

Particle Size Effect on Mechanical and Physical Properties of Rice Straw Epoxy Resin Particleboard

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Abstract— Rice straw is one of the agricultural residues that can be used to form a composite such as particleboard. In this study, the effect of rice straw particle size on the mechanical and physical properties of rice straw epoxy resin particleboard has been investigated. The rice straw particles sizes were varied for 40 mesh, 50 mesh, and 60 mesh. The ratio of rice straw to epoxy resin was also varied for 80 : 20 vol.%, 85 : 15 vol.%, 90 : 10 vol.%, and 95 : 5 vol.%. Our results revealed that the mechanical properties (modulus of elasticity, modulus of rupture, and tensile strength) of particleboard strongly depend on the rice straw particle size. This behavior is the same for the physical properties (density and water absorption) of particleboard. The highest flexural strength (modulus of rupture), elastic modulus, and tensile strength of rice straw epoxy resin particleboard are obtained at the 50 mesh of rice straw particle size with its value of 6.15 kgf/mm², 3280 kgf/mm², and 0.60 kgf/mm², respectively. However, the highest density is obtained at the 60 mesh of rice straw particle size, which is 0.87 g/cm³. The lowest water absorption (23%) is also obtained at the 60 mesh of rice straw particle size. Our finding indicates that the particle size plays a vital role in the reinforcement of particleboard.

Keywords— rice straw; epoxy resin; composite; particleboard.

I. INTRODUCTION

One of the residues from rice production is rice straw. Currently, there are about 500 million tons of rice produced from many countries [1]. There is abundant rice straw found in many Asian countries, such as in Indonesia. According to Rice Market Monitor in April 2018, Indonesia produced about 70 million tons of rice in 2017 [1]. Assuming the production of rice and straw has a ratio of 10:5; then, it was about 35 million tons of rice straw produced in Indonesia in 2017. Unfortunately, almost all rice straws are burned or left in the fields by farmers. Only a little is used for animal feed or fertilizer. While some previous studies suggested that some residues from the agricultural product could be used to form composites [2-6]. Rice straw contains about 40% of cellulose [7], which can be used to create a composite. Akyildiz et al. evaluated the possibility of using rice straw to form a composite by using urea-formaldehyde. This study showed that rice straw is the potential for making particleboard [8]. Yang et al. argued that rice straw mixed with a wood particle could be formed to produce a composite that can be used for sound absorbing wooden construction material [9].

Urea-formaldehyde has been used as a matrix or composite binder in the majority of the particleboard studies reported in the literature [8-12]. The previous research found that the bending strength and modulus of elasticity of particleboard made of rice straw and urea formaldehyde are rather low (the modulus of elasticity is 39 – 71 kgf/mm² and the bending strength is 0.15 – 0.33 kgf/mm²) [8]. The study of rice straw composite using urea formaldehyde as a matrix by Han Seng Yang et al. found that the modulus of rupture is 1400 – 2900 psi (0.98 – 2.04 kgf/mm²) [9]. Its modulus of rupture is reasonably good, which is fulfilled the industrial particleboard requirement. Nonetheless, the particleboard using urea formaldehyde can produce emission of formaldehyde, which is not good for health. According to the Japanese Industrial Standard, the emission of formaldehyde should be under 0.4 mg/L for particleboard type 18 [13]. Consequently, it would be better to have particleboard by using another matrix.

Epoxy is a type of thermo-set resin which has excellent adhesion and a non-hazardous material [14]. Thus, this material can be used as a binder or a matrix to form a composite, which could have an excellent mechanical property. Nonetheless, to-date, there are very few studies about the rice straw composite using epoxy resin matrix

found in the literature. Recent works found that the particleboard made of rice straw and epoxy resin matrix has excellent mechanical properties [15], [16]. Thus, the particleboard made of rice straw and the epoxy adhesive is quite promising.

