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Fabrication of Thermal Bio-insulator from Oil Palm Trunk Fiber: Analysis of Thermal, Physical and Mechanical Properties

Debi Yana[1], Ropiqotul Husna [1], Intan Kusmawati [1], Delovita Ginting[1], Romi Fadli Syahputra[1]*, and Erman Taer[2]

[1] *Dept. of Phyics, Faculty of Mathematics, Natural Sciences and Health, Universitas Muhammadiyah Riau, Indonesia.*

[2] *Dept. of Phyics, Faculty of Mathematics, Natural and Sciences, Universitas Riau, Indonesia*

Corresponding Authors E-mail: debiyana1410@gmail.com, romifadli@umri.ac.id

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Abstract

The majority of air conditioning systems, including both cooling and heating systems, consume a significant amount of electrical energy as a result of their high electrical consumption and prolonged periods of operation. The use of thermal insulation materials in the building can help conserve electrical energy used for room conditioning systems. Natural fibers are used as an alternative in the production of thermal insulation, which is commonly referred to as bio-insulators. The utilization of oil palm trunk (OPT) fiber as the primary material for thermal insulation shows promise. This study aims to determine the specific attributes of OPT fiberboard that make it suitable for use as a thermal bio-insulator. The features examined encompass physical, mechanical, thermal, and fire-resistant attributes. The OPT fiber underwent a treatment process involving boiling at a temperature of 80℃ for a duration of 30 minutes. The fiberboard is manufactured using epoxy adhesive and calcium carbonate additive, and then printed using the hand lay-up process and cold-compaction technique. The physical characteristics of fiberboard indicate that there is a direct relationship between its density and water absorption. Testing revealed that fiberboard has a low thermal conductivity and high heat capacity value. By including calcium carbonate, the burning time of the fiberboard was tested and seen to decrease, indicating a delay in the fiberboard burning process, as evidenced by the extended flame suppression time. The density of OPT fiberboard varies between 0.48 and 0.70 gr/cm^3. The absorbency of water is inversely related to its density. Water absorption capacity generally rises with decreased density. The obtained heat capacity value is 1.28-2.38 J/(g℃). The mechanical value ranges from 1.00 to 3.55 MPa. The incorporation of calcium carbonate significantly impacts the thermal and mechanical characteristics of the fiberboard. The produced OPT fiberboard satisfies the requirements for good thermal, physical, and mechanical characteristics, making it a suitable bio-insulation material for buildings.

Introduction

The utilization of fossil energy leads to a substantial emission of carbon dioxide (CO_2) into the atmosphere, hence inducing the greenhouse effect. The sectors that contribute to the emission of greenhouse gases are industry, transportation, and buildings [1]. The building sector accounted for 30-40% of the total electrical energy consumption in 2018, mostly driven by the usage of electricity for lighting, heating and cooling, and electronic gadgets [2]. The high electricity consumption in the room conditioning system is attributed to both the substantial power supply and the extended time of usage [3]. The installation of thermal insulation materials is a method employed to decrease the consumption of electrical energy in buildings, particularly in room cooling systems.

Thermal insulation refers to a material's capacity to regulate heat. Thermal insulation materials possess low thermal conductivity values and high heat capacity [4]. Synthetic-based thermal insulation materials, such as wool, polyurethane, polystyrene, and fiberglass, are commonly employed due to their low thermal conductivity, which ranges from 0.02 to 0.05 W/mK [5]. Natural fibers serve as a viable alternative to synthetic fibers in the form of a thermal insulation material known as bio-insulator. Liu et al. [6] did a study where they utilized wheat straw fiber and geopolymers. The heat conductivity is 0.101 watts per meter Kelvin, the compressive strength is 1.2 megapascals, and the density is 302.4 kilograms per cubic meter. Additional natural fibers that are utilized as bio-insulators and have been documented to possess low thermal conductivity include fiber derived from empty palm oil fruit bunches (0.0938 W/mK) [7], bamboo particles (0.101-0.01 W/mK) [8], rice husk (0.082-0.184 W/mK) [9], date palm fiber (0.0475-0.0679 W/mK) [10], and fir bark fiber (0.044-0.063 W/mK) [11]. Palm oil trunk fibers are a kind of natural fibers that exhibit potential as bioinsulators.

Indonesia possesses an immense area of oil palm plantations, suggesting a substantial capacity for natural fiber resources. In 2021, the oil palm plantation area in Riau Province climbed to 2.86 million hectares [12]. A large amount of oil palm trunk (OPT) is generated as the tree ages and the replanting initiative is planned. The vast availability of resources should be harnessed to manufacture diverse processed commodities, such as the laminated veneer wood products created by Sulaiman et al [13] employing OPT. In their work, Selamat et al. [14] conducted a comparison between the utilization of OPT and rice husk as fillers in gypsum composites for the production of construction products. Lee et al. have developed a wood plastic composite (WPC) by investigating the characteristics of polypropylene mixed with chemo-thermomechanical pulp from OPT [15].

