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Article

Influence of Physical–Mechanical Strength and Water Absorption Capacity on Sawdust–Waste Paper–Recycled Plastic Hybrid Composite for Ceiling Tile Application

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Abstract: In recent times, there has been a notable surge in the interest in promoting environmentally conscious products, particularly within the building industry where the focus has shifted towards sustainable materials. In this study, as a sustainable building material, ceiling tiles have been fabricated as a composite board containing waste materials, namely waste paper, sawdust, recycled polyethylene terephthalate (PET), and epoxy resin, and characterized comprehensively through physical and mechanical tests, density, thickness swelling (TS), modulus of elasticity (MOE), modulus of rupture (MOR), and flexural strength (FS) for product stability. A total of nine composites were fabricated with different ratios through molding techniques, and the characterization results were compared to determine the optimized stable ratio of composite composition. The composition of 25% waste paper, 15% sawdust, 10% recycled PET, and 50% epoxy resin presented the maximum FS compared to the other composite ratios. Water absorption (WA) and thickness swelling were evaluated after immersion durations of 1–24 h. The findings revealed that as the density increased, the sawdust content within the matrix decreased from 25–35%. Concurrently, an increase in recycled PET content resulted in decreased water absorption and thickness swelling. Significantly, the MOE, MOR, and FS demonstrated optimal values at 864.256 N/mm^2, 12.786 N/mm^2, and 4.64 MPa, respectively. These observations represent the excellent qualities of this hybrid composite board, particularly in terms of sustainability, stability, and water absorption capacity. Moreover, its lightweight nature and ability to support ceiling loads further enhance its appeal for construction applications. This study not only advances the discourse on sustainable construction materials but also fosters opportunities for broader acceptance and innovation within the industry.

Keywords: hybrid composite; recycled PET valorization; water absorption; ceiling tile production

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1. Introduction

The construction sector is seeking sustainable materials that have a long lifespan. Ceiling tiles are essential for buildings as they contribute to maintaining warmth and reducing noise, while also enhancing the overall appearance of the ceiling. Ceiling boards made from typical materials like gypsum and mineral wool lack durability and have the potential to harm the environment [1]. Recently, there has been a growing interest in utilizing composite materials for construction purposes. With the combination of various types of waste materials, highly effective construction or building materials have been actively researched by composite scientists worldwide for efficient waste management and circular economy [2,3].

Composite materials can be used in many different industries, like making things for planes, cars, and sports equipment. They are durable and lightweight, making them strong and long-lasting with additional positive attributes [4]. Composite boards are usually created by blending various elements such as wood, fibers, plastic, cement, and adhesives. These boards are commonly employed in a variety of engineering projects and as ceiling tiles. They are favored because of the numerous advantages they offer. They are light and affordable, can withstand the environment, and have strong mechanical properties. Furthermore, composite materials can be controlled and changed to have specific properties and structures, which makes them very flexible and easy to adjust [1]. Polymer matrix composite materials are widely chosen for their exceptional properties. This enables industries to manufacture products that are light, robust, and adaptable for a wide range of applications [5]. Recently, there has been increased attention on creating new materials through the use of recycled materials and natural substances [6,7]. This study aimed to investigate the physical and mechanical properties characterization of sawdust, waste paper, and recycled PET composite board for ceiling tile application [8].

PET is a type of material that is clear and does not have a specific shape. PET undergoes a transformation from a rigid, glassy state to a flexible, rubber-like state when heated above 72 °C. A portion of the polymer is composed of crystals because the polymer is semi-crystalline [9]. PET plastics are the most widely used thermoplastics in the packaging and textile sectors. PET is a commonly utilized plastic that does not biodegrade naturally [6,10]. It is a strong and flexible type of plastic that is partly crystalline and has good see-through abilities and safety [11]. Polyethylene terephthalate, also known as PET, is made from terephthalic acid and ethylene glycol. It is a type of long molecule $(C_{10}H_8O_4)_n$ made up of smaller units. It is from a group of plastics called polyesters. The display exhibits a combination of well-defined and partially developed features [9,11]. PE is commonly used by packing industries to make bottles and containers for food and other products that people buy. Later, PET started to be used in injection-molded and extruded items, mainly to make them stronger with glass fiber [12]. These things do not break when they are outside. Recently, people have been very interested in recycling plastic, especially PET, to stop pollution.

Sawdust is a waste product from making things. It can harm the environment unless it is reused to make things like particle board or pulp. Paper is a durable and flexible substance created from moist pulp fibers found in materials such as wood, fabric, or plants. These fibers are pushed together and dried to make thin sheets. Paper serves many purposes, including writing, printing, packaging, and cleaning, and is utilized in different industries and construction. Paper possesses various characteristics, such as weight, thickness, texture, and moisture content [13]. Recycled plastic (PET), sawdust, and paper waste can be used to make boards for ceiling tiles.

