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Building with Waste: An Upcycled Sandwich-Structure Insulation Panel from Plastic Bottles and Rice Husk Based-Materials

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***Abstract*—*The growing demand for sustainable and cost-effective construction materials has led to the exploration of agricultural and plastic waste for insulation applications. This study aimed to design and evaluate a non-load bearing sandwich-structured insulation panel using upcycled plastic bottles (PET) and rice husk-based materials. The panel consisted of a 70% rice husk core and a 30% PET–rice husk ash (RHA) composite coating. Two formulations were tested: Composite 1 (10% RHA–90% PET) and Composite 2 (15% RHA–85% PET). The panels were successfully fabricated, although minor defects such as cracks and uneven coating were observed due to PET shrinkage during molding. Both composites exhibited self-extinguishing behavior, indicating good fire resistance. Physical testing showed relatively consistent thickness and density, with Composite 2 performing better in terms of density and water absorption. Thermal analysis revealed similar performance between the two composites, with thermal conductivity values of 0.08033 W/m·K and 0.08006 W/m·K, and thermal resistance values of 3.897 m^2·K/W and 3.858 m^2·K/W for Composite 1 and Composite 2, respectively. Composite 2 was identified as the optimal formulation. Compared to commercial Extruded Polystyrene (XPS), Composite 2 demonstrated better fire behavior but showed higher density, greater water absorption, higher thermal conductivity, and lower thermal resistance, indicating poorer insulation performance. Cracks have been observed in the panels also contributed to reduced efficiency.*

The study recommends improving PET–RHA composites by using plasticizers for flexibility, coupling agents and compatibilizers for better bonding, and fibers and fillers for strength and stability. It also emphasizes proper processing—avoiding PET overheating, ensuring uniform RHA dispersion, applying adequate compaction, and controlling cooling rates to reduce defects, stress, and cracking while enhancing overall structural performance.

I. Introduction

1.1 Background of the study

Plastic bottle made of Polyethylene Terephthalate (PET) is one of today's major waste pollution problems, while rice husk, a common by product of rice production, is often left unused. Many research has shown that both materials can be used in composites, but most studies mainly look at their strength. Fewer have examined how they perform in terms of thermal properties. This creates a research gap that this study aims to address by testing their potential as thermal insulation panels.

Plastic has been a game-changer in modern materials, often called "the material with a thousand uses." This review highlights the latest research on plastics and the growing concern around plastic waste pollution. Thanks to its lightweight nature, durability, flexibility, and low manufacturing cost, plastic has become deeply integrated into nearly every aspect of daily life (Pilapitiya and Ratnayake 2024). Research shows that, every year, more than 1.4 trillion beverage containers are sold, where 500 billion of those are plastic. Of the 78 million tons of plastic packaging produced every year, only 14% is collected for recycling. A huge 40% of plastic packaging is simply sent to landfill, and 32% ends up in nature as litter (TOMR, 2024). With this we need to consider reused the available waste resources especially plastic bottle or PET into new practical materials.

The urban growth and household consumption greatly increases the volume of rice husk especially plastic waste generate. Improper disposal of these plastic and Rice Husk (RH) can cause environmental problems, while the rice milling industry produces large amounts of rice husk that are under-utilized. By utilizing these wastes to generate a building new material that addresses both waste management and sustainable construction needs.

This study investigates the feasibility of manufacturing sandwich insulation panels composed of recycled plastic and Rice Husk Ash (RHA) and a core of RH. The sandwich design uses thin, durable composite skin to protect and bind a low-density RH core that provides thermal insulation. This proposed panel aims to be lightweight, thermally efficient, water-resistant, and largely made from waste.

1.2 Statement of the Problem

The global construction industry faces a dual challenge: the escalating demand for affordable and sustainable building materials and the environmental burden of unmanaged waste. Two of the most abundant waste streams are plastic bottles and rice husk by-products. Plastic bottles, which take centuries to degrade, contribute heavily to solid waste pollution. Meanwhile, RH, an agricultural residue generated in large volumes in rice-producing countries like the Philippines, is often burned or dumped, releasing harmful emissions and contributing to environmental degradation. Traditional insulation panels used in construction are typically made from synthetic or non-biodegradable materials such as polyurethane or polystyrene, which not only rely on fossil fuels for production but also pose long-term disposal challenges. With

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the construction sector increasingly shifting toward green building practices, there is a pressing need for innovative, upcycled, and eco-friendly alternatives that balance performance, cost, and sustainability. This study seeks to address these concerns by developing and evaluating a sandwich-structure insulation panel made from plastic bottles and rice husk-based materials.

1.3 Objective of the Study

The general objectives of this study is to design and evaluate a non-load bearing upcycled sandwich-structure insulation panel using plastic bottles and rice husk-based materials as skin and with core of rice husk for sustainable alternatives in building applications. Specifically this study aims to:

1. Design and fabricate a sandwich-structured insulation panel with 70% core compose of pure Rice Husk and 30% coat PET + RHA incorporating plastic bottles and RHA as reinforcement and rice husk-based materials as insulating layers with the following ratio in terms of weight. Skin Mixture: Composite 1: 10% rice husk ash and 90% plastic bottles Composite 2: 15% rice husk ash and 85% plastic bottles
2. Characterize the physical properties of rice husk and its derivatives for potential use as insulation material to include the ignitability, thickness, density and water absorption.
3. Determine the thermal conductivity and thermal resistance of the upcycled insulation panel.
4. Compare the optimal developed panel's performance from two mixture ratios with a commercial Extruded Polystyrene (XPS) Foam Board materials insulation in terms of physical properties, thermal conductivity and thermal resistance.

1.4 Significance of the study

This study promotes environmental sustainability by transforming plastic bottles and rice husk residues into practical construction materials, reducing waste and lowering greenhouse gas emissions. It supports the circular economy by re-purposing waste into valuable resources, making construction practices more eco-friendly. This study adds to the growing body of knowledge on waste-to-resource technologies and sustainable construction materials. It serves as a foundation for further research and encourages innovation in eco-friendly engineering solutions.

1.5 Scope and limitations

This study was focus on the development and testing of a sandwich-structured insulation panel made with a rice husk core and a composite skin composed of recycled PET and RHA. The RHA to be used were commercially available in amorphous form. Two skin formulations were prepared, with ratios of 10% RHA:90% PET and 15% RHA:85% PET, while maintaining a fixed skin-to-core ratio of 3:7. The fabricated panels were tested for their physical and thermal properties, including ignitability, thickness, density, water absorption, thermal conductivity, and thermal resistance. Ten trials were conducted for each parameter to ensure accuracy and reliability of the results. These parameters were adopted from the study of Maulida et al. (2015), which focused on the development of composite panels using two selected mixture ratios. Based on the study of Maulida et al. (2015) on PET and RHA, the 95:5 mixture ratio exhibited less significant performance compared to the other ratios. For this reason, only two mixture ratios were selected and evaluated in this study. The test setup was modified by allowing direct contact between the heat source, insulation panel, and cold source without the use of a metal plate.

This approach minimizes additional thermal resistance and simplifies the setup. Sensors were placed at the hot surface, cold surface, and mid-plane of the specimen to monitor temperature distribution across the material. The performance testing using the fabricated guarded hot plate, were calibrated prior to testing using a known value of thermal conductivity insulation to ensure the accuracy and reliability of the apparatus. The testing were conducted at the researcher's place in Ayala Zamboanga City. The optimal developed insulation was also be compared with a commercially available insulation to determine performance differences. However, the study were limited to short-term laboratory testing. It was not cover long-term durability or the effects of prolonged exposure to environmental factors such as heat, humidity, and aging on the PET–RHA composite skin and rice husk core. Large-scale production, alternative materials, and applications other than roof insulation was also be excluded. In standard thermal conductivity testing, power input is typically controlled within a ±2% fluctuation range to ensure reliable results.

