Flexural and fractography behavior of unsaturated polyester composite filled with bangkirai wood fiber

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A B S T R A C T

In this work, we report the modification of the woods by increasing their mechanical properties in a composite structure. Wood that is formed into tables, chairs, cabinets, etc. there are remnants such as powder, sawdust after production. This rest, called waste, if used properly, will produce its benefits. However, for wood waste to be useful as a new product, its strength must be tested. The focus of this research is wood waste, such as bangkirai wood, which needs to be strengthened. The focus of this study is wood waste, such as bangkirai wood that required to be mechanically improved. Composite technology derived from natural fibers in wood is the solution to find new materials that are expected to be applied to various applications. In this observation, the composite materials were made using the hand lay-up method with variations in filler fractions of 40% and 60% of bangkirai fiber. The origin material formed bangkirai wood is used as the control variable in the flexural test. The flexural test results obtained the highest average modulus of elasticity of 2.22 GPa in the 60% filler fraction. It is also found that fracture patterns from flexural tests based on scanning electron microscopy (SEM) observations showed that there was a failure in the form of voids. It concludes that the higher the filler fraction, the higher the modulus of elasticity.

A B S T R A K

Pada penelitian ini, kami melaporkan modifikasi kayu dengan meningkatkan sifat mekanisnya dalam struktur komposit. Kayu yang dibentuk menjadi meja, kursi, lemari, dan lain-lain terdapat sisa-sisa seperti serbuk (*sawdust*) setelah produksi. Sisa ini yang disebut limbah bila dimanfaatkan dengan baik akan menghasilkan keuntungan tersendiri. Namun, agar limbah kayu bermanfaat menjadi produk baru, perlu diuji kekuatannya. Fokus penelitian ini adalah limbah kayu seperti kayu bangkirai yang perlu ditingkatkan kekuatannya. Teknologi komposit yang berasal dari serat alami dalam kayu adalah solusi untuk menemukan bahan baru yang diharapkan dapat diterapkan pada berbagai aplikasi. Dalam observasi ini, material komposit dibuat menggunakan metode *hand lay-up* dengan variasi fraksi *filler* 40% dan 60% serat bangkirai. Bahan asal yang dibentuk kayu bangkirai digunakan sebagai variabel kontrol dalam uji tekuk. Hasil uji tekuk diperoleh rata-rata modulus elastisitas tertinggi yaitu 2,22 GPa dalam fraksi *filler* 60%. Selain itu ditemukan bahwa pola fraktur dari uji tekuk berdasarkan pengamatan *scanning electron microscopy* (SEM) menunjukkan bahwa ada kegagalan dalam bentuk rongga. Dari penelitian ini, dapat disimpulkan bahwa semakin tinggi fraksi *filler* mengakibatkan semakin tinggi nilai modulus elastisitasnya.

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1. Introduction

People throughout the world have widely used various wood for thousands of years. The construction of high buildings of wood increases with the headway of buildings. Woods are the only important building material planted on the ground and good for the environment. Several kinds of woods are produced in the forest throughout the world. The wood is used in large and small buildings. The potential for broader use of wood as a construction material is very important. Increasing wood used does not need to raise concerns regarding deforestation as long as it is sourced from responsibly managed forests. Forests are part of the supply chain of softwood and hardwood used in the construction industry. Wood is the only widely used building material that can be considered genuinely sustainable [1].

Waste from the wood processing industry in the form of sawdust has not been widely used or has not been utilized optimally. Non-wood raw materials are widely used with consideration because they contain many hemicelluloses, which is known to have a significant role in the auto-glueing mechanism. Research using wood materials done by Okamoto et al. using a mixture of softwood and hardwood fibers using steam injection presses was conducted [2].

Kalimantan has abundant natural resources in the forestry sector, such as timber, which is diverse from many types of wood used. In East Kalimantan, Indonesia has very abundant wood, and some of it is used as biomass. Most species of woody plants in this area are fast-growing and utilized for the production of fibers, such as pulp and paper [3]. As a biodegradable material, of course, with these conditions, it will produce a lot of residual production waste and its potential needs to be utilized other than as biofuel. One of the wood in East Kalimantan is bangkirai (*Shorea laevifolia endert*). Bangkirai wood has a high selling price because of its excellent durability. It is widely used for household needs, such as furniture and frames. Wood manufacture produces wood waste such as sawdust that can be utilized. Based on research from Rizki Kacida Reana Company, Paser Regency, East Kalimantan Province, the percentage for bangkirai wood waste is 18.09% [4]. Considering the price of wood is expensive. If waste is not utilized optimally, it will be very detrimental.

Composite materials are used frequently in every way, including spacecraft, aeroplanes, automobiles, boats, sports equipment, bridges, and buildings. The use of composite materials widespread in the industry is due to the characteristics of the strength. These improved characteristics are believed to use the latest technology and various manufacturing methods to increase the range of applications. The term composite can mean broad if taken at all materials consist of different components when viewed closely. However, in the engineering of modern materials, this term usually refers to "matrix" material reinforced with fiber. Heterogeneous materials were combining the best aspects of dissimilar. The fiber is the main part in terms of holding the load. While the purpose of the matrix is to provide shape and form to protect the fibers from structural damage and adverse chemical attack, to distribute stress, and to provide toughness. The matrix also stabilizes the composite against bending in compressive loading situations [5]. With material technology, wood waste can be combined with a matrix and form a material called composite. Composite materials in this study use polyester. Polyester resins are widely used because of the binding ability to natural fibers without causing reactions and gases and low prices with good characteristics as a matrix. Polyesters are mostly chosen because of their easily fabricated, light, strong, and corrosion resistance. Using a reinforcing fiber to produce unsaturated polyester composites enhances the tensile and flexural properties [6].

