to retain heat for an extended period of time and subsequently release it into the surrounding atmosphere is demonstrated. Therefore, materials with high specific heat capacities have a large potential for heat storage (George *et al.,* 2010), and the results support this assumption.

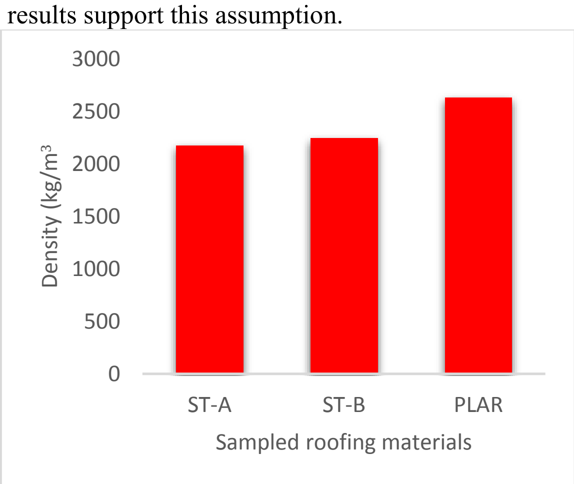

Figure 1: Comparison of density for ST-A, ST-B and PLAR

Figure 2 shows that sample C has the highest thermal conductivity, indicating that PLAR conducts heat more quickly. In contrast, samples A and B conducted less heat due to their surface texture and insulating qualities. PLAR, a composite roofing material of Plywood (PLW) and Aluminium (CH-A0.7), exhibited exceptional heat resistance. Additionally, PLAR combined its conductivity and insulating properties to create a composite material that effectively blocked the flow of heat into the space. The two roofing materials have the appropriate characteristics that ensure thermal comfort of the dwelling, according to (Calderon, 2019). These dual properties of PLAR contributed to its capacity to prevent excessive heat from passing through it into the interior space. This also guarantees maximum comfort for any room(s) under such roofs.

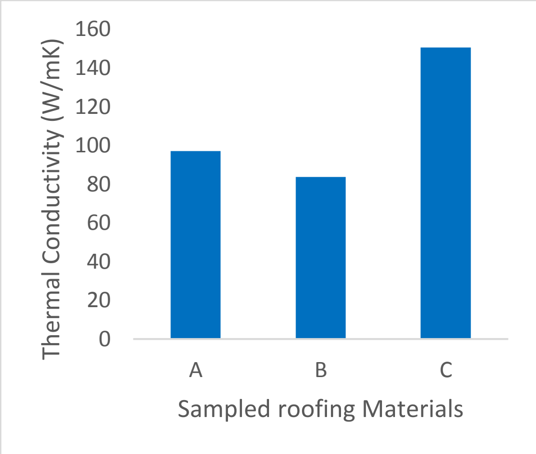

Figure 2: Comparison Thermal Conductivity of Partially insulated materials

Figure 3 suggests that the material's TR decreases as the TC increases. However, ST-A has the highest TR value for any partially insulated sheet, followed by ST-B. This implies that sample A (ST-A) tends to resist heat flow into the room as good insulating material, better than ST-B and PLAR. This actually obeyed the thermophysical principle that says, the greater the material's TC value, the more heat is conducted and the lower the material's resistivity. The texture of its surface also allows heat to be diffused back into the environment to a greater extent.

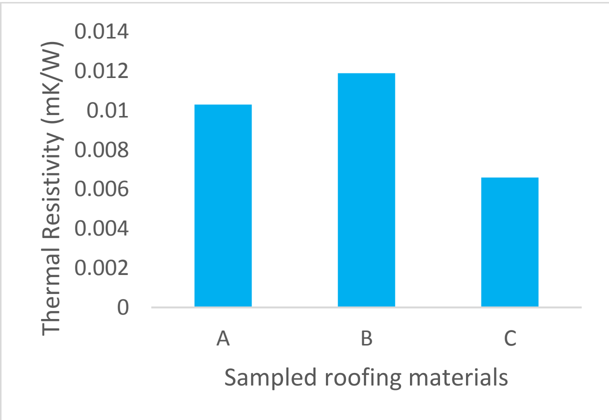

Figure 3: Comparison of Thermal Resistivity (TR)
For Partially Insulated Sheet ST-A, ST-B and PLAR

Figure 4 shows the specific heat capacities (c) of ST-A, ST-B, and PLAR. The result revealed that the samples have a relative higher specific heat capacity and, therefore, possess good storage capacities. Although ST-B possesses better heat storage capacity than ST-A and PLAR. This implies that excessive heat is being absorbed and store for a period of time before steadily diffusing into the surrounding space.