In this study, a modified and locally fabricated apparatus was utilized, which may not achieve the same level of precision due to inherent limitations in power regulation. Consequently, slight variations in power input were considered as part of the system limitations. The fabricated and modified thermal conductivity testing apparatus used in this study did not include a metal (steel) plate between the heat source and the sample. Instead, direct contact was established between the heat source and the sample, as well as between the cold source and the sample. Additionally, temperature sensors were placed directly on both the hot and cold surfaces of the sample. These modifications may have influenced heat distribution and measurement accuracy compared to standard guarded hot plate configurations.

II. Methodology

This section explained the approach of the researcher in collection, analysis and interpretation of the data. This chapter includes details such as data gathering, research locale, research design, Insulation panel production, and testing. This Will serve as a guideline of the entire research process to ensure that the study is done accordingly.

2.1 Data Gathering

The aim for this study were through extensive research of the related studies, journals, articles and published thesis from the dependable online source and were used as a reference in this study, and a comparison of common commercial insulation. Through comprehensive reviews the researchers ensured that the study gathered is sufficient information to assess its feasibility.

2.2 Research Locale

This study was conducted in researcher residence at Ayala Zamboanga City, where the developed insulation was fabricated and test. In addition, prior to testing the fabricated guarded hot plate apparatus were calibrated by using a XPS Foam Board with known thermal conductivity to ensure the accuracy and credibility of the fabricated apparatus.

2.3 Research Design

This study employed an experimental research design with an evaluation component. This involves: (1) material characterization, (2) design and fabrication of prototype sandwich-structure insulation panels using plastic bottles, rice husk and its derivatives, (3) laboratory testing of physical properties, thermal conductivity, and thermal resistance, and (4) compare the best develop insulation panel to commercially available insulation specifically XPS Foam Board (Extruded Polystyrene).

2.4 Flow of the Study Figure

Figure 2.1 illustrates the overall flow of the study, beginning with the collection of raw materials needed for the development of the insulation. This is followed by the production phase, where the materials are processed and formed into insulation samples. After production, the samples undergo a series of physical and thermal tests to evaluate their properties and performance. Finally, the gathered data are analyzed to determine the effectiveness and suitability of the developed insulation.

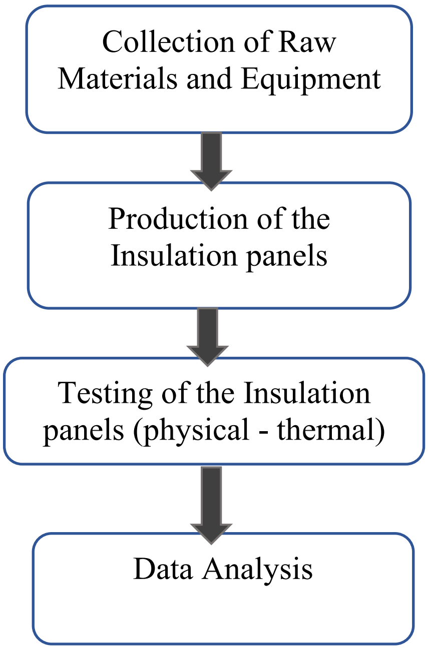

Figure 2.1. Flow of the Developed Insulation Panel Study

2.4.1 Collection

The collection and preparation of materials were carried out within Zamboanga City, where rice husk and PET were obtained locally. Additional materials required for producing the insulation panels were purchased through online platforms such as Lazada and Shopee, as well as from physical store like SM Store. Shown in Table 3.1 are the materials, tool, equipment, and require quantities for the insulation panel production.

Table 2.1. Materials, Tools, and Quantities

ITEM	QUANTITY
Mold	10
Baking tray	5
Plastic bottle (Polyethylene)	112 kg
Rice Husk	25 kg
Rice Husk Ash	10 kg
Weight scale	1
Steal tape	1
Inkbird ITC 1000	5
Heat sink	2
Peltier module	2
Bulb	2
Small fan	2
Thermal paste	1
Kill a watt	1
XPS Foam Board (Extruded Polystyrene)	30

The Plastic bottles (PET) – were collected from local recycling facility in Ayala National High School, Zamboanga City to ensure the use of post-consumer waste. The collected bottles of 112 kg were thoroughly cleaned with water to remove dirt and impurities, followed by sun-drying 2 days to eliminate moisture. Once dried, the bottles were shredded, making them ideal for use in the composite skin mixture.

The RH – rice husk were sourced from local rice mills within Zamboanga City to utilize readily available agricultural by-products. The collected rice husk of 25 kg was sun-dried to reduce its moisture content. After drying, the RH were processed using mortar to produce smaller RH.

The RHA – 10 kg were sourced from online allows for uniformity in the composite skin mixture and reduces preparation time. platforms such as Shopee and Lazada it is also sundry to remove moisture, ensuring a consistent and ready-made material for use in the study. Since it is pre-processed, no further treatment was conducted before use.

2.4.2 Production of the Insulation Panel Production

This section presents the detailed procedure for creating the sandwich-structured insulation panel and in Figure 3.2 shows the process. It explains the preparation of materials, mixing ratios, molding, curing, and assembly of the panel layers. The step-by-step process ensures consistency and reliability, allowing the panel's physical properties to be accurately tested and evaluated.

Figure 3.2 illustrates the systematic procedure employed in the production of the insulation panel, highlighting a parallel preparation of two outer layers followed by core integration both first and second layers underwent identical procedures, beginning with weighing of materials (shown in Figure 3.3) to ensure accurate preparation, followed by the melting of PET to achieve a workable consistency. The RHA was then added gradually in the molten materials and it is subjected to mixing to ensure homogeneity before being poured to mold to form the respective layer. Subsequently, prepared layers were combined through the incorporation of RH core, resulting in a composite, sandwich-type structure. The configuration formulated the formation of the insulation panel, where the PET-RHA layers function as hardy surfaces while the RH core serves as the primary insulating material.

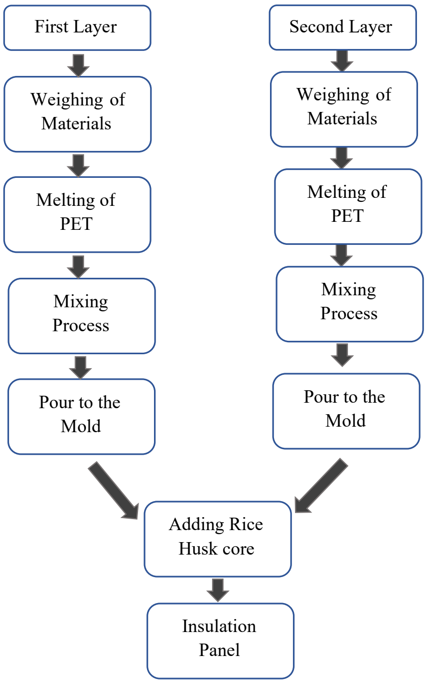

Figure 2.2. The Flow Process Production of the Insulation Panel

Material Preparation - the PET plastic and rice husk ash are first weighed according to the required proportions (Composite 1 90:10 and Composite 2 85:15).

