Bio-based composites of sugarcane bagasse: effect of bagasse particle size

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Abstract

Exploiting agro-industrial residues, such as sugarcane bagasse, as feedstock to develop biodegradable and renewable materials can bring about great benefit to economics and environment. Sugarcane bagasse is a fibrous residue produced in large quantities by the sugar and alcohol industrials up to 20 million tons per year in Thailand. The main composition of bagasse residue is cellulose; therefore, it can be effectively used as reinforcement in bio-based composite materials. In this research, the composites of sugarcane bagasse reinforced in wheat gluten were prepared by a thermo-molding technique at 130 C° and 60 tons for 10 min. Bagasse residue with three different ranges of particle size i.e. <250 μm, 250-500 μm, and 500-2500 μm was used to prepare the composites. It was found that the bulk density of all composites with bagasse particles of different sizes was close in range of 1.31-1.35 g/cm^3. However, the flexural strength and strain at break of the composites tended to decrease when size of the bagasse particles used was increased. The series of SEM images indicated that the composite prepared with the smallest bagasse particles had the best interfacial adhesion with the matrix. This allowed the largest extension before failure which accordingly led to the highest strength and toughness in this composite. In contrast, the modulus of elasticity of the composites showed an increasing tendency with integration of the larger bagasse particles. It is possible that the higher rigidity of the larger bagasse particles contributed a stiffer behavior to the composites.

Keywords: bio-based composites, sugarcane bagasse, wheat gluten, mechanical properties, scanning electron microscopy

Introduction

There has been an increasing trend towards utilizing agro-industrial residues, such as sugarcane bagasse, as feedstock to develop biodegradable and renewable materials. With this approach, great benefit to economics and environment would gain without conflicting with food and energy production (Sun et al. 2004a; Zhang et al. 2014). Sugarcane bagasse is a fibrous residue produced in large quantities by the sugar and alcohol industrials. Typically, bagasse residue is produced about 32% of every tons of sugarcane after juice extraction (Lee and Mariatti 2008). In Thailand, from database of the Department of Industry, the amount of sugarcane bagasse produced is up to 20 million tons per year (OK nation. 2008). The bagasse residue generally has a large distribution in size and a great morphological heterogeneity, consisting of fibers bundles and other hollow structural elements. About 40-50% of the bagasse residue is cellulose (polymer of glucoses) in a semi-crystalline structure. Another 25-35% is amorphous hemicellulose and the remainder of roughly 25% is mostly lignin with a

cross-link or network structure (Sun et al. 2004b; Xu et al. 2010). From its composition, bagasse residue is considered to be one promising alternative to use as reinforcement in bio-based composite materials. Hence, the purpose of this research was to prepare the bio-based composites of sugarcane bagasse reinforced in wheat gluten-based matrix. Wheat gluten, a by-product of wheat starch industry, is another interesting choice as raw material for bio-based materials due to its renewability, abundant availability, low cost, biodegradability, and unique network forming properties (Jansens et al. 2011; Montano-Leyva et al. 2013). The influence of different bagasse particle sizes on structure and properties of the bio-based composites was investigated in this study.

Materials and methods

Materials

The bagasse residue was kindly supplied by Mae Wang Sugar in Lampang Province, Thailand. The bagasse residue was sieved into three ranges of particle size i.e. <250 μm, 250-500 μm, and 500-2500 μm. Then, the bagasse residue was dried to remove moisture in a hot-air oven at 80°C for 10 min and kept in an air-tight container. Vital wheat gluten was purchased from Zhangjiagang Hengfeng Starch Products Co. Ltd., China. Glycerol used was of commercial grade (Unionscience Co. Ltd., Thailand).

Preparation of bio-based composites

Bagasse residue, wheat gluten, and glycerol were hand-mixed until homogeneous for approximately 10 min. The ratio of bagasse residue (dispersed phase) to wheat gluten and glycerol (matrix phase) was 5:5 in weight, while the ratio of wheat gluten to glycerol was 7:3 in weight. The bagasse residue with different size (<250 µm, 250-500 µm, and 500-2500 µm) was used to prepare each mixture. After mixing, the resultant materials were compression molded (Labtech LP-S-80) at 130°C and 60 tons for 10 min. Before testing, the samples were conditioned at relative humidity of 50±5% in a chamber of saturated $Mg(NO_3)_2$ solution at 25°C (according to ASTM E104) for 40 h.