The previous study conducted by Mohammadi et al. indicated that the type of matrix and fiber loading influenced the flexural and tensile strengths of the composite [17]. Besides the matrix, particle size may also affect the physical and mechanical properties of the particleboard [18]. However, the particle size effect on the mechanical and physical properties of composite has not been widely studied. Astari et al. showed that the physical and mechanical properties of wood-waste particleboard depend on the size of the particle [19]. Other studies found that the mechanical property of composite may depend on particle sizes [20-22]. The previous work of rice straw epoxy resin composite was only studied for 20 mesh particle size of the rice straw [16]. To our knowledge, there is no study of rice straw epoxy resin composite reported for other particle sizes in the literature. Meanwhile, the mechanical and physical properties of a composite could be influenced by the particle size of the filler. Thus, it is essential to study the mechanical and physical properties of the composite for various particle sizes to obtain the best mechanical and physical properties.

Based on the discussions above, this study investigates the effect of particle size (rice straw) on the mechanical properties (modulus of rupture, modulus of elasticity, tensile strength) and physical properties (density and water absorption) of rice straw epoxy resin particleboard. The results are presented and discussed in this paper.

II. MATERIALS AND METHOD

The rice straw for the particleboard samples in this study was obtained from the rice fields near Banda Aceh city in Indonesia. The rice straw was cleaned using clean water and dried under the sun for two days, and then chopped to be finer using a chopper. The chopped rice straw was then dried in an oven at a temperature of 105 °C for 4 hours. After that, the rice straw was milled and sieved to obtain 40, 50, and 60 mesh rice straw particles. Furthermore, rice straw particles were mixed homogeneously with epoxy resin at room temperature. The ratio of rice straw particles to epoxy resin for all samples is shown in Table 1. The mixture of rice straw with epoxy resin was poured into a sample mold, which was then pressed with a load of 9 tons for 30 minutes at room temperature to produce particleboard samples. The samples were prepared by using ASTM D790 for flexural strength and bending modulus test, ASTM D638, for the tensile strength test. The Universal Testing Machine manufactured by Hung Ta Company was used to measure the mechanical properties of all samples. The bending strength or modulus of rupture (MOR) of the sample is evaluated by using the equation (1).

$$MOR = \frac{3.P.S}{2.b.t^2} \quad (1)$$

Where t is the thickness of the sample, b is the sample width, S is the span, and P is the maximum load. The bending

modulus of elasticity (MOE) is determined by using equation (2).

$$MOE = \left(\frac{\Delta F}{\Delta y}\right) \frac{S^3}{4.b.t^3} \quad (2)$$

Where t is the thickness of the sample, b is the sample width, S is the span, and $(\Delta F/\Delta y)$ is the slope of the force against deformation. The tensile strength (TS) of particleboard is determined by equation (3).

$$TS = \frac{F_{max}}{A} \quad (3)$$

Where F_{max} is the maximum force, and A is the cross-section area of the sample. The density (ρ) of particleboard is determined by using the equation (4).

$$\rho = \frac{m}{V} \quad (4)$$

Where V is the volume and m is the mass of the sample. The water absorption of the sample (WA) is determined by equation (5).

$$WA = \frac{m_2 - m_1}{m_1} \times 100\% \quad (5)$$

Where m_1 and m_2 are the mass before and after the sample was immersed in water, respectively.

TABLE I
COMPOSITION OF PARTICLEBOARD SAMPLES

No.	Size of rice straw particle (mesh)	Rice Straw (vol. %)	Epoxy Resin (vol. %)
1	40	80	20
2	40	85	15
3	40	90	10
4	40	95	5
5	50	80	20
6	50	85	15
7	50	90	10
8	50	95	5
9	60	80	20
10	60	85	15
11	60	90	10
12	60	95	5

Two sample replications were tested for each type of composite. Each data point of MOR, MOE, TS, WA, and density of particleboard was the average value from the test of two different samples. The error-bar of each data point was calculated by using the standard deviation formula.

III. RESULTS AND DISCUSSIONS

The results of our measurement for modulus of rupture or flexural strength (MOR) of particleboard samples are shown in Fig. 1.

