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Insulation Properties of Rice-Based Materials in Hot and Moderate Climates

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Abstract **-** Although many advanced insulation materials have been recently developed, very few are eco-friendly and their production requires a substantial amount of energy and complex manufacturing processes. To address this issue, a bio-based thermal insulation material was developed using short- and long-grained puffed rice. A set of experiments was subsequently carried out to identify the best rice type and the optimal range for the most influential parameters (sample amount, temperature, and moisture level). Our findings revealed that short-grained rice exhibited greater puffing ability and was thus adopted in further material optimization experiments. These assessments indicated that the most optimal thermal conductivity of the insulation material and the highest puffing ratio was attained at 12–15% moisture, 260–270°C temperature, and 15–18 g sample weight. The thermal properties, including thermal conductivity and fire reaction, and thermal performance of samples obtained using these parameters were similar to those of common insulation materials.

Keywords**:** green material; building insulation; thermal conductivity; bio-based insulation; energy consumption

1. Introduction

The Middle East is characterized by long hot and humid summers that extend for more than six months. Due to such a harsh climate, AC systems are one of the biggest power consumers in this region and contribute up to 50% to the total energy consumption [1]. Using air-conditioning systems is very crucial to provide thermal comfort in buildings of the United Arab Emirates (UAE). These systems have the largest amount of energy consumption; for example, in Middle Eastern countries the energy consumption for space cooling in the residential sector is approximately 50% of the total energy consumption [1,2]. To mitigate this issue, more effective thermal insulation materials should be installed, especially in new buildings, to increase energy efficiency and decrease greenhouse gas emissions.

Most insulating materials are human made (organic and inorganic). Several studies have investigated the thermo-physical properties of such materials; hence, increasing attention has been given to the ecological and environmental impacts and overall sustainability of construction materials [3]. Bio-based insulation materials are produced from renewable biological resources, such as lignocellulose, agricultural plant waste, and animal materials such as fur and wool [4]. Their high internal porosity provides a low bulk density and a low thermal conductivity [5]. These features enable bio-based insulation materials to fulfil their required needs without significant and often costly transformation [6]. However, the greatest advantage of these materials is their biological origin, and thus the potential to reduce the landfill waste due to their high biodegradability. However, owing to high moisture absorption, they tend to suffer from low mold resistance, reduced durability, and suboptimal fire reaction [7].

Many types of bio-based insulation materials are already available on the market and many more are still in the early experimental stages. The majority of the materials listed in [8] are not completely characterized, and many parameters such as specific heat, fire classification, and water resistance are lacking, but their thermal conductivity is always reported.

2. Material

In 2011, the UN Food and Agriculture Organization estimated the annual waste food Carbon footprint at around 3.5 billion tons of CO_2, which exceeds the CO_2 output of all industrial countries except the US and China. In most Asian countries, rice is considered a staple grain, as it can be cheaply produced to meet the food demand of the rapidly growing population [9]. However, according to the analysis conducted by the UN, considerable quantities of rice are wasted each year, contributing to about 610 million tons of CO_2.

The UAE, despite being a developed country, is one of the highest per capita consumers of rice. Statistics released by the state of Dubai indicate that around 772 million kg of rice were imported to the UAE in 2014, and 40% of this amount is disposed yearly, even though rice can be reused in an environmentally friendly way. For example, rice can be separated from food waste collected from different sources (homes, hotels) and reused in non-food sectors. In particular, rice grains can be puffed by heating in a sealed chamber at high pressure to modify their properties, such as malleability. Rice has a smooth surface, high porosity between molecules, and high interfacial areas, making it ideal for use in insulation. In this study, two types (long- and short-grained) of raw rice readily available in the UAE, were used to obtain the puffed rice samples utilized in the fabrication of a novel thermal insulation material for the construction market. Samples produced from both rice types were subjected to several tests in order to identify the most suitable raw material for use in insulation fabrication.

3. Description of Puffing Techniques

In the food industry, expansion can be achieved through popping or puffing. The popping method is used to obtain popcorn from maize, while grains, which do not contain enough water to reach the explosive expansion, are puffed. The puffing method affects the porosity of the produced sample and can create large areas characterized by high porosity, which has a direct effect on the heat transmission within the material and decreases the overall thermal conductivity. Thus, as puffed rice was chosen to develop a new bio insulation material in this study, we subjected it to extensive tests to ensure that it had the most optimal characteristics.

