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The RPUF Composite's Physical and Mechanical Properties with Ramie Stem Particle Reinforcement

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ABSTRACT

Rigid polyurethane foam (RPUF) is a common insulation material that has low thermal conductivity and good mechanical properties. The qualities of RPUF may be enhanced by adding natural fiber reinforcing. The purpose of this work is to examine how the mechanical and physical characteristics of RPUF composite are affected by the amount of ramie stem particles present. Japanese Industrial Standard (JIS) A 5908-2003 is the basis for the mechanical test (modulus of elasticity, modulus of rupture, compressive strength, internal bond) and the physical test (density, moisture content, water absorption). The study's findings suggest that the physical properties of the RPUF composite were affected by the addition of ramie particles for reinforcement. The density increase in particle content 2.5% – 7.5% range, is not statistically significant. The MC and WA increased statistically significantly. The values of MOE and MOR were not significantly different. In fact, with the addition of 2.5% and 5% ramie particles, the compressive strength value was higher than the RPUF composite without ramie particle filler. Then overall, the IB value was increased by increasing the ramie particles in the RPUF composite. The addition of 2.5-5% ramie particles into the RPUF composite showed optimum results in mechanical properties. Thereby, the addition of ramie particles in the RPUF composite means reducing the use of polyurethane. Therefore, it can reduce production costs. Then the product is more environmentally friendly.

Keyword: Composite, Isocyanate, Polyol, Ramie Stem, Rigid Polyurethane Foam

1. Introduction

The number of motorized vehicles in Indonesia has increased every year. It reaches 148 million units in 2022 [1]. The high number of motorized vehicles will cause noise pollution from exhausts, horns, and the sound of vehicle engine vibrations, especially in diesel-engine vehicles which have a higher engine vibration sound. High levels of traffic noise can disturb the comfort of residents of houses or buildings in urban areas. To reduce these problems, currently many environmentally friendly insulation systems have been developed in building construction.

Insulation systems in building construction are usually located on walls, doors, roofs, and floors. This insulation system should have good physical and mechanical characteristics to support the durability and strength of building components. One common insulation material developed for building construction is rigid polyurethane foam (RPUF). RPUF has low thermal conductivity and good mechanical properties. Thus, it can be used as an insulating material in pipelines, automotive, refrigeration equipment, and building materials [2].

In the industrial setting, filler is typically used to improve the properties of RPUF. Fillers are added to polymers to assist give the pure polymer more strength and stiffness [3]. The interfacial interactions between the fibers and matrix are primarily responsible for the improvement in mechanical and thermal properties [4]. PU foam has been filled with a variety of fillers, including natural and synthetic materials. Rubber, carbon fiber, PET, carbon nanotubes, and other synthetic fillers are excellent at improving the characteristics of polymers. However, they have negative effects on living things. When carbon fibers and nanotubes enter the lungs in large enough concentrations, they are known to be extremely persistent in the environment and to cause health issues for living things [5].

Natural fibers are an environmentally beneficial substitute for fillers. The mechanical, thermal, and acoustic properties of the RPUF composite can be enhanced by adding natural fiber filler, according to experimental data provided by Tao et al. in [6]. The hydroxyl group (-OH) on the lignocellulosic fiber's surface can provide an excellent interfacial bond between the fiber and the polyurethane, which is one benefit of employing natural fibers [7]. Natural fiber is a relatively inexpensive, renewable and sustainable resource [6]. In addition, research on natural fiber-reinforced composite materials has been widely developed, because consumer awareness of the environment continues to increase, and is estimated to have good prospects in the future [8].