While natural fibers have impressive mechanical and thermal insulating properties, they are not effective in preventing combustion. The enhancement of the thermal properties of fiberboard by the incorporation of fire-retardant qualities will play a crucial role in fire prevention [16]. The fire retardant qualities of the fiberboard are achieved through the incorporation of chemicals that hinder or postpone the propagation of fire following ignition [17]. Calcium carbonate ($CaCO_3$) is a commonly used component in fire retardants. In their study, Yusof et al. [18] investigated the effects of adding citric acid and calcium carbonate as additives to particle boards made from poly(vinyl) alcohol palm stems. They found that the addition of 10% calcium carbonate had a significant impact on the board's fire resistance. Specifically, it delayed the ignition time of the fire, reduced the heat of combustion, and inhibited thermal decomposition, thereby increasing the fire resistance of the particle boards.

The objective of this study is to produce OPT fiberboard that is both fire-resistant and acts as a bio-insulator by using a calcium carbonate filler. The fiberboard is defined by its physical, mechanical, and thermal qualities [19][20]. The fabricated fiberboard is anticipated to possess favorable physical, mechanical, and thermal insulation characteristics.

Experimental Method

The investigation employed several instruments, such as a steel mold with dimensions of 10 cm×10 cm×5 cm, extrusion machines, press machines, and hand mixers. The main elements of the fiberboard consist of OPT, epoxy resin, and calcium carbonate ($CaCO_3$).

The primary component of the fiber, known as OPT, is sourced from plantations held by local residents in the Tapung sub-district of the Kampar area in Riau. The palm palms have become unproductive and have reached an age of approximately 10 years. The OPT samples were sectioned into compact blocks to facilitate the extraction of the fiber and rinsed with flowing water to eliminate any sap or debris that may have been present during the cutting procedure. The extruder pulverizes the OPT bits into fibers measuring 2–3 cm in size. The OPT fibers were subsequently subjected to boiling water at a temperature of 80°C for a duration of 30 minutes (see to Figure 1). The boiling process with hot water is conducted on OPT fiber with the purpose of enhancing the mechanical characteristics of the resulting fiberboard [21]–[24]. The boiling OPT fiber is dried by a sun-drying technique.

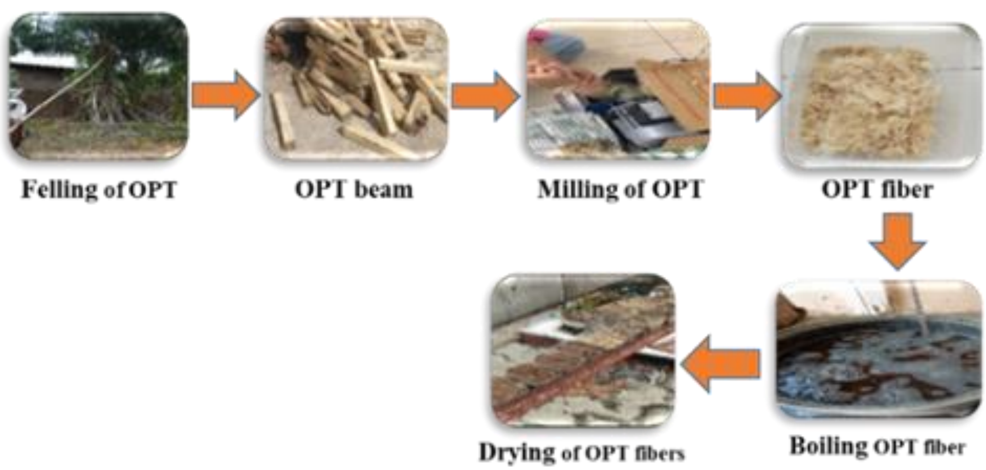

Figure 1. Preparation of OPT fiber

Figure 2. Stages of fiberboard fabrication

Figure 2 illustrates the procedure for producing OPT fiberboard by the manual lay-up technique and cold compaction [25]. Fabricated fiberboards can be classified into two categories: those that include 5 grams of calcium carbonate (OPTC) and those that do not include calcium carbonate (OPT). The adhesive employed is epoxy resin. The printing process commences by combining OPT fiber with epoxy resin to create OPT fiberboard. Utilize a hand mixer to agitate the mixture, then incorporate calcium carbonate until a uniform mixture is achieved. The fiber was inserted haphazardly into the mold and left undisturbed for a duration of 30 minutes. The mold was subjected to a compressive force of approximately 2 tons for a duration of 5 minutes at an ambient temperature of 26 degrees Celsius [26]. Allow the resin to undergo a 24-hour drying process and subsequently store it at an ambient temperature for approximately 7 days to achieve full hardening.