Weighing of Materials - weighing for Composite 1 (90:10) 1912.5 grams of PET and 212.5 grams of RHA and for Composite 2 (85:15) 1806.25 grams of PET and 318.75 grams of RHA, shown in Figure 2.3 is weighing PET bottles and Figure 2.4 weighing RHA, half of each weigh is for first layer and the remaining is for the second layer.

Figure 2.3. Weighing of the PET Plastic Using a Calibrated Digital Balance Prior to Processing

Figure 2.4. Weighing of RHA Using a Calibrated Digital Balance Prior to Mixing

Melting of PET – half of the PET plastic is put in bake tray then placed in 230 °c pre-heated oven and heated 1.5 hours until it becomes fully melted.

Figure 2.5. Insulation Panel Molder Used Shaping and Forming the Composite Panel

Mixing Process - The melted PET is removed from the oven, and half RHA is gradually added while continuously mixing. If the mixture becomes hard, it is returned to the oven and reheated, then mixed again until the PET and rice husk ash are fully mixed, shown in Figure 2.5 is the mold for producing the insulation panel.

First Layer Formation - The prepared composite mixture is poured into a mold with a dimension of 300 mm width, 300 mm length, and 25 mm thickness to form the first layer and is allowed to cool and solidify, Core Addition - After the first layer has cooled, rice husk is added on top to serve as the core material. Shown in Figure 2.6 is the first layer formation and adding the core RH.

Figure 2.6. Photo Shows the Addition of the RH Core in the First Layer

Second Batch Preparation - Another batch of PET and RHA, was processed following the previous procedure and then the mixture was poured into mold to have a second layer. Final Layer Formation - The second composite mixture was poured over the rice husk layer to cover it completely and form the outer layer. Final Cooling and Product Formation - The entire material was allowed to cool completely, resulting in a final product with a rice husk core and a PET–RHA composite outer layer. Shown in Figure 3.7 the insulation final product.

Figure 2.7. Photo Showing the Insulation Panel After Composite Blending and Layering Formation, Stabilize Through 1-2 Days of Passive Cooling

2.4.3 Natural Curing

Natural curing was done by leaving the panel in a clean, dry, and shaded area at room temperature for 24–48 hours. This procedure allowed the material to harden and stabilize naturally without the use of additional heat.

2.5 Testing of Insulation Panel

This section presents the physical tests conducted to evaluate the characteristics of the developed and commercial insulation panel. The tests performed include the thickness, density, water absorption, thermal conductivity, and thermal resistance.

2.5.1. Physical Properties

Physical properties play an important role in understanding how materials behave and perform. It describes how substances interact with its surroundings and reacts to external influences. The parameters to be tested are ignitability, density, thickness, water absorption, thermal conductivity, and thermal resistance.

2.5.1.1 Modified Ignitability

The ignitability test followed the procedure outlined in ISO 11925-2 (Reaction to Fire Tests). A small flame approximately 20 mm high were applied to the edge or surface of the insulation sample for 15 seconds. During and after exposure, ignition, flame spread, and dripping behavior was observed and recorded. Figure 2.8 and 2.9 show the results of the developed and XPS insulation respectively after the modified ignitability test.

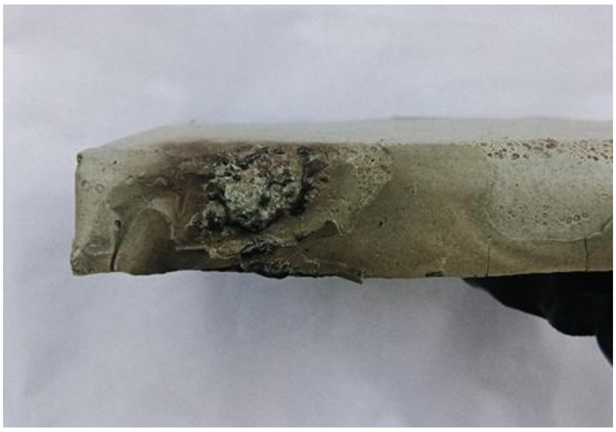

Figure 2.8. The Developed Insulation Panel after Subjected to Modified Ignitability Test

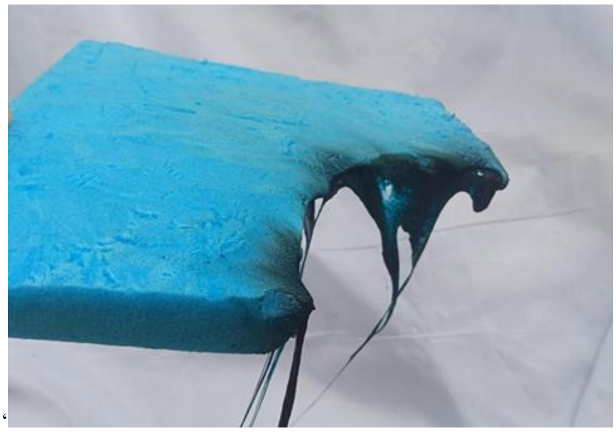

Figure 2.9. The Results of the XPS Panel After the Modified Ignitability Test

2.5.1.2 Thickness Test

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The samples were placed in the flat surface and measured from 3 points the thickness using a digital caliper or steel tape.


Figure 2.10. Measuring the Thickness of the Developed Insulation Panel Using Steel Tape

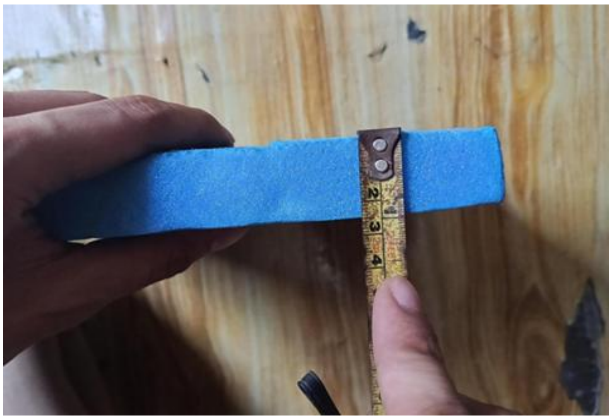
Figure 2.11. Measuring the Thickness of the XPS Insulation Panel Using Steel Tape

2.5.1.3 Density Test

The panels were first weighed using a digital balance to obtain their mass. Since the samples were of a regular shape, their dimensions (length, width, and thickness) were measured using a steel tape or caliper to calculate its volume. Equation 2.1 was used to compute the density. Figure 2.12 and 2.13 show the developed insulation and XPS insulation weight being measure, respectively.

Density = mass / volume (2.1)

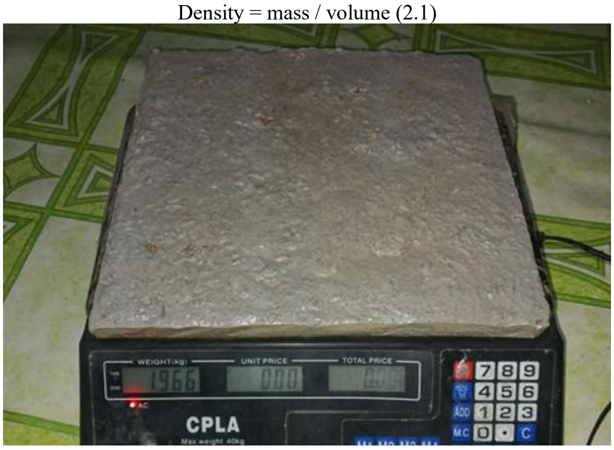

Figure 2.12. Weighing the Developed Insulation Panel During Digital Weighing Scale

Figure 2.13. Weighing the XPS Insulation Using Digital Weighing Scale

2.5.1.4 Water Absorption

In measuring the water absorption, the dry weight of the specimen was first recorded. The sample was then immersed in water for 24 hours. After immersion, the surface water was gently wiped off with a cloth, and the specimen was then weighed again to obtain its wet weight. The percentage of water absorption was calculated using this formula: Water Water absorption = (wet weight – dry weight) / dry weight (2.2)

2.5.1.5 Thermal Conductivity Test (Guarded Hot plate)

The thermal conductivity of the sandwich-structured insulation panels was tested using a custom-built guarded hot-plate apparatus based on the steady-state method described in ASTM C177. In the experiments, the hot and cold chambers were operated at the same time to create a one-direction heat flow through the sample. The hot plate was set to 38 °C and the cold plate to 27 °C, giving a temperature difference of about 11 °C across the panel, Shown in Figure 2.14 is the modified thermal conductivity apparatus.