Density

A free-flowing bagasse residue was filled to the known volume container of 416.7 cm^3 (V) and then weighed (M). Bulk density (D) of the bagasse residue with different ranges of particle size was then calculated according to D = M/V in unit of g/cm^3. For bulk density of the bio-based composites, the samples were weighed using a 4-digit balance (Denver Instrument, SI-234) and measured for their dimensions (length, width, and thickness) using a digital caliper (TCM). The bulk density (D) of the composites was then calculated according to their weights and volumes.

Mechanical properties

The flexural test (4-point bending) of the composites was performed on a universal testing machine (Instron 5560) equipped with a load cell of 1 kN according to the standard method ASTM D6109-13. The rate of crosshead motion was 2 mm/min. Given flexural strength, modulus of elasticity, and strain at break (%) are the means of five replicates for each bio-

based composites. Standard deviation was also calculated and the results were expressed in mean ±SD.

Scanning electron microscopy (SEM)

The surface morphologies of the bagasse particles as well as the fracture surfaces of all composites after failure under flexural test were examined by scanning electron microscope (SEM) LEO 1450 VP with 10 kV accelerating voltage. All sample surfaces were sputter coated with gold before SEM observation.

Results and discussion

Morphological observation of the bagasse residue

Figure 1 shows SEM photos of the bagasse residue with three different ranges of particle size (<250 μm, 250-500 μm, and 500-2500 μm). It can be observed that in each range, bagasse particles were not homogeneous in size, shape, and appearance. For the lagre particles, the hollow tube structure of the bagasse residue can be obviously seen (Figure 1d).