Table 1. Composition and variation of fiberboard

Type	Notation	Fiber (%)	Resin (%)	$CaCO_3$ (gr)
Without $CaCO_3$	OPT-1	76	24	0
	OPT-2	78	22	
	O PT-3	80	20	
	OPT-4	82	18	
With $CaCO_3$	OPTC-1	76	24	5
	OPTC-2	78	22	
	OPTC-3	80	20	
	OPTC-4	82	18	

Physical Properties Test

This examination has three physical assessments, specifically density, spatial density, and water absorption. The test was conducted in compliance with the SNI 01-4449-2006 regulations. The fiberboard density distribution test was conducted by utilizing a two-dimensional plot with the assistance of Matlab software. Calculation of fiberboard density via Equation (1):

$$\rho = \frac{m}{V} \quad (1)$$

where ρ density (g/cm^3), m mass of fiberboard (gr) and, V volume of fiberboard (cm^3).

A water absorption test was carried out by weighing the mass of each sample before immersion in water for ±26 hours. Fiberboard water absorption can be calculated by Equation (2):

$$W_r\ (\%) = \frac{W_f - W_i}{W_i} x\ 100 \quad (2)$$

where W_r (%) the percentage of water absorption in the sample, W_f and W_i respectively initial weight (before immersion) and final weight (after immersion) of fiberboard.

Mechanical Test

Mechanical testing of the fiberboard that has been prepared is tested in the form of flexural strength. The test is carried out using a material testing machine test tool. Flexural strength testing is calculated by Equation (3):

$$\sigma = 3PL/2bd^2 \quad (3)$$

where σ bending strength (MPa), P maximum load (N), L span length (mm), b width (mm), d thickness (mm).

Thermal Properties Test

The specific heat capacity (c_s) test was conducted to identify the ability of the fiberboard to absorb heat which was determined using the calorimeter method. The fiberboard is heated on a hotplate at 70-80 ℃ for 15 minutes. The fiberboard is then put into the calorimeter containing distilled water. Increase the temperature of the distilled water using a thermometer for 2 minutes. Thermal conductivity (k) using a PHT 320 thermal conductivity test tool (Pundak Scientific). Specific heat capacity and thermal conductivity tests are calculated by equations (4) and (5).

$$\Delta Q = c_s m \Delta T \quad (4)$$

where ΔQ heat change (J), c_s specific heat capacity (J/m℃), m sample mass (kg), dan ΔT temperature change (℃).

$$\text{k} = \frac{R_0 L_f h}{A \Delta T} \quad (5)$$

Where k thermal conductivity (W/mK), R_0 ice melting rate (kg/s) , L_f ice melting heat (J/kg), h sample thickness (m), A sample area (m) dan ΔT temperature change (K).

Microstructure Analysis

Two microstructural analyzes were performed by Scanning Electron Microscopy (SEM) and Fourier Transform Infrared (FTIR). The SEM test was carried out as a way of observing the surface morphology of the board fibers. FTIR test is carried out to determine the chemical functional groups of fiberboard. Fiberboard is scanned in the frequency range of 500–400 cm^{-1}. The FTIR test is used for functional group data and chemical bond fibers on the board.

Burning Test

A sample burning test is conducted to assess the fire resistance and burning time of the fiber. This test follows the simplified approach outlined in the ASTM D-6413 Standard Test approach [27] [28]. In order to save time, the burning test will only be conducted on samples of OPT-1, OPTC-1, OPT-4, and The OPTC-4. The dimensions of each sample are 2.5 cm x 2.5 cm × 2 cm. They are positioned vertically alongside the burner.