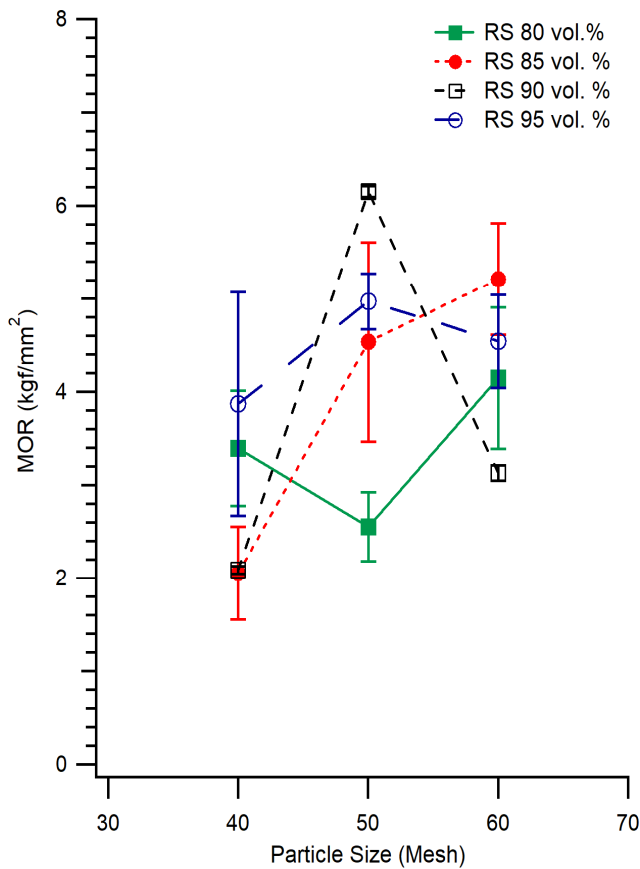


Fig. 1 Modulus of rupture of particleboard for RS 80 vol. %, RS 85 vol. %, RS 90 vol. %, and RS 95 vol. %.

For the composition of rice straw (RS) 80 vol. % (epoxy resin 20 vol. %), it was obtained that the value of MOR is 3.39 kgf/mm² at 40 mesh of rice straw particle size. As the particle size decreases to 50 mesh, the MOR decreases to 2.55 kgf/mm²; however, its value increases to 4.15 kgf/mm² at 60 mesh of rice straw particle size. For 85 vol. % of rice straw composition (15 vol. % of epoxy resin), the value of MOR for 40 mesh particle size is 2.05 kgf/mm². The MOR increases to 4.54 kgf/mm² at 50 mesh particle size. The highest MOR for 85 vol. % composition of rice straw is found to be 5.2 kgf/mm² at 60 mesh of rice straw particle size. This behavior is similar for other rice straw compositions (90 vol. % and 95 vol. % of rice straw). For 90 vol. % of rice straw composition (10 vol. % of epoxy resin), the highest MOR for this condition is found to be 6.15 kgf/mm² at 50 mesh of rice straw particle size. For the composition of rice straw 95 vol. %, the highest MOR for this condition is found to be 4.97 kgf/mm² at 50 mesh of rice straw particle size. The highest MOR for rice straw compositions 80 vol. % and 85 vol. % is obtained at the 60 mesh rice straw particle size. However, the highest MOR for rice straw compositions 90 vol. % and 95 vol. % are found to be at the 50 mesh particle size. Our results indicate that the MOR of particleboard significantly depends on the rice straw particle size for all compositions. The highest value of MOR among all rice straw compositions and particle sizes is 6.15 kgf/mm², which is obtained at 90 vol. % of rice straw and 50 mesh of particle size.

The comparison of modulus of rupture (MOR) from this study with the results of previous studies is shown in Table 2. As seen in Table 2, the type of matrix influences the MOR of particleboard. The MOR for particleboard using epoxy resin has better value compared to those from other adhesive. The rice straw epoxy resin particleboard for 50 mesh of particle size has MOR value of 6.15 kgf/mm², which is significantly higher than the MOR of rice straw particleboard for 20 mesh of particle size.

