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The effect of sorghum bagasse particles and composite density on the physical, mechanical and morphological properties of rigid polyurethane foam composites

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Abstract. The sorghum bagasse (SB) particle was used as a filler for the manufacture of rigid polyurethane foam composites (RPUFC). The purpose of this research was to investigate the effect of SB particle content and variation of composite density on the physical, mechanical, and morphological properties of RPUFC. The RPUFC was created with five different volume fractions of SB particles (0, 2.5, 5, 7.5, and 10 wt.%) and three different composite densities (40, 50, and 60 kg/m^3). The SB particles, polyols, and isocyanate were mixed, poured, and formed in a closed mould. The physical and mechanical properties of the RPUFC were determined according to standard methods. The physical properties (moisture content, water absorption, thickness swelling) were increased with increasing SB particle content in the RPUFC. Meanwhile, the mechanical properties (flexural and compressive strengths) tended to decrease with increasing SB particles but increase with increasing density of RPUFC. The best RPUFC, which had properties equivalent to RPUFC without the addition of particles, was produced with the addition of 2.5% particles at densities of 50 and 60 kg/m^3.

Keywords: isocyanate; polyol rigid; polyurethane foam composite; sorghum bagasse particle

1. Introduction

The population in Indonesia has reached 270.2 million people in 2020 [1], which causes a high demand for house building components. The high demand for building components is the reason for the development of prefabricated components. Prefabricated components are structural components that are manufactured to factory standards that are located far from the building and then transported to the location for assembly. These components are mass-produced to construct buildings in a short time [2]. Prefabricated building components are widely used because the construction time is faster [3]. Prefabrication is widely used in the pharmaceutical industry, clean rooms, modern factories, food processing industries and storage warehouses, cold rooms and cold storage, mining industries, base camps, project mess and site offices, etc. [4].

Prefabricated materials that are currently being developed are sandwich panels. Sandwich panels can be made with a core material of polyurethane foam (PUF) and a coating of plywood, zinc alum, glass fiber reinforced cement (GRC), and others. This sandwich panel product is designed to get a lightweight structure but has high rigidity and strength, making it suitable to withstand bending, impact loads, dampening vibrations and sound. Sandwich panels can be used or applied to building walls, tables, doors, ceilings and wooden floors [5].

The core materials for sandwich panel products that are commonly developed is rigid polyurethane foam composites (RPUF). RPUF has a low thermal conductivity and good mechanical properties, hence RPUF can be used as an insulating material in pipelines, automotive equipment, refrigeration equipment, and building materials [6]. RPUF is lightweight, comfortable and durable. RPUF in the industry is usually modified by using fillers to improve properties such as density, dimensional stability, and mold prevention [7]. In addition, the fillers are useful for modifying mechanical properties and reducing production costs [6].

One type of material that can be used as RPUFC filler is lignocellulosic materials such as wood fibers, natural fibers, and others. The advantage of using natural fibers in the manufacture of RPUFC is the presence of hydroxyl groups on the surface of lignocellulosic fibers that can react with isocyanate groups. This interaction triggers the formation of an excellent interfacial bond between the fiber and the polyurethane [8]. The use of treated natural fibers can improve the thermal stability, energy absorption, physical and mechanical properties of PUF [9]. A previous study investigated the effect of straw fiber filler on the characteristics of the RPUF and resulted in increased sound absorption properties, decreased thermal conductivity, increased insulating ability, and decreased compressive strength [10].