Result and Discussion

Photograph of Fabricated Fiberboard

Physical Properties

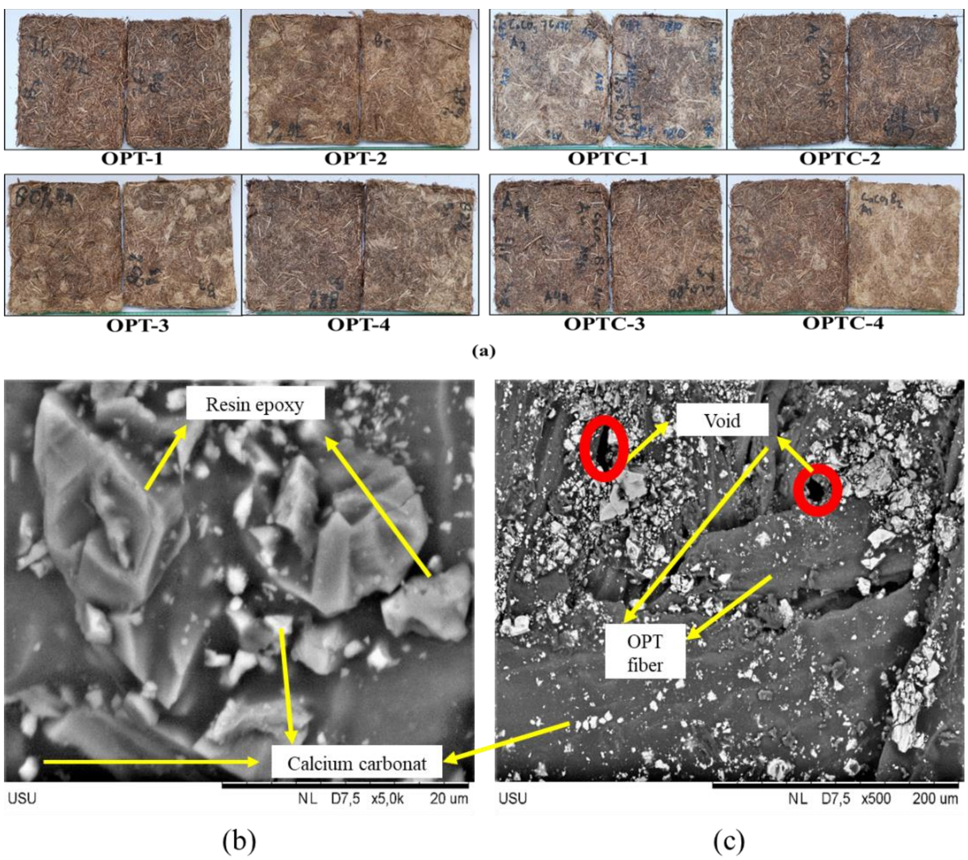

Figure 3. (a) Visual photograph of the fabricated fiberboard: Control sample/OPT (without calcium carbonate) and OPTC (with calcium carbonate), (b) SEM image of OPTC-2 at magnification of 5 times and (c) SEM image of OPTC-2 at magnification of 5 times 500 times

Figure 3 shows that the fiberboard has different colors. The difference in the color of the fiberboard is in the chemical composition. The chemical composition of OPT has a high lignin content in the range of 17.21% to 20.47% [29], extractive content [30], and amylopectin 90.12% [14]. Extractive content yield is the main factor causing the dark skin color of opt.

The density distribution of fiberboard has uneven homogeneity, as seen from the color distribution in Figure 4. Yellow has the highest distribution, while blue has the lowest distribution in determining the density distribution of fiberboard. The non-homogeneous density distribution on the fiberboard is caused by the imperfect mixing of the fiber and resin [31].

Table 2. Density and water absorption of the fiberboards

Sample	Density (g/cm^3)	Water absorption (%)
OPT-4	0.56 (±0.07)	174.17 (±65.82)
OPTC-1	0.67 (±0.09)	96.05 (±36.33)
OPTC-2	0.59 (±0.10)	122.66 (±80.24)
OPTC-3	0.48 (±0.09)	197.11 (±81.24)
OPTC-4	0.70 (±0.10)	132.29 (±65.37)

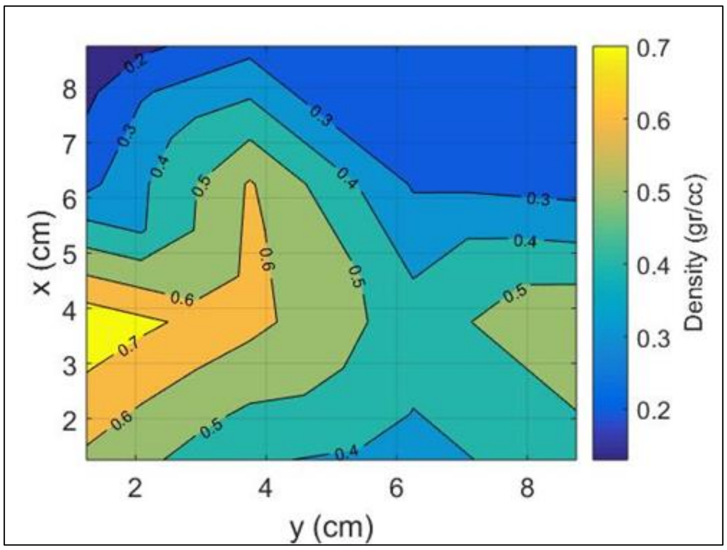

Figure 4. Density distribution of OPT fiberboard sample.