Ceiling tiles are significant in buildings as they improve their aesthetics, provide insulation, and hide unsightly pipes and wires [14]. Ceiling boards are necessary in households to reduce noise, maintain a cooler temperature, and enhance aesthetic appeal. In hot climates, it is advisable to have a ceiling that deflects heat and prevents it from lingering [15]. Additionally, a ceiling helps reduce noise in the room and minimize the area that requires air conditioning for cooling [14]. Ceiling tiles that reflect a higher amount of UV light are more effective at eliminating germs. It is important to take into account how the ceiling tiles reflect light when installing UV germicidal systems for effective sanitization. In places where upper-room UV lights are used to kill germs, it is a good idea to use special ceiling tiles that will not be damaged by the UV light. This will contribute to the durability of the tiles [16–18]. Typically, gypsum, wood fiber, and mineral wool are used to make traditional ceiling tiles. These materials cannot be readily replaced and are not good for the environment. There are environmentally friendly solutions available that can help promote sustainable building methods and cut waste [19]. Ceiling tiles made from breadfruit seed coat and recycled plastic are a cheap and eco-friendly option instead of the usual materials. We can use waste materials to make highly stable ceiling tiles that do not absorb water and have high heat-holding capacity. This new way of doing things helps the environment by using less waste and not needing as many new materials [20]. In terms of the thermal conductivity of plant fibers, some earlier studies [21,22] introduced the potential use of plant fibers as thermal insulation materials in construction which can reduce environmental impacts in comparison with currently used synthetic thermal insulation materials.

This study aimed to investigate the physical and mechanical properties of sawdust, waste paper, and recycled PET composite boards for ceiling tile application. The study explores recent advancements in ceiling board manufacturing, discussing plastics as matrices, waste materials as alternatives, and the properties of composites using conventional techniques in construction sectors. There is abundant sawdust, waste paper, and recycled PET in the country, so local government is focusing on utilizing these wastes for value-added products and effective waste management. Therefore, this study took the initiative to perform the study on these materials for a sustainable environment.

2. Materials and Methods

2.1. Collection of Materials

The sample developed a ceiling tile by utilizing waste paper, sawdust, epoxy resin, and PET as raw materials. The materials selected depend on their availability, cost, and environmental impacts. The waste paper was collected from governmental institutions, business centers, and households and milled into particles. Sawdust was collected from wood processing (furniture making) which used medium-density fiberboard (MDF). MDF is a wood product composed of fibers from various hardwood species such as pine, spruce, eucalyptus, oak, and maple. The impurities were filtered from the sawdust through the process of filtration. The samples were processed through 24 h drying at 103 ± 2 °C in the oven until they attained a moisture level of 2%. Both waste paper and sawdust are common in all industries and can easily be sourced locally in Adama City, Ethiopia. In addition, recycled PET is an easily accessible material that is characterized by high mechanical strength and helps reduce plastic waste collected from the environment such as beverage bottles, food containers, and packaging materials. Epoxy resin, RG01, and an amine-based hardener, CA01, Epocure, China, Shanghai, Shanghai Trading Co., Ltd., purchased from the local market in Ethiopia, were used in the composite's preparation for binding purposes. The purity of the epoxy resin and hardener was 99.5%, and they were of analytical grade. The raw materials used in this study are presented in Figure 1. The dried sawdust, paper, and plastic materials were sorted using a standard sieve with mesh (250 µm). A pan was positioned to accumulate the smallest substances at the bottom. The PET powder was then dried in an oven at 103 ± 2 °C for 24 h to reach a moisture content of 3% or less. The density, melt flow index, and melting point of recycled PET were 1370 (kg/m^3), 18.4 g/10 min, and 260 °C, respectively.

(**a**) (**b**) (**c**)

Figure 1. Raw materials for experimented composite manufacturing: (**a**) sawdust, (**b**) waste paper, and (**c**) recycled PET.

Preparation of Composites

The number of materials for each board was measured and mixed well with the binder before spreading it into the mold to make a mat. The mat was shaped in a mold and then placed in a hot oven at 80 °C for 1 h to dry, before being pressed by the pressure of 1.23 N/mm^2 again to assist in the hardening of the resin for 48 h. Later, the mold was opened, and the item was preserved at room temperature (25 °C) for 24 h and then put in the oven for 3 h at 110 °C. After baking in the oven, the panels were put in a place with 74%

humidity and a temperature of 24 °C for 2 weeks. Waste materials were mixed to create composite materials, which were then hardened using a hardener, and ASTM standards were used to characterize the composite's properties. This step was performed to increase the stability of the panels. The overall preparation techniques are presented in Figure 2. The composite boards are presented in Figure 3. From each group of samples, three test pieces that were 50 mm × 15 mm were taken for testing for the physical tests, and three other pieces were taken for the mechanical tests to make sure the results could be repeated.