Among lignocellulosic materials that can be used for RPUFC filler is sorghum bagasse particles [11]. Sorghum (*Sorghum bicolor* L. Moench) is one of the plants that is mainly used in Indonesia. Recently, sorghum plants have been developed in several regions in Indonesia, especially in Java, South Sulawesi, Southeast Sulawesi, West Nusa Tenggara (NTB), and East Nusa Tenggara (NTT). On the other hand, sorghum stalks are not yet maximally utilized by the Indonesian people. The average productivity of sorghum stalks ranges from 30-50 tons per hectare in West Java [12]. Large amounts of sorghum stem have been used as raw material for fodder [13], bio-pellets [14], bio-fuel production in China [15], and the United States [16], and used as animal feed in Australia [12]. However, there has been no research on the manufacture of rigid polyurethane foam composites using sorghum bagasse particles as filler. Therefore, an investigation of the effect of sorghum bagasse particles on the morphological, physical and mechanical properties of RPUFC was conducted in this study.

2. Materials and Methods

2.1. Preparation of materials

This study used sorghum bagasse from sweet sorghum (*Sorghum bicolor* L. Moench), which juice had been extracted. The sweet sorghum was obtained from the research area of the LIPI Cibinong Innovation Center. The bagasse particles were screened with a vibrating sieve machine that passed through a 4-mesh screen and was retained in 14-mesh screens. The ARK isocyanate (ARK R32040/P) and polyol (ARK R32040/P) were supplied by PT Anugerah Raya Kencana. Isocyanate appeared as a dark brown liquid with a specific gravity at 25 °C of 1.22–1.26 g/cm^3 and a viscosity at 25 °C of about 150–250 mPas. Polyol, on the other hand, appeared as a light yellowish liquid with a specific gravity of 1.04–1.06 g/cm^3 and a viscosity of about 110–210 mPas. The used materials are shown in Figure 1.

(a) (b) (c)

Figure 1. The used materials for RPUFC: (a) sorghum bagasse particle, (b) isocyanate, (c) polyol.

2.2. RPUF reactivity test

The reactivity of the RPUF was determined by observation of cream time and tack-free time. The polyol was mixed with sorghum bagasse particles using a stirrer in a 1000 ml container until the polyol was evenly distributed over the surface of the sorghum bagasse particles. The isocyanate was added to the mixture of polyol and particles, the mixture was stirred using a stirrer (IKA RW 20 Digital) at approximately 2000 rpm for 10 seconds. The ratio between polyol and isocyanate was 1:1.1 (w/w%). After that, the foam was expanded freely, and the cream time and tack-free time were observed. Cream time was the time required after mixing polyol and isocyanate until the mixture began to react. This phase was indicated by the mixture turning into a creamy texture and starting to expand. Meanwhile, the tack-free time was defined as the time at which the surface of the foam became settled and no longer sticky [17].

2.3. Manufacture of RPUFC

The manufacture of RPUFC began with mixing the polyol with sorghum bagasse particles using a stirrer in a container until the polyol was evenly distributed over the surface of the sorghum bagasse. The isocyanate was then added to the mixture of polyol and particles, and the mixture was stirred using an agitator and Sapphire Power Drill for 10 seconds. The ratio between polyol and isocyanate was 1:1.1 (w/w%). After that, the mixture was poured into a closed mould with a size of 40 cm × 40 cm × 5 cm and allowed to expand for 45 min (Figure 2). RPUFC composites were made with a target density of 40, 50, 60 kg/m^3 and four different percentages of sorghum bagasse particles (2.5, 5, 7.5, and 10% of the composite weight). RPUFC composites without bagasse sorghum as reinforcement was made as a control. The RPUFC composites were conditioned at room temperature for two weeks before testing. The research design of the RPUFC composite is shown in Table 1, and each variation of RPUFC was made with three replications.

Figure 2. Manufacture of the RPUFC.

Table 1. Sorghum bagasse content on the RPUFC.