The scanning electron microscopy (SEM) images shown in Figure 2 indicate that during the puffing process, air bubbles form between cells causing the grains to expand without bursting [10]. The resulting rice cakes were subjected to the AACC rapeseed displacement method to determine the true and bulk volume of the puffed rice layers and thus the overall porosity. The true volume was obtained by compressing the sample until no pores remained, whereas the bulk volume was determined using a regular sample without compressing [11].

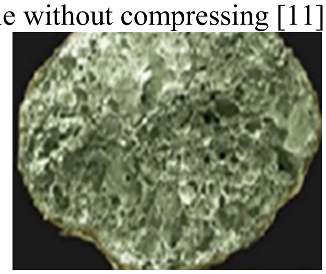


Fig. 1: SEM cross section of a puffed rice grain showing air cells and a compact grain surface [12].

4. Method of Production

Prior to puffing, raw rice was soaked in water for about 12 h to remove starch, as it prevents grain expansion. Next, the rice was dried by exposing it to room temperature for 12 to 24 h, during which the moisture level was assessed using a moisture analyzer to ensure that the desired moisture percentage was achieved, as shown in Figure 2. Once the required moisture level was attained, rice grains were exposed to high temperature (250–270°C) and 40 bar pressures. The apparatus used in the production of the bio-insulation samples had a small gear-shaped motor, driven by a protruding wheel, as well as a temperature and a pressure controller, as shown in Figure 2. The adjusted mold had a circular shape of 8 cm in diameter.

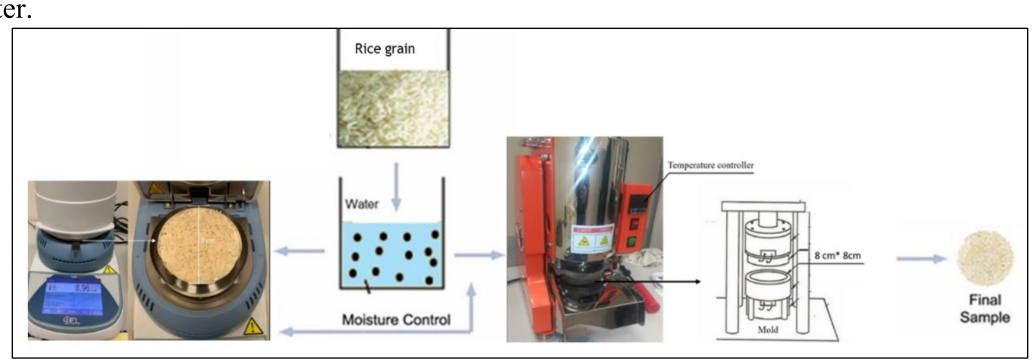


Fig 2: The production process of the rice-based insulation material.

4.1. Testing the Thermal Conductivity

Thermal conductivity is defined as: the “time rate of steady-state heat flow (W) through a unit area of 1 m thick homogeneous material in a direction perpendicular to isothermal planes, induced by a unit (1 K) temperature difference across the sample” [13]. In general, thermal conductivity of any material depends on the operating temperature and on the moisture content. Several studies were conducted to determine the effect of operating temperature on the thermal conductivity of insulation materials. Most of these studies showed a linear relation between the thermal conductivity and the operating temperature. This effect can cause a higher cooling or heating load in the building envelope with varying the temperature [14-18].

The thermal conductivity of the proposed new “puffed rice insulation” sample was tested using the Fox 200 thermal conductivity device, the device has an upper and lower thermal plate to hold the sample. The centers of both plates start to generate a heat flux at the beginning of the test as shown in Figure 3.

Fig 3: Laser Comp heat flow meter instrument (Fox200).

4.2. Testing the Reaction of Fire

Several tests must be carried out and many requirements must be achieved before selecting the building’s insulation materials. One of the most important tests is the ignition temperature and smoke production, this test is considered as one of the most important tests of the insulation materials because it can prevent peoples ‘death in cases of fire accident [19]. Thus, interaction of the insulation material with fire is a very important issue. Based on the European rating system, A1 classification of the material fire reaction represents the best performance of the material, while E classification is the worst [20].