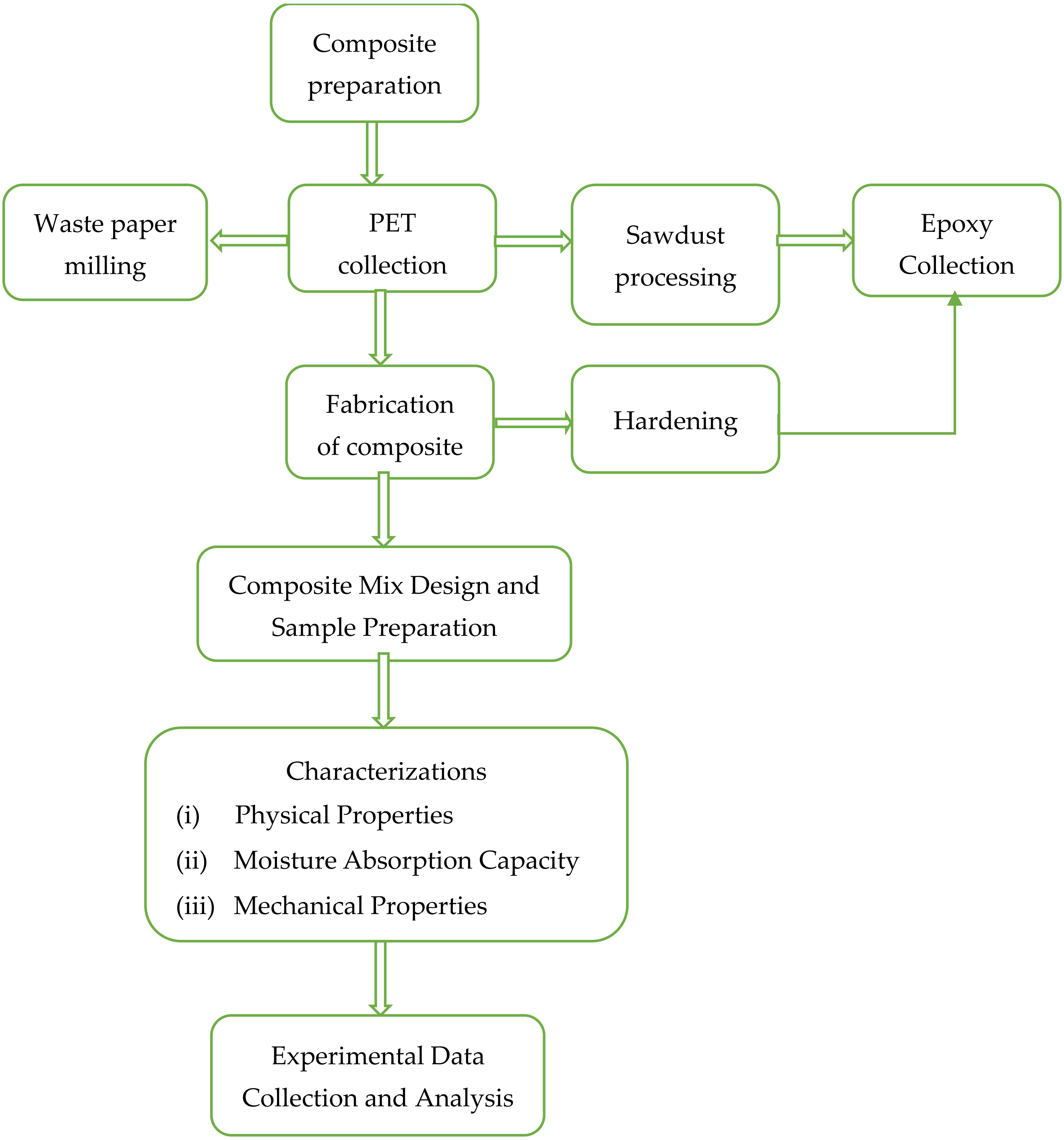

Figure 2. Process flow diagram of the composite manufacturing.

Figure 3. Composite board fabricated for this study.

2.2. Composite Mix Design

The ceiling boards were made in panels 350 mm × 350 mm × 30 mm in size by varying the number of composite materials utilized in the production of the composites presented in Table 1.

Table 1. Experimental design of ceiling boards with different composition ratios.

Sample	% Sawdust	%Waste Paper	%Recycled PET	%Resin
1	40	0	10	50
2	35	5	10	50
3	30	10	10	50
4	25	15	10	50
5	20	20	10	50
6	15	25	10	50
7	10	30	10	50
8	5	35	10	50
9	0	40	10	50

2.3. Physical Tests

Density tests were carried out on the ceiling boards to determine the mean density for each board type. Besides the mechanical properties of the composites, the density of the fiber is a crucial parameter for determining the fiber's potential for being a lightweight material when used as a reinforcement in a composite [18,23] according to the British Code of Standards BS EN323 [24] as illustrated in Equation (1) [25].

$$\sigma = \frac{m}{v}\ \mathrm{kg/m^3} \tag{1}$$

where σ is density, m is the mass of each test piece (kg), and v is the volume of the test piece (m^3).

2.4. Water Absorption Tests

Natural fibers are hydrophilic materials that absorb water used for manufacturing elements or composite fiber [21,22]. For the water absorption test of the composite, the recommendation of RILEM TC 236-BBM (RILEM Association, Paris, France) was followed [21]. Natural fiber was used as a standard sample for comparison with experimented composites. The measurement of water absorption was based on the difference in the of dry and undergoing immersion at different times. The dry weight of the specimens for the water absorption test was recorded as the initial weight, and the specimens were then put horizontally in distilled water at 20 °C temperature. The check specimens were left inside the water for 1 h, and then they were dried with a chunk of material to takeaway extra water from the soaked specimens before they were finally weighed on a weighting balance.