Figure 2.14. The Modified Thermal Conductivity Apparatus used to Measure the Thermal Conductivity of the Sandwich-Structured Insulation Panel

Thermocouples were positioned on both faces of the panel to measure the temperature gradient, while heater power input were monitored with a kill a watt meter. Data collection continued until steady-state conditions were reached, defined as having less than ±0.5 °C temperature fluctuation and less than ±2% power variation for a period of 30 minutes.

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In standard thermal conductivity testing, power input is typically controlled within a ±2% fluctuation range to ensure reliable results. In this study, a modified and locally fabricated apparatus was utilized, which may not achieve the same level of precision due to inherent limitations in power regulation. Consequently, slight variations in power input were considered part of the system limitations. Ideally, power fluctuations should remain within ±2% during the testing period. However, due to the limitations of the modified setup and the available measuring devices, maintaining the ±2% power fluctuation criterion was not consistently achievable. If steady-state conditions were not initially met, the test was continued until stable temperature readings were obtained. The total recorded power input during the testing period was then used in the thermal conductivity calculations.

Steady state is reached when the hot-side temperature (Th), cold-side temperature (Tc), and wattmeter readings stay stable for 30 minutes, with temperature changes at each thermocouple not exceeding ±0.5 °C. Once steady state is confirmed, the average values of Th, Tc, and the electrical power (Q) were recorded over the 30-minute period, along with readings from the guard plates and the mean thickness of the specimen measured at several points Equation 2.3 was used to compute the power. The test was then be repeated for each specimen, and for every composite ratio ten independent trials were carried out to ensure reliable results. The Q is the net heat flow. Watt/hour is determined from the measured power input where 0.5 is the 30 minutes duration converting it into hours is 0.5 and average time(seconds) takes of 66 seconds to reach or utilize 1 watt of power.

$Q = time/(66 \times 0.5)$. (2.3)

In Equation 2.4 A is the metering area and ΔT was the temperature difference. Thermal conductivity (k) is subsequently computed as:

$K = (Q/(A\Delta T))d$ (2.4)

With d representing the panel thickness. Ten trials were performed for each composite ratio (10:90 and 15:85), and results were expressed as mean ± standard deviation.

Figure 2.15. The Photo of XPS Insulation During the Modified Thermal Conductivity Test

The first layer of the structure or the outer is an insulation to prevent heat loss, then a guard use to give same temperature as the main heater but is purpose is to prevent a heat loss of the main heat source it was provide a heat surround the 5 sides of the main heater. The main source of the heat was the bulb, a Peltier was used for the cold source and a fan was attached to it to distribute the cold.

Once the guarded hot plate had been fully fabricated, it was calibrated using an insulation panel with a known thermal conductivity value. This calibration process is to ensure the accuracy and reliability of the apparatus. After successful calibration, the guarded hot plate was used to conduct performance testing on the developed insulation panel. The Figures 2.15 and 2.16 show the developed insulation and XPS insulation thermal conductivity being measured, respectively.

Figure 2.16. The Photo of XPS Insulation During the Modified Thermal Conductivity Test

2.4.1.6 Thermal Resistance Test

The specimen thickness was measured at three evenly distributed points across the sample. It was placed on the flat surface then carefully measure it using a steel tape or digital caliper, the arithmetic mean thickness was calculated and converted to meters. In Equation 2.5, K is the thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$) under the ASTM C – 177 standard of testing for getting the thermal conductivity, the thermal resistance per unit area R ($m^2 \cdot K \cdot W^{-1}$) of the sample was calculated using the relation:

R = thickness / (K x area) (2.5)

2.5 Data Analysis

The data obtained from ten trials of the developed insulation panels composite 1 and 2 and Commercial XPS were summarized using descriptive statistics, including mean, and standard deviation values. An Independent Samples t-test was conducted to compare the mean values between the developed insulation ratios. The ratio that exhibited better performance was then compared with the commercial insulation (XPS) using the same statistical test. This analysis was performed to determine whether there were statistically significant differences between the groups. The level of significance was set at $p < 0.05$, indicating that any difference with a probability value less than 0.05 was considered statistically significant.

2.6 Fabricating Process of Modified Guarded Hot Plate

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First, the skeleton of the structure is built, followed by the installation of insulation for the main heater. The inner insulation has dimensions of 30 cm × 30 cm × 30 cm, while the outer insulation layer measures 50 cm × 50 cm × 50 cm. Inside the main heater, an incubator bulb is used as the primary heat source. Another heat source is installed in the outer insulation layer to maintain the same temperature provided by the main heater. The main heater is connected to a Kill A Watt device to monitor and record its power consumption. This entire setup is intended for the hot-side box. The hot-side box contains three Inkbird temperature controllers, each equipped with a temperature sensor and connected to a specific heat source or monitoring function. The incubator bulb is wired to one of the Inkbird devices. The temperature controller is set to maintain a temperature of 38°C with a differential setting of 0.4°C. When the temperature inside the chamber reaches 38°C, the Inkbird automatically turns the bulb off. Once the temperature drops to 37.6°C, the controller turns the bulb back on. This heating cycle continuously repeats throughout the testing process until the required test conditions are achieved. The same temperature settings are also applied to the main heater, while another Inkbird device is dedicated solely to monitoring the temperature on the hot-side surface of the developed panel.

For the cold-side box, the insulation structure has dimensions of 30 cm in length, 30 cm in width, and 50 cm in height. An additional insulation layer is added with dimensions of 30 cm in height and 30 cm in length, resulting in a total inner chamber dimension of 30 cm × 30 cm × 30 cm. The cold-side box is equipped with two Inkbird temperature controllers. One sensor is embedded in the middle of the developed panel to measure the internal temperature, while the other sensor is used to monitor the surface temperature on the cold side of the developed panel. The second Inkbird controller is connected to two Peltier modules, which serve as the cooling source of the system. The controller is set to maintain a temperature of 27°C with a differential setting of 0.4°C. When the temperature inside the cold box reaches 27°C, the Inkbird automatically turns the Peltier modules off. Once the temperature rises to 27.4°C, the controller turns the Peltier modules back on. This cycle continuously repeats throughout the testing process to maintain the desired cooling condition. In addition, the two Peltier modules are equipped with heat sinks and cooling fans to improve heat dissipation and ensure stable system performance.

III. RESULTS AND DISCUSSION

This chapter shows the data of the developed insulation in these six parameters, which includes, thickness, density, water absorption, Ignitability, thermal conductivity, and thermal resistance. These parameters are the key factors that shows the performance of the developed insulation, and the best of the two ratios were then compared to the commercial insulation XPS extruded polystyrene.