In 2015 Palumbo investigated the fire reaction of six bio-based insulation materials and the binder’s usage effect in the composites. The results showed that all the tested composites evaluation were better than the commercialized insulation materials such as polystyrene or polyurethane and that the binders had a massive effect on the composite fire behaviour [7]. A set of steps has been reported to enhance the fire resistance ability, for example, remove the flammable matter form the bio insulation composite and use the fire retardants [21].

The flammability test UL94 V was performed in the present study, as this small-scale fire test was initially developed to examine the ignition and flame spread for different types of plastics and bulk materials [22]. A sample of 8 cm length and 1 cm thickness was investigated using the experimental setup shown in Figure 4.

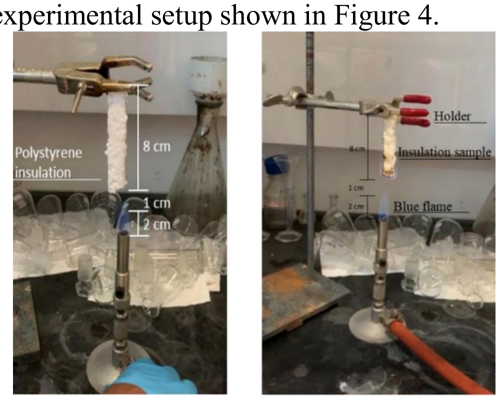


Fig 4: UL94 V experimental setup of flammability test for the rice-based insulation and polystyrene insulation.

5. Results and Discussion

5.1. Sample Screening

A set of screening experiments was carried out to determine whether long- or short-grained rice was more suited for puffing and to establish the optimal values of other influential parameters. One factor at a time was tested in the screening step to determine the significant factors affecting sample thickness, sample shape, surface smoothness, and puffing ratio. Our findings revealed that shorter grains exhibited greater puffing ability, while also yielding better results in terms of puffing ratio, sample thickness, circular shape, and surface smoothness. Thus, in the subsequent steps, short-grained rice was used in the material optimization, aiming to improve thermal conductivity and overall performance.

5.2. Sample Weight, Temperature, and Moisture Level

As some samples burned when exposed to 280°C, while the moisture ratio was too high for sufficient puffing to occur in others, or the sample shape was inconsistent due to the variations in the amount of raw material used (Figure 5), we eliminated these issues by restricting the temperature, moisture level, and sample weight to 260–270°C, 12–16%, and 15–17 g, respectively.

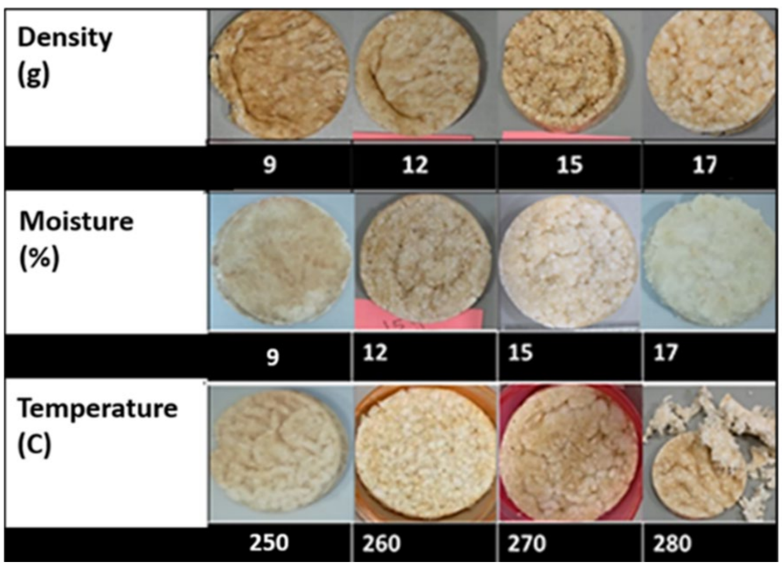


Fig 5: The produced insulation samples with different levels of moisture, density, and temperature.

