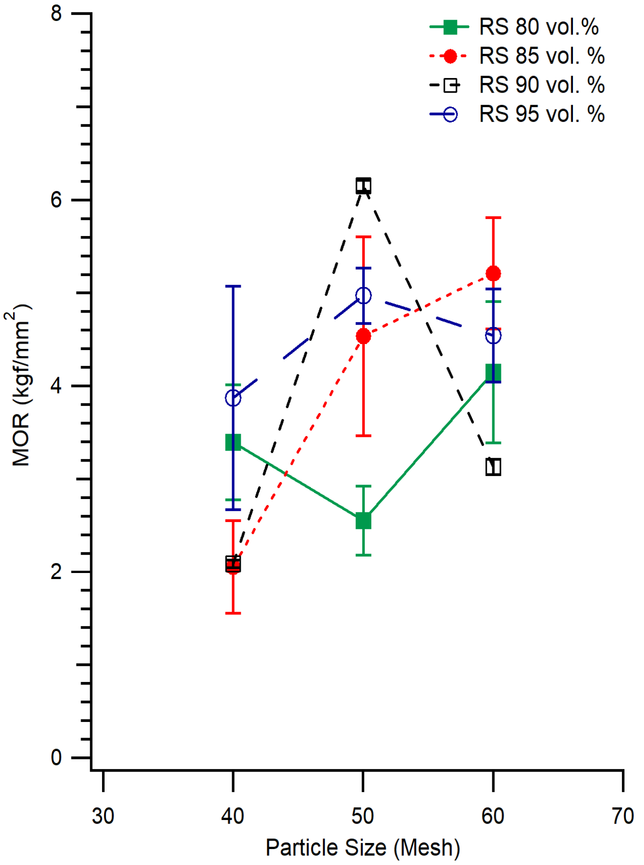

Fig. 1 Modulus of rupture of particleboard for RS 80 vol. %, RS 85 vol. %, RS 90 vol. %, and RS 95 vol. %.

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/mm^2 at 40 mesh of rice straw particle size. As the particle size decreases to 50 mesh, the MOR decreases to 2.55 kgf/mm^2; however, its value increases to 4.15 kgf/mm^2 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/mm^2. The MOR increases to 4.54 kgf/mm^2 at 50 mesh particle size. The highest MOR for 85 vol. % composition of rice straw is found to be 5.2 kgf/mm^2 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/mm^2 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/mm^2 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/mm^2, 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/mm^2, 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/mm^2. When the particle size decreases to 50 mesh, the MOE of particleboard increases to 1900 kgf/mm^2. For the particle size of 60 mesh, the MOE of particleboard is 1866 kgf/mm^2, 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/mm^2 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/mm^2 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/mm^2. 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/mm^2. This value is significantly higher than the MOE at the 20 mesh of particle size, which is 1490 kgf/mm^2 [16]. Thus, the particle size affects the MOE of particleboard remarkably. This behavior is similar to the MOR case.

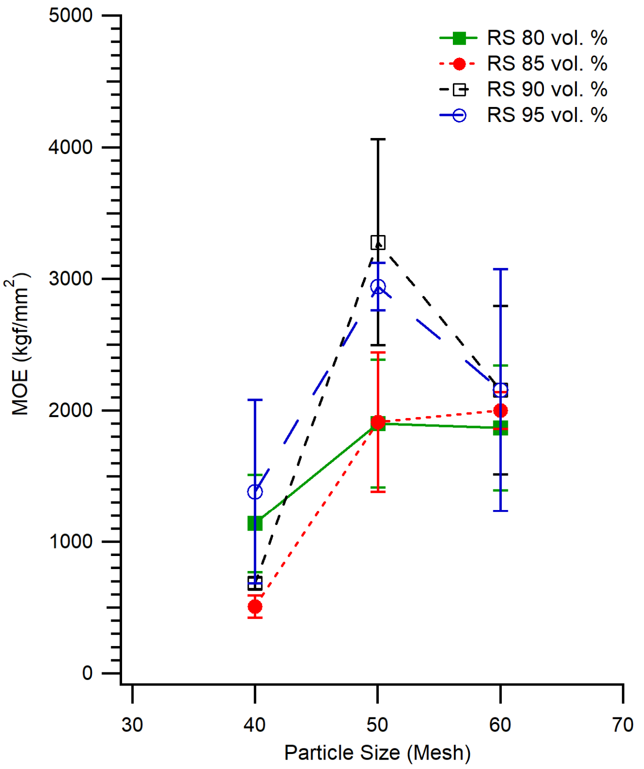

Fig. 2 Elastic modulus of particleboard for RS 80 vol. %, RS 85 vol. %, RS 90 vol. %, and RS 95 vol. %.