3.1. Physical Properties

This section displays the physical test of the developed insulation undergoes. The physical properties of the developed insulation are important as basis for future improvements, in terms of production and formulations additives in the PET.

3.1.1 Modified Ignitability Test

Ignitability testing was conducted to determine the flammability characteristics of the material when exposed to a flame source. This test evaluates how easily the sample ignites and how it behaves when subjected to fire. In this study, the sample was exposed to a flame for a specified period and observed to determine whether ignition occurred and how the material responded during the test.

Table 3.1

Modified Ignitability Results Composite 1

Trial	Time to Ignite	Flame Behavior	Burning after 60 seconds
1	No within 15 seconds	Self-extinguish	No
2	No within 15 seconds	Self-extinguish	No
3	No within 15 seconds	Self-extinguish	No
4	No within 15 seconds	Self-extinguish	No
5	No within 15 seconds	Self-extinguish	No
6	No within 15 seconds	Self-extinguish	No
7	No within 15 seconds	Self-extinguish	No
8	No within 15 seconds	Self-extinguish	No
9	No within 15 seconds	Self-extinguish	No
10	No within 15 seconds	Self-extinguish	No

As presented in Table 3.1 the modified ignitability test of the Composite 1, developed insulation samples were evaluated using a procedure adapted from EN ISO 11925-2 to assess their reaction to flame exposure. When subjected to direct flame contact, Composite 1 samples showed only slight, localized surface burning confined to the area of exposure. Once the ignition source was removed, the flames did not spread further and the samples extinguished on their own. The material exhibited self-extinguishing behavior and limited flame propagation, this behavior may be linked to the presence of RHA in the PET bottles, which improved the material's fire-resistant properties, consistent with the findings of Basri et al. (2021). The material exhibited no flame spread and no dripping during testing, and flame extinguished upon removal of the ignition source, indicating compliance with the ignitability criteria of EN ISO 11925-2.

As shown in Table 3.2 of the modified Ignitability test of Composite 2, upon direct flame exposure, Composite 2 also exhibited only minor surface burning localized at the point of flame contact. After removal of the ignition source, the flame did not continue to propagate and the samples self-extinguished. This performance may be associated with the incorporation of RHA into the PET bottles, which enhanced the fire resistance of the material, supporting the observations reported by Basri et al. (2021), which is compliance to EN ISO 11925-2.

Table 3.2

Modified Ignitability Results Composite 2

Trial	Time to Ignite	Flame Behavior	Burning after 60 seconds
1	No within 15 seconds	Self-extinguish	No
2	No within 15 seconds	Self-extinguish	No
3	No within 15 seconds	Self-extinguish	No
4	No within 15 seconds	Self-extinguish	No
5	No within 15 seconds	Self-extinguish	No
6	No within 15 seconds	Self-extinguish	No
7	No within 15 seconds	Self-extinguish	No
8	No within 15 seconds	Self-extinguish	No
9	No within 15 seconds	Self-extinguish	No
10	No within 15 seconds	Self-extinguish	No

The behavior of both Composite 1 and Composite 2 behaviors indicate limited flame spread and a tendency toward self-extinguishing characteristics, which is favorable for insulation applications.

Table 3.3

Flame Spread and Dripping Behavior Results of the Composite 1

Trial	Flame Spread (mm)	Dripping Behavior
1	17.3	Non-Dripping
2	18.1	Non-Dripping
3	15.5	Non-Dripping
4	15.1	Non-Dripping
5	16.0	Non-Dripping
6	15.8	Non-Dripping
7	20.6	Non-Dripping
8	19.7	Non-Dripping
9	18.3	Non-Dripping
10	19.3	Non-Dripping
Mean	17.57	

In Table 3.3 composite 1 showed only minimal flame spread and did not produce dripping during fire exposure, suggesting that its fire resistance properties were enhanced. According to Basri et al. (2021), this improved behavior may be linked to the presence of rice husk ash (RHA), which is rich in silica and can act as a thermal barrier that slows heat transfer. In addition, the formation of a protective char layer on the composite surface helped delay combustion and prevented molten material from dripping.

Table 3.4

Flame Spread and Dripping Behavior Results of the Composite 2

Trial	Flame Spread (mm)	Dripping Behavior
1	16.2	Non-Dripping
2	15.4	Non-Dripping
3	16.7	Non-Dripping
4	14.1	Non-Dripping
5	15.1	Non-Dripping
6	15.5	Non-Dripping
7	15.3	Non-Dripping
8	17.0	Non-Dripping
9	16.3	Non-Dripping
10	15.7	Non-Dripping
Mean	15.73	

Table 3.4 shows that Composite 2 exhibited minimal flame spread and did not produce dripping during fire exposure. This influence can be attributed to the of RHA in the PET bottles, which enhanced the material resistance properties supported by Basri et al. (2021). Furthermore, improving the proportion of the RHA contributed to improved flame resistance of the material.

Table 3. 5

Modified Ignitability Results of XPS Insulation

Trial	Time to Ignite	Flame Behavior	Burning after 60 Seconds
1	4 Seconds	Sustained burning	Yes
2	3 Seconds	Sustained burning	Yes
3	4 Seconds	Sustained burning	Yes
4	4 Seconds	Sustained burning	Yes
5	4 Seconds	Sustained burning	Yes
6	4 Seconds	Sustained burning	Yes
7	3 Seconds	Sustained burning	Yes
8	4 Seconds	Sustained burning	Yes
9	5 Seconds	Sustained burning	Yes
10	4 Seconds	Sustained burning	Yes
Mean	3.9 Seconds		

The XPS insulation samples shown in Table 3.5 exhibited rapid ignition behavior, with flame initiation occurring at an average of approximately 4 seconds upon direct flame exposure. Once ignited, the material demonstrated self-sustained combustion, indicating continuous burning even after removal of the ignition source. This observation is consistent with the findings of Han et al. (2013) which reported that increased heat exposure significantly reduces ignition time in XPS materials, highlighting their susceptibility to fire under elevated thermal conditions, additionally, of Han et al. (2013), indicates that XPS typically ignites at temperatures ranging from 355–370 °C, depending on thickness and heat flux conditions.

3.1.2. Thickness Test

The thickness of the samples was measured to ensure uniformity and consistency of the material used in the testing. Thickness is an important parameter because variations in thickness can affect the accuracy of the experimental results, particularly in thermal conductivity measurements. In Table 4.6 shows the results of the thickness test Composite 1 and Composite 2, mean, standard deviation, and t-test value.

Table 3. 6

Thickness Test Results in Developed Panel

Trial	Composite 1 (mm)	Composite 2 (mm)
1	25.5	27.5
2	27.4	27.8
3	28.3	25.8
4	27.7	27.8
5	26.6	27.7
6	27.7	27.6
7	28.8	28.6
8	28.6	26.6
9	27.3	27.9
10	25.9	28.4
Mean	**27.38**	**27.57**
Standard Deviation	**1.04**	**0.77**
T-test value	**0.666**	

As shown in the Table 3.6 the fabricated insulation samples were designed with a mold thickness of 25 mm; however, the measured mean thicknesses were 27.38 mm and 27.57 mm for Composite 1 and Composite 2, respectively. The results indicate that both composite samples slightly exceeded the intended thickness. This increase may be attributed to the presence of internal voids and the heterogeneous structure of the PET–RHA composite with a rice husk core. Despite this deviation, the relatively low standard deviations of 1.07 and 0.77 indicate acceptable thickness uniformity, with Composite 2 demonstrating more consistent results. The presence of voids within the material may also contribute to improved insulating as illustrated in the study of Liu and Zao 2022.