Mechanical Properties

The results of the mechanical testing of the fiberboard can be seen in Figure 5 and Table 3. Figure 3 the relationship between deflection and maximum force in bending strength testing illustrates how the deflection of an object occurs in response to the application of force to the object. Deflection increases as the force applied to the sample increases. The highest bending strength value of 3.55 MPa is found in the OPTC-3 fiberboard, and the lowest is 1.00 MPa, namely the OPTC-4 fiberboard. Fiberboard experienced a significant decrease in mechanical properties due to an increase in the percentage of OPT fiber filler and the addition of calcium carbonate. Hongzhen et al. [32] researched that more than 10% calcium carbonate additives can weaken intermolecular bonds, cause inadequate internal structural stability, and cause a decrease in bending strength values. The bending strength value increases when the quantity of calcium carbonate is below 10%, owing to the fortifying impact of calcium carbonate on the polymer [32]; apart from calcium carbonate, an increase in the percentage of filler results in a decrease in mechanical properties. This is due to the availability of more fiber, and the possibility of forming empty spaces contained in the fiberboard. The empty space contained in the fiberboard causes low mechanical strength [14] [19].

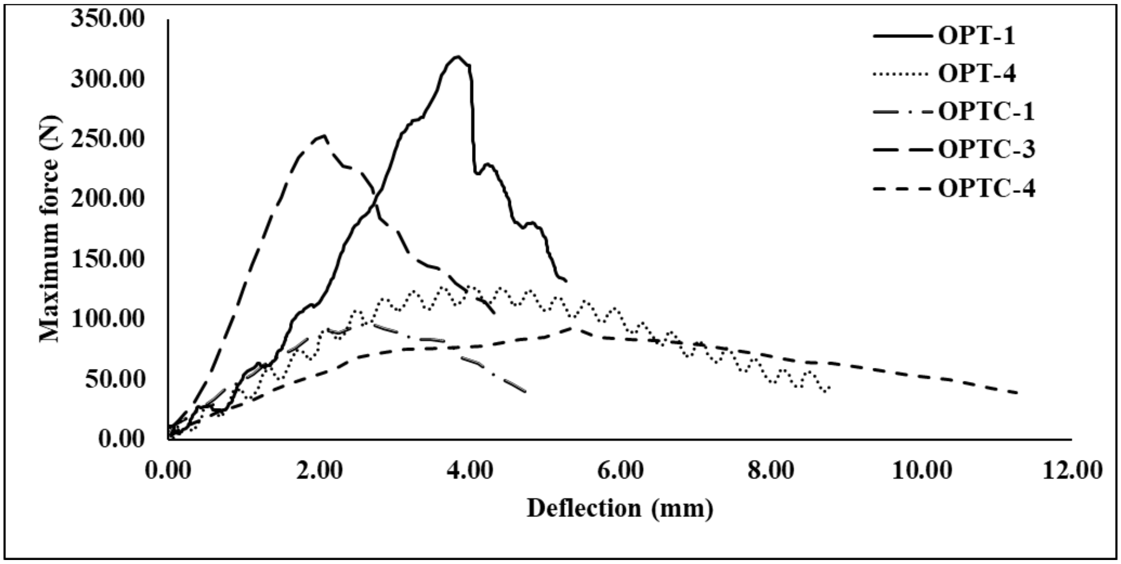

Figure 5. Bending strength profile of OPT fiberboard

Table 3. Data of bending strength

Sample	Maximum force (N)	Bending strength (MPa)
OPT-1	319.8	2.57
OPT-4	127.9	2.40
OPTC-1	94.6	2.28
OPTC-3	250.3	3.55
OPTC-4	91.8	1.00

Thermal Properties

The specific heat capacity and conductivity values of fiberboard can be seen in Table 4. The specific heat capacity and thermal conductivity values of fiberboard vary from 1.28 to 2.38 J/g°C and 0.0008 to 0.0040 W/mK, respectively. The specific heat capacity of the fiberboard with the addition of calcium carbonate was higher with a lower k value than the fiberboard without the addition of calcium carbonate, respectively 1.3 J/g°C and 0.0014 W/mK. The highest specific heat capacity and thermal conductivity values were 2.38 J/g°C and 0.0013 W/mK in OPTC-3. The larger the specific heat capacity value, the lower the thermal conductivity value. Internal conductivity is important for thermal insulation in buildings. The heat will flow faster through a higher thermal conductivity material [7]. The fiberboard studied showed a higher specific heat capacity with a measuring tolerance of 10-20% than other composites such as palm tree fiber, which has 0.891 to 1.621 J/g°C [33], and *Phoenix dactylifera* (date palm) 1.487 J/g°C [34]. *Posidonia oceanica* fiber has a higher heat capacity of 2.533 J/g°C [35] (Table 5).