The same steps have been carried out for 24 h. The readings for water absorption after 1 h and 24 h were taken, and the result was determined by Equation (2).

$$WA = \frac{W_{f\_}W_i}{W_i} \times 100\ \% \quad (2)$$

where W_f is the final weight, W_i is the initial weight, and WA is the water absorption.

Thickness Swelling Test

This is a dimensional analysis test that is used to determine the change in the thickness of the sample after it has been immersed in water for a given period. It is used to determine the effect of water on the thickness of the ceiling board. It was carried out based on the code of standards BS EN 317 [26] using Equation (3) [25].

$$TS = \frac{t_2 - t_1}{t_1} \times 100\% \quad (3)$$

where t_1 is the initial thickness, t_2 is the final thickness, and T_s is the thickness swelling.

2.5. Mechanical Test

A static bending test was carried out by using a universal testing machine (Bairoe, Shanghai, China by considering the central concentration loading method. From this test, the modulus of the rupture (*MOR*) and modulus of elasticity (*MOE*) of the specimen were determined. *MOR* and *MOE* are measured in N/mm^2. It was carried out based on the BS EN 310 [27] standards as shown in Equations (4) and (5) [25].

$$MOE = \frac{(F_2 - F_1)l_1^3}{4bt^3(a_2 - a_1)} \quad (4)$$

$$MOR = \frac{3F_{maxl_1}}{2bt^2} \quad (5)$$

where $F_2 - F_1$ is the gradual increase in load on the straight-line portion of the load–deflection curve and is measured in newtons. F_1 is approximately 10% of the maximum load, while F_2 is approximately 40%; F_{max} is the maximum load measured in newtons; b is the breath of the specimen measured in mm; t is the thickness of the specimen measured in mm; l_1 is the distance between the centers of the support and is measured in mm; $a_2 - a_1$ is the deflection of the specimen at the mid-point, corresponding to $F_2 - F_1$ and also being measured in mm.

2.5.1. Flexural Test of the Composites

The FS of the composite was tested according to ASTM standard D790 [28,29], and the specimens were set up for a three-point bending test using a universal test machine (Bairoe, Shanghai, China) at test speeds ranging from 0.5 to 1 mm/mi. The sampling procedure for this test is presented in Figure 4.

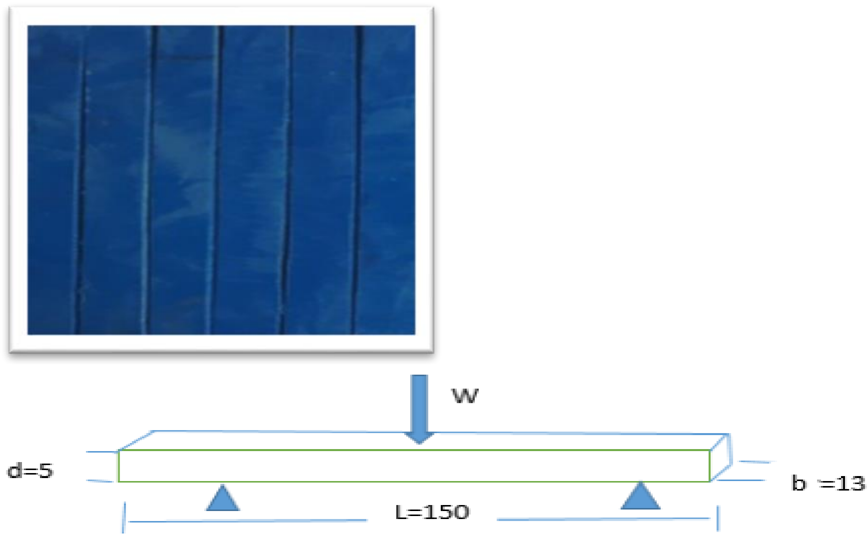

Figure 4. Sampling measurement of the composite board for FS.

The flexural strength of the composite was calculated by Equation (6).

$$F = \frac{3WL}{2bd^2} \tag{6}$$

where W is force, L is the span length of the specimen (mm), d is specimen thickness (mm), b is the width of the specimen (mm), and F is flexural strength (MPa).

2.5.2. Measurement of Thermal Conductivity

Thermal conductivity λ, defined by the steady-state heat flow moving through a unit area of a homogeneous material, 1 m thick, induced by a 1 K difference temperature on its faces, is one of the most interesting characteristics of thermal insulation materials [22]. The temperature analysis of the composite ceiling boards was carried out according to ASTM C-518 standards [30,31]. This involved the use of accurate digital thermocouples kept at 25 °C. An external heat sensor was placed on the board. This enabled us to accurately measure temperature, allowing us to determine the convection coefficient (h) required for calculating thermal conductivity. The method used for the calculation depended on our approach. The process remained unchanged like a straight line over time. The heat conductivity properties of the composite boards were measured by Equation (7).

$$K = \frac{h \times T_2 - T_a \times L}{T_1 - T_2} \text{ W/m.K} \tag{7}$$

where K is the thermal conductivity of the material in W, h is the convective heat transfer coefficient, T_2 is the temperature on one side of the wall, T_a is the ambient temperature, T_1 is the temperature on the inner surface in K, and L is the thickness of the composite ceiling board in m.

