Terbit *online* pada laman web jurnal : http://metal.ft.unand.ac.id

METAL: Jurnal Sistem Mekanik dan Termal

| ISSN (Print) 2598-1137 | ISSN (Online) 2597-4483 |

Research article

Sessile Drop Method Prediction of Particleboard Mechanical Properties

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Article Information

Article History:
Received: 18 February 2024
Revised: 12 March 2024
Accepted: 27 April 2024

Keywords

Sessile drop method
mechanical properties
rice straw
particleboard

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A B S T R A C T

Agriculture waste-based materials have considerable potential as wood-based particleboard alternatives. It has been produced abundantly from nature and considers an eco-friendly material. One of the enormous resources is the paddy by-product, rice straw (about 500 million tonnes per year worldwide). In this work, the mechanical properties of rice straw-based particleboard are predicted easily and quickly using the sessile drop method. Rice straw was crushed into 2-5 mm diameter powder-like materials, and corn starch was used as the binder. The rice straw particleboard was formed under a hot press machine (5 MPa, 180°C and 120 minutes). Conventionally, the sample mechanical property was tested through Universal Testing Machine (UTM). Unfortunately, the process is costly and difficult to access. It is necessary to have a rapid and low-cost presumption of the mechanical particleboard properties toward more efficient manufacturing. This work proposes a simple sessile drop method to indicate particleboard mechanical properties. Multiple linear regression was performed to see the correlation between sessile drop and UTM testing. It was found statistically that the sessile drop method could be used as an early prediction of particleboard mechanical properties.

1. INTRODUCTION

Woods-based product is ubiquitous in our daily life with various functions and applications. As the world population rises, the demand for wooden materials will continue to grow. Particleboard is one of the most used wood product derivatives. Only in 2020, particleboards demand more than twenty-million-meter cubes, with Europe as the highest consumer in the world. As a result, the competitiveness to find a substitute for wooden materials became an important topic. Agricultural waste-based particleboards would be promising solutions to the problem (Fiorelli et al., 2018; Lee et al., 2022; Neitzel, Hosseinpourpia, Walther, & Adamopoulos, 2022) [1][2].

Proper treatment and manufacturing methods of agriculture waste-based particleboard could substitute for its wood-based counterparts and fulfill the standard requirement (Syamani et al., 2022) [3]. One of the prominent candidates is rice straw-based particleboard (Ranjan, 2021) [4]. This material has excellent properties to form a composite (Ismail et al., 2019) [5]. From an economic point of view, agricultural waste-based particleboard is more attractive because it charges low material costs. The materials are available freely after harvesting the

https://doi.org/ 10.25077/metal.8.1.6-13.2024

crop, although the packaging and collecting costs still need to be considered. On top of that, emerging international demand for more sustainable agriculture waste management should be considered. Unmanaged rice straw conventionally ends up in open field burning (Bhattacharyya et al., 2021) [6], a significant environmental issue (Romasanta et al., 2017)[7].