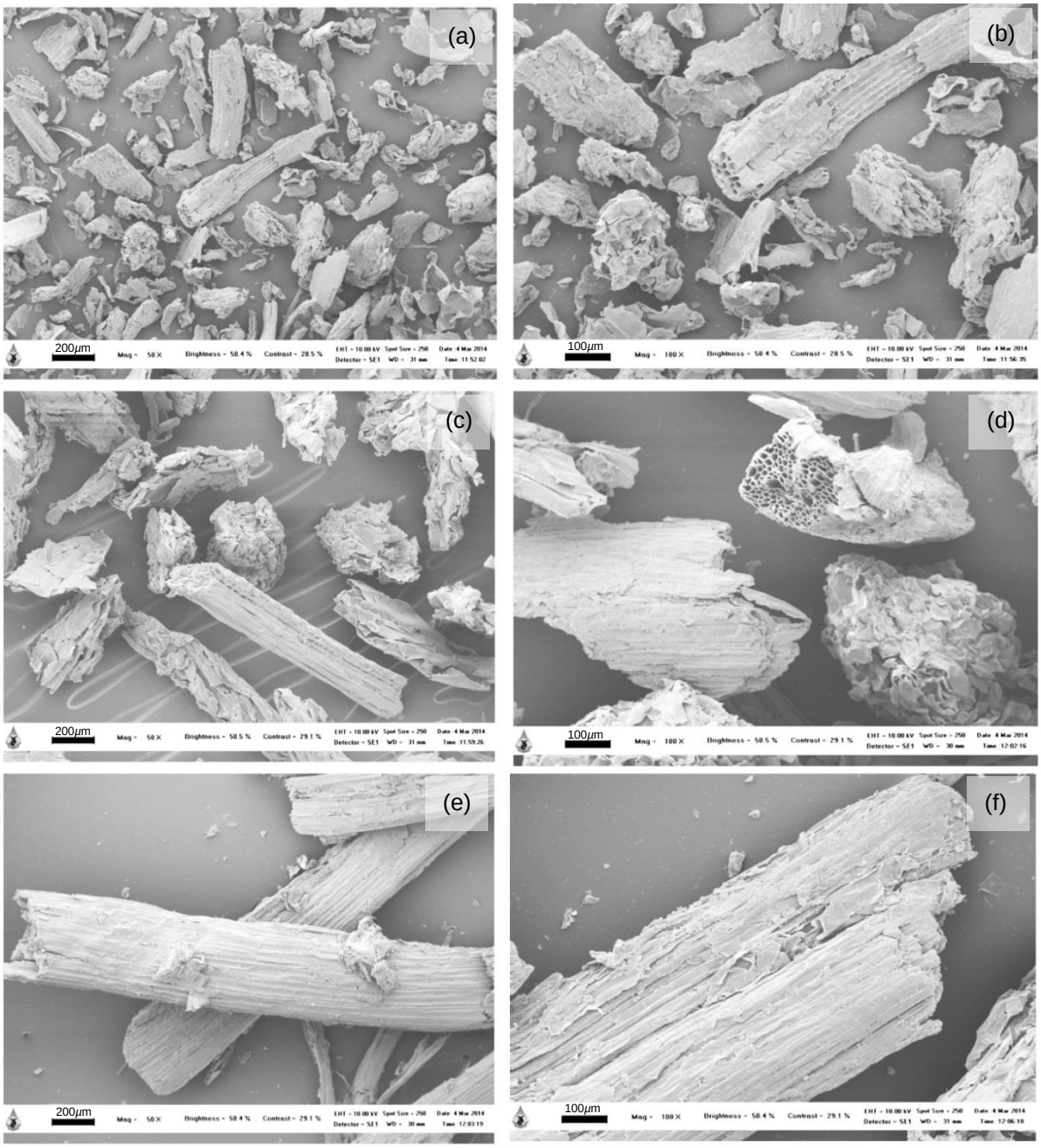

Figure 1: SEM images of bagasse residue of particle size (a-b) <250 μm, (c-d) 250-500 μm, and (e-f) 500-2500 μm.

Bulk density of the bagasse residue and its bio-based composites

It was found that the smallest bagasse residue had the highest bulk density as expected (see Table 1) since the smaller particles generally possess a greater ability to compact themselves. In the bio-based composites, the similar trend was observed. The density of the composites decreased with increasing bagasse particle size. The composite prepared with the smallest bagasse particles presented the highest density. However, the values of bulk density of all composites are close in range of 1.31-1.35 g/cm^3.

Table 1: Bulk density of the bagasse residue and mechanical properties of the bio-based composites

Particle sizes (μm)	Bulk Density (g/cm^3)		Strength (MPa)	Modulus (MPa)	Strain at break (%)
	Bagasse residue	Composites			
< 250	0.164±0.001	1.354±0.028	15.33±0.21	1466.20±36.40	2.51±0.12
250-500	0.130±0.001	1.322±0.021	14.13±0.45	1599.94±47.84	2.18±0.12
500-2500	0.117±0.023	1.312±0.027	13.02±0.95	1620.68±189.65	2.10±0.36

Mechanical properties of the bio-based composites

From the results of flexural test, the bio-based composites prepared with the three different ranges of bagasse particle size exhibited similar mechanical properties as shown in Table 1. The flexural strength and strain at break of the composites tended to reduce when the bagasse particles used were in larger size. On the other hand, the modulus of elasticity was likely to increase with the larger bagasse particle sizes.

