SUSTAINABLE COMPOSITE INSULATION PANELS: INVESTIGATING DIVERSE ALTERNATIVES FOR INSULATING APPLICATIONS UTILIZING COCONUT HUSK AND AGRO-INDUSTRIAL RESIDUE COMPOSITES

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Abstract: The current economic crisis emphasizes the need for cost-effective and sustainable construction practices, given that the construction sector remains a significant environmental polluter, generating harmful residues and consuming substantial energy and resources. This study investigates the use of agro-industrial waste materials, particularly coconut husk, combined with innovative adhesives such as rice water, rubber wastewater, bael fruit (Aegle marmelos) extract and lime to develop eco-efficient insulation boards. The research focuses on evaluating key attributes including thermal properties, mechanical strength characteristics and resistance to mold growth, while also considering the influence of lime as a factor. Standard testing methods were employed, including thermal conductivity tests to assess insulation efficiency, adhesive strength tests to measure bonding performance and mold resistance tests to compare the durability of different adhesives. The study highlights the potential of utilizing agro-industrial waste materials to produce sustainable insulation solutions, addressing both environmental and economic challenges in the construction sector. Findings indicate that each adhesive type exhibited unique properties with some binders showing promise as viable options for bio-based insulation panels. However, further improvements are needed to enhance the biological resistance of the natural adhesive, possibly by integrating synthetic materials.

Keywords: *Agro-industrial waste, coconut husk, eco efficient insulation , Innovative adhesives , sustainable construction*

1. Introduction

Amidst the ongoing economic crisis, which has led to a critical need for cost-effective and sustainable construction practices, the construction sector has been under increased scrutiny due to its significant environmental impact. Researchers have highlighted its role as a major contributor to pollution, characterized by the generation of harmful residues and substantial energy and resource consumption (Circo, n.d.; Kubba, 2010; Moavenzadeh, 1994; Warnock, 2005). In Europe, it stands out as the sector responsible for the highest emissions and the largest energy consumption (Neagu & Teodoru, 2019; Nejat et al., n.d.). This environmental burden extends to building materials, both in their production and application phases, emphasizing the urgency of adopting eco-efficient and environmentally friendly solutions (Yadav et al., 2024). In this context, a promising avenue of research involves the utilization of agro-industrial waste materials for construction purposes. These locally abundant waste materials offer numerous advantages, including the potential to produce composites with properties akin to conventional materials, biodegradability and non-toxicity (Boey et al., 2021; Keya et al., 2019). Furthermore, harnessing local agro-industrial waste for building material production serves the dual purpose of reducing carbon emissions and managing solid waste disposal, thus addressing pressing environmental concerns (Maraveas, 2020).

Within the realm of sustainable construction, panels and particleboards are pivotal due to their ease of on-site installation. Various techniques, such as compression, thermal treatment and the use of adhesives, coupled with materials like wood chips, fibers and agro-industrial waste, have been explored as efficient solutions for waste management (Alavez-Ramirez et al., n.d.; Lotfi et al., 2019; Panyakaew, Passive, et al., n.d.; Schiavoni et al., n.d.). Past studies have prominently focused on evaluating the thermal insulation properties of boards and panels derived from agro-industrial waste. For instance, Tudor (2023) scrutinized binderless compacted particleboards fabricated from flax shives (Linum usitatissimum L.) and sunflower stems (Helianthus annuus L.), yielding thermal conductivity values of 0.077 W/(m·K) for both at a density of 500 kg/m3 and 0.066 W/(m·K) for flax shives and 0.070 W/(m·K) for sunflower stems at a density of 350 kg/m3 (calculated under steady-state conditions) (Tudor, 2023). Comparing short-cut rapeseed and short-cut wood chips, they obtained thermal conductivity values of 0.048 W/(m·K) for rapeseed and 0.065 W/(m·K) for wood chips (calculated under steady-state conditions) (Cintura et al., n.d.). Ramos et al.,(2021) delved into the properties of particleboards composed of corn cob and polyvinyl acetate (PVA) with Fabricol AG222 (FAG222) as a binder, shedding light on their suitability for insulation applications.