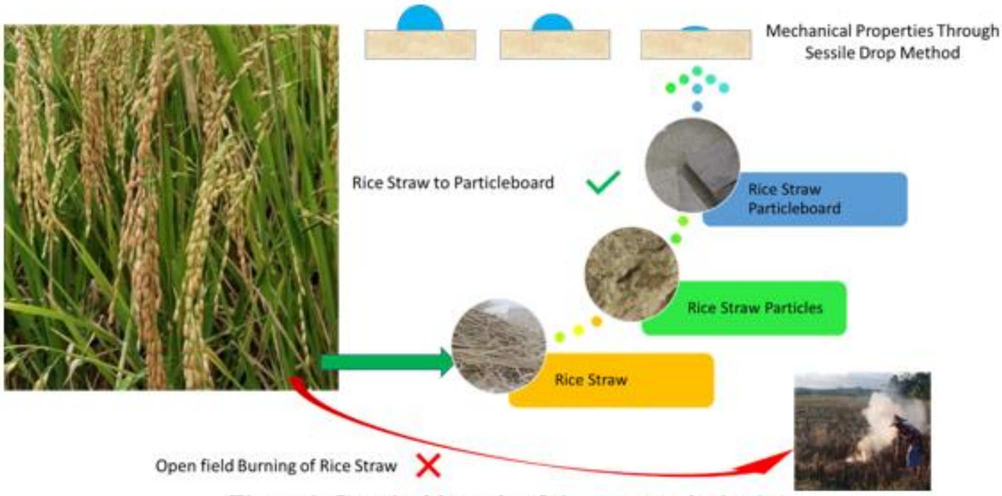

Figure 1. Sustainable path of rice straw valorisation

As a by-product of paddy plantation, rice straw is one of the most significant biomass resources in the world. In 2019 world rice consumption achieved more than 750 million tonnes and fed more than 50% world's population, which makes it one of the world's most important staple food trades (*FAO Publications Catalogue 2022*, 2022; "This Is How Much Rice Is Produced around the World - and the Countries That Grow the Most," 2022) [8]. For each kilogram of milled rice harvested, about an equal amount of rice straw waste is generated (Saini, Kuhad, & Sharma, 2023) [9]. Therefore, behind the vast world rice production, there is inherent rice straw waste in great numbers as well. Appropriate rice straw waste management is necessary for greener rice field management (Gupta et al., 2022) [10].

Poor rice straw waste management leads to an unsustainable path for paddy plantations. In most cases, rice straws are thrown away as a residue with open field burning. It is the easiest way to deal with rice straw waste from a farmer's point of view. Unfortunately, open field burning of rice straw contaminates our environment (land, water, and air). Proper rice straw waste management has a significant advantage both environmentally and economically. This path will lead to more sustainable rice production in the future (see Figure 1). Another emerging environmental issue is the adhesive of particleboard. Eco-friendly adhesives should be a priority consideration. The common adhesive urea-formaldehyde is harmful to human health and contaminates the environment. The solution uses natural resources that has adhesive characteristic and are biodegradable at the same time, such as corn starch. Combining rice straw waste and corn starch binder fulfills a sustainable development pathway. Rice straw has excellent physical and chemical properties. It is a lignocellulose material with low density, biodegradability, high toughness, and excellent mechanical properties (Van Hung et al., 2020) [11]. Those properties are indeed what is necessary for particleboard formation. However, compared to wood-based particleboards, it needs further treatment to satisfy commercial product specifications.

Particleboard properties improvement could be made by additive addition (Baskaran et al., 2019) [12] or better treatment and making processes (Luo, Yang, Zhao, Lu, & Wang, 2018) [13]. Any attempt to improve the properties of particleboard need reliable measurement and vast indicator of the particleboard quality. One of the critical properties is particleboard density. Monitoring and controlling particleboard density are essential steps to ensure the quality of the final product. High-density profile confirmed the yield of better internal bonding (IB) and tensile strength (TS) ("High-Density Particleboard Made from Agro-Industrial Waste and Different Adhesives," 2019) [14]. Particleboard density determines mechanical properties and water resistance (Cravo et al., 2017; Luo, Yang, Li, & Wang, 2019) [15][16]–however, all the measurement is taken by UTM testing, which is costly and difficult to access directly.

Therefore, it is necessary to have an early detection method to determine mechanical properties before going to take UTM testing. This work performs the least square method to calculate the relation between density and particleboard mechanical properties of particleboards. An alternative sessile drop method is presented here as a comparable approach to indicate particleboard mechanical properties.

2. MATERIAL AND METHOD

2.1. Materials

The rice straw was collected directly from local farmers from rural rice field areas in Banten Province, Indonesia. Commercial pure corn starch was purchased from Tereos FKS Indonesia Ltd, and sodium thiosulfate from Merck KGaA 64271 Darmstadt, Germany.

Corn starch powder and distilled water were weighed 40% and 75% of the total board mass and then dispersed through constant mixing for 10 minutes. An additive substance of sodium thiosulfate was added for 1.2 % on a dry basis of corn starch to prevent deterioration.