3. Results and Discussion

3.1. Physical Properties

3.1.1. Measurement of Weight

Three carefully chosen specimens were measured to determine the weight of each trial. The weight of each trial was determined by carefully selecting and measuring three specimens. Figure 5 shows the weight of the composites with different ratios of composition elements.

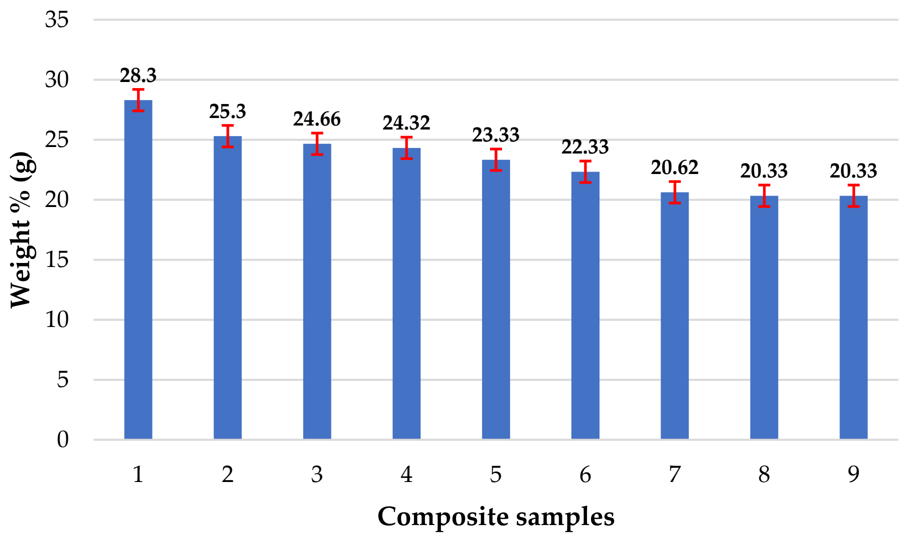

Figure 5. Weight (%) of fabricated composites in this study.

Experimentally, the absolute density of the ceiling board tested in the study is tabulated in Table 2. These results are in line with the observations already made in [9,21]. This value is less in comparison with commonly used fibers like steel, carbon, and glass fiber [21,32]. This is the reason behind the suggestion of sawdust, recycled PET, waste paper, and epoxy resin fiber being used in the production of structural lightweight composites [21].

Table 2. Results for volume, density, and relative density.

S. N	Volume (m^3)	Mass in (kg)	Density (kg/m^3)	Relative Density
1	13×10^{-4}	0.0254	21.42	0.02642
2	13×10^{-4}	0.0243	20.69	0.02432
3	13×10^{-4}	0.0238	19.48	0.01932
4	13×10^{-4}	0.0235	18.82	0.01826
5	13×10^{-4}	0.0225	17.92	0.01726
6	13×10^{-4}	0.0206	15.86	0.01651
7	13×10^{-4}	0.0205	15.74	0.01654
8	13×10^{-4}	0.0204	15.62	0.01632
9	13×10^{-4}	0.0203	15.54	0.01622

Figures 6 and 7 represent the variation in density and thickness swelling of the manufactured composites, respectively, for this study. The density value of a composite material system is an important property that determines its performance in the service environment. As presented in Figure 8, the density of the developed ceiling board decreased with the increase in the weight % of sawdust. The board with the lowest density (15.54 kg/m^3) has a 0:40:10:50 weight ratio, while that with the highest density (21.42 kg/m^3) has a 25:15:10:50 weight ratio of composite materials. According to the ANSI 208 standard [25,33], 0:40:10:50 boards can be classified as low-density particle boards, while 25:15:10:50 boards are classified as medium-density particle boards [25]. As observed from the result of thickness swelling, the boards having lower sawdust percentage were more susceptible to thickness swelling than those having higher sawdust fiber percentage. The lowest thickness swelling was found for 25:15:10:50 composites when compared to the other composition ratios.

