

DEVELOPMENT AND CHARACTERIZATION OF FIRE-RESISTANT CEILING BOARDS FROM LOW-DENSITY POLYETHYLENE-REINFORCED BREADFRUIT SEED COATS

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Abstract

The increasing demand for sustainable composite materials has led to the exploration of agricultural waste as an alternative to wood-based particleboards. This study develops and characterizes a fire-resistant composite ceiling board using breadfruit seed coats (BSCs) reinforced with low-density polyethylene (LDPE) and kaolin. The study investigated the effects of mixture ratio, press temperature, pressure, and time on water absorption, thermal conductivity, flexural strength, and fire performance. Results showed that the lowest water absorption (2.941 percent) was achieved at 60 wt percent BSCs, 200°C, 15 MPa, and 10 min, ensuring resistance to moisture-related deterioration. The lowest thermal conductivity ($0.106 \text{ Wm}^{-1}\text{K}^{-1}$) was recorded at 80 wt percent kaolin, 190°C, 11 MPa, and 15 min, indicating superior insulation properties. Flexural strength was highest (0.833 MPa) at 0 wt percent kaolin, while increased kaolin content significantly improved fire resistance, with a maximum Time to Ignition (224 sec) and lowest heat release rate (103 kW/m^2) at 80 wt percent kaolin, 190°C, 11 MPa, and 15 min. The optimal processing conditions were 190°C, 11 MPa, and 15 min. These findings demonstrated the potential of breadfruit seed coat-based composites as fire-resistant, moisture-resistant, and thermally insulating ceiling boards, providing a sustainable alternative to conventional materials.

1. Introduction

Waste refers to an unwanted, useless byproduct that needs to be swiftly discarded, often without considering the environmental consequences of disposal methods. Nigeria generates more than 10 million tons of agricultural waste annually. Among these are wheat straws, fruit bunches, hazelnut shells and husks, peanut shells, kenaf, coffee husks, rice straws, maize husks, rice husks, and breadfruit seed coatings [1-5].

In Southeastern Nigeria, agricultural waste such as breadfruit seed coats is often incinerated, carelessly burned, or abandoned, leading to significant environmental challenges. The improper disposal of these waste materials results in greenhouse gas emissions from burning and pollution of land, water, and air through indiscriminate dumping. Despite the significant attention given to recycling post-consumer waste such as glass bottles, aluminium cans, plastic containers, and newspapers, the recycling potential of agricultural waste, particularly breadfruit seed coats, has remained largely underexplored [6, 7].

One promising approach to utilising agricultural waste is the production of composite materials such as ceiling boards [8-11]. Breadfruit seed hulls (seed coats or seed shells) are a form of agricultural waste produced in abundance worldwide, posing health and environmental risks if not properly managed. The potential for recycling such waste into functional, eco-friendly products offers a viable solution to these challenges while contributing to Nigeria's economic development. Studies have explored the use of various agricultural residues in ceiling board production, including cereal straw, sugarcane bagasse, cornstalks, cotton stalks, sunflower seed husks, rice husk and straw, cassava peels, coir pith, sawdust, and palm kernel shells [12-15]. The increasing demand for ceiling

boards in developing nations like Nigeria has exerted immense pressure on forests, leading to deforestation, environmental degradation, and rising timber prices.

The increasing demand for composite materials from agricultural waste as an alternative to wood-based particleboards has garnered significant attention. This research seeks to develop a fire-resistant composite ceiling board using breadfruit seed coats.

2. Experimental Procedure

2.1. Breadfruit seed coat processing and ceiling board consolidation

Breadfruit seed coat, kaolin, low-density polyethylene (LDPE), acetic Acid (CH₃COOH), and sodium hydroxide (NaOH) are essential materials used for this experimental study. The breadfruit seed coats (BSCs) were thoroughly washed with water to remove dust, residual particles, and fine sand. The BSC was then treated with 1mol/dm³ sodium hydroxide (NaOH) solution to eliminate cellulose, hemicellulose, and lignin properties. After treatment, the seed coat was neutralised with 0.5mol/dm³ acetic acid solution, rinsed with distilled water, and dried until all moisture was removed. The dried seed coat was ground and sieved to 60 µm. Following the previous studies [6, 7], this research introduced kaolin as a fire retardant while maintaining the filler-to-binder ratio. The proportions of kaolin were varied using the Central Composite Design (CCD) tool in the Design Expert software, as shown in the formulation presented in Table 1.