2.2. Methods

The freshly collected rice straw was soaked in water to remove impurities, mainly dust then the rice straw was pretreated mechanically and chemically. Rice straw was chopped into smaller pieces (2.5 - 4 cm). Subsequently, 4% NaOH solution was used to soak the chopped rice straw for one hour. The NaOH-soaked rice straw was milled through a ring flaker machine into fine fibers and filtered according to size using a siever that passed the size of 20 mesh. The combination of mechanical and chemical pre-treatment through chopping and NaOH soaking has proven to reduce ash content and maintain the alpha-cellulose content of rice straw.
The rice straw and corn starch adhesive were mixed in a rotating drum mixer through spraying. The mixture was then dried in an oven at 105°C for 15 minutes to reach 12% moisture content. High moisture content could lead to blister failure during the hot-pressing process. The drying process is intended to lower the moisture content to prevent that from happening. The drying process is done by universal oven UF450 memmert GmbH+Co.KG, Schwabach, Germany. The moisture content of rice straw is controlled by the moisture analyzer Shimadzu MOC63u, Japan.

The process continues to form the rice straw mixture in a square mold (25x25 cm) with a thickness of one centimeter. Initial pressure, without heat, is given to make the rice straw mixture fill the mold appropriately and reduce the possibility of voids. This sample was put on the hot press machine to be manufactured with constant variables of pressure (5 MPa), temperature (180°C), and time (25 minutes). Two replicates of each rice straw-based particleboard were produced for sample characterization. The samples were stored in a chamber at room temperature for seven days before the characterization process. Particleboard characterization was prepared following the Japanese Industrial Standard (JIS) A 5908 for testing purposes.

2.3. Analysis

Particleboard density (g/cm³) is the ratio of the rice straw particle board mass to the volume after hot press treatment. According to JIS A 5908, the thickness, length, width, and mass shall be measured to the nearest 0.05 mm, 0.1 mm, and 0.1 grams, respectively. The density should be calculated to 0.01 (g/cm³).

For the moisture content test, the procedure is akin to water absorption, and here fluid is air instead of water. The particleboard was put in an air drier with

 https://doi.org/ 10.25077/metal.8.1.6-13.2024

a controlled temperature (103 ± 2 °C), and then the mass decreased due to the moisture evaporation on the surface of the particleboard. The mass of moisture is the mass difference before and after drying.

The mechanical properties were measured by a universal testing machine (UTM) Shimadzu AGS-3 X series 10 kN, Japan. The test for every varied density specimen was conducted three times.

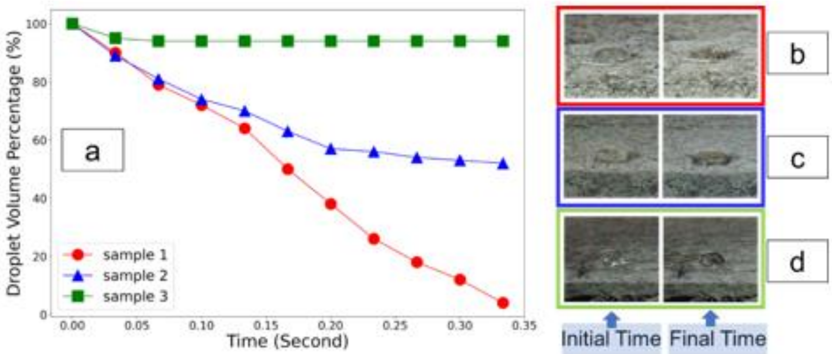

Figure 2. a) Volume decreasing percentage of a droplet on the particleboards, b) sample density 0.67 g/cm³, c) sample density 0.72 g/cm³, d) sample density 0.80 g/cm³

3. RESULTS AND DISCUSSION

3.1. Result

3.1.1 Mechanical Properties

Table 1 shows the rice straw particleboard mechanical properties for three different densities with a 95 percent confidence level. Board density plays a significant role in determining the mechanical properties of particleboard. As the highest density, sample three yields higher MOR, MOE, and IB values than samples one and two. The increasing value of MOR and MOE is only three to four times higher. On the other hand, the IB value escalates much faster, leaving a big gap between sample three and the others.