TABLE II
MOR FOR SOME PARTICLEBOARDS

Kind of particleboard/ fiberboard	MOR (kgf/mm ²)	Ref.
Rice straw & polymeric diphenylmethane diisocyanate	2.31	[18]
Rice straw & urea formaldehyde	0.92	[18]
Rice straw & polyethylene	2.55	[17]
Rice straw & polypropylene	2.24	[17]
Rice straw & urea formaldehyde	2.04	[9]
Rice straw & polypropylene	1.34	[23]
Rice straw & epoxy resin (20 mesh of rice straw)	3.31	[16]
Rice straw & epoxy resin (50 mesh of rice straw)	6.15	This study

The results of modulus of elasticity (MOE) measurement of particleboard for several particle sizes (40 mesh, 50 mesh, and 60 mesh) for several rice straw compositions are shown in Fig. 2. For the composition of rice straw 80 vol. %, the MOE for 40 mesh particle size of rice straw is found to be 1139 kgf/mm². When the particle size decreases to 50 mesh, the MOE of particleboard increases to 1900 kgf/mm². For the particle size of 60 mesh, the MOE of particleboard is 1866 kgf/mm², which is about the same for the MOR for 50 mesh particle size. For particleboard sample having 85 vol. % of rice straw, the MOE is obtained at 60 mesh of rice straw particle size, that is 1998 kgf/mm² which is about the same for the value of MOE at 50 mesh of particle size. For rice straw (RS) 90 vol. %, the highest MOE is found to be 3280 kgf/mm² at the 50 mesh of particle size. Similar to RS 95 vol. %, the highest MOE is obtained at the 50 mesh of particle size which is 2942 kgf/mm². Similar to MOR, the highest value of MOE among all rice straw compositions and all particle sizes is obtained at 90 vol. % of rice straw and 50 mesh of particle size, which is 3280 kgf/mm². This value is significantly higher than the MOE at the 20 mesh of particle size, which is 1490 kgf/mm² [16]. Thus, the particle size affects the MOE of particleboard remarkably. This behavior is similar to the MOR case.

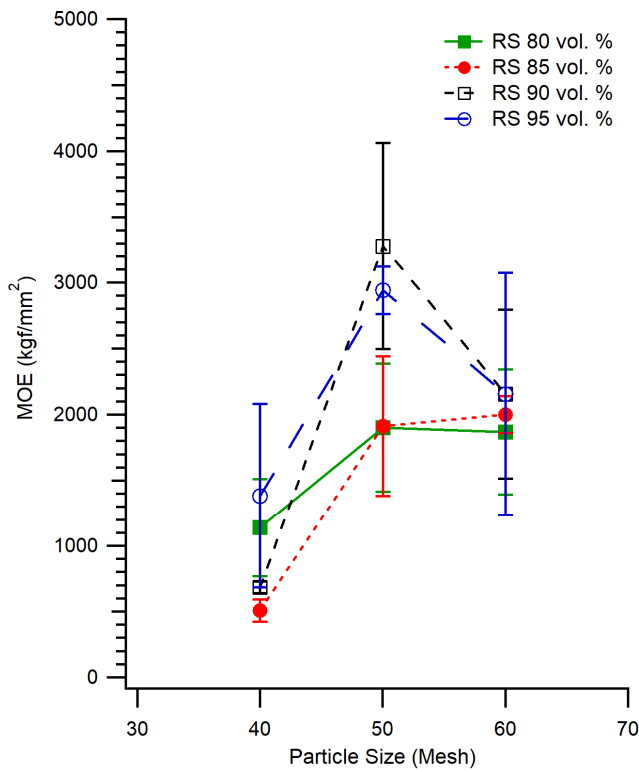


Fig. 2 Elastic modulus of particleboard for RS 80 vol. %, RS 85 vol. %, RS 90 vol. %, and RS 95 vol. %.

Now, let's compare the highest MOE value obtained from this study with some of the results of other rice straw particleboard studies (see Table 3).