5.3. Thermal Conductivity Test

The thermal conductivity of the proposed new "puffed rice insulation" sample was tested using the Fox 200 thermal conductivity device, as well as a low-density polystyrene as it is the insulation material commonly used in the UAE construction market. A dry sample of 8 cm in length and 1 cm in thickness was prepared to be investigated for both specimens. The Fox 200 device is an accurate instrument and well-suited to measuring slices with different thicknesses up to 0.025 mm according to ASTM C518 and ISO 8301. The Fox 200 device has an upper and lower thermal plate to hold the sample. The centres of both plates start to generate a heat flux at the beginning of the test.

The thermal conductivity tests were performed at five different mean temperatures: 5, 15, 25, 35, and 45°C. The daily average temperature ranges from 18°C in January to around 35°C in August, which is within the used device minimum and maximum temperature range for each run, thereby providing rapid and accurate results. The thermal conductivity values measured at different temperatures for both insulation samples are reported in Figure 6.

The results show that, according to the thermal conductivity k-values, the newly developed bio-insulation material "puffed rice insulation" is suitable for use as insulation material, especially when compared with other commercially available alternatives, as shown in Figure 7.

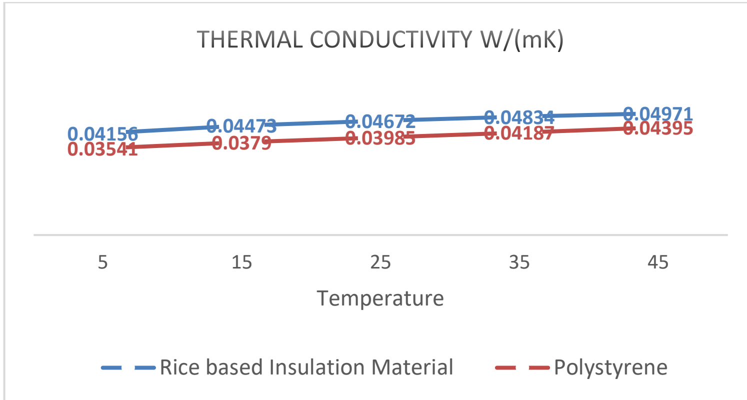


Fig 6: The thermal conductivity values for puffed rice insulation and polystyrene insulation samples.

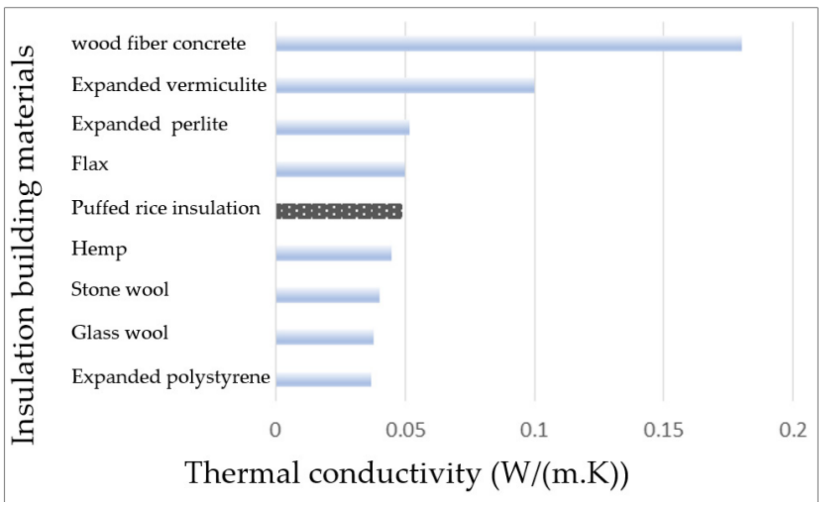


Fig 7: Thermal conductivity comparison between building insulation materials.

5.4.Fire Test

Table 1 shows the phases that the puffed rice insulation samples underwent during the fire test. As explained previously, a blue flame for methane gas, indicates "the temperature is about 1960°C, according to the flame color temperature chart", of 2 cm length was applied for a 10 s first round, while ensuring that it remained at a 1 cm distance from the specimen. Next, the sample was removed from the flame field to measure t_1, after which the flame was applied for a further 10 s second round to measure t_2 and t_3.