There has been extensive research and development done on RPUF reinforced with natural fiber. The use of natural fibers can enhance PUF's mechanical, physical, and thermal stability as well as energy absorption [8]. Soberi *et al*. in [9] examined the effect of kenaf fiber content (*Hibiscus cannabinus* (L.)) on RPUF characteristics and produced an increased modulus value. It is also necessary to research the usage of other natural fibers such as Ramie (*Boehmeria nivea* (L.)) stem particles as reinforcement for RPUF composite. Ramie stems are waste from the textile industry. Recently, they have been used only as raw materials for compost. The usage of ramie stems as reinforcement for RPUF composites is expected to provide added value and become an alternative choice of natural fibers to be used as composite products that are more environmentally friendly. It can also reduce production costs for polyurethane materials.

2. Method

2.1 Preparation of Materials

Ramie stem chips of the Ramindo variety were obtained from ramie plantations in Wonosobo Regency. The raw material was processed into small particles using a grinding machine and filtered using a 4-14 mesh vibrating sieve. After the ramie particles were filtered, they were dried for 24 hours at 60°C until the moisture content was less than 7%.

2.2 Manufacture of RPUF Composite

The manufacture of RPUF composite is shown in Figure 1. Particles of ramie stem were combined with polyol, and isocyanate was subsequently added. A mechanical stirrer was used to agitate the mixture for 10 seconds at a speed of roughly 2000 rpm. The proportion of isocyanates to polyols was 1:1.1 (w/w). The liquid was rapidly poured into a polyethylene (PE) plastic-coated, sealed mold measuring 40 cm by 40 cm by 5 cm. The mold was closed and locked tightly using clamps to prevent foam leakage during the reaction. The molding process was carried out for 1 hour until the composite hardened completely. Then the RPUF composite was peeled and cut into several test samples using a chainsaw and cutter. The goal density of 50 kg/m^3 was used to make the RPUF composites, and they were distinguished according to the amount of ramie stem particles they contained (Table 1). Each type of RPUF composite was made in 3 replicates.

2.3 Density of RPUF Composite

The RPUF composite's (apparent) densities were measured in accordance with JIS A 5908:2003 [10]. Following a 24-hour moisture conditioning period at 23°C and 50% relative humidity, the samples (Figure 2) with dimensions of 50 × 50 × 50 mm (length × breadth × thickness) were cut from the RPUF composite. M/V was used to calculate the density, where M is the mass of each specimen. The volume, or V, is the product of the specimen's length, width, and thickness. Five specimens' average density was given.