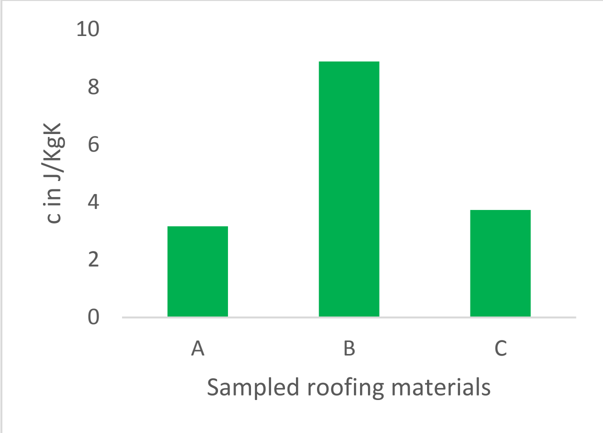

Figure 4: Comparison of Specific Heat Capacity (c)
For Partially Insulated Sheet ST-A, ST-B and PLAR

The thermal diffusivity in Figure 5 shows that PLAR diffused heat slowly and comparatively amongst the three partially insulated samples. This suggests that the ST-B has significantly larger specific heat capacities than the ST-A and PLAR. This implies that the specific heat capacity of a material decreases with an increasing material diffusion rate and vice versa.

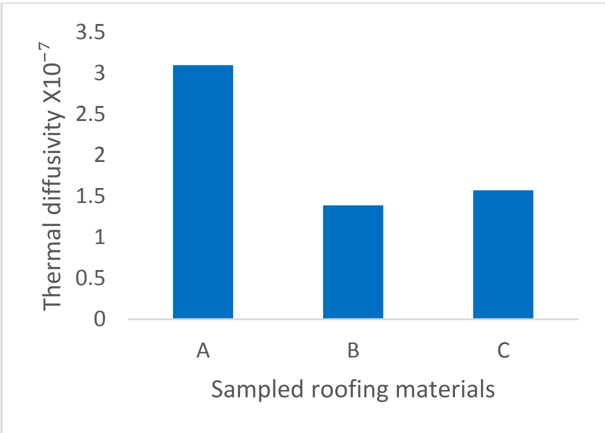

Figure 5: Comparison of Thermal Diffusivity (TD) for ST-A, ST-B and PLAR

II. Conclusion

The paper reports present a study carried out on the thermophysical properties of selected partially insulated roofing sheet in Ibadan, Nigeria. This aim to determine the thermal conductivities of the samples and understand their insulating properties against heat infiltrations.

The introduction of PLAR as a composite material has helped to reduce the infiltration of incident temperature to the nearest minimum. This is because sample C (PLAR), which possesses the dual properties of aluminium (a conductor) and plywood (an insulator), has the highest thermal conductivity of 150.62 W/mK, compared with ST-A and ST-B (97.068 & 83.680 W/mK, respectively). The specific heat capacity c of ST-A, ST-B and PLAR were; 3.164, 8.887, 3.726 (x 10^3) J/kgK, respectively, proving that they were good absorber and excellent at storing heat. Also, their thermal diffusivities were 3.095, 1.390, 1.570 (x 10^{-7}) m^2/s, suggests that they have the tendency to conduct and release heat quickly.

In this regard, PLAR is recommended as an excellent roofing material in this tropical region to reduce the amount of heat penetrating through the roof into the interior spaces.