It is noteworthy that materials with a thermal conductivity not exceeding 0.065 W/(m.K) are generally considered suitable for classification as thermal insulations (Danaci, 2021), while earlier research even allowed values up to 0.1 W/(m.K)

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(environment & 2005, n.d.; Kalhor et al., n.d.). These previous studies underscore the feasibility of employing agro-industrial waste materials to manufacture thermal insulation boards that meet established standards. For further details on the density and thermal conductivity of commercial panels with various functions (not limited to thermal insulation panels) and values reported in prior investigations on the thermal performance of bio-based panels and boards, please refer to Table 1.

Table 1: Values of density and thermal conductivity of commercial panels

Insulation Name	Commerical Product	Density	Thermal conductivity [W/(m.K)]	Cost per square meter in Dollars	Country of origin	Ref
Fiberglass Insulation	Blanket or Batts	Varies (typically 11-48 kg/m3)	0.025 - 0.040 W/(m·K)	$5 - $15	Available worldwide	[Online]. Available: https://www.owenscorning.com/insulation. [Accessed: September 10, 2023].
Cellulose Insulation	CertainTeed InsulSafe Cellulose Insulation	typically 32-48 kg/m3	0.037-0.040 W/(m-K)	$5 - $15	Availability varies by region	Certain teed of specific manufacturer
Mineral wool insulation	Rockwool Comfortbatt Insulation	varies (typically 40-200 kg/m3)	0.030 - 0.044 W/(m-K)	$10 - $20	Available worldwide	Rockwool or specific manufacturer
Polyurethane (PU) Foam Insulation	Dow Froth-Pak Insulation	Varies (typically 25-50 kg/m3)	0.020 - 0.030 W/(m·K)	$10 - $20	Available worldwide	Dow or specific manufacturer
Polystyrene (EPS) Foam Insulation	Styrofoam Brand XPS Insulation	Typically 15-35 kg/m3	0.030 - 0.038 W/(m·K)	$5 - $15	Available worldwide	Styrofoam or specific manufacturer
Polyisocyanurate (PIR) Foam Insulation	Kingspan Kooltherm Insulation	Typically 30-50 kg/m3	0.022 - 0.030 W/(m·K)	$10 - $20	Available worldwide	Kingspan or specific manufacturer
Aerogel Insulation	Aspen Aerogels Spaceloft Insulation	Typically 100-300 kg/m3	Extremely low, around 0.013 - 0.025 W/(m·K)	$50 - $100	Available worldwide	Aspen Aerogels or specific manufacturer
Cork Insulation	Amorim Isolamentos Cork Insulation	Typically 80-240 kg/m3	0.040 - 0.050 W/(m·K)	$10 - $30	Availability varies by region	Amorim Isolamentos or specific manufacturer
Perlite Insulation	Perlite Institute Perlite Insulation	Typically 32-96 kg/m3	0.035 - 0.050 W/(m·K)	$10 - $20	Availability varies by region	Perlite Institute or specific manufacturer
Vermiculite Insulation	Vermiculite Association Vermiculite Insulation	Typically 80-192 kg/m3	0.035 - 0.045 W/(m·K)	$10 - $20	Availability varies by region	Vermiculite Association or specific manufacturer

The choice of binders and adhesives is crucial in producing sustainable insulation boards, significantly affecting their performance and environmental impact. While urea-formaldehyde resins are effective, their toxicity raises concerns.

Natural alternatives such as tannins, lignin, proteins, carbohydrates, and vegetable oils are being explored for bio-based adhesives (Shanefield, 1995; Wolderufael, 2022; Antov et al., 2020; chemistry & 2019, 2019; Islam et al., n.d.). Formaldehyde-free adhesive systems for wood have been reviewed, with both synthetic and renewable options considered. (Solt et al., 2019). Kariuki et al., (2019) compiled previous studies that explored starch and starch derivatives as alternatives to formaldehyde-based resins.Starch, particularly potato starch, has been used as a binder for thermal insulation particleboards, demonstrating feasibility as an eco-friendly solution (Kariuki et al., 2019; Monteiro et al., 2016). Wheat gluten and sour cassava starch are also promising natural adhesives Starch stands out due to its availability and production volume, making it a viable option for sustainable binders (Zhang et al., 2023).