To determine whether the difference between the two ratios was statistically significant, a t-test was performed. The computed t-test value was 0.666, which indicates that the difference between the mean thickness of Composite 1 and Composite 2 is very small and not statistically significant. This means that the change in ratio did not have a meaningful effect on the thickness of the developed panels.

Table 3.7

Thickness Test Results in XPS

XPS Panel	
Trial	**Thickness (mm)**
1	25
2	25.5
3	25.8
4	26
5	25
6	26
7	25.5
8	25.9
9	25
10	26.4
Mean	**25.81**

Shown in the Table 3.7 the measured thickness of the cut XPS insulation samples which exhibited a mean value of 25.81 mm with a standard deviation of approximately 0.44. This indicates that the samples are relatively uniform in thickness with low variation among measurements. The results are close to the intended reference thickness of 25 mm, suggesting that the cutting and preparation process was generally consistent. Minor deviations may be attributed to manual cutting of the original 50 mm XPS board into smaller specimens, which can introduce slight dimensional inaccuracies.

3.1.3 Density Test

Density testing was conducted to determine the mass per unit volume of the prepared samples. The density of the material is an important property because it can influence the thermal behavior and insulation performance of the sample. The obtained values were then used to analyze the physical characteristics of the material. In Table3.8 shows the results of the density test Composite 1 and Composite 2, mean, standard deviation, and t-test value.

As shown in Table 3.8, the fabricated insulation material exhibited mean density values of 810.03 kg/m³ and 807.47 kg/m³ for Composite 1 and Composite 2, respectively. The results indicate that both formulations produced nearly identical density levels, suggesting consistency in the material composition and fabrication process. The minimal variation between the two composites may be attributed to slight differences in particle packing, porosity, and material distribution during molding and compaction. According to Ashby (2011), small density variations are common in composite materials due to differences in internal structure and processing conditions. Similarly, Saba et al. (2019)

explained that the density of composite materials is influenced by the arrangement and dispersion of reinforcement particles within the matrix, which may result in minor inconsistencies between samples.

Table 3. 8

Density Test Results in Developed Panel

Trial	Composite 1 (kg/m ³)	Composite 2 (kg/m ³)
1	787.7	854.8
2	830.3	810.1
3	801.8	824
4	835.7	794.3
5	836.2	809.1
6	735.2	831.7
7	793.9	787.7
8	769	781
9	857.2	840.6
10	853.3	741.4
Mean	**810.03**	**807.47**
Standard Deviation	**37.36**	**31.36**
T test	**0.876**	

In terms of uniformity, Composite 2 demonstrated a lower standard deviation of 31.36 kg/m³ compared to 37.36 kg/m³ for Composite 1, indicating a more consistent internal structure. This suggests that Composite 2 exhibits improved homogeneity in material distribution, which may contribute to more stable physical and thermal performance. Lower variability in density is often associated with better particle dispersion and reduced void formation within composite materials, leading to more uniform mechanical and thermal behavior. According to Gibson (2016), uniform density distribution in composites is a key indicator of structural consistency, as it reflects efficient mixing and reduced defects such as clustering or porosity. Similarly, Ashby (2011) explains that improved homogeneity in composite materials generally enhances predictable physical properties, including thermal stability and mechanical reliability. To determine whether the difference between the two ratios was significant, a t-test was conducted. The computed t-test value of 0.876 indicates that the difference in density between Composite 1 and Composite 2 is not statistically significant. This suggests that the variation in density is minimal and may only be caused by normal differences during sample preparation or measurement rather than the effect of the ratio.

In the Table 3.9 the measured density of the XPS insulation samples exhibited a mean value of 33.407 kg/m³ with a standard deviation of 1.5 kg/m³. The XPS panel results measurements clustering around 29.73–34.66 kg/m³. According to IXL Panel (n.d.) commercial XPS density of approximately 28 kg/m³, the measured samples show a higher density. This difference may be due to variations in material composition, aging, or differences in measurement conditions, particularly since the samples were manually cut from a larger board. However, one lower value (29.73 kg/m³) was observed, which may be attributed to sample irregularity or measurement variation during specimen preparation, according to Ashby (2011), foamed and cellular materials often exhibit spatial density fluctuations due to manufacturing and handling processes, which can lead to deviations between measured and nominal values.

Table 3. 9

XPS Panel Data in Density Test

XPS Panel	
Trial	Density (kg/m ³)
1	33.77
2	34.42
3	33.16
4	32.9
5	34.66
6	34.18
7	33.11
8	33.03
9	35.11
10	29.73
Mean	33.407
Standard Deviation	1.5

3.1.4 Water Absorption Test

Water absorption testing was conducted to determine the ability of the samples to absorb water when immersed for a specific period. This property is important because it affects the durability and performance of the material, especially when exposed to moisture. In this study, the samples were weighed before and after immersion in water, and the increase in weight was used to calculate the percentage of water absorbed by the material. Table 4.10 shows the results of the density tested Composite 1 and Composite 2, mean, standard deviation, and t-test value.

Table 3.10 shows that the water absorption test in both ratios produced very similar values. The fabricated PET–RHA insulation panel exhibited mean water The absorption values of 5.92% and 5.57% for Composite 1 and Composite 2, respectively. The results indicate that both formulations have relatively similar water absorption behavior, with Composite 2 showing slightly lower water uptake. However, the observed water absorption is higher, this can be attributed to the presence of cracks in the fabricated panels, which allowed water penetration into the internal rice husk core. Since rice husk is a porous material, it naturally promotes water absorption once exposed, according to Mohanty et al. (2005), natural fiber composites tend to exhibit higher water absorption because of their hydrophilic nature and porous microstructure.

Table 3. 10

Water Absorption Results in Developed Panel

Trial	Composite 1 (%)	Composite 2 (%)
1	6.76	4.09
2	4.26	3.13
3	5.68	5.09
4	6.51	5.04
5	7.54	9.90
6	11.28	3.66
7	5.05	3.70
8	4.24	5.66
9	3.31	5.82
10	4.58	9.61
Mean	**5.92**	**5.57**
Standard Deviation	**2.177**	**2.25**
T test	**0.74**	

The standard deviations of 2.177% and 2.25% indicate moderate variability in the results, which may be associated with uneven coating coverage and crack distribution across samples. A t-test was performed to evaluate the difference between the two ratios, yielding a value of 0.74, which indicates no statistically significant difference between their mean values. This suggests that the observed variation is likely due to normal testing or preparation differences rather than the ratio itself. Overall, both ratios showed similar performance, with no significant impact from changing the ratio.

Standard Deviation 0.66 In the Table 3.11 shows that the XPS insulation samples exhibited water absorption values ranging from 0% to 1.31%, with a mean value of 0.519% and a standard deviation of 0.66. The results indicate that most samples showed no measurable water absorption, while a few samples exhibited localized absorption around 1.28–1.31%. This suggests that water penetration may have occurred only in specific regions, likely due to edge exposure or minor surface defects introduced during specimen cutting. Compared to the reported literature value of less than 0.5% for XPS insulation (IXL Panel, n.d.), the measured mean value is slightly higher. This deviation may be attributed to weighing scale, including manual cutting of the original material and exposure of internal cell structures at the edges, which can allow localized moisture ingress.