As can be seen from Table 1, the fire never reached the holding clamp and no burning drops or toxic gases were detected in any of the five repeated tested samples, which used the same burning time of 20 s in total. On the other hand, the UL94 V fire test was applied to the polystyrene insulation material samples under the same conditions described earlier for the puffed rice insulation. The specimens burned completely in a shorter time than that recorded for the puffed rice insulation samples. After applying the flame to the polystyrene sample for 1 s, it started to ignite very quickly and the gases began to emit dramatically, which led to the complete burning of the sample after 6 s.

On the other hand, polystyrene insulation material showed larger variations when it was tested under the same conditions. Table 2 shows how long the polystyrene sample took to burn completely after exposed to a blue flame with the same first test specification: 8cm sample long, 1cm sample thickness, 2cm blue flame, and a distance of 1 cm between the sample and the top of the flame. The required time to burn the specimens completely was much less than the time required to burn the puffed rice insulation sample. After 1 second of applying the flame to the polystyrene, the sample started to ignite very quickly, and the gases began to emit dramatically which led to the complete burning of the sample after 6 sec.

Table 1: The puffed rice insulation sample phases under the UL94 V Fire test.

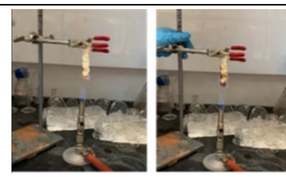
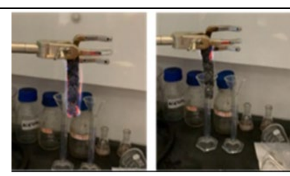
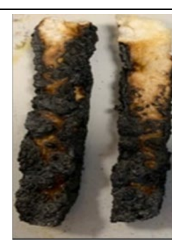
Time	**Burning level**
2 second	
4 seconds	
6 seconds	
8 seconds	
10 seconds	
20 seconds	

Table 3 shows the difference between the develop puffed rice insulation material and polystyrene insulation materials as a second fire inspection was conducted to observe how the puffed rice insulation versus the polystyrene insulation interact with fire. The two samples were exposed to a blue flame to measure the total time required to be completely burned, toxic gas emissions and burning drops 52 appearance were listed. The newly developed bio insulation material shows magnificent stability and no toxic gases were noticed, the bio and organic component give it a big distinction.

Table 2: The polystyrene insulation sample phases under the UL94 V Fire test.

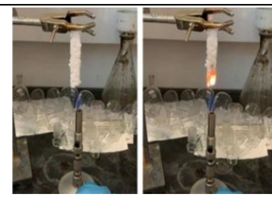
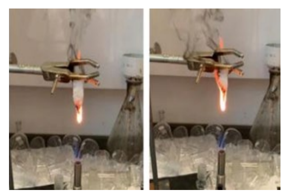
Time	Burning level
2 seconds	
4 seconds	
6 seconds	

Table 3: Evaluation of the puffed rice and polystyrene insulation materials according to burning time, gas emission and burning drops appearance.

Insulation Material	Burning Time (s)	Burning Drops	Material Vanishing
Puffed rice	20	No	No
Polystyrene	6	Yes	Yes

6. Conclusions

In this research, a bio-based thermal insulation material was developed using short-grained puffed rice and was subjected to extensive tests to optimize its thermal conductivity. These assessments indicated that the most optimal thermal conductivity of the insulation material and the highest puffing ratio was attained at 12–15% moisture, 260–270°C temperature, and 15–18 g sample weight. The thermal properties, including thermal conductivity, fire reaction, and thermal performance of samples obtained using these parameters were similar to those of common insulation materials. Specifically, the minimum thermal conductivity value was 0.04971 W/mK and according to the UL94 V flammability test, the puffed rice insulation material exhibited good fire reaction (V1).

Consequently, this bio-based thermal insulation material has considerable commercialization potential, as it is environmentally friendly, exhibits high thermal stability, produces no toxic gas emissions, and has thermal performance comparable to that of common insulation materials. These advantages make this newly developed material a strong competitor in the thermal insulation market.

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