RPUFC density (kg/m^3)	Sorghum bagasse content (%)				
	0	**2.5**	**5**	**7.5**	**10**
40	D40S0	D40S25	D40S50	D40S75	D40S100
50	D50S0	D50S25	D50S50	D50S75	D50S100
60	D60S0	D60S25	D60S50	D60S75	D60S100

2.4. RPUFC testing

The RPUFC were tested for their physical and mechanical properties, and the morphology was observed as well. Morphological observations were carried out using an optical microscope. The moisture content (MC), water absorption (WA), and thickness swelling (TS) tests were carried out using samples with a size of 5 cm × 5 cm × 5 cm according to JIS A 5908-2003 [18]. The flexural strength (FS) test was carried out using three-point bending (40 cm × 5 cm × 5 cm) according to ASTM D790 [19], and the compressive strength (CS) test was determined according to ASTM D1621 [20] with a sample size of 5 cm × 5 cm × 5 cm using a Universal Testing Machine (UTM, 50 kN, Shimadzu, Japan). Each test was conducted for three replications. Figure 3 is an illustration of the foam size that was used for the testing process of the polyurethane composite foams.

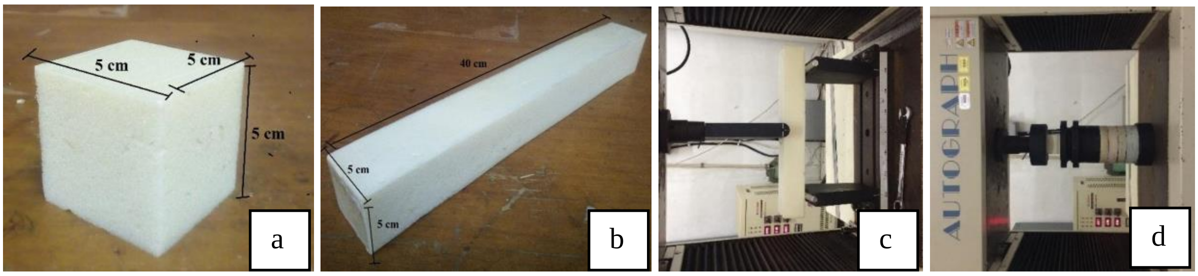

Figure 3. Foam size and testing process: (a) foam 5 × 5 × 5 cm, (b) foam 40 × 5 × 5 cm, (c) FS test, and (d) CS test.

3. Results and Discussion

3.1. RPUF reactivity

Polyurethane is a polymer resulting from a polymerization between a polyol and an isocyanate that contains a urethane functional group in the main chain. With the addition of lignocellulosic material, there might be an effect on the foaming process. Therefore, a free-rising foaming test was conducted to determine the effect of the addition of SB particles on the polyurethane foaming process. The RPUF reactivity was observed for the cream time and tack-free time of each composite foam. The results of the cream time and tack-free time are shown in Table 2.

Table 2. The characteristic time of RPUFC.

Particle content (%)	Time (s)		Free-rise height/ Expansion Rate (cm)
	Cream time	Tack-free time	
0	43	568	15.4
2.5	37	475	16.6
5	33	463	17.9
7.5	24	462	18.6
10	39	481	18.3

Table 2 shows that the cream time and tack-free time of polyurethane foam tend to decrease along with the increasing fraction of SB particles, except for 10% of particle content. This could be due to the presence of chemical components such as lignin (23.02%) and cellulose (34.87%) in the sorghum bagasse that provide free OH groups that could react with isocyanates and increased the reaction rate [13]. This observation was similar to previous studies, which stated that the decrease in characteristic time was due to the presence of lignin which provided free OH groups that could play a role in the polarization between the matrix and reinforcement [21]. On the other hand, when the particle in the RPUFC was 10%, cream time and tack-free time increased. The increase might be due to the inhibition of the movement of the polyurethane so that it became creamy.

0% 2.5% 5% 7.5% 10%

Figure 4. RPUF free rise foaming conditions by the effect of adding SB particles.

The expansion rate of RPUFC also increased when the particle content was increased (Figure 4). The RPUF foaming process without the addition of SB particles was slightly vertical, while by adding SB particles, RPUF foaming was greatly vertical. The final foaming height of RPUF without adding SB particles was shorter than that of RPUF after adding SB particles, and the RPUF height increased with increasing SB particles. The polyurethane foaming process was inhibited by the presence of particles. The addition of SB particles affected the size of the foam cells. However, the expansion rate of the RPUFC could affect the size of foam cells [22].