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/mm^2 for 40 mesh of particle size. As the particle size becomes smaller to 50 mesh, the tensile strength increases to 0.60 kgf/mm^2. For the rice straw composition 85 vol. %, the tensile strength is 0.26 kgf/mm^2 for 40 mesh of particle size. The tensile strength increases to 0.39 kgf/mm^2 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.

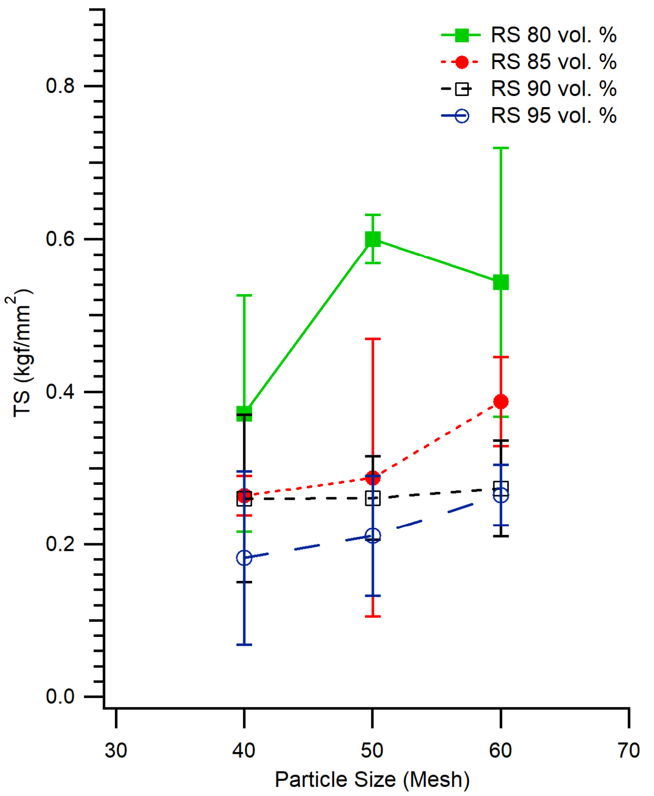

Fig. 3 Tensile strength of particleboard for RS 80 vol. %, RS 85 vol. %, RS 90 vol. %, and RS 95 vol. %.

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/cm^3 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/cm^3 obtained at 60 mesh particle size of rice straw. The highest density for 85 vol. % of rice straw is 0.823 g/cm^3 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/cm^3. 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.

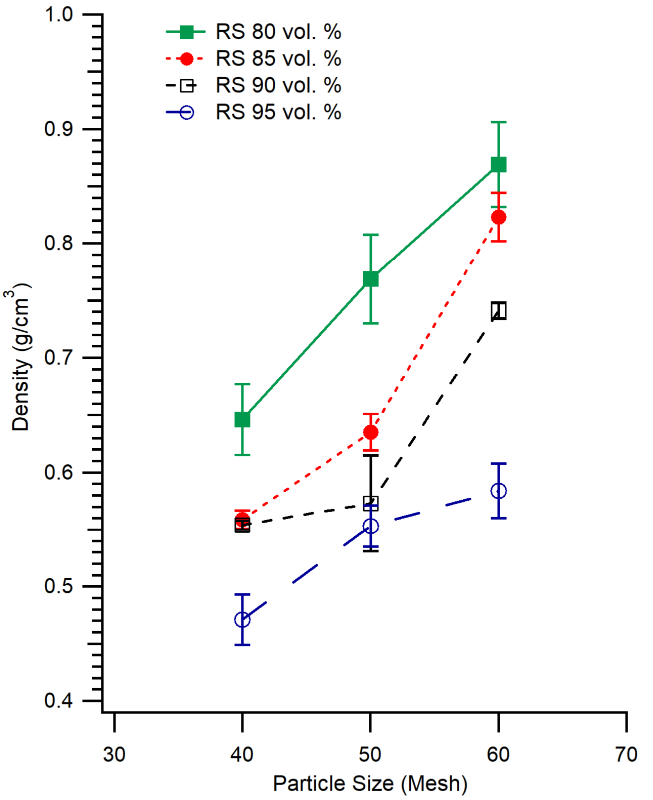

Fig. 4 Density of particleboard for RS 80 vol. %, RS 85 vol. %, RS 90 vol. %, and RS 95 vol. %.