TABLE III
MOE FOR SOME RICE STRAW PARTICLEBOARDS

Kind of particleboard/ fiberboard	MOE (kgf/mm ²)	Ref.
Rice straw & polymeric diphenylmethane diisocyanate	255	[18]
Rice straw & urea formaldehyde	163	[18]
Rice straw & Urea Formaldehyde	40	[24]
Rice straw & soy adhesive	293	[25]
Rice straw & polypropylene	450	[23]
Rice straw & epoxy resin (20 mesh of rice straw)	1490	[16]
Rice straw & epoxy resin (50 mesh of rice straw)	3280	This study

As seen in Table 3, it is found that the MOE values of rice straw particleboard using epoxy resin adhesives are significantly higher than those from particleboards using other adhesives (urea-formaldehyde, polymeric diphenylmethane diisocyanate, soy adhesive, polypropylene).

Thus, the type of resin and particle size influence the MOE value of the particleboard significantly.

The measured tensile strength (TS) of rice straw epoxy resin particleboard for various particle sizes and compositions is shown in Fig. 3. For the composition of RS 80 vol. %, the tensile strength of particleboard is 0.37 kgf/mm² for 40 mesh of particle size. As the particle size becomes smaller to 50 mesh, the tensile strength increases to 0.60 kgf/mm². For the rice straw composition 85 vol. %, the tensile strength is 0.26 kgf/mm² for 40 mesh of particle size. The tensile strength increases to 0.39 kgf/mm² for the 60 mesh of particle size. As seen in Fig. 3, our error-bar of each data point is rather large. So, the tensile strength does not depend significantly on the particle size of rice straw.

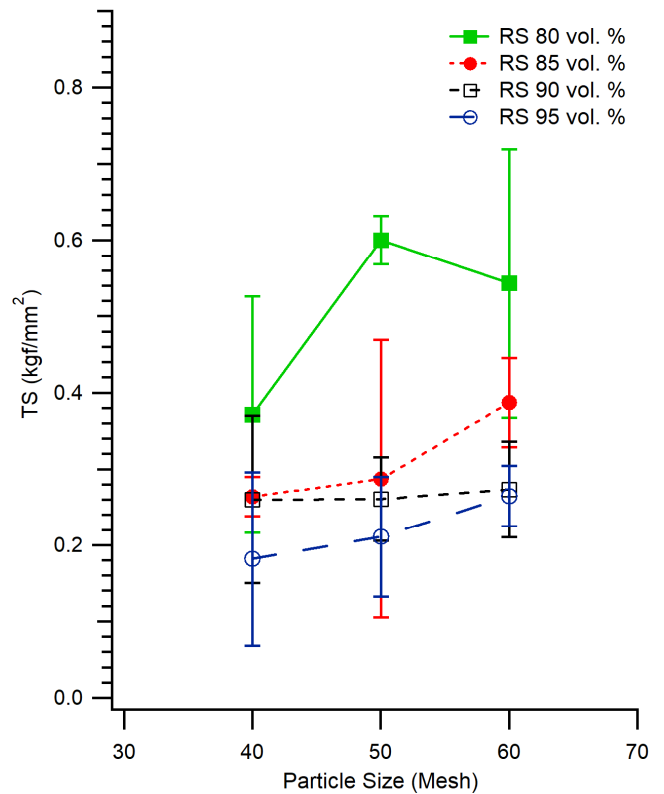


Fig. 3 Tensile strength of particleboard for RS 80 vol. %, RS 85 vol. %, RS 90 vol. %, and RS 95 vol. %.

The comparison of the tensile strength from this study to the results of previous studies is listed in Table 4. The tensile strength of our particleboard is slightly smaller than the particleboard using the polypropylene matrix. However, the tensile strength of particleboard using epoxy resin is larger than those of particleboards using polyurethane or gum Arabic resin.

The density of particleboard made of rice straw particle using epoxy resin matrix has been measured for various particle sizes and RS compositions. Our results are shown in Fig. 4. For the composition of RS 80 vol. %, our measured density of particleboard is 0.65 g/cm³ for 40 mesh particle size of rice straw. As the particle size decreases, the density increases. The highest density for the composition 80 vol. % of rice straw is 0.87 g/cm³ obtained at 60 mesh particle size

of rice straw. The highest density for 85 vol. % of rice straw is 0.823 g/cm³ obtained at 60 mesh particle size.