3.2. Density

Table 3 shows the comparison between the target density and apparent density of RPUFC composites. The target densities in this study were 40, 50 and 60 kg/m^3. The apparent density was calculated for use in the calculation of further RPUFC properties.

Table 3. Comparison between target density and apparent density of RPUFC.

Target Density (kg/m^3)	Sorghum bagasse content (%)	Apparent density (kg/m^3)
40	0	35.57
	2.5	35.32
	5	39.36
	7.5	40.24
	10	44.59
50	0	49.51
	2.5	45.30
	5	42.87
	7.5	45.67
	10	46.68
60	0	54.49
	2.5	54.50
	5	52.16
	7.5	52.29
	10	51.71

The result shows that the apparent density was lower than the target density. This may be due to the lack of material calculations during the manufacture of RPUFC, whereas the weight of the material was reduced due to the gas that came out from the reaction between polyol and isocyanate. Besides, the density of polyurethane also depended on the pore size. The enlarged pore size would cause a decrease in foam density [23]. Another research showed that with the addition of particle fraction, the pores of the polyurethane foam matrix were filled by the particles themselves [24], so the pore size became smaller and resulting in an increased density value. To obtain an apparent density that was equal to target density, the calculation of the weight composition between the particles and the polyurethane had to be more precise.

3.3. Moisture content

The average value of the moisture content (MC) test on RPUFC was from 1.84 to 6%. The results show that MC values tended to increase when the bagasse content and density increased. This was because the sorghum bagasse was hygroscopic and could absorb water. The composite with more bagasse would have a higher MC [25]. On the other hand, the composite with a higher density would have a lower MC. It was because composites with high density had compact intermolecular bonds between matrix and reinforcement, so the water molecules could not fill the voids inside the composite [26].

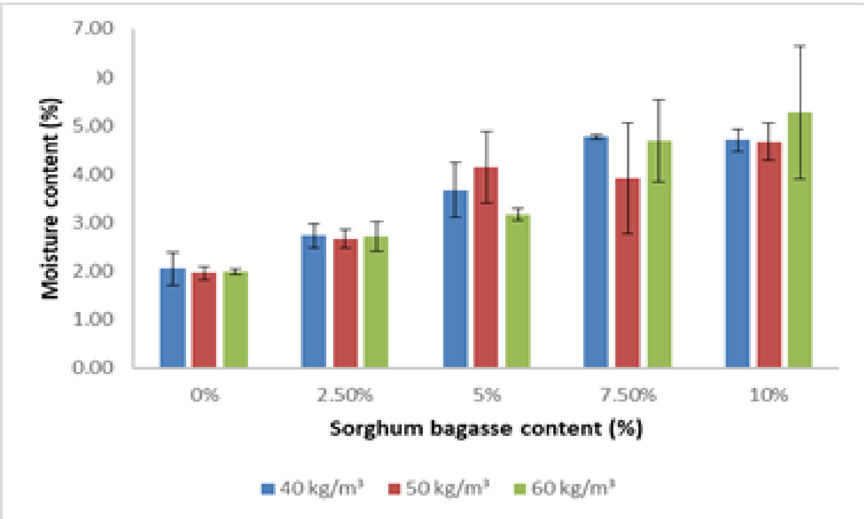

Figure 5. The moisture content of RPUFC.

3.4. Water absorption

The average value of the water absorption (WA) test on RPUFC ranged from 20.57 to 93.33% (Figure 6). It can be noticed that the WA increased with the addition of sorghum bagasse to RPUFC composites. This was caused by the presence of hydroxyl groups which was hydrophilic. The more bagasse used on RPUFC, the higher the WA [27]. On the other hand, the WA decreased when the density increased. The composite density affected the bonding between matrix and reinforcement. A higher composite density would strengthen the bonding cavity. The smaller the cavity made it difficult for water to fill the cavity in the composite and thus reduced water absorption [28].