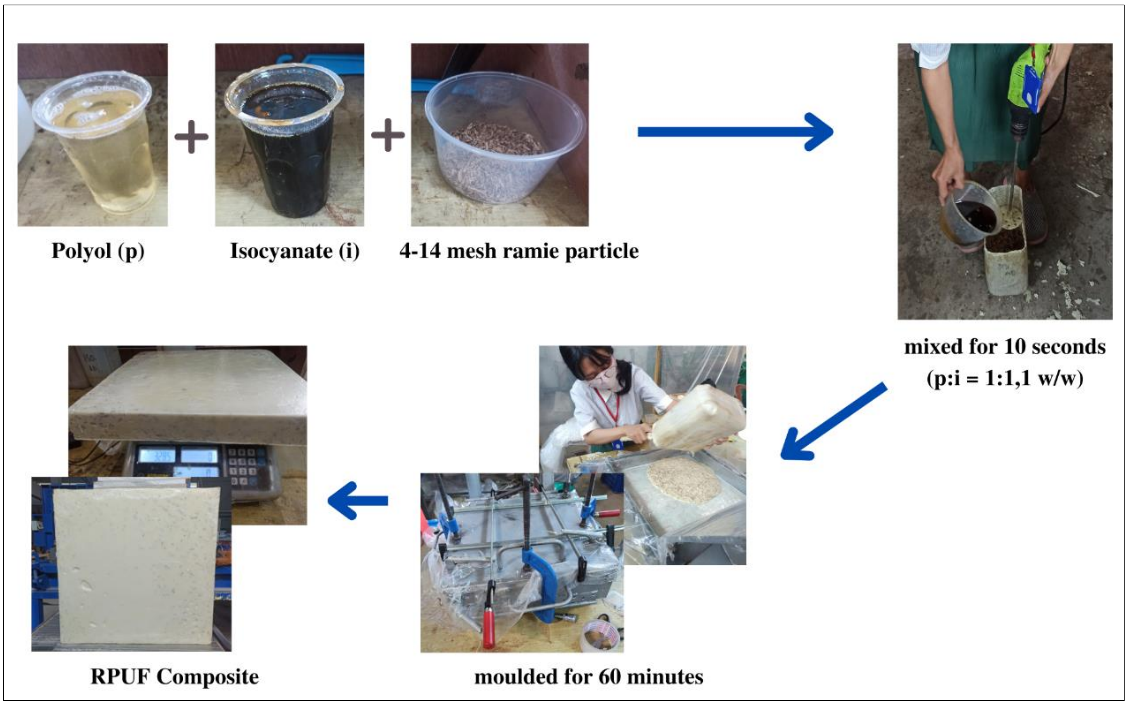


Figure 1. Illustration of RPUF composite manufacturing

Table 1. Type of RPUF Composite

Types	Density (kg/m^3)	Ramie stem particle content (%)
D50R0		0
D50R2.5		2.5
D50R5	50	5
D50R7.5		7.5
D50R10[a]		10

[a]RPUF with 50 kg/m^3 density and 10% particle content

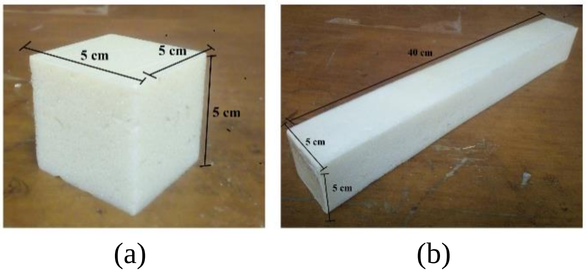


Figure 2. Testing sample of (a) density, moisture content, water absorption, internal bonding, and compression strength and (b) modulus of elasticity and modulus of rupture

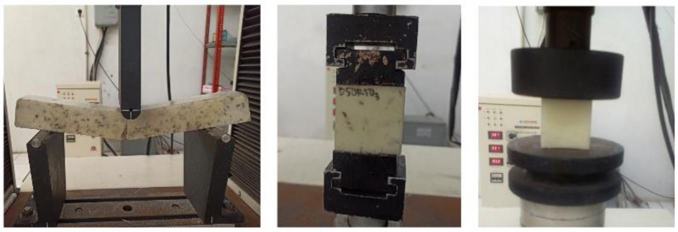
2.4 Evaluation of Physical Properties

According to JIS A 5908:2003 [10], the physical characteristics of the RPUF composite—density, moisture content (MC), and water absorption (WA)—were examined. On the 50 x 50 x 50 mm samples, the MC and WA were computed. The samples intended for assessment in MC were promptly weighed following their oven-dried state at 103°C for ± 24 hours or until they attained a consistent weight. Water at 25°C was used for the 24-hour WA test submersion. Following submersion, the samples were weighed and cleaned to remove any remaining water from the surface.

2.5 Evaluation of Mechanical Properties

Compression strength (CS), internal bonding (IB), modulus of elasticity (MOE), and modulus of rupture (MOR) were the mechanical parameters assessed in accordance with JIS A 5908:2003 [10]. Using specimens measuring 50 x 50 x 50 mm, the IB and CS were computed. A universal testing machine (UTM type AG-IS

50 kN, Shimadzu, Japan) with a load capacity of 50 kN was used to evaluate MOE, MOR, IB, and CS (Figure 3). On 400 x 50 x 50 mm, the loading speed and effective span were 10 mm/min and 150 mm, respectively, during the testing of the MOE and MOR. In contrast, the IB test loaded at a pace of 2 mm/min.