Biological susceptibility is another critical consideration for agro-industrial waste-based composites, as it can affect material properties, durability, and potentially impact the health of building occupants, depending on the application (Singh & White, 1997). Several factors influence biological susceptibility, including chemical composition (e.g., cellulose, hemicellulose, lignin content), temperature, relative humidity (RH), moisture content, surface conditions, and pH (Pyrolysis, 2012; Skyba, 2008). Both the aggregates and the adhesives contribute to the biological resistance of the final product (Skyba, 2008).

The present study outlines preliminary investigations aimed at producing eco-efficient boards using a novel combination of materials. The emphasis is on evaluating different adhesives in conjunction with coconut husk as the primary component, which is complemented by a diverse range of supplementary materials, including rice water, rubber waste water, bael fruit (Aegle marmelos) extract, and lime as potential fillers. These selections were made based on the following criteria:

To explore sustainable and environmentally friendly alternatives in the production of insulation boards.
To assess the thermal properties and suitability of these novel materials for thermal insulation applications.
To determine their potential for meeting established standards for thermal conductivity in insulation materials.
To evaluate their biological resistance and resistance to microbial attacks, ensuring long-term durability and safety.
To consider the feasibility of large-scale production using these eco-efficient materials and adhesives.

2. Materials and Methods

2.1 MATERILAS

Coconut coir fiber is a natural, renewable material characterized by its biodegradability and sustainability (Hasan et al., n.d.). With a density of 80 to 150 kg/m^3 and low thermal conductivity, it is ideal for insulation. Abundant in tropical regions, coconut coir is durable and moisture-resistant, making it a suitable primary insulation material for this study. Inorganic insulation materials pose health and environmental risks through hazardous emissions, high energy consumption, and difficult disposal (Panyakaew, 2008). Renewable fiber insulation from plants, trees, and animals, such as coconut coir, offer a more sustainable alternative (Yhaya et al., 2018). Natural fibers like coconut coir are being explored for building insulation due to their biodegradability and lower production energy requirements. Studies show fibers like oil palm, coconut, and sugarcane have acceptable thermal conductivity for insulation. These materials reduce processing costs and are environmentally friendly. Coconut fiber-filled walls can lower building temperatures and energy usage, with studies showing a 10°C reduction compared to conventional construction. Additionally, coconut fiber-insulated walls resist moisture ingress (Iwaro & Mwasha, 2019).

Lime is a versatile, durable material with a density of 1600 to 1700 kg/m^3 and low thermal conductivity, making it suitable for insulation. Lime's long history in construction and resistance to decay and pests enhance its appeal. It is used as a filler to improve thermal properties and structural integrity (Arizzi et al.,2016; Kontoleon et al., 2023). Research shows lime-based plasters have lower thermal conductivity than other materials, confirming lime's efficiency as an insulator. Lime also regulates moisture and resists pests and fungi, contributing to its long-term durability (El-Otmani et al., 2011).

Rice water, a byproduct of rice cultivation, has a density similar to water (1000 kg/m^3) and serves as a binder in insulation production (TAYALAN & MANOHARAN,2014). Rubber wastewater, a byproduct of rubber processing, varies in density and acts as an adhesive(Chang et al., 2023). Bael fruit (Aegle marmelos) extract, derived from the bael fruit, has potential thermal properties and is used as an adhesive binder(Sharma et al., 2024).

2.2 METHOD

In this research, a systematic quantitative methodology is employed to develop and optimize insulation boards with specific properties, emphasizing thermal conductivity, density, moisture resistance, and adhesive strength. The methodology involves a step-by-step approach aimed at achieving the desired characteristics for these boards. The first crucial step is to determine the precise attributes required for the insulation boards. These attributes include a target thermal conductivity value, a specified density range, a desired level of moisture resistance, and a predefined adhesive strength criterion. These parameters serve as the foundation for the entire research process.

Test results are critically examined, and adjustments are made based on the findings. For example, if the adhesive strength falls short of the desired levels, the proportions of the adhesive components (rice water, rubber waste water, and bael fruit extract) are modified to enhance the adhesive properties while preserving effective insulation characteristics. The research methodology is iterative in nature, allowing for continuous testing, adjustment, and optimization until the insulation boards meet the desired criteria for both insulation properties and adhesive strength. Upon finalizing the optimal material proportions and characteristics, the research culminates in documenting the final mix design, specifying the exact percentages or volumes of each component. Quality control measures are then implemented during the production phase to ensure that the actual mix aligns precisely with the final design.