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Plate 1: Laboratory thermodynamic (ice and steam) apparatus for thermal conductivity

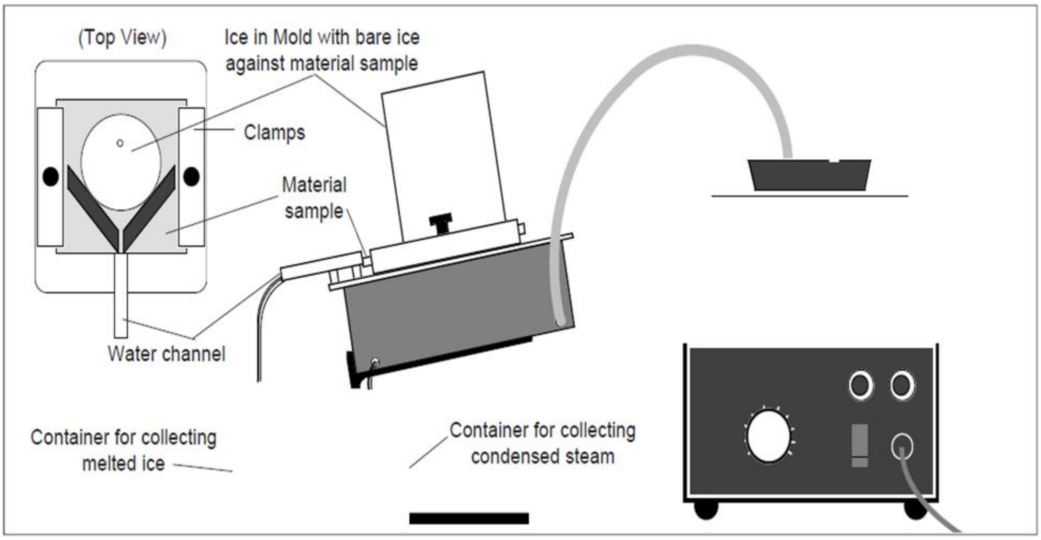

Figure 2: Schematic experimental setup of ice and steam for thermal conductivity

Plate 2: Stone coated roofing sheet

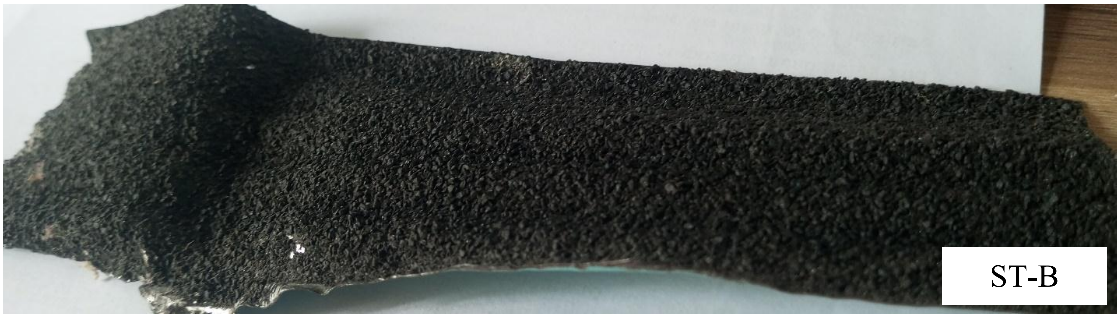

Plate 3: Stone coated roofing sheet

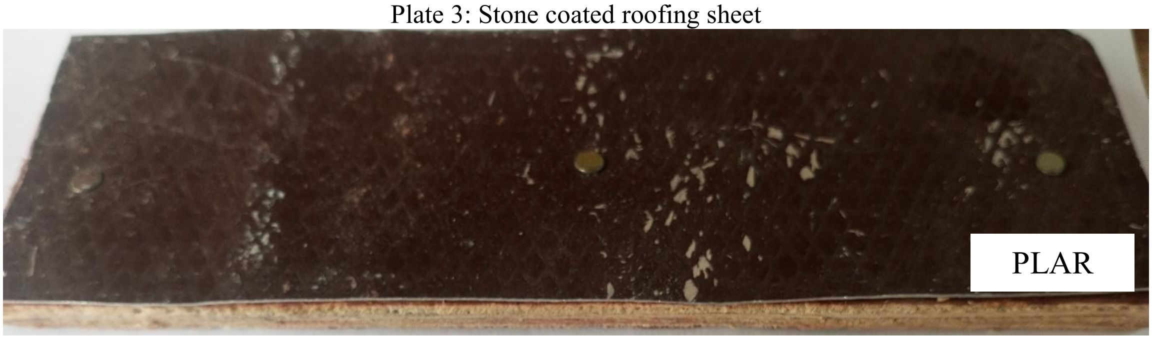

Plate 4: Plywood-lined aluminium roofing sheet