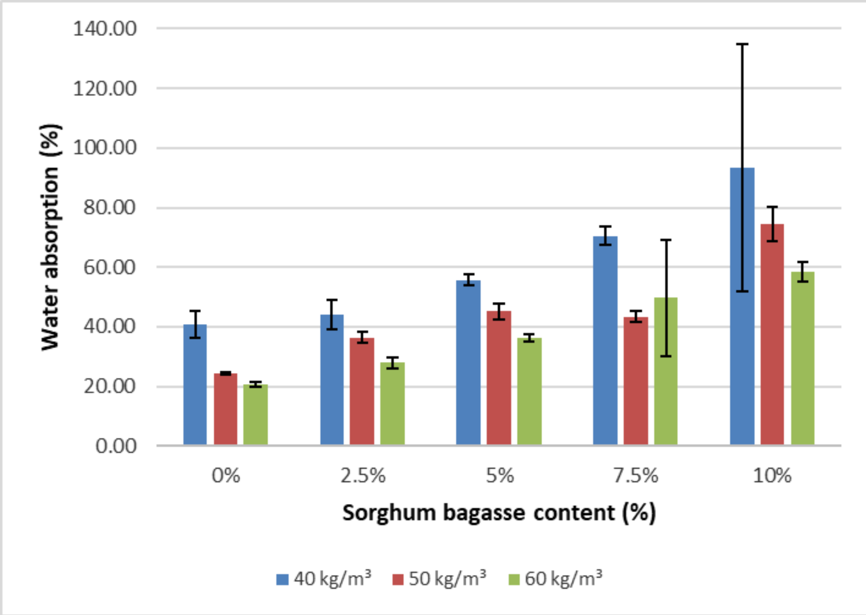

Figure 6. Water absorption of RPUFC.

3.5. Thickness swelling

Thickness swelling (TS) determines the dimensional stability of the RPUFC that is important for some applications in various fields [29]. The average value of the TS test on RPUFC ranged from 0.27 to 1.81% (Figure 7). The TS tended to increase with the addition of sorghum bagasse. This could be caused by the particle factor used in the manufacture of RPUFC which had a non-uniform size, as well as the random and uneven distribution of particles. The TS was influenced by the raw materials used; the more water that could be absorbed and enter the polyurethane foam would cause a change in dimensions [30]. Increasing the composite density caused the particles to become more compact that resulting in smaller cavities, making it difficult for water to fill the voids in the composite [31].

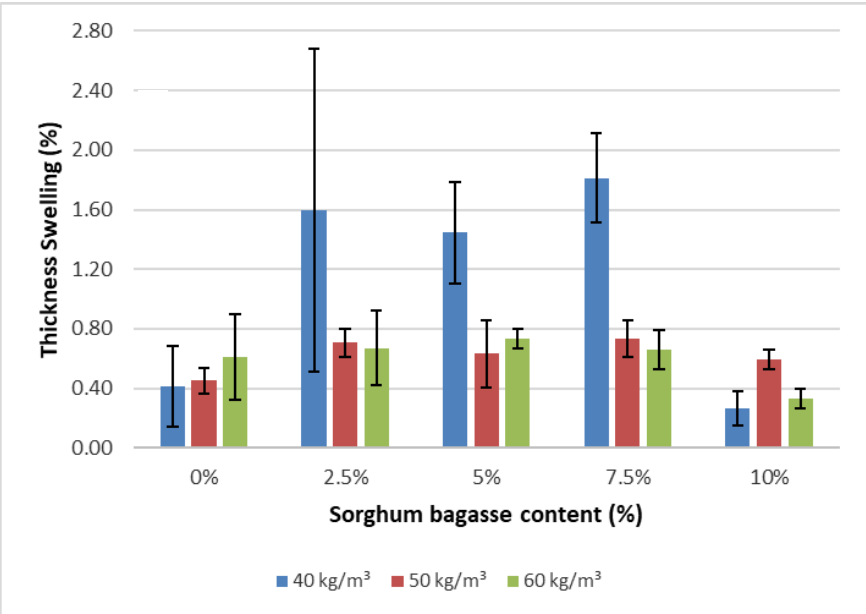

Figure 7. Thickness swelling of RPUFC.