(a) (b) (c)

Figure 3. Mechanical testing of (a) MOE and MOR, (b) IB, and (c) CS

2.6 Statistical Analysis

Following the collection of each experiment's results, the average values and standard deviations were computed. IBM SPSS 23.0 was used to do a one-way analysis of variance (ANOVA) on the data (SPSS Inc., Chicago, Il, USA). For p-values < 0.05, the significance threshold was taken into account.

3. Result and Discussion

3.1 Density

One significant factor that may have an impact on the mechanical characteristics of RPUF is density [11]. The greater density of PUF with natural fiber hybrids can boost its strength, according to Sridar et al. in [12]. The pore size affects polyurethane's density. The density decreases with increasing pore size [13]. The average RPUF density in this study ranged from 42.11 - 45.40 kg/m^3 (Figure 4) and close to the target density (50 kg/m^3). The density of the RPUF composite at 0% fiber content was 42.11 kg/m^3. Meanwhile, the density value with a particle content of 2.5% -7.5% increased from 44.99 to 45.40 kg/m^3. Along with the addition of the fiber fraction, the pores of the RPUF matrix were filled with the fiber particles themselves [14], so it can increase density because the cell pores size became smaller. The increase in density for the 2.5-7.5% particle loading may also indicate that the particles support the isocyanate processes without interfering with the polyol isocyanate crosslinking activities [15]. However, the density value of the RPUF composite in this study tended to be uniform, because based on statistical tests, the addition of ramie stem particles to the RPUF did not have a significant effect on density (Table 2).

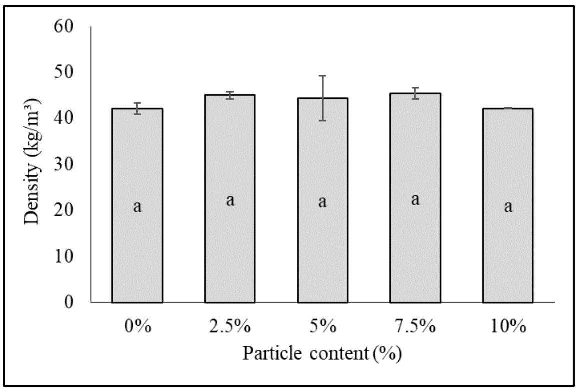


Figure 4. Effect of particle content on the density of RPUF composite

Table 2. Variance analysis summary of ramie particle content

Physical properties	ANOVA	Mechanical properties	ANOVA
Density	0.330^{ns}	MOE	0.663^{ns}
Moisture content	0.000**	MOR	0.618^{ns}
Water absorption	0.000**	Compressive strength	0.005**
		Internal bond strength	0.064^{ns}

^{ns}not significant, **highly significant difference

3.2 Moisture Content

In this investigation, the average MC of RPUF varied between 1.99% and 4.70% (Figure 5). The study's findings suggest that the RPUF composite's water content is influenced by the particle content. If more ramie particles are introduced to the RPUF composite, the MC will rise. The ramie particles' -OH groups are the cause of it. There are more free -OH groups in the fiber due to the larger fiber content, which is obtained from cellulose and hemicellulose. The moisture content rises as a result [16]. The MC of RPUF was considerably affected by the inclusion of ramie particles in this investigation (Table 2), although there was no significant difference in the composition of 5%, 7.5%, and 10% ramie particles.

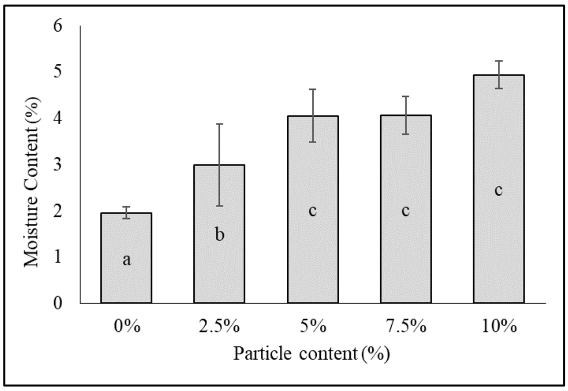


Figure 5. Effect of ramie particle content on the moisture content of RPUF composite