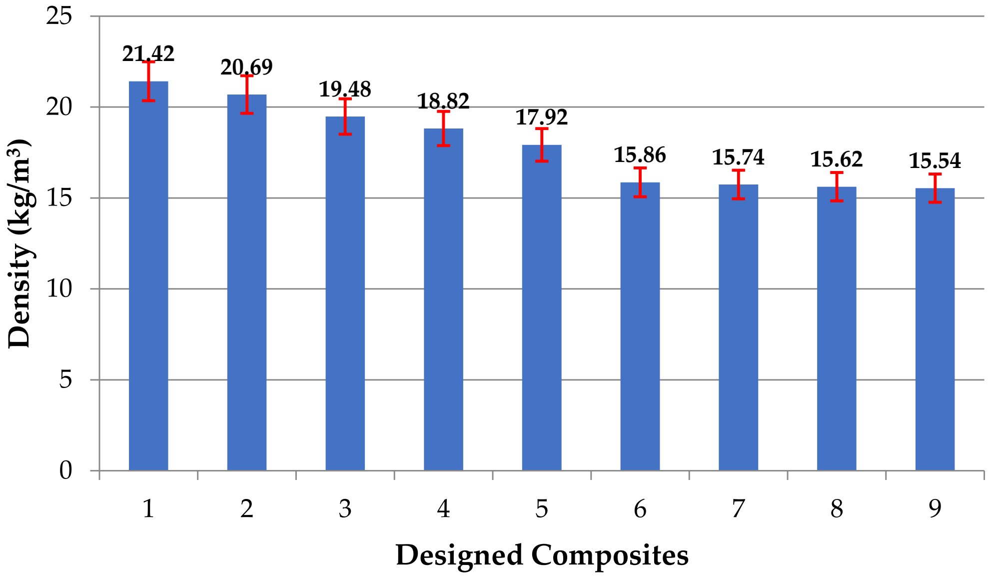

Figure 6. Variation in density against board samples.

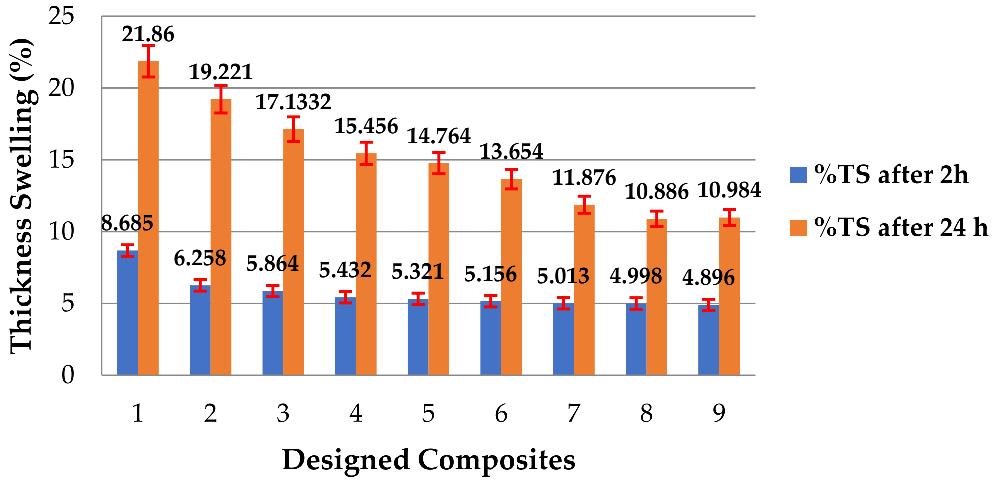

Figure 7. Variation in thickness swelling against board samples.

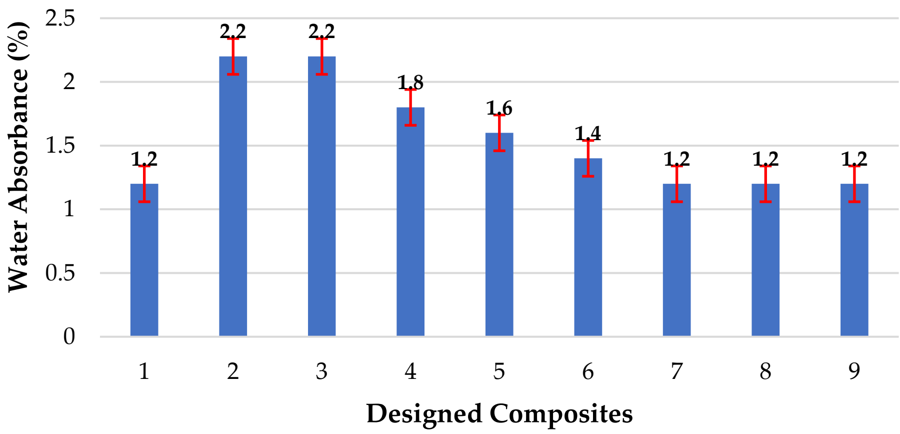

Figure 8. WA of the manufactured composites.

3.1.2. WA

The WA of the ceiling boards at a temperature (20 °C) after 2 h and 24 h of immersion in water shows that the rate of water absorption decreases with the reduction in sawdust and waste paper. The results of water absorption by different samples of this study are presented in Figure 8. The composites led to a decrease in the absorption capacity of the composites. As shown in Figure 8, the fibers absorb water rapidly in the initial step until a saturation level is achieved. However, after 6 h of immersion, the level rises gradually to reach a constant value at the end of the process. From these observations, the water uptake of the fibers is considered as sufficiently stable at 24 h. According to the data, the 25:15:10:50 ratio of the composite absorbs more water than the other composition ratios of the composite, and the 0:40:10:50 ratio of the composite absorbs less water than the other composite ratios, as illustrated in Figure 9. Due to a greater amount of sawdust, the water absorption of the composites increased, and the water absorption decreased when the amount of sawdust decreased in the composite ratio. The fiber–matrix compatibility can help to reduce water absorption in natural fiber composites without any chemical treatment [34]. Furthermore, there was an investigation of the use of a product with the ability to absorb water within the range of 0% to 3% for ceiling tiles [35]. Moreover, a different scholar's research showed that a product can absorb water at rates of 4.3% to 12.5% for ceiling applications [36]. Based on these results, the composite boards designed in this study have water absorption rates between 1% and2%, and 2% is the best choice for this application.