Table 3. 11

XPS Panel Data in Water Absorption Test

XPS Panel	
Trial	**Water Absorption (%)**
1	1.31
2	0
3	0
4	1.29
5	1.28
6	0
7	1.31
8	0
9	0
10	0
Mean	**0.519**
Standard Deviation	**0.66**

3.1.5 Modified Thermal Conductivity Test

Thermal Conductivity testing was conduct to determine of the ability sample to transfer heat. This property is important in evaluating the effectiveness of the material as a thermal insulator. In this study heat was applied on one side of the sample while the temperature difference across the material was measured. The obtained data were then used to calculate the thermal conductivity of the sample. The results of the modified thermal conductivity test shown in Table 3.12 is for commercial XPS insulation.

In Table 3.12 the test produced a mean thermal conductivity value of 0.0394 W/m·K for the XPS sample. According to Hou et al. (2025), the typical thermal conductivity range for XPS insulation is approximately 0.026 to 0.035 W/m·K. Based on this comparison, the obtained result falls slightly outside the reported range, indicating a higher measured thermal conductivity than expected for standard XPS materials. This deviation may be attributed to the limitations of the modified thermal conductivity testing apparatus used in the study. The increased value suggests the presence of heat losses within the system, leading to an overestimation of thermal conductivity. The estimated error is approximately 12.5%, which reflects experimental limitations such as imperfect insulation of the setup and non-ideal heat transfer conditions. Despite this deviation, the results indicate that the modified apparatus is capable of measuring thermal conductivity trends, although with a measurable experimental error. This observation is supported by Hanif (2023), who defined thermal conductivity as the ability of a material to transfer heat across a temperature gradient.

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Table 3.1 2

Modified Thermal Conductivity Test Results in Test in the XPS

Trial	XPS (W/m •k)
1	0.0410
2	0.0389
3	0.0420
4	0.0384
5	0.0378
6	0.0368
7	0.0410
8	0.0399
9	0.0399
10	0.0390
Mean	**0.03947**
Standard Deviation	**0.0015**

The study further emphasized that laboratory measurements of thermal conductivity often contain errors due to heat loss to the surroundings, limitations of measuring instruments, and human reading errors during data collection. In laboratory experiments. An experiment studies on thermal conductivity measurements report that percentage errors typically range from approximately 5% to 20%, depending on the measurement technique, instrumentation, and experimental conditions (Zarr, 2009). Similarly, the study on thermal transport measurement methods by Design of the Sensor and Experiment (2023) reported that differences between measured and literature values can reach approximately 10%, depending on experimental conditions. The authors explained that variations in sample positioning, contact resistance, and setup configuration significantly influence the final calculated thermal conductivity.

In the Table 3.13 shown that the fabricated PET–RHA insulation material exhibited thermal conductivity values of 0.08033 W/m·K and 0.08006 W/m·K for Composite 1 and Composite 2, respectively. The results indicate that both formulations have nearly identical thermal conductivity performance, with only a minimal difference between the two ratios. The standard deviations of 0.00380 and 0.00268 further suggest relatively consistent measurements, with Composite 2 showing slightly better uniformity. However, the obtained thermal conductivity values are relatively higher than typical insulation materials, indicating reduced insulating efficiency. This increase may be attributed to the presence of cracks within the fabricated panels, which allow direct heat transfer pathways to the rice husk core. Since rice husk is a porous material, once exposed through cracks, it can facilitate heat conduction and reduce overall thermal resistance.

The thermal insulation performance of the fabricated rice husk–based composite is influenced by its porous structure, which is designed to trap air and reduce heat transfer. According to Ji et al. (2023), porous materials improve insulation by creating air-filled voids that act as barriers to heat flow, and in very small pores, the Knudsen effect can further reduce thermal conductivity by limiting gas molecule movement.

Table 3.1 3

Modified Thermal Conductivity Test Results in Test in Developed Panel

Trial	Composite 1 (W/m•K)	Composite 2 (W/m•K)
1	0.0740	0.0781
2	0.0807	0.0766
3	0.0857	0.0760
4	0.0775	0.0795
5	0.0744	0.0775
6	0.0786	0.0784
7	0.0806	0.0830
8	0.0836	0.0744
9	0.0821	0.0804
10	0.0719	0.0824
Mean	**0.08033**	**0.08006**
Standard Deviation	**0.00380**	**0.00268**
Ttest	**0.863**	

In this study, the binder-free rice husk core supports this concept by maintaining void spaces that enhance air entrapment and reduce thermal conduction pathways. However, the effectiveness of this mechanism depends on structural integrity. Cracks in the fabricated samples disrupted the trapped air network and created direct pathways for heat transfer, which increased thermal conductivity. Thus, while the material design supports insulation through porosity and trapped air, defects in the structure significantly reduce its performance. To determine whether the difference between the two ratios is statistically significant, a t-test was performed. The computed t-test value of 0.863 indicates that the difference between the thermal conductivity values of Composite 1 and Composite 2 is not statistically significant. This means that the slight difference in their mean values may only be due to normal variations during the testing process rather than the effect of the ratio itself.

Table 3.14 shows the adjustment of the data for the developed insulation panel after calibration, using the average error of 12.5% obtained during the calibration process. This means that the initial recorded values had a slight deviation from the expected or reference measurements, indicating the presence of systematic error in the data collection. To improve accuracy and reliability, the data were adjusted by applying the computed average error, helping to correct these deviations and better reflect the true performance of the insulation panel.

As a result, the adjusted values in Table 3.14 provide a more accurate and dependable basis for analysis and interpretation of the panel's effectiveness.

Table 3.1 4

Adjusted Data of the Developed Insulation Panel

Trial	Composite 1(W/m•K)	Composite 2(W/m•K)
1	0.0647	0.0683
2	0.0706	0.0670
3	0.0749	0.0665
4	0.0678	0.0695
5	0.0651	0.0678
6	0.0687	0.0686
7	0.0705	0.0726
8	0.0731	0.0651
9	0.0718	0.0703
10	0.0629	0.0721
Mean	0.0702	0.0700

Table 3. 15

Thermal Resistance Test Results in Test in Developed Panel

Trial	Composite 1(m²·K/W)	Composite 2(m²·K/W)
1	3.828	3.940
2	3.772	4.030
3	3.593	3.771
4	3.971	3.885
5	3.972	3.971
6	3.915	3.911
7	3.970	3.828
8	3.801	3.972
9	3.694	3.855
10	4.002	3.747
Mean	**3.897**	**3.858**
Standard Deviation	**0.075**	**0.098**
T-test	**0.361**	

3.1.6 Thermal Resistance Test

Thermal insulation reduces heat transfer by resisting the flow of heat. In this test, a sample insulation material is evaluated to determine its thermal resistance by measuring temperature differences and heat flow across it. This helps assess how effectively the material prevents heat loss or gain shown in Table 3.15 is the results of thermal resistance test for Composite 1 and Composite 2.

The results shown in Table 3.15 for the two composite ratios show mean values of 3.897 and 3.858 for Composite 1 and Composite 2, respectively. The small difference between the two values indicates that both formulations exhibit nearly similar performance characteristics. This suggests that the variation in composition between the two ratios has minimal influence on the overall measured property. In terms of consistency, Composite 1 exhibited a lower standard deviation of 0.075 compared to 0.098 for Composite 2, indicating that Composite 1 has slightly more uniform results across samples. The minor variations observed may be attributed to inconsistencies in material distribution during fabrication.

To determine whether the difference between the two ratios is statistically significant, a t-test was performed, an Independent Samples t-test yielded a value of 0.361, which is greater than the significance level of 0.05. This indicates that there is no statistically significant difference between the thermal resistance values of Composite 1 and Composite 2. Overall, both Composite demonstrates comparable performance, with Composite 1 showing slightly better stability in terms of measurement consistency.