TABLE IV
TENSILE STRENGTH FOR SOME PARTICLEBOARDS

Kind of particleboard/ fiberboard	TS (kgf/mm ²)	Ref.
Fonio husk and gum Arabic resin	0.08	[26]
Wood – bamboo and polyurethane resin	0.17	[27]
Rice straw – polypropylene	1.05	[17]
Rice straw & epoxy resin (50 mesh of rice straw)	0.60	This study

For the RS 90 vol. %, the highest density is also obtained at 60 mesh particle size; its value is 0.74 g/cm³. This situation is similar for the RS 95 vol. % where the highest density is also obtained at 60 mesh particle size. Clearly, the density of particleboard strongly depends on the rice particle size for all rice straw compositions, as seen in Fig. 4.

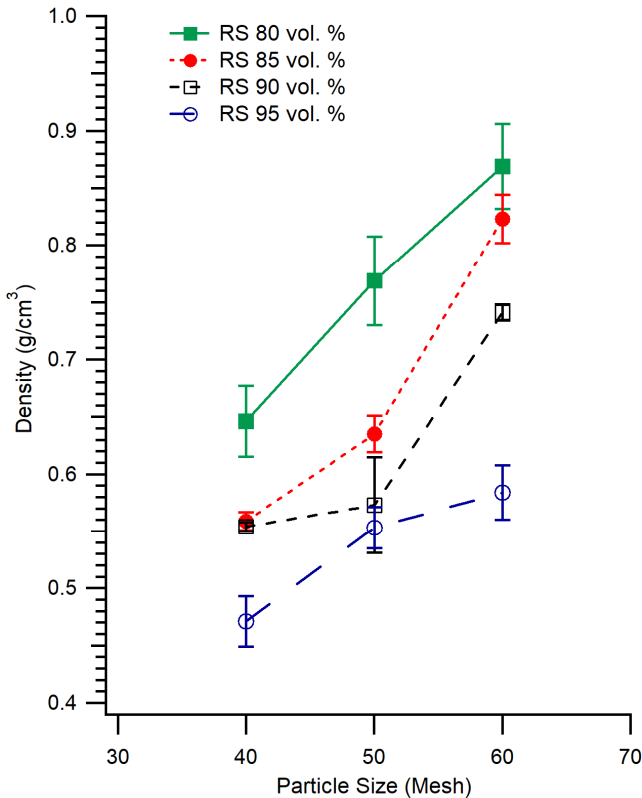


Fig. 4 Density of particleboard for RS 80 vol. %, RS 85 vol. %, RS 90 vol. %, and RS 95 vol. %.

The comparison between the density of this study and the density obtained from previous studies is shown in Table 5. The highest density of study is 0.87 g/cm³ obtained at RS 80 vol. % and 60 mesh of particle size. This value is about the same for the density of particleboard using polypropylene and polyethylene matrix. The density of particleboard with a particle size of 60 mesh is much larger than the density with a particle size of 20 mesh.

TABLE V
DENSITY FOR SOME PARTICLEBOARDS

Kind of particleboard/ fiberboard	Density (g/cm ³)	Ref.
Rice straw & urea formaldehyde	0.62	[8]
Rice straw & urea formaldehyde	0.79	[24]
Rice straw & polyethylene	0.90	[17]
Rice straw & polypropylene	0.88	[17]
Rice straw & polypropylene	0.56	[23]
Rice straw & epoxy resin (20 mesh of rice straw)	0.48	[16]
Rice straw & epoxy resin (60 mesh of rice straw)	0.87	This study

The water absorption of particleboard has been determined for various particle sizes. Fig. 5 shows the result of water absorption where the particleboard sample was immersed in the water for 2 hours.