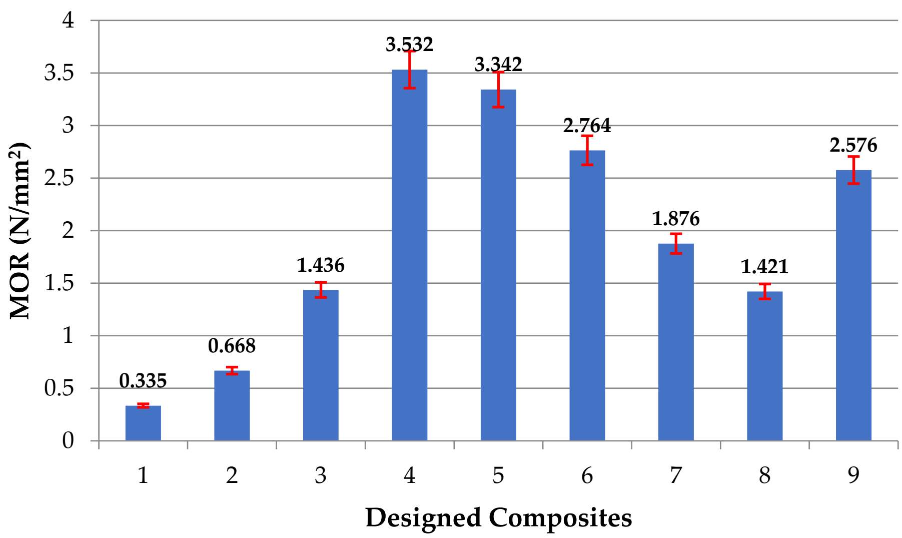

Figure 9. MOR results of experimented ceiling board composites.

3.2. Thermal Conductivity

The test results showing the thermal conductivity of the composites are provided in Table 3. It is clear from the results that there is no significant difference in thermal conductivities for the composites considered. That means the composition ratio does not influence the thermal conductivity of the produced ceiling board according to this composition volume ratio.

In summary, the thermal conductivity of the manufactured composite (ceiling board) falling in the range of 0.00097867 to 0.0016770 is too low and aligns well with human comfort. This means the ceiling board is quite adept at insulation, which is great for keeping human comfort. Conductivities observed for each ceiling board are smaller than 0.1 W/m.K, and according to Asdrubali et al. [21,37], materials with a thermal conductivity lower than 0.1 W/m.K are considered thermal insulators. Thus, the produced ceiling board is an excellent candidate for building insulation materials. Thermal insulation systems and materials help to stop heat from moving. The ability of a material to keep heat in or out is measured by how well it conducts heat and how much heat it lets through. Thermal conductivity is a measure of how efficiently heat is transferred through a material with a temperature gradient.

Table 3. Thermal conductivity of the composites.

Sample Number	Average Temperature (°C)	Thermal Conductivity (W/m.K)
1	32	9.7867×10^{-4}
2	32	9.7867×10^{-4}
3	32	9.7867×10^{-4}
4	31	1.6770×10^{-3}
5	31	1.6770×10^{-3}
6	31	1.6770×10^{-3}
7	31	1.6770×10^{-3}
8	32	9.7867×10^{-4}
9	32	9.7867×10^{-4}

3.3. Mechanical Properties

FS

The maximum load was applied in the middle of a freely supported beam specimen in the three-point bending test, and the flexural strength of the produced composites was analyzed. As shown in Figure 10, a composition ratio of 35% sawdust, 5% waste paper, 10% recycled PET, 50% epoxy resin resulted in a higher flexural strength (5.5 MPa), and a 15%, 25% 10%, and 50% ratio resulted in a low flexural strength (3.5 MPa). According to the FS results in this study, the composites had stronger FS compared to previous research findings. For example, according to an earlier study, tiles made from household trash, boards made from sawdust, and boards made from plant waste can bend without breaking with the strength of 2.09 MPa, 152 MPa, and 1.35 MPa, respectively [38]. It was hypothesized based on all previous studies that a product with a high flexural strength of 1.57 MPa was good for making ceiling tiles [19,39].