3.6. Flexural strength

The average values of modulus of elasticity (MOE) ranged from 2.14 to 7.83 N/mm^2 (Figure 8). Meanwhile, the average values of modulus of rupture (MOR) ranged from 0.17 to 0.56 N/mm^2 (Figure 9). The MOE value tended to fluctuate with the addition of sorghum bagasse and the higher the density of the RPUFC composite. This could be due to the bagasse particles having a non-uniform size, as well as a random and uneven distribution of particles. Meanwhile, the MOR value of the control RPUFC composite was higher than that of the reinforced RPUFC composite. The MOR value decreased along with the increasing content of sorghum bagasse in the RPUFC. This could be caused by the presence of bagasse as a reinforcing macroparticle, which could disrupt the macroscopic cell structure of the foam. This disruption of the foam cells resulted in a decrease in the stiffness and resistance of the foam when it was loaded [32]. These results were also the same as the results of previous studies [9].

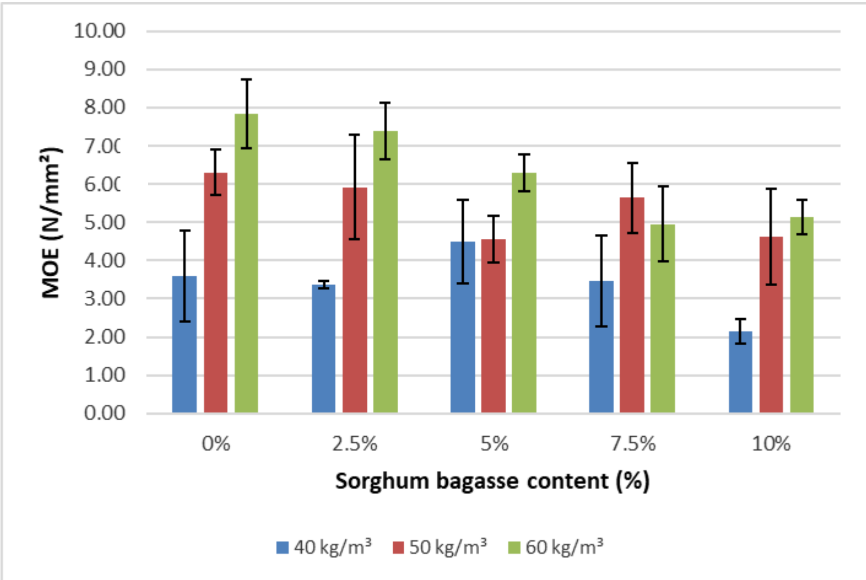

Figure 8. MOE of RPUFC.