3.3 Water Absorption

Water that absorbs quickly can lead to foam breakdown and dimensional instability. Water resistance is also a crucial PUF feature, particularly for outdoor applications [17]. In this investigation, the average WA of RPUF varied from 25.95 to 85.78% (Figure 6). The WA of RPUF was considerably affected by the addition of ramie particles in this investigation (Table 2), although there was no significant difference observed in the contents of 2.5%, 5%, and 7.5%. According to the findings, the RPUF composite's WA rises as the amount of ramie particles increases. The foam cell structure will become more heterogeneous as additional particle content is introduced. The capacity of the RPUF to absorb water can be increased by the more diverse structure of foam cells [18]. Furthermore, the increased water absorption can also be attributed to the foam's open cell percentage exceeding its closed cell proportion [19]. The addition of ramie particles caused some closed cell formations to break. Higher fiber concentration was associated with more open cells and much lower cell diameters. A few cells broke, most likely as a result of the fiber causing deformations in the cells and preventing the development of foam [6].

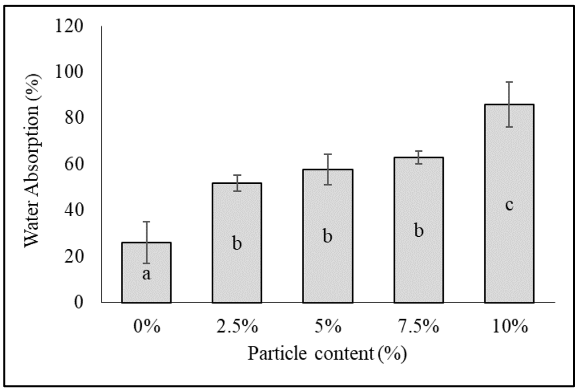


Figure 6. Effect of ramie particle content on water absorption of RPUF composite

3.4 MOE and MOR

In this investigation, the MOE value varied between 4.85 and 6.00 N/mm2 (Figure 7a). Figure 7b shows that the MOR varied between 0.34 and 0.45 N/mm2. As the number of particles increased, both RPUF composite values tended to drop. However, Table 2 shows that the MOE and MOR of RPUF were not significantly affected by the inclusion of fiber. The reason for this is that the absence of lignin-containing -OH groups makes -OH from polyols compete with it for interactions with NCO from isocyanates. As the fiber counts rise, this will cause irregular cell structures to emerge in the foam composite. Poor load transfer is linked to irregular cell structure, which lowers the cell's strength [20]. The content of 10% shows the lowest MOE and MOR values. It could be caused by the presence of ramie particles, which could disrupt the macroscopic cell structure of the foam. This disruption of the foam cells results in a decrease in the stiffness and resistance of the foam when it is loaded [21]. These results were also the same as the results of previous studies [22].

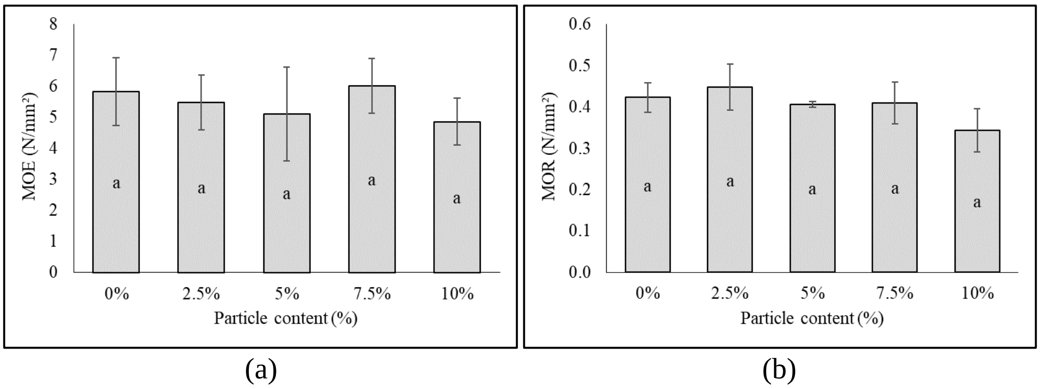


Figure 7. Effect of ramie particle content on (a) MOE and (b) MOR of RPUF composite