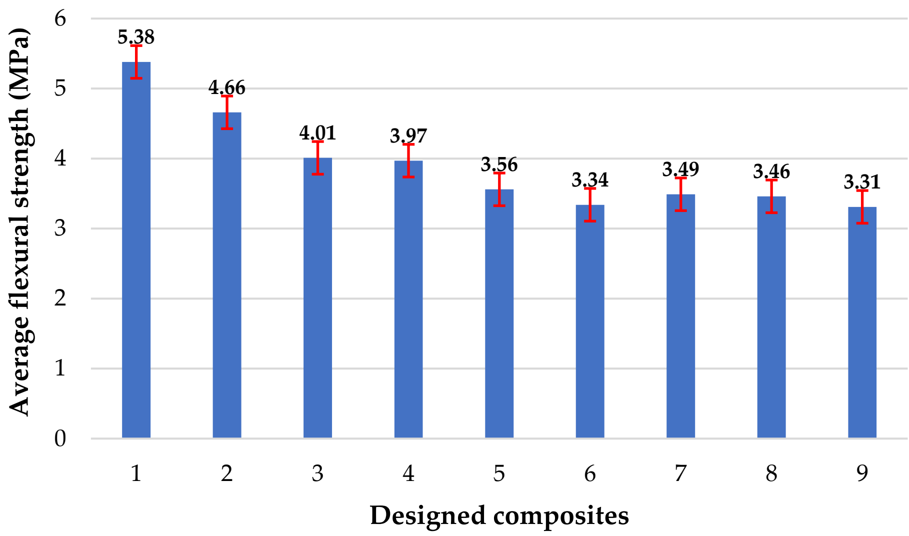

Figure 10. FS of the composites (MPa).

The MOR and MOE results are presented in Figures 9 and 11, respectively. The value ranges from 0.264 N/mm^2 to 3.432 N/mm^2 for the MOR and ranges from 1512 N/mm^2 to 9136 N/mm^2 for the MOE. The values obtained for the MOR for epoxy-resin-bonded ceiling board produced as shown in Figure 9 reveal that as the sawdust content was reduced, the value of the MOR increased, and as waste paper content increased, the value of the MOR also increased. The minimum acceptable value of MOE as specified by the American National Standard Institute standard is 550 N/mm^2; this shows that all the boards produced met the requirement. The produced ceiling board made of sawdust, recycled PET, waste paper, and epoxy resin can play a major role in the building sector.

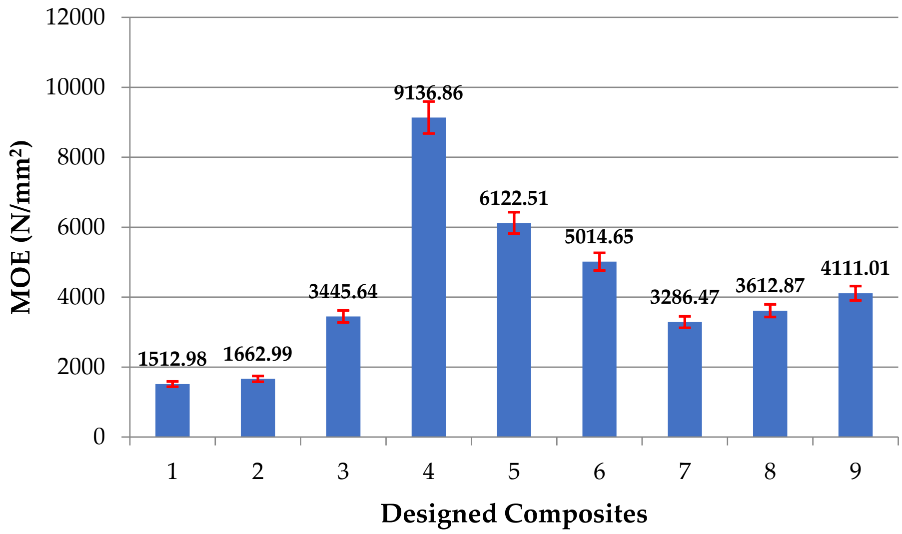

Figure 11. MOE results of experimented ceiling board composites.

4. Conclusions

This study presented that the differences in the robustness and resilience of ceiling boards are a result of the distinct materials employed and the methods of their combination. An increase in PET contents decreases the values of the thickness swelling and water absorption properties. An increase in PE contents also decreases the moisture contents, water absorption, and thickness swelling of the produced composite materials. The modulus of rupture and modulus of elasticity of the ceiling boards manufactured increased significantly as the sawdust content decreased and the plastic fiber content increased. In this study, three bending test specimens were prepared for each of the samples, and the maximum bending strength recorded was 5.52 MPa during the experiment with a 35:5:10:50 ratio of the composite. The ceiling board with sawdust, waste paper, PET, and epoxy resin at a ratio of 25:15:10:50 gives the highest values of MOE and MOR. Generally, the addition of plastic fiber increases the bending strength of the ceiling board composites. Therefore, this study recommends valorizing local waste plastics to produce the experimented composites in the future for effective waste management and circular economy. Also, an environmental (including carbon footprint, waste utilization, land footprint), social, and feasibility analysis is highly recommended to be performed further through a comprehensive techno-economic and life cycle assessment.

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Conflicts of Interest: The authors declare no conflicts of interest. The facts and views in the manuscript are solely ours, and we are responsible for authenticity, validity, and originality. We also declare that this manuscript is our original work, and we have not copied it from anywhere else. There is no plagiarism in our manuscript.

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