As production scales up, maintaining strict adherence to the proportions outlined in the final mix design is paramount. Furthermore, to ensure ongoing quality and consistency, regular testing and monitoring of the manufactured insulation boards are conducted to verify their continued compliance with the desired properties. This research methodology places a strong emphasis on optimizing the adhesive and binder components (rice water, rubber waste water, and bael fruit extract) to achieve the required adhesive strength while concurrently preserving the effective insulation properties offered by coconut coir and lime as core materials.

2.2.1 Materials Preparation

The fabrication of the coconut fiber coir Insulated Sandwich Panel involves a systematic manufacturing process aimed at optimizing the composition and properties of the final product. The figure 1 shows steps detail the material preparation phase.

Figure 1: Material preparation process (Source: Author, 2023)

We conducted blind mix designs with coconut coir content ranging from 0% to 95%, while gradually reducing lime content from 95% to 0%. The adhesive component was kept constant at 5% of the total weight as shown in Table 2. This approach enabled a thorough exploration of material proportions without prior assumptions. Adhesive strength and flexural strength were subsequently assessed to validate the suitability of the various mix designs. Extensive testing confirmed that the adhesive and flexural strengths were within an acceptable range.

Table 2: Blind mix design (Source: Author, 2023)

Mix Design code	Coconut Coir	Lime	Adhesive Rubber Wastewater, Rice Water & Bael Fruit Extract
CC0L95RWW5	0%	95%	5%
CC10L85RWW5	10%	85%	5%
CC20L75RWW5	20%	75%	5%
CC30L65RWW5	30%	65%	5%
CC40L55RWW5	40%	55%	5%

CC50L45RWW5	50%	45%	5%
CC60L35RWW5	60%	35%	5%
CC70L25RWW5	70%	25%	5%

2.2.2 Experimental Design

For the purpose of develop and optimize insulation boards with specific properties , standard tests were employed, including thermal conductivity tests to assess insulation efficiency, adhesive strength tests to measure bonding performance and mold resistance tests to compare the durability of different adhesives.

In Test 1, a thermal conductivity test aimed to determine the insulation material's ability to prevent heat conduction. In this process, the insulation material sample preprepared with the validated mix design, was placed between two plates of the thermal conductivity apparatus [one heated and one chilled] as shown in figure 2.

Figure 2: Thermal Conductivity Test Process (Source: Author, 2023)

A controlled temperature differential was maintained between the plates, allowing heat to pass through the material. The apparatus continuously monitored the heat transfer rate and temperature differential across the insulation material. These measurements were used to calculate the material's thermal conductivity. Lower thermal conductivity readings indicated better insulating properties, reflecting the material's ability to resist heat transfer. To thoroughly understand the insulating qualities, thermal conductivity tests were conducted at various temperatures. These tests were performed at the facilities of The Open University of Sri Lanka.

In Test 2, the strength of the insulation board was assessed through adhesive strength test and strength of the coconut coir, lime, rubber waste & rice water and bael fruit extract mixture was evaluated using a controlled compression method. The mixture was compressed between two cladding boards, each measuring 15 cm in length and width. The resulting sample was dried in natural sunlight for 3 days to achieve a stable and consistent state. The dried sample was then suspended as illustrated in Figure 3 , with a bucket positioned below it. Water was gradually poured into the bucket, ensuring a systematic and controlled application of load to the material. The experiment was closely monitored, and the elapsed time was measured from the initiation of water filling until the bucket detached. The weight of the bucket at the point of detachment provided a quantitative measure of the load-bearing capacity of the material. This test allowed us to assess the adhesive strength and durability of the material under stress.