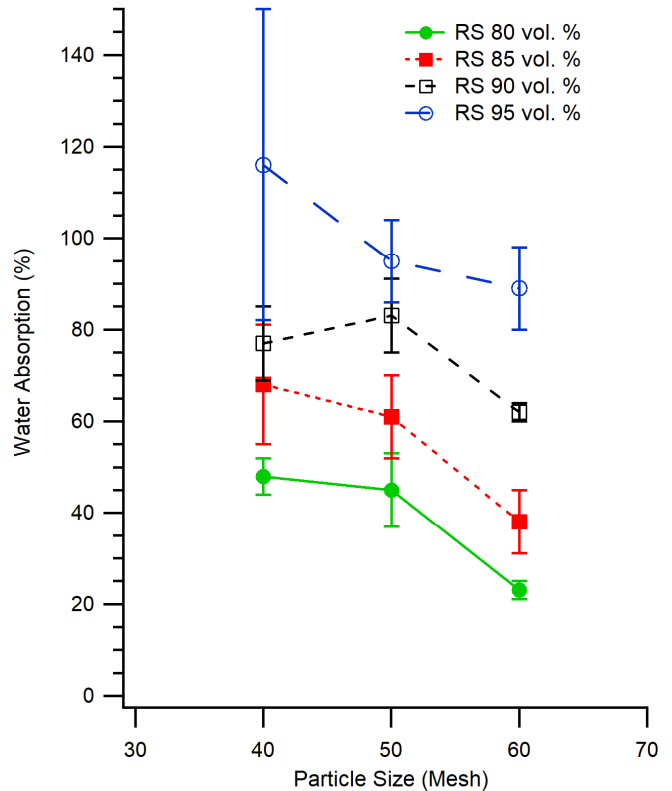


Fig. 5. Water absorption of particleboard for RS 80 vol. %, RS 85 vol. %, RS 90 vol. %, and RS 95 vol. %.

For RS 80 vol. %, the water absorption is about 48 % for 40 mesh of particle size. Its value decreases to 23% as the particle size decreases to 60 mesh of particle size. For RS 85 vol. %, the water absorption is 68% for 40 mesh of particle size. The water absorption reduces to 38% for 60 mesh of particle size. For RS 90 vol. %, the water absorption is 77% at 40 mesh particle size and 62% at 60 mesh of particle size. Thus, the water absorption is affected by the size of particle

size. When the particle size decreases, the water absorption decreases. The water absorption also depends on the composition. The increasing of RS composition will increase the percentage of water absorption.

We have also measured the water absorption of particleboard after the sample was immersed in water for 24 hours. For RS 80 vol. %, the water absorption of rice straw particleboard is 65% for 40 mesh of particle size. As the particle size reduces to 60 mesh, the water absorption decreases significantly to 27%. For RS 85 vol. %, the water absorption is 73% for 40 mesh of particle size. As the particle size reduces to 60 mesh, the water absorption decreases to 50%. Thus, the percentage of water absorption significantly depends on the particle size. The percentage of water absorption also depends on the percentage of rice straw.

The American National Standards Institute (ANSI) classifies several types of particleboards, namely LD grade particleboard (LD-1), M grade particleboard (M-1 and M-2) and H grade particleboard (H-1, H-2, and H-3). The requirement values of MOR and MOE of particleboard for ANSI are listed in Table 6 [28].

TABLE VI
MOR AND MOE REQUIREMENTS FOR PARTICLEBOARD (ANSI 208.1-2009)

Grade	MOR (kgf/mm ²)	MOE (kgf/mm ²)
H-1	1.52	220
H-2	1.89	220
H-3	2.15	252
M-1	1.02	158
M-2	1.33	204
LD-1	0.29	51

Our data showed that the MOR of each sample is larger than 2 kgf/mm². The MOE of each sample is also larger than 250 kgf/mm². So, based on the MOR and MOE values, all our samples fulfill the H-grade particleboard requirement. The highest MOR and MOE of our particleboard are obtained at RS 90 vol. % and 50 mesh of rice straw particle size. Thus, it is recommended to manufacture the particleboard at this composition (90 vol % of rice straw and 10 vol. % of epoxy resin) and rice straw particle size 50 mesh. For this composition and particle size: the MOR is 6.15 kgf/mm², MOE is 3280 kgf/mm², TS is 0.26 kgf/mm², density is 0.57 g/cm³, and water absorption is 83%. Thus, the rice straw particleboard for RS 90 vol. % and 50 mesh are suitably produced for usage in the dry place such as indoor furniture or ceiling board.