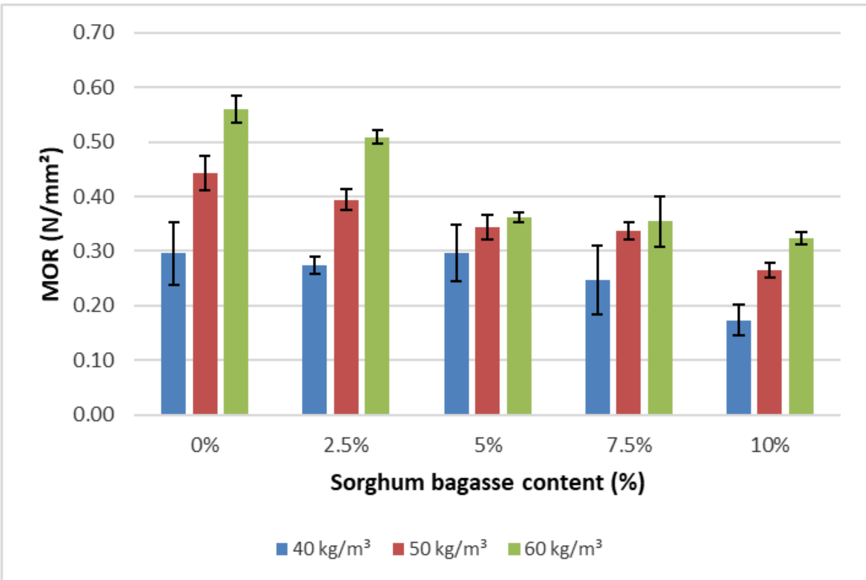

Figure 9. MOR of RPUFC.

The decrease in mechanical strength could be caused by the increase in the lignin content in bagasse, which affected the shape of the foam cell structure to become irregular, and caused defects in the foam structure when given a load [33]. Based on the density of the composite, the MOR results tended to increase with the higher density used. That was because density correlated with the cellular structure of the foam. The higher the density, the more compact the cell structure and the greater the mechanical strength of the RPUFC [34].

3.7. Compressive strength

The average values of compressive strength (CS) ranged from 0.08 to 0.32 N/mm² (Figure 10). The CS decreased with increasing bagasse content in the RPUFC. The decrease in compressive strength was caused by the presence of particles in the foam which had an impact on the foam structure, while the cells became distorted and uneven. The more particles used, the more difficult it was to obtain a uniform dispersion of particles and mixtures. As a result, the polymer structure became more brittle and weak. Foams with a weak cell wall structure could not support the applied load and caused the splitting of the polyurethane foam [35]. Meanwhile, the CS increased with the higher composite density due to the effect of density on the stiffness of the cell wall. At a higher composite density, the foam cell structure became more compact and compression strength increased [33].

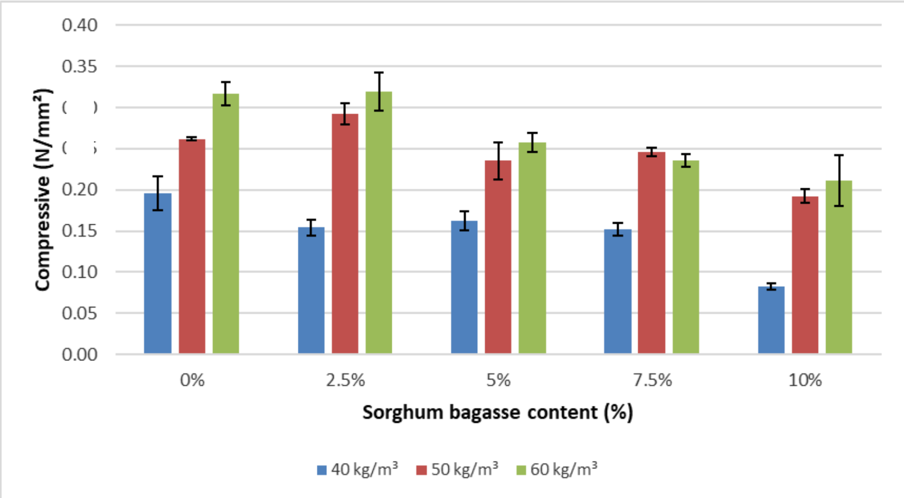

Figure 10. Compressive strength values of RPUFC.

3.8. Morphological observation

The RPUFC with a density of 40, 50, 60 kg/m^3 is shown in Figures 11, 12 13, respectively. From these figures, it can be observed that there was a significant difference between RPUFC with and without reinforcement. In the composite with 2.5% bagasse, the sorghum bagasse began to appear at random points. Then in the composite with 5% bagasse, the presence of sorghum bagasse increased and spread to the foam. Similarly, the composite containing 7.5% and 10% bagasse showed that the sorghum bagasse was evenly distributed over the entire surface of the polyurethane foam.