Figure 3: Test 2 Adhesive Strength Test Process (Source : Author,2023)

In Test 3 a mold resistance test was conducted to simulate tropical conditions and assess the susceptibility of composite samples to mold formation. Composite samples consisting of Coconut Coir, Lime, Rubber wastewater, Rice water, and Bael extracts were prepared and placed in a tropical conditions simulation box for three weeks of 30^{o}c and 85% humidity, typical of tropical environments. The Copper Sulfate is widely recognized because of its anti-fungal properties was incorporated into same samples to reduce the mold growth (Alwash et al., 2022). The efficiency of mold prevention is supported by previous studies highlighting its capability to inhabit fungal growth in humid conditions (Brambilla et al., 2020.; Menneer et al., 2022; Sterflinger,K, 2010). For the sample preparation, Copper Sulfate was added to the composite at two concentrations range 0.5% and 1% by weight of the total composite material, that could assess the optimal concentration for mold resistance and was mixed thoroughly with the prepared composite to ensure uniform distribution within the samples. Without the Copper Sulfate, untreated samples were prepared as controls that allowed the direct comparison.

Figure 4: Mold Samples prepared by applying different ratios of mixture (Source: Author, 2023)

3. Results

Test 01 , the results of the thermal conductivity test has highlighted values of thermal conductivity, Thermal diffusivity, Specific heat, Penetration Depth (Pr Depth), Temperature increment (Tem.Incr) Mean deviation (Mean Dev) and Disk resilience. According to the each of these values relevant curves has derived as shown in figure 5.