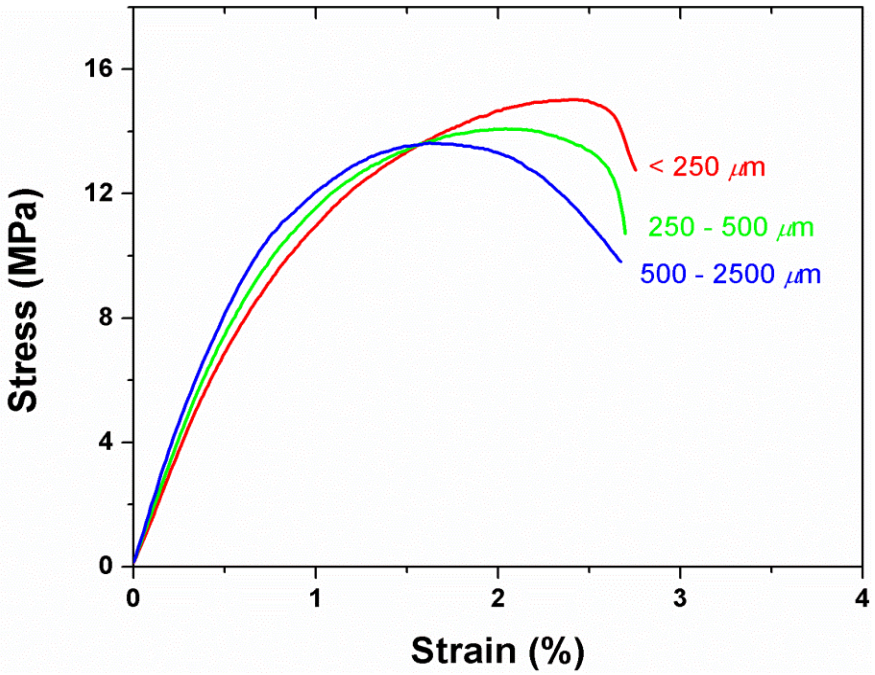

Figure 2: Stress-strain curves of the bio-based composites prepared with the three different ranges of bagasse particle size.

Stress-strain curves of the bio-based composites are shown in Figure 2. It can be seen that the composite prepared with the smallest bagasse particles exhibited the highest strength and strain at break. Possibly, the smallest particles (possessing the highest surface area) could provide the best interfacial adhesion with the matrix phase (wheat gluten/glycerol), leading to

the greatest degree of extension before failure. This allowed the composite to withstand larger amount of force or higher stress and hence being a stronger and tougher composite material. Meanwhile, the composite prepared with the largest bagasse particles showed the highest modulus and also the lowest strain at break (or flexibility). Perhaps, larger bagasse particles possessed higher rigidity which then contributed to the composite behavior, leading to a stiffer and more brittle character of the material as shown in Figure 2.