Table 4. Thermal properties of OPT fiberboard

Sample	Specific heat coefficient (J/g°C)	Thermal conductivity (W/mK)	Burning times (s)
OPT-1	-	-	263
OPT-4	1.3 (±0.5)	0.0014	190
OPTC-1	1.87 (±0.5)	0.0040	263
OPTC-3	2.38 (±0.5)	0.0013	-
OPTC-4	1.28 (±0.5)	0.0008	278

Microstructure Analysis

SEM images of the fiberboard can be seen in Figure 3 (b). The calcium carbonate particles are seen to be evenly distributed throughout the fiberboard. Figure 3 (b) can be seen calcium carbonate attached to OPT fibers and empty space. OPT fibers consist of parenchyma cells, fibrous sheaths, phloem cells, xylem, and parenchyma cells [36]. OPT fibers treated with boiling water can remove starch granules in the parenchyma [21].

FTIR analysis

FTIR analysis was carried out to investigate the functional groups of the fiberboard due to the addition of calcium carbonate and the OPT fiber boiling treatment. Figure 7 shows the fiberboard frequency of about 3338.11 cm^{-1} due to the vibration of the O-H groups. . The presence of OH functional groups is due to the presence of hydroxyl groups in cellulose, hemicellulose, and lignin [18]. The frequency 2923.74 cm^{-1} occurs due to C-H vibrations. The frequency 1738.76 cm^{-1} comes from the C=O functional group of the conjugated carbonyl compound [37]. The frequency 870.94 cm^{-1} menunjukkan perlakuan perebusan serat OPT karena indicates the boiling treatment of OPT fiber due to an indication of the α-glycosidic relationship in the polysaccharide fraction which proves that the high starch content in the polysaccharide fraction is soluble in hot water[21].

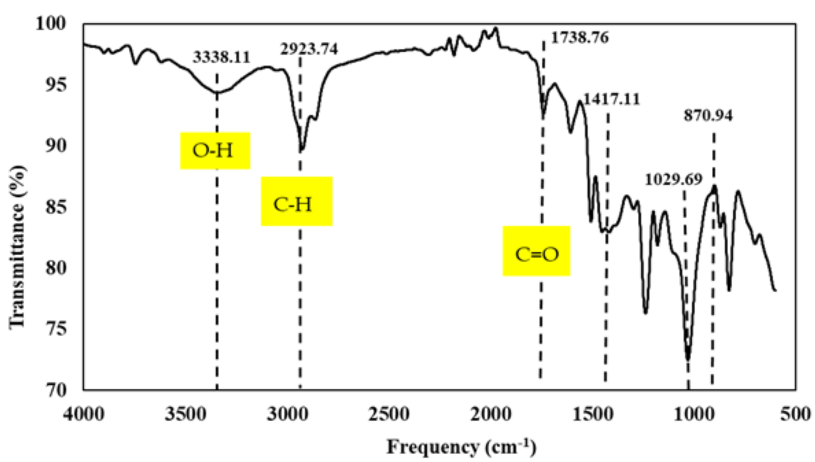

Figure 7. Spectrum profile of FTIR OPTC-2.

Burning Time Results

The condition of the fiberboard after the combustion test and the burning time can be seen in Figure 8 and Table 4. The average flame on the fiberboard is 2-6 seconds. In general, there is a marked difference between OPT and OPTC fiberboard in terms of burning time. OPT samples tend to burn longer than OPT fiberboard. The addition of calcium carbonate can inhibit the combustion process due to the presence of burning carbon dioxide [32].

The fire-resistant fiberboard can be seen in Figure 8. Fire resistance tests were conducted on fiberboards to assess their fire-retardant or fire-damping properties after the addition of calcium carbonate. The flame on the fiberboard averages 2-6 seconds. The time of fiberboard combustion can be determined from Table 4. Fiberboards OPT-1 and OPTC-1 show simultaneous fire damping, but the residual burn size of OPTC-1 fiberboard is larger than that of OPT-1 fiberboard. Fiberboard OPT-4 initially dampens the fire because the fiberboard has already burned out. Fiberboard OPTC-4 is still aflame because calcium carbonate slows down the burning process of OPT fiberboard. Calcium carbonate can enhance fire retardancy due to the release of carbon dioxide in the process.