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/cm^3 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.

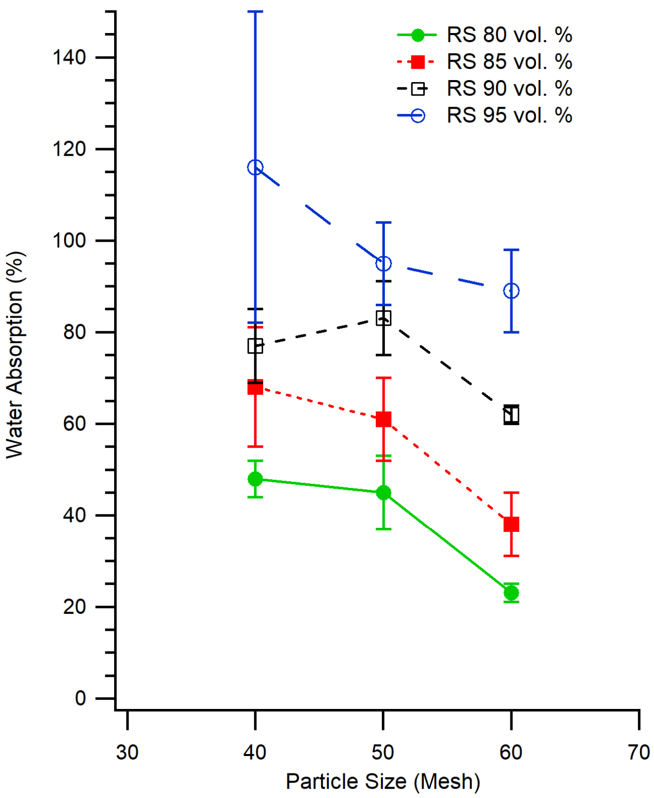

Fig. 5. Water absorption of particleboard for RS 80 vol. %, RS 85 vol. %, RS 90 vol. %, and RS 95 vol. %.

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/mm^2. The MOE of each sample is also larger than 250 kgf/mm^2. 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/mm^2, MOE is 3280 kgf/mm^2, TS is 0.26 kgf/mm^2, density is 0.57 g/cm^3, 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.

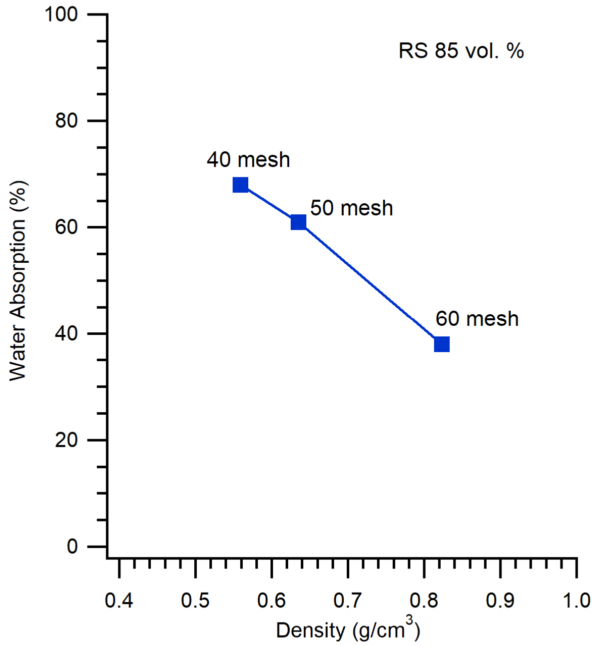

Fig. 6. Water absorption of particleboard versus density for RS 85 vol. %.

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	%

ACKNOWLEDGMENT

Universitas Syiah Kuala funded this research under contract number 288/UN11/SP/PNBP/2018. Also, we are grateful to anonymous reviewers for reviewing the initial draft of this manuscript.

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