As discussed previously above, the mechanical properties (MOE and MOR) of rice straw epoxy resin particleboard strongly depend on the rice straw particle size. The effect of particle size on mechanical properties happens for all different rice straw compositions (80, 85, 90, and 95 vol. %) as shown in Figures 1 and 2. We believe that this behavior is

related to the porosity of particleboard. As shown in Fig. 4, the density of particleboard is significantly dependent on particle size. The density increases if the particle size decreases. The water absorption is also dependent on particle size as shown in Fig. 5. Now let's plot the water absorption versus the density for the rice straw composition 85 vol. % case. As shown in Fig. 6, the water absorption decreases significantly as the density increases.

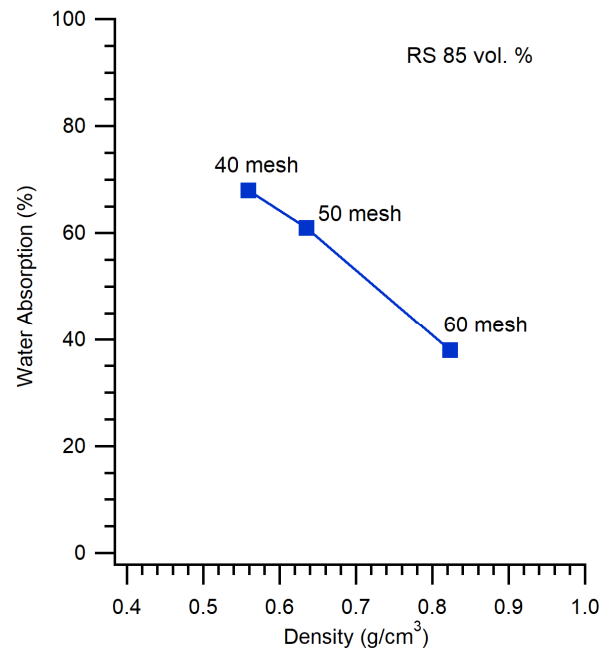


Fig. 6. Water absorption of particleboard versus density for RS 85 vol. %.

The previous study showed that there is a relationship between water absorption and porosity. As the percentage of porosity increases, the water absorption increases [29]. We believe that this also happens to the rice straw particleboard. Smaller particles can fill up more space than larger particles. Accordingly, if the particleboard has many small particles, its density will increase (see Fig. 4). As a result, loads would be more transferred to the rice straw particles, which causes the mechanical properties of particleboard to increase. This finding indicates that the particle size is a matter that must be considered in particleboard production.

IV. CONCLUSION

Our results revealed that there is a strong effect of rice straw particle size on the MOR and MOE of particleboard. The highest value of MOR and MOE was obtained at 50 mesh particle size for the composition 90 vol. % of the rice straw. However, there is a less significant effect of rice straw particle size on the tensile strength of particleboard. The density of particleboard is strongly dependent on the rice straw particle size. The density increases as the particle size decrease. The highest density was obtained at 60 mesh of particle size for 80 vol. % of rice straw. The rice straw particle size also has a strong effect on water absorption. The water absorption decreases as the particle size decreases. Our finding shows that the particle size is an important matter in the composite industry.

NOMENCLATURE

MOR	modulus of rupture	kgf mm ⁻²
MOE	modulus of elasticity	kgf mm ⁻²
TS	tensile strength	kgf mm ⁻²
P	maximum load	kgf
S	span	mm
b	width	mm
t	thickness	mm
F _{max}	maximum force	kgf
A	area	mm ²
TS	tensile strength	kgf mm ⁻²
m	mass	g
V	volume	cm ³
ρ	density	g cm ⁻³
WA	water absorption	%

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