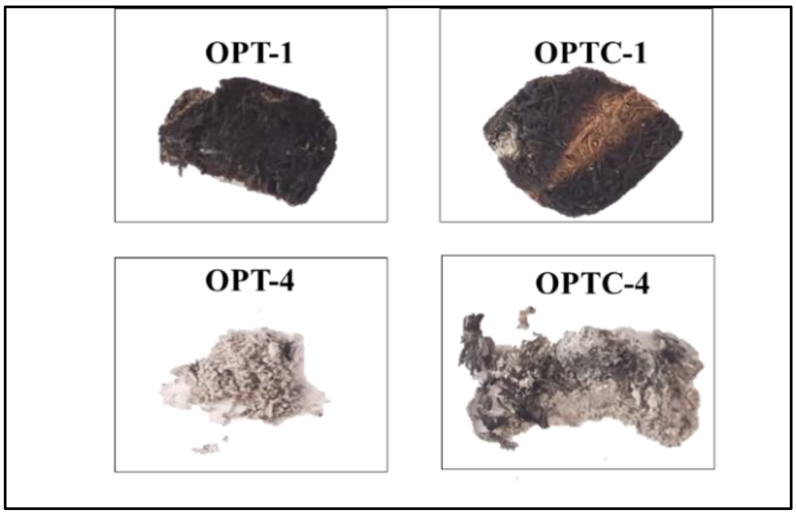

Figure 8. Fiberboard condition after burning test.

Discussion

Correlation of density and water absorption

The correlation of the physical properties of the OPT fiberboard can be seen in Table 2 and Figure 9. Table 2 shows that the water absorption of the fiberboard with the lowest addition of calcium carbonate is 96.05%. The highest water absorption was found in fiber boards without adding calcium carbonate, namely 174.17%. OPT fiber also has hydrophilic properties so it tends to absorb water. In addition, water absorption increases with lower density. This is due to the fact that fiberboard has many cavities that have the potential to absorb water [38]. The high porosity between OPT fibers without the addition of calcium carbonate allows water to seep in resulting in high water absorption [22]. Previous studies reported that fiberboard without chemical additives or modifications could easily absorb water [23]. The addition of calcium carbonate to the fiberboard has increased its barrier and water resistance. Reducing the value of water absorption is associated with the nature of additives that inhibit water absorption on fiberboard [24]. The correlation between fiberboard density and water absorption has a linear relationship, namely R^2 of 0.6385.

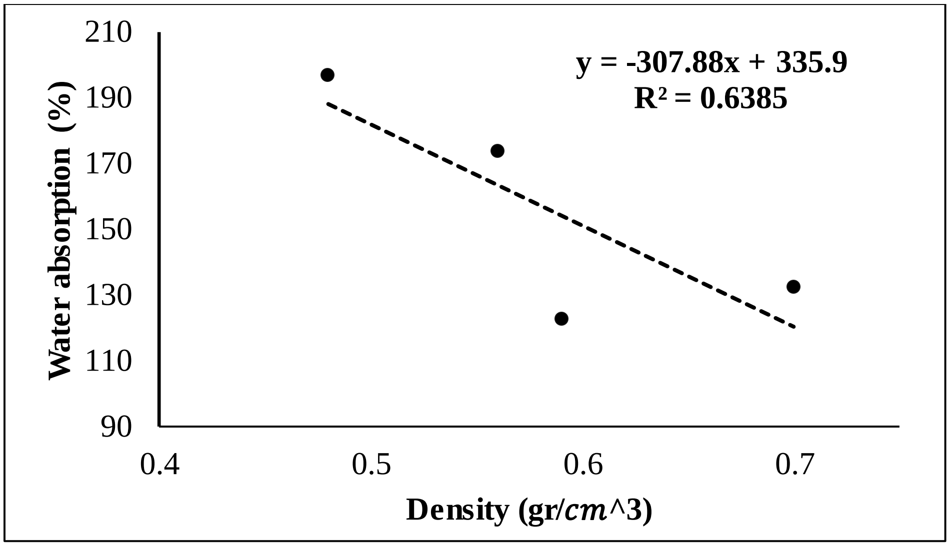

Figure 9. Correlation of density and water absorption of the fiberboard

Correlation of thermal and mechanical properties

Mechanical parameters are very important for measuring the thermal performance of fiberboard. The flexural strength of fiberboard ranged from 1.00 MPa to 3.55 MPa, which showed the lowest and highest values, respectively (see Table 4). Figure 10 shows the correlation between the specific heat coefficient and bending strength. Specific heat coefficient has strong correlation with bending strength with a coefficient of R^2 of 0.6774. In general, the heat capacity decreases with decreasing flexural strength. This is also related to the addition of calcium carbonate. The addition of calcium carbonate causes a weakening of intermolecular bonds [14], resulting in a decrease in the value of bending strength as well as the coefficient of specific heat [22], [39].