Table 1: Design layout of low-density polyethylene-reinforced breadfruit seed coats formulation

Std	Factor 1 A: Mixture Ratio (wt%)	Factor 2 B: Press Temp. (°C)	Factor 3 C: Press Pressure (MPa)	Factor 4 D: Press Time (min)
1	20	180	7	10
2	60	180	7	10
3	20	200	7	10
4	60	200	7	10
5	20	180	15	10
6	60	180	15	10
7	20	200	15	10
8	60	200	15	10
9	20	180	7	20
10	60	180	7	20
11	20	200	7	20
12	60	200	7	20
13	20	180	15	20
14	60	180	15	20
15	20	200	15	20
16	60	200	15	20
17	0	190	11	15
18	80	190	11	15
19	40	170	11	15
20	40	210	11	15
21	40	190	3	15
22	40	190	19	15
23	40	190	11	5
24	40	190	11	25
25	40	190	11	15
26	40	190	11	15
27	40	190	11	15
28	40	190	11	15
29	40	190	11	15
30	40	190	11	15

The breadfruit seed coat was ground and sieved to a particle size of 60 µm. The low-density polyethylene was also sieved to a particle size of 60 µm to ensure uniformity, while the kaolin was already in a fine powdered form. The weight per cent of fillers and binders was measured as

presented in Table 1. The required weight per cent of filler, binder, and retardant were properly mixed in a bowl using a stirring rod. The homogeneous mixture was poured into the prepared rectangular mould covered with metal sheets and placed into a constant-temperature hydraulic press. The hydraulic press compressed the mixture at the temperature, pressure, and time specified in Table 1. After compression, the resultant composite sample was allowed to cool for a few minutes and subsequently cut into smaller sizes to conduct various tests.

2.2. Water absorption test

The water absorption test followed the ASTM standard method (D1037-99, ASTM, 1999). Initially, the specimens underwent drying in an oven at 80°C for 24 h and weighed with a precision of 0.001g. They were then partially immersed in distilled water for 24 h, removed from the water, and surface dried using tissue paper. The percentage of water absorption was determined using Equation 1.

$$WA = \frac{M_1 - M_0}{M_0} (1)$$

M_0 represents the dry mass of the material before submerging, and M_1 represents the wet mass after submerging in water.

2.3. Fire performance test

The specimen underwent a fire performance test using a cone calorimeter (Fire Testing Technology LTD., UK) following the ISO 5660-1 standard method. The samples were tested horizontally, with a heat flux of 35kW/m² applied using an edge frame. The data obtained from the test included the heat release rate, expressed in kilowatts per square meter (kW/m²), and the time to ignition, indicating the time required for the entire sample surface to sustain a luminous flame. To ensure repeatability, three identical samples were tested under the same conditions.

2.4. Flexural strength test

The flexural strength was determined using a Universal Testing Machine, following the ASTM D1037 (1999) standard. The axial bending strength of the board was determined using a three-point bending method. The study applied a concentrated load at the centre of a beam specimen (200 × 20 × 10 mm) supported at both ends to determine the flexural strength using Equation 2.

$$FS = \frac{3PL}{2BD^2}$$

Where FS is the flexural strength (N/mm²), L is the length between the centre of support (mm), B is the width of the specimen (mm), P is the applied load (N), and D is the thickness of the specimen (mm).

2.5. Thermal conductivity test

The thermal conductivity of the samples was determined using an automated Lee's Disc apparatus (ASTM method 1553). Heat was supplied from the source at a steady state, transferring through the sample to the sink in a temperature-controlled environment. The initial temperature of the heating element was 50°C. The base plate temperature was recorded every five minutes for sixty minutes. After removing the sample, the metal disc was heated to 10°C above the original heating temperature and then allowed to cool steadily for five minutes below the final heating temperature to determine the rate of heat loss. The experiment was repeated thrice under controlled conditions, and the thermal conductivity K was calculated using Equation 3.

$$\frac{de}{dt} = \frac{kA\theta B - \theta A}{d}$$

Where K is the thermal conductivity, A is the cross-sectional area of the sample, given as $A = (\pi D^2)/4$, de/dt is the rate of heat loss, and $(\theta B - \theta A)$ is the temperature difference.