Table 1. Rice straw particleboard mechanical properties

	Density g/cm3	MOR N/mm2	MOE N/mm2	IB N/mm2	MC %
1	0.67 ± 0.1	5.79 ± 0.45	349 ± 47.4	0.06 ± 0.005	12.90
2	0.72 ± 0.1	12.02 ± 1.64	596 ± 23.8	0.13 ± 0.040	11.71
3	0.80 ± 0.1	15.36 ± 0.68	1235 ± 88.8	0.73 ± 0.136	11.27

3.1.2 Sessile Drop

The sessile drop method was performed using Canon Ixus145 Camera. This camera recorded the images of droplets on the rice straw particleboard. Those photographs then analyze using the open-source software ImageJ. The water on the top of the rice straw particleboard decreased over time and was measured by calculating the volume for each consecutive time (Figure 2, part a). Figure 2, parts b, c, and d are the images of different conditions between initial and final times for samples 1, 2, and 3, respectively. The density differences among the samples exhibit a droplet's peculiar behavior on the particleboard's surface. The lowest density (0.67 ± 0.1 g/cm³) adsorbs the water ultimately in less than half a second. Higher density (0.72 ± 0.1 g/cm³) also adsorb the water at a lower rate. It can retain more than 50% of its initial volume of the water droplet. Finally, a high-density particleboard sample (0.80 ± 0.1 g/cm³) holds the water droplet at about 90% of its initial volume on the surface.

3.1.3 Multiple Linear Regression

The general equation for multiple regression describes by the equation below:

$$y_i = \beta_0 + x_{i1}\beta_1 + x_{i2}\beta_2 \qquad (1)$$

Where y_i indicates the parameter value to be investigated for the correlation with other parameters, y_d represents the density variable, and y_v represents droplet volume. On the other hand, x_{i1} and x_{i2} indicate the variable of particleboard mechanical properties, which MOR and IB represent. Each variable's accumulation was represented by the $\sum Y$, $\sum X_1$, and $\sum X_2$, respectively. The least square method could determine parameters (β's). They are coefficients that examine the correlation between each variable involved.

$$\sum Y = N\,\beta_0 + \beta_1 \sum X_1 + \beta_2 \sum X_2 \qquad (2)$$

$$\sum Y\,X_1 = \beta_0 \sum X_1 + \beta_1 \sum X_1^2 + \beta_2 \sum X_1\,X_2 \; (3)$$

$$\sum Y\,X_2 = \beta_0 \sum X_2 + \beta_1 \sum X_1\,X_2 + \beta_2 \sum X_2^2 \; (4)$$

They are simultaneously solving the equation yield correlation between the parameter of interest with the mechanical properties' counterpart. The table below displays equations of two parameters: particle board density and decreasing droplet volume (sessile drop method).

Table 2. Multiple linear regression of density and sessile drop method correlation with particleboard mechanical properties.

Parameters	Equation	Correlation (r)
Particle board density	$y_d = 5.83 - 0.84\,x_1 + 13.67\,x_2$	$r_{y-x_1} = 0.953$ $r_{y-x_2} = 0.956$ $r_{x_1-x_2} = 0.824$
Decreasing droplet volume	$y_v = 1.79 + 21.76\,x_1 - 551.35\,x_2$	$r_{y-x_1} = -0.979$ $r_{y-x_2} = -0.921$ $r_{x_1-x_2} = 0.824$

3.2. *Discussion*

3.2.1 Mechanical Properties

Particleboard mechanical properties represent how strongly the particles and adhesive attracted each other (Mahieu, Vivet, Poilane, & Leblanc, 2021)[17] - binding between them. It determines by several factors. First, the chemical composition and its natural binding ability, especially the adhesive part, make the particles stick together. Second, continuing with mechanical treatment (pressing and heating simultaneously), the particleboard mechanical properties depend on the setting value of pressure and temperature at the hot press machine. Finally, the number of particles on the particleboard changes its density properties. The binding and mechanical treatment aspects are the control variable in this study. They are kept constant for every sample formed because different binding and mechanical treatments will affect the particleboard density (Boruszewski, Borysiuk, Jankowska, & Pazik, 2022) [18]. So, the density difference is solely due to adding the rice straw particles.