Table 3. 16

Thermal Resistance Test Results in Test in XPS Insulation

Trial	XPS(m²·K/W)
1	6.775
2	7.140
3	6.613
4	6.961
5	6.775
6	6.613
7	6.775
8	6.961
9	6.961
10	6.444
Mean	**6.8001**
Standard Deviation	**0.209**

In the Table 3.16 the measured thermal resistance of the XPS insulation samples resulted in a mean value of 6.801 m²·K/W. When compared to the reported commercial thermal resistance value of approximately 7.9 m²·K/W, the obtained results are lower. This deviation may be attributed to experimental conditions such as heat loss to the surroundings, sample preparation variations, and edge effects introduced during cutting of the material from a larger insulation board, according to Incropera et al. (2011), experimental heat transfer measurements are highly sensitive to boundary conditions and contact resistance, which can significantly affect calculated thermal properties. Despite the difference, the results still

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demonstrate the insulating capability of XPS as a reference material.

The observed variation highlights the influence of experimental setup and measurement conditions on thermal resistance values, particularly in modified or small-scale testing environments. Overall, the results confirm that XPS maintains high thermal resistance performance, although measured values may vary from published commercial specifications. 4.1.7 Comparison This section presents an overall comparison between the developed insulation and XPS insulation using t-test, in Table 3.15 shows the results for thickness, modified thermal conductivity, thermal resistance, water absorption, density, and modified ignitability, to determine if there are significant differences in their performance.

Table 3.1 7

All T test Results Between Composite 2 and XPS Insulation

Type of test	T-test results
Modifi ed Ignitability	Self-extinguish and Self -sustained
Thickness	2.96829E ^(-15)
Density	8.15691 E^(-24)
Water Absorption	5.99278E ^(-15)
Modified Thermal Conductivity	7.68279 E^(-19)
Thermal Resi stance	4.0904E^(-19)

A statistical t-test analysis was conducted to compare the properties of the fabricated PET–RHA Composite 2 and XPS insulation across multiple parameters, including thickness, density, water absorption, thermal conductivity, and thermal resistance. The results showed extremely low t-test values ranging from 10^ (-15) to 10^ (-24), indicating a statistically significant difference between the two materials for all measured properties. These results confirm that the fabricated Composite 2 and XPS insulation exhibit fundamentally different physical and thermal behaviors. The differences are attributed to variations in material composition, structural configuration, and internal morphology, particularly the presence of a porous rice husk core in the composite compared to the closed-cell foam structure of XPS.

For the modified ignitability test, the PET–RHA composite exhibited self-extinguishing behavior, while XPS showed self-sustained combustion, further highlighting significant differences in fire response characteristics between the two materials. The t-test results indicate that the fabricated PET–RHA Composite 2 and XPS insulation differ significantly across all evaluated properties. The extremely low t-values confirm that these differences are statistically significant and not due to random variation. This demonstrates that the two materials exhibit fundamentally distinct physical, thermal, and fire-response behaviors, with the composite showing self-extinguishing characteristics compared to the sustained combustion observed in XPS.

IV. Conclusion and Recommendations

5.1 Conclusion

The fabrication of the sandwich-structured insulation panels was successfully carried out using a 70% rice husk core and a 30% PET–rice husk ash (RHA) composite coating. Two skin mixture ratios were developed: 10% RHA–90% PET and 15% RHA–85% PET. The panels were formed; however, minor defects such as surface cracks and uneven coating were observed, mainly due to the rapid hardening and shrinkage behavior of PET during the molding process. The physical characterization of the developed insulation panels revealed that both composites exhibited self-extinguishing behavior during ignitability testing, demonstrating strong fire resistance performance.

The thickness and density measurements were generally uniform across samples, although minor variations were observed during fabrication, with Composite 2 showing a slightly lower weight compared to Composite 1. In terms of thermal performance, the measured thermal conductivity values for Composite 1 and Composite 2 were 0.08033 W/m·K and 0.08006 W/m·K, respectively, indicating nearly identical insulating capabilities. Similarly, the thermal resistance values were closely comparable at 3.897 m^2·K/W for Composite 1 and 3.858 m^2·K/W for Composite 2. Although Composite 1 showed a marginally higher thermal resistance, both formulations performed within a similar range.

Overall, Composite 2 is considered the more optimal formulation, as it demonstrated slightly better performance in thermal conductivity, density, and water absorption, suggesting improved overall efficiency as an insulation material. When compared to commercial Extruded Polystyrene (XPS) foam board, Composite 2 insulation panels exhibited self-extinguishing behavior in the modified ignitability test, whereas XPS showed self-sustained burning behavior. In terms of thickness, Composite 2 had a mean value of 27.57 mm, while XPS measured 25.81 mm.

For density, Composite 2 recorded 807 kg/m^3, which is significantly higher than the 33.4 kg/m^3 of XPS, indicating that it is much heavier than the commercial insulation. In terms of water absorption, Composite 2 showed a value of 5.47%, whereas XPS had only about 0.519%, indicating an almost negligible absorption rate. The thermal conductivity of Composite 2 is 0.08006 W/m·K, while XPS has a lower value of 0.03947 W/m·K. In terms of thermal resistance, Composite 2 recorded 3.858 m^2·K/W, whereas XPS reached 6.81 m^2·K/W. These results indicate that the lower thermal resistance of Composite 2 reflects poorer insulation performance compared to XPS. Composite 2 exhibits poorer insulation performance compared to XPS insulation, and the presence of cracks in the Composite 2 panels contributed to the degradation of its overall performance.

5.2 Recommendations

Based on the findings of this study, the following recommendations are proposed to improve the quality and performance of the developed insulation panels:

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1. Optimize Heating Time and Temperature – Adjusting the heating process of PET during molding may help reduce shrinkage and minimize cracking in the panels.
2. Consider Alternative Core Materials or Blends – Exploring blends of rice husk with other natural fibers or additives that also have a high potential in insulation.
3. Focus on Fire Safety Advantages – Given that the panels exhibit self-extinguishing behavior, future development can explore applications where fire resistance is more important than thermal insulation, making the panels more suitable for niche uses.
4. Explore Alternative Coating Materials – Instead of PET-RHA, other coating materials can be considered to better preserve the core and prevent cracking while maintaining or improving insulation performance. Materials that adhere well to RHA, shrink less during heating, and resist water penetration may be ideal.
5. Add an Additives in PET Composite – add Polyethylene (PE) wax – reduces brittleness and improves flow or Chain extenders stabilizers – to reduce PET degradation during heating.
6. Incorporate Plasticizers – to improve PET flexibility and reduce brittleness, thereby minimizing internal stress cracking.
7. Coupling Agents – should be used to enhance bonding between PET and RHA, reducing microcracks and improving overall strength.
8. The Addition of Binders or Compatibilizers – is advised to ensure mixture uniformity and stronger structural cohesion.
9. Reinforcing Fibers – are recommended to act as crack arrestors and improve stress distribution within the composite.
10. Fillers and Modifiers – should be included to control shrinkage and enhance dimensional stability.
11. Avoid Thermal Degradation – of PET by maintaining processing temperatures within the recommended range, as overheating leads to polymer chain scission and increased brittleness.
12. Ensure Homogeneous Dispersion of Rice Husk Ash (RHA) – within the PET matrix to prevent agglomeration and stress concentration points.
13. Apply Adequate and Uniform Compaction During Molding – to minimize void formation and enhance interfacial bonding between components.
14. Control the Cooling Rate After Molding – as rapid cooling can induce thermal stresses and result in crack formation.