3. Results and discussion

Table 2 shows the combined effects of mixture ratio, press temperature, pressure, and time on the water absorption, thermal conductivity, flexural strength, and fire performance of a low-density polyethylene-reinforced breadfruit seed coat-based ceiling board. The results clearly showed variations in the physical, mechanical, and thermal behaviours of the ceiling boards at various combinations of parameters. The ceiling board containing a 60 wt% mixture ratio and consolidated at press temperature, pressure, and time of 200°C, 15 MPa, and 10 min, respectively, recorded the minimum water absorption (2.941%), making it not susceptible to breakdown due to water infiltration, swelling, warping, or deterioration when exposed to humidity. The ceiling board recorded maximum water absorption (23.809 %) at 0 wt% mixture ratio (without kaoline), 190°C press temperature, 11 MPa press pressure, and 15 min press time. The ceiling board containing an 80% mixture ratio (Kaolin content) and consolidated at 190°C press temperature, 11 MPa press pressure, and 15 min press time demonstrated lower thermal conductivity of 0.106 Wm⁻¹K⁻¹, indicating its ability to reduce heat transfer between the roof and indoor space, keeping rooms cooler in hot weather and warmer in cold weather. The ceiling board containing a low concentration of kaolin demonstrated better flexural properties with a maximum value of 0.833 MPa recorded at 0wt% mixture ratio. Table 2 shows that the increased contents of kaolin led to a significant increase in the fire performance of the ceiling board. Maximum Time to Ignition (224.00 sec) and the lowest heat released rate of 103 Kw/M² was recorded by the ceiling board containing 80 wt% mixture ratio and consolidated at 190°C press temperature, 11 MPa press pressure, and 15 min press time. Overall, press temperature, pressure, and time of 190°C, 11 MPa, and 15 min, respectively, demonstrated the effective combination of factors for enhancing the physical, mechanical, and thermal behaviors of the low-density polyethylene-reinforced breadfruit seed coats-based ceiling boards.

Table 2: Water absorption, thermal conductivity, flexural strength, and fire performance of low-density polyethylene-reinforced breadfruit seed coats

Samples	Water Absorption (W _A), %	Thermal conductivity (Wm ⁻¹ K ⁻¹)	Flexural strength (MPa)	Time to Ignition (Sec)	Heat release rate (Kw/M ²)
1	4.762	0.313	0.613	113.80	135.00
2	11.538	0.204	0.411	200.90	119.50
3	4.762	0.317	0.659	115.60	139.00
4	5.556	0.315	0.410	198.80	120.56
5	8.333	0.210	0.628	109.60	141.20
6	9.091	0.209	0.412	198.50	118.50
7	3.571	0.360	0.661	115.90	140.00
8	2.941	0.205	0.418	200.00	120.70
9	5.001	0.360	0.615	111.30	140.00
10	15.385	0.218	0.415	200.50	117.90
11	4.167	0.360	0.653	113.00	140.60
12	3.448	0.219	0.416	198.60	119.00
13	9.091	0.336	0.662	111.50	143.80
14	19.048	0.205	0.413	200.70	118.65
15	9.524	0.365	0.671	109.60	140.80
16	11.765	0.207	0.397	200.00	118.00
17	23.809	0.317	0.833	105.00	263.80
18	4.001	0.106	0.308	224.00	103.00
19	4.762	0.180	0.511	175.80	128.70
20	5.556	0.194	0.517	177.00	122.99
21	3.846	0.190	0.508	175.30	125.60
22	10.714	0.190	0.510	175.60	125.80
23	8.696	0.188	0.513	176.00	125.50
24	4.348	0.190	0.511	175.30	125.00
25	8.001	0.190	0.509	175.90	127.50
26	3.846	0.193	0.511	175.60	125.60
27	3.845	0.190	0.510	176.00	125.80
28	4.001	0.189	0.508	175.80	125.80
29	3.846	0.190	0.511	175.80	125.90
30	4.001	0.191	0.512	175.90	125.90

4. Conclusion

This study focuses on developing and characterising a fire-resistant composite ceiling board using breadfruit seed coats reinforced with low-density polyethylene and kaolin. It examines the effects of mixture ratio, press temperature, pressure, and time on water absorption, thermal conductivity, flexural strength, and fire performance to optimise the board's physical, mechanical, and thermal properties for better durability and performance. Results indicate that water absorption varied significantly based on these factors, with the lowest water absorption of 2.941% achieved at 60 wt% mixture ratio, 200°C, 15 MPa, and 10 minutes, making the board resistant to swelling, warping, and deterioration. Conversely, the highest water absorption of 23.809% occurred at 0 wt% mixture ratio (without kaolin), 190°C, 11 MPa, and 15 minutes, demonstrating poor moisture resistance. The lowest thermal conductivity of $0.106 \text{ Wm}^{-1}\text{K}^{-1}$ was observed in boards with 80 wt% kaolin, 190°C, 11 MPa, and 15 minutes, indicating excellent heat insulation properties. In terms of mechanical strength, the highest flexural strength of 0.833 MPa was recorded at 0 wt% kaolin, suggesting that reduced kaolin content enhanced strength. Fire performance improved significantly with increased kaolin content, reaching a maximum Time to Ignition of 224 seconds and a minimum heat release rate of 103 kW/m^2 at 80 wt% kaolin, 190°C, 11 MPa, and 15 minutes. The study concludes that optimal processing conditions for a balance of properties were 190°C press temperature, 11 MPa press pressure, and 15 minutes press time. Overall, breadfruit seed coats show great potential as a sustainable alternative for developing fire-resistant, moisture-resistant, and thermally insulating composite ceiling boards.

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