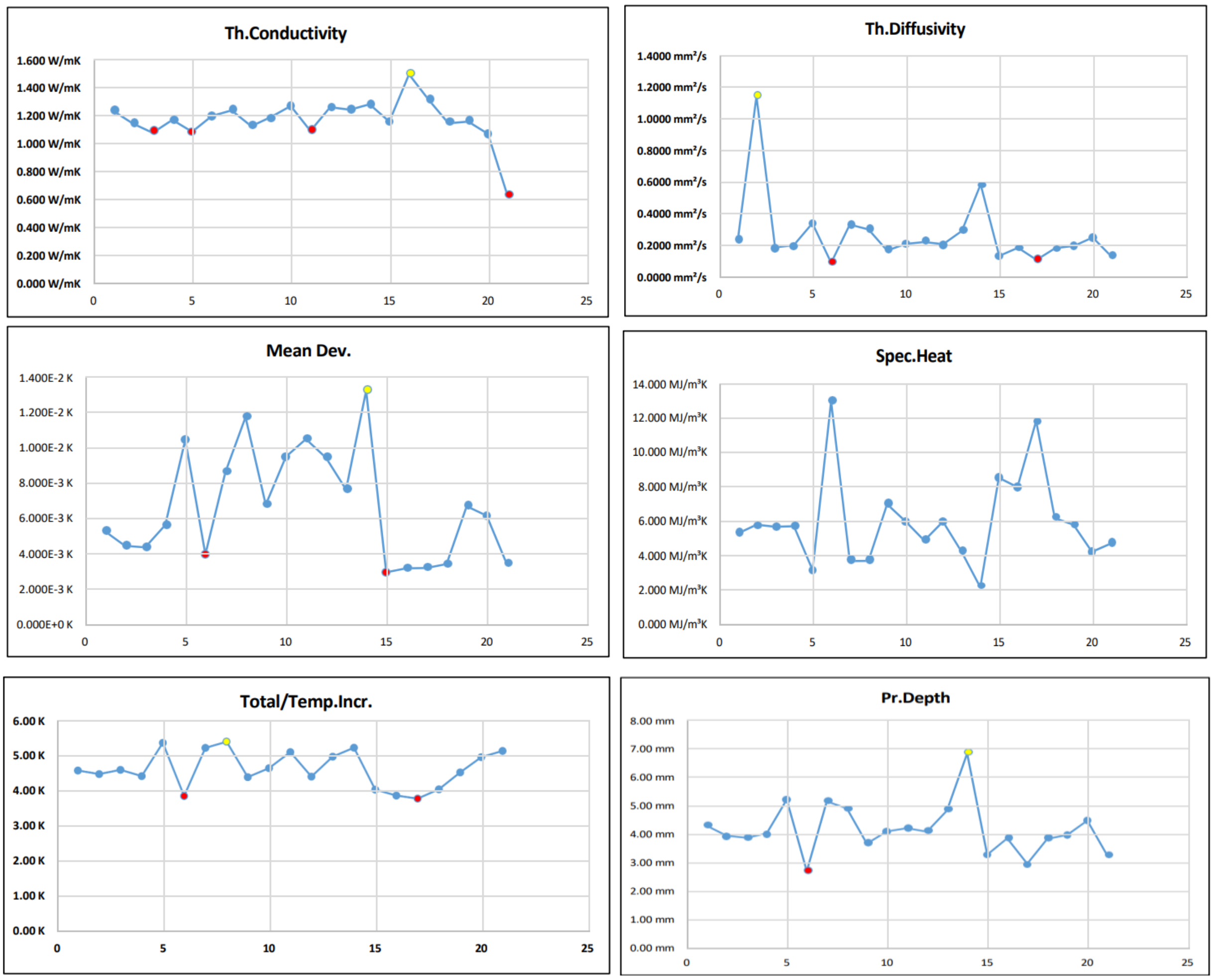

Figure 5: Results of Test 1 (Source : Author,2023)

The findings of thermal properties presented in figure 5 reveals distinct variations among the samples. Notably, the samples with the lowest thermal conductivity values are CC10RW5LM85, CC20RW5LM75, CC50RW5LM45, and

CC100RW00LM00, indicating superior insulation properties. Conversely, the sample with the highest thermal conductivity value is CC75RW5LM20. The thermal diffusivity curve indicates that samples CC25RW5LM70 and CC80RW5LM15 exhibit the lowest values, suggesting a slower rate of heat propagation. In contrast, the sample CC5RW5LM90 shows the highest thermal diffusivity value, indicating a faster rate of heat transfer.

The "temperature increment." values, representing the total temperature increment during testing, are lowest for samples CC80RW5LM15 and CC25RW5LM70, indicating enhanced thermal stability. The highest total temperature increment is observed in sample CC35RW5LM60, with a value of 5.40 K, suggesting significant heat absorption or retention. Specific heat, a measure of thermal storage capacity, varies among the samples. The Mean Deviation curve for thermal conductivity highlights that samples CC20RW5LM75 and CC50RW5LM45 exhibit the lowest values, indicating high consistency and homogeneity.Conversely, higher Mean Deviation values suggest greater variability in thermal conductivity. Penetration depth measurements reveal variability, with the lowest value in sample CC25RW5LM70 at 2.71 mm, and the highest in sample CC65RW5LM30 at 6.84 mm. This range signifies diverse material characteristics and penetration extents among the samples.

The thermal properties analysis of coconut coir concentrations reveals key findings, including the observation that the lowest thermal diffusivity occurs at a 25% coir concentration (CC25RW5LM70), indicating the slowest rate of heat conduction. Thermal conductivity values are lowest within 10% to 50% coir concentrations, suggesting that enhanced insulation properties. Moreover, the lowest penetration depth is at 25% coir concentration (CC25RW5LM70), measuring 2.71 mm, indicating limited external factor penetration and the lowest mean deviation values occur in the 20% to 50% coir range (CC20RW5LM75 and CC50RW5LM45), reflecting high consistency. The lowest total temperature increment is seen in the 25% to 80% coir range (CC25RW5LM70 and CC80RW5LM15), indicating superior insulation. These findings suggest that the optimal composition for thermal insulation consists of 10% to 50% coconut coir, 5% rice flour, and wash water, with potential adjustments to lime content to minimize thermal conductivity.

Furthermore, Coconut coir, lime, and agricultural waste adhesive-insulated steel sandwich panels exhibit thermal conductivity between 1.079-1.093 W/mK, comparable to materials like clay, limestone, and sandstone and superior to metals such as aluminium, copper, and silver (Table 3). These panels also demonstrate high specific heat (5.694-5.999 MJ/m^3K), enhancing their capacity for heat storage and energy efficiency. This makes them suitable for applications where minimizing heat transfer is crucial, surpassing most other materials in thermal mass and heat storage capacity.

Material	Thermal conductiv-ity W/(m/K)	Material	Thermal conductivity W/(m/K)
Glass	1.38	Aluminum	200
Bricks	0.5 – 1.0	Bronze	110
Steel	45	Copper (Cu	400
Concrete	0.6 - 3.6	Iron (Fe)	80
Clay	1.2	Lead (Pb)	35
Granite	3	Silver (Ag)	450
Limestone	1.5		
Cement plaster	1		
Marble	2.2		
Porcelain	1.5		
Sandstone	1.5		

Figure 6: Thermal conductivity for other construction materials ((Standardization E. C.)