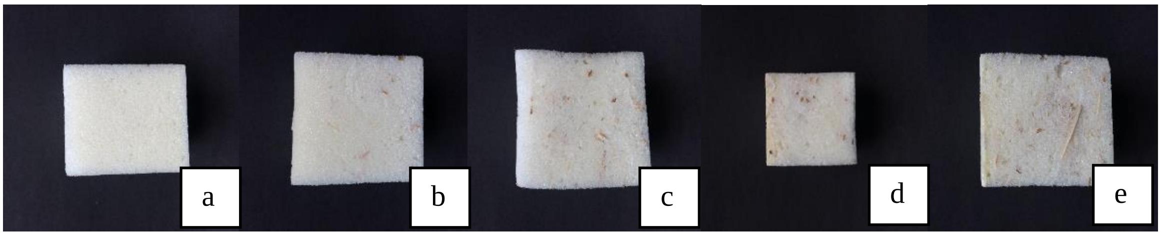

Figure 11. Cross section of RPUFC with density 40 kg/m³: (a) 0% bagasse; (b) 2.5% bagasse; (c) 5% bagasse; (d) 7.5% bagasse; and (e) 10% bagasse.

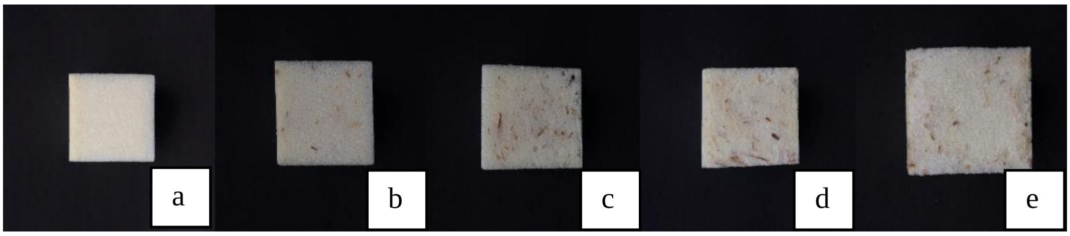

Figure 12. Cross section of RPUFC with density 50 kg/m³: (a) 0% bagasse; (b) 2.5% bagasse; (c) 5% bagasse; (d) 7.5% bagasse; and (e) 10% bagasse.

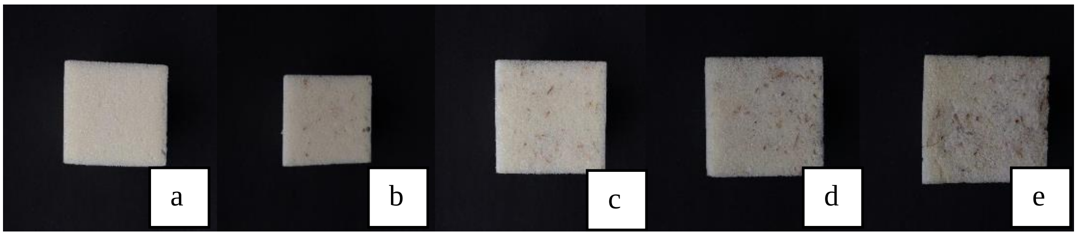

Figure 13. Cross section of RPUFC with density 60 kg/m³: (a) 0% bagasse; (b) 2.5% bagasse; (c) 5% bagasse; (d) 7.5% bagasse; and (e) 10% bagasse.

4. Conclusion
The addition of SB particles to the polyurethane foam improved the reactivity of the foam. As the fraction of bagasse increases, the rise time and tack-free time of polyurethane foam become shorter. In general, MC, WA and TS increase with increasing sorghum bagasse content in the RPUFC composites and decrease with increasing density of foam composites. Meanwhile, MOE, MOR and CS tend to decrease along with increasing sorghum bagasse content but increase with increasing density of foam composites.

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