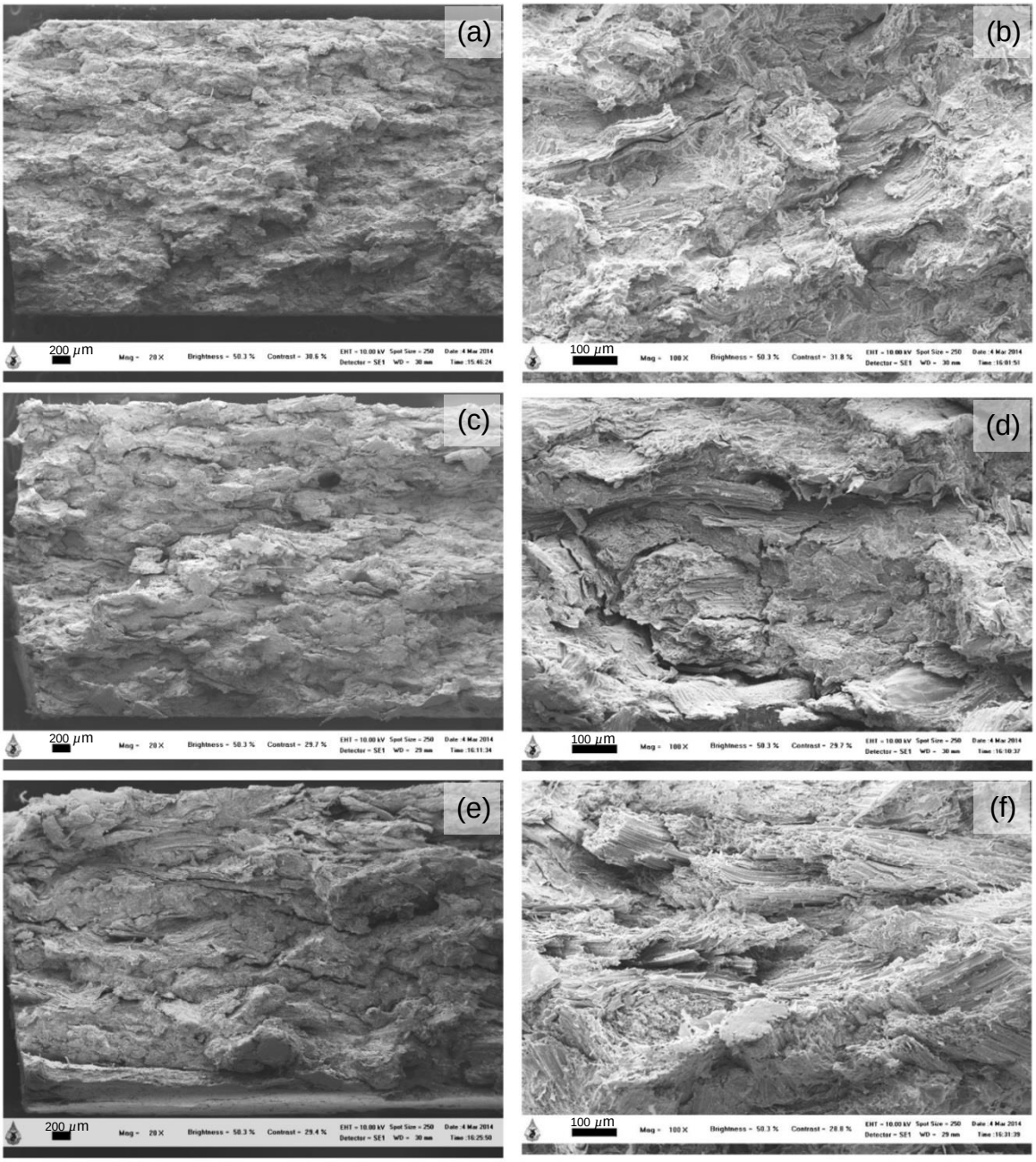

Figure 3: SEM images of fracture surfaces of the bio-based composites prepared bagasse residue of particle size (a-b) <250 μm, (c-d) 250-500 μm, and (e-f) 500-2500 μm.

Fracture surface characterization

An examination of the fracture surfaces of bio-based composites was conducted to investigate failure behavior and interfacial adhesion between the bagasse residue and matrix phase. For the composite prepared with the smallest bagasse particles (Figure 3 a-b), only very short fiber pull-outs were observed and no large hole could be noticed on the fracture surfaces, indicating a stable interface in this composite. This result was in line with the mechanical test result which suggested the best interfacial adhesion in this sample. Besides, the fact that the smallest particles would certainly have the highest surface area to bond with the matrix phase. With the larger bagasse particle sizes, the fracture surfaces of the composites showed longer fiber pull-outs and some deeper holes were also observed (Figure 3 c-f). As have been previously reported in many works, this was typically indicative of a weak interface in the composites (Diao et al. 2014; Hemsri et al. 2012; Song and Zheng 2009). Consequently, the strength of these composites prepared with the larger particle sizes of bagasse residue was found to decrease.

Conclusion

It was found that the particles of bagasse residue were inhomogeneous in size, shape, and appearance. The smaller bagasse particles had the higher bulk density as well as their corresponding bio-based composites due to a greater compaction. However, the bulk density of all composites prepared with three different ranges of bagasse particle size; i.e. <250 μm, 250-500 μm, and 500-2500 μm, was observed to be close in range of 1.31-1.35 g/cm^3. These bio-based composites also exhibited similar mechanical properties. Nevertheless, it was found that the flexural strength and strain at break of the composites tended to decrease when the bagasse particle size was increased. Conversely, the modulus of elasticity of the composites presented an increasing tendency with the larger bagasse particles. SEM results indicated that the composite prepared with the smallest bagasse particles had the best interface between the bagasse residue and matrix (wheat gluten and glycerol). This might be the reason for the largest extension before failure which allowed the highest strength and toughness in this composite. Meanwhile, the composite prepared with the largest bagasse particles exhibited the highest modulus. Possibly, the higher rigidity of the larger bagasse particles contributed to this stiffer mechanical behavior of the composite.

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