Test 2, the dynamic loading scenario, created by gradually filling a bucket with water, simulates incremental stress on the material. The results have indicated that material supported a 4.875 kg load for 3 minutes and 54 seconds before failure as shown in figure 6, demonstrating its ability to withstand gradual stress buildup. This combined adhesive strength and bucket test provides a comprehensive evaluation of the material's strength and performance, indicating significant structural integrity and load-bearing capacity under varying conditions.

Test 3, the findings highlighted that mold growth was significantly inhibited after adding copper sulfate to the composite material. The untreated samples exhibited extensive mold coverage with approximately 70% of the surface that indicating visible mold growth by the end of the third week. The reduction of mold growth showed as 30% surface coverage of samples of treated with 0.5% copper sulfate. However samples treated with 1% showed in most effective resistance by the end of the test period. As shown in figure 7, these results indicating the possibility of using this method to lessen mold-related problems at 1% concentration providing optimal resistance under tropical conditions.

Figure 7: Results of Strength Test (Source: Author, 2023)

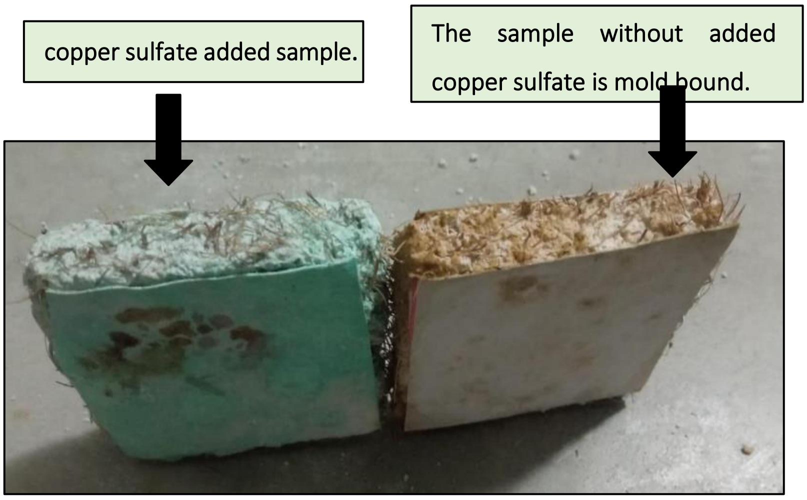

Figure 8 The difference between copper sulfate added sample and other sample (Source: Author,2023)

4. Conclusion

This study investigated the feasibility of producing agro-industrial waste-based insulation boards with promising hydrothermal performance. Using agricultural waste-derived adhesives, lime, and coconut coir between steel panels, we assessed their potential for insulating air-conditioned spaces in tropical climates. From thermal conductivity, adhesive strength, and dynamic load-bearing tests, offering insights into heat transfer control and stress endurance.

The results indicate that the optimal composition for the Coconut Fiber Coir Insulated Steel Sandwich Panel consists of 10% to 50% coconut coir, 5% rubber wastewater and 5% rice wash water. This composition exhibits superior thermal insulation, with thermal conductivity values ranging from 1.079 to 1.093 W/mK. These values are comparable to those of materials such as clay, limestone, and sandstone and significantly lower than those of common metals like aluminum, copper, and silver. Furthermore, these panels possess a high specific heat capacity, enabling effective heat storage and dispersion, thereby enhancing energy efficiency. In addition, the adhesive strength and bucket tests confirmed the material's structural integrity and load-bearing capacity, which are essential for real-world applications. Mold resistance testing highlighted the necessity of copper sulfate for enhanced durability. The results offers viable solution to enhance the durability and resilience of these composites against mold related issues by adding 1% copper sulfate by weight. However, further research is required to optimize the concentration of copper sulfate and assess long-term efficacy.

This study highlights the importance of sustainable insulation materials in reducing environmental impact and energy consumption. Despite promising results, limitations include the need for large-scale production, economic viability assessments, comprehensive environmental impact analysis, and long-term performance evaluations. Future research should focus on field testing, optimizing material composition, enhancing mold resistance, and integrating these materials with building systems to promote sustainable practices in tropical climates.

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