3.5 Compressive Strength

In this investigation, the RPUF composite's CS value varied between 0.21 and 0.30 N/mm2 (Figure 8). The maximum CS is displayed for a particle load of 2.5%. After the particle content increases to 2.5%, the CS value tends to decline. High filler content may also result in an uneven dispersion of the filler-polyol mixture in the matrix, as per Czlonka et al. [23]. As a result of the filler clumping together and the interfacial adhesion between the filler and active reaction sites being weaker, the discontinuous domain would arise. The foam's compressive strength decreased as a result. Meanwhile, the increase in density for 2.5% particle content is due to the highest density value. At a higher composite density, the foam cell structure became more compact, and the compression strength increased [24].

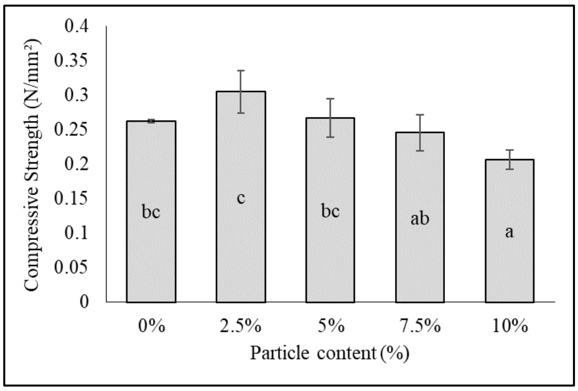


Figure 8. Effect of particle content on compressive strength of RPUF composite

3.6 Internal Bond Strength

The IB strength reflects the quality of the bonds between polyurethane and particle filler in the RPUF composite. The average IB of RPUF in this study ranged from 0.11 to 0.26 N/mm^2 (Figure 9). As the fiber content increases, the IB value of the RPUF composite tends to increase up to 7.5% and decrease to 10%. This result is related to the higher density at particle contents of 2.5% and 7.5%. According to Munawar *et al*. [25], the higher density results in higher IB values. The 5% and 7.5% particle content produced the highest IB values significantly, while the 2.5% and 10% fiber content were not statistically significant.

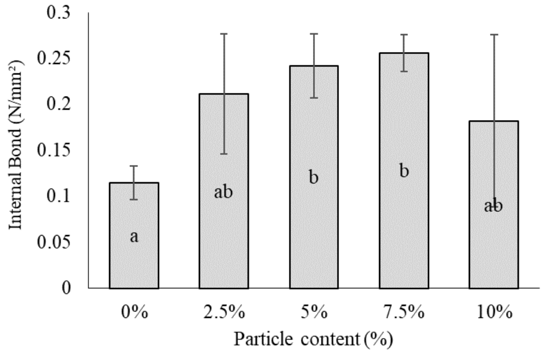


Figure 9. Effect of ramie particle content on internal bond strength of RPUF composite

4. Conclusion

The reinforcement of the RPUF composite with ramie particles resulted in a decrease in physical properties. The addition of ramie stem particles to the RPUF had a significant effect on MC and WA. MC and WA increased at 2.5–10% particle content. Meanwhile, density didn't have a significant effect. The values of MOE and MOR with and without the ramie particle addition were not significantly different. In fact, with the addition of 2.5% and 5% ramie particles, the CS value was higher than that of the RPUF composite without ramie particles. Overall, the RPUF composite's IB value rose as the number of ramie particles grew. RPUF composites with 2 and 5% ramie particles showed optimal mechanical properties. Therefore, the RPUF composite can be more environmentally friendly and lower in production costs due to the addition of ramie particles.

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