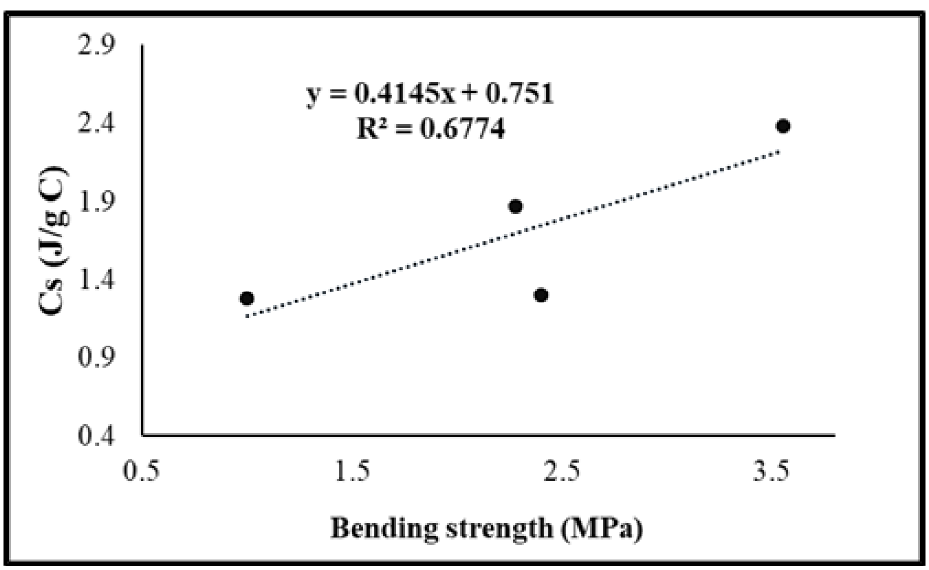

Figure 10. Correlation of specific heat coefficient and mechanical properties

Table 5. Comparison of fiberboard properties with previous study

Fiberboard composition	Density g/cm^3	Bending strength (MPa)	Thermal conductivity (W/mK)	C_s (J/g°C)	Ref
Fiber of *Posidonia oceanica*	-	-	0.043-0.070	2.533	[35]
OPT (5-25%)	-	2.61 ($\pm$0.02)-3.52 ($\pm$0.05)	-	-	[14]
OPT fiber + 10% PVOH + 10% CA + 20% $CaCO_3$	-	0.7	-	-	[18]
Date 50%	-	-	0.0757	1.487	[34]
Phoenix dactylifera fiber 10%	-	-	0.0737	1.292	[34]
Wood board particle	-	2.15 ($\pm$0.11)	-	-	[40]
OPT board	0.303 – 0.476	-	-	-	[41]
Pinus radiate fiber	0.15 – 0.20	-	-	-	[42]
Common woods	0.1-1.2	-	-	-	[43]
Straw fiber	-	-	-	1.010	[44]
Olea europaea fiber	-	-	-	1.111	[44]
OPT-1	-	2.57	0.0023	0.63 ($\pm$0.5)	This work
OPT-4	0.56 ($\pm$0.07)	2.40	0.0014	1.3 ($\pm$0.5)	This work
OPTC-1	0.67 ($\pm$0.09)	2.28	0.0040	1.87 ($\pm$0.5)	This work
OPTC-4	0.70 ($\pm$0.1)	1.00	0.0008	1.28 ($\pm$0.5)	This work

Conclusion

This research examines the physical, mechanical, and thermal properties as well as fire retardance of OPT fiberboard as a bio-insulator. The density value of OPT fiberboard ranges from 0.48−0.70 gr/cm^3. Water absorbency is inversely proportional to density. The ability to absorb water tends to increase when the density is low. The heat capacity value obtained is 1.28−2.38 J/g°C. Mechanical value of 1.00−3.55 MPa. The addition of calcium carbonate greatly affects the thermal and mechanical properties of the fiberboard. The best fiberboard is the OPTC-3 fiberboard. Calcium carbonate can affect the resistance of OPT fiberboard to fire by looking at the duration of the burning of the fiberboard. The results of the burning time test revealed that OPT fiber-based fiberboard could be used as a fire-resistant thermal bio-insulation material. The fabricated fiberboard meets the criteria for good thermal, physical, and mechanical properties as a thermal bio-insulation material in buildings.

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