3.2.2 Sessile Drop

The sessile drop method is already used in developing bio based materials. Zhang and Hu observed that contact angle measurement effectively detects the different quantities of wax and silica content in rice straws (Zhang & Hu, 2014) [19]. Another work found that the particle size of composite materials dictates how liquid absorption behaves (Pinem et al., 2020) [20]. The sessile drop method depends on the physical and chemical properties of the solid and liquid use (Pinem, Wardhono, Clausse, Saleh, & Guénin, 2022) [21].

The interaction between them is repeatable and consistent. Here, the method used corresponds to particleboard mechanical properties. As particleboard densities increase, the water droplet penetration on the surface decreases slower, although they have a similar value of MC (table 1). The indifference state of particleboard MC is important to ensure that this factor does not affect the water absorption rate in the sessile drop method. The amount of rice straw particles represents the total mass fill in the mold of the particleboard. Density becomes a parameter that indicates the quantity of the rice straw particles under constant molding volume. Tinier particleboard density means fewer rice straw particles in it. That allows some voids in the particleboards that lead to weak mechanical properties. It can affect heat transfer during hot press rice straw particleboard manufacturing (Rebolledo, Cloutier, & Yemele, 2018)[22]. After manufacturing, the voids are prone to be penetrated by water. The particleboard is like porous material that water could penetrate through imbibition.

The sessile drop method considers a stable measurement that indicates the surface tension, adsorption, and interaction between the solid and liquid phases (Krainer & Hirn, 2021)[23]. The rate of a water droplet on the rice straw particleboard decreases differently for each density. The data

 https://doi.org/ 10.25077/metal.8.1.6-13.2024

exhibit a decreasing rate inversely proportional to the density of the particleboard. It will be investigated further by performing simple multiple linear regression statistical tools.

3.2.3 Multiple Linear Regression

Density strongly correlates to particleboard's mechanical properties (table 2). The sessile drop method also shows a strong correlation, although associated inversely as described by the negative value. Low densities imply a larger region of the void within the particleboard. The behavior of water droplets on the top of the rice straw particleboard surface results from balancing forces to spreading and penetrating the void inside the particleboard. The mechanism begins with the spreading and absorption simultaneously until the liquid advancement stops (Chebbi, 2021)[24]. Compared to nonporous mediums, contact line movement is dominantly driven by the adhesive force between the solid and liquid phases that only occur on the particleboard surface. However, contact line movement pulls toward the void (Gambaryan-Roisman, 2014)[25], implying less spreading radius. Rice straw particleboard permeability is the porosity function indicated by the density parameter. As density increases (adding more rice straw particles to the molding), the distance between rice straw particles gets a more compact rice straw particleboard. It is also implying that the quantity of particles of particleboard contributes to its mechanical properties. The bonding of each particle adds more adhesive force when the solidifying process is done using a hot press machine.

4. CONCLUSION

Density is an excellent indicator of particleboard mechanical properties. The sessile drop method perfectly does the job as well. It is statistically significant, shown by the simple multiple linear regression method. The correlation coefficient of density and sessile drop method are more than 0.9 and -0.9, respectively, indicating a strong correlation to rice straw particleboard mechanical properties. The interaction between IB and MOR has an order of more than 0.8. The method could be used for rapid and low-cost technique identification of particleboard mechanical properties. It can reduce unnecessary sample tests in a universal testing machine, which is costly and time-consuming.

Acknowledgments

We are grateful for the support from Universitas Sultan Ageng Tirtayasa, which is funding this work under contract number B/246/UN.43.9/PT.01.03/2023.

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