Whereas the bangkirai wood powder waste (*Shorea laevifolia endert*) was chosen because it has good durability so that it is utilized maximally to be used as something useful. Previous research on structural component applications showed that bangkirai wood, when made into concrete-wood composites, showed higher strength (modulus of elasticity of bending value of 18.7 GPa) than camphor wood (*Cinnamomum camphora*) [7]. In the same application, research had been carried out on bangkirai concrete-wood composite plates with sliding joints using steel pegs and keruing wooden boards. The results conducted from the flexural test obtained the value of the flexural stiffness of 1.56 kN/mm [8]. The research from Laksono et al. concerning the effect of alkalization with the same sample, bangkirai-polyester composite, showed that the value of optimal bending strength occurs in the alkalization treatment of 5% with a value of 65.63 MPa [6]. However, it is not yet apparent what role the volume fraction of the filler has on the bending strength value. The previous studies prove that bangkirai wood has the potential to be developed into better composite materials for various applications.

The purpose of this study, in general, is to utilize the abundant bangkirai wood waste in East Kalimantan to be an environmentally-friendly finished product, such as wall panels and sound absorber. The specific one was to determine the various volume fraction effect of the elastic modulus of bending and the morphology of composite fractography that would be supported using the Scanning Electron Microscope (SEM).

2. Research Methodology

2.1. Moisture testing

This test serves to determine the moisture content of bangkirai wood powder, which is used as a composite filler. The testing of moisture content is intended to determine the parameters of the drying of bangkirai fiber waste. Tests were conducted at the Faculty of Forestry, Mulawarman University, Samarinda City. The testing stages include preparing bangkirai wood powder, which has been sieved with a size of 40 mesh or size of about 425 μm. The obtaining data is processed with the following equation where WA is water absorption (%), Ww is wet weight, and Dw is the dry weight. The equation (1) explains that it is a dry basis or a percentage of water absorption [6].

$$WA = \frac{(Ww - Dw)}{Dw} \times 100\% \qquad (1)$$

2.2. Natural bangkirai wood powder preparation

Bangkirai wood powder is prepared as a filler to be used. Preparation of wood powder size is the same as when testing moisture, content, and then dried with drying parameters after obtaining water absorption data on bangkirai wood powder waste. The dried powder is then weighted based on the volume fraction of the fiber.

2.3. Mold making

The mold design is adapted to the ASTM D 790 international standard, as shown in Figure 1. Infraboard made of bending test molds, as in Figure 1. The finished mold is coated with aluminum foil so that the resin does not stick and does not enter the mold cavity.
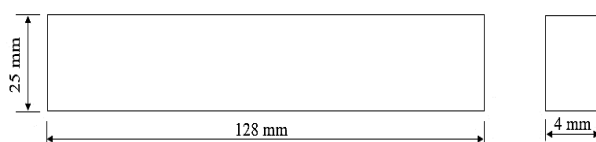

Figure 1. Sample dimensions based on ASTM D 790.

2.4. Composite manufacturing

Composites manufacturing was done by the hand lay-up method. The variations used in this study were composites with bangkirai wood powder volume fraction of 0%, 40%, 60%, and 100% with the unsaturated polyester matrix. The first step was to prepare a mixing container of unsaturated polyester resin, bangkirai wood powder, and a catalyst that will be made into a composite. The catalyst used is from Chemika Surabaya, which functions as curing; thus, the resin hardens faster. Unsaturated polyester resin with bangkirai wood powder are mixed and added with six drops of a catalyst into the container then stirred until well blended. The mixing results were poured into a mold and flattened using a roller. Then the composite was dried at 25° Celsius for a few days. After drying, the composite was taken, and dimensional validation was carried out according to ASTM D 790 standards. The composite products that had excess dimensions were smoothed using 80-1000 grade sandpaper. The results of composites manufacturing, as seen in Figure 2.
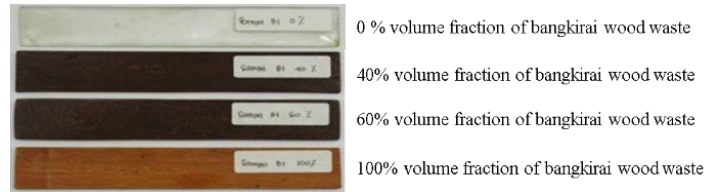

Figure 2. Bending test samples with varying volume fractions of bangkirai wood waste.

2.5. Bending testing

This test serves to determine the elastic modulus of the composite that has been made based on ASTM D 790 standards. Modulus of elasticity of test samples was measured by ASTM D790 by Equation (2) [9].

$$MOE = \frac{L^3 m}{4bd^3}$$ (2)

Where:

MOE = Modulus of Elasticity in bending
L = Gauge Length
m = Slope of the tangent to the initial straight-line portion of the load-deflection curve of the deflection
b = Width
d = Depth

Tests are carried out at the Surabaya Industrial Research and Consultation Agency. Composite samples are subjected to bending testing with a load.

2.6. Fractography

The purpose of fractography testing is to analyze failures after bending tests in the form of fracture patterns with morphological observations using optical microscopy and Scanning Electron Microscope (SEM; Hitachi TM 3000). Furthermore, it could reveal the porous structures of composite, even for the nanometer-scale [10]. Tests carried out at the Biology Department Laboratory of the University of Muhammadiyah Malang using SEM machines.

3. Results and Discussion

3.1. Moisture test results

Based on the results of testing the water absorption, it was found that the bangkirai wood powder waste used as reinforcement had a water absorption of 10.09%. From the experiments, the water absorption in the bangkirai wood powder waste was lost after being heated for 30 minutes using an oven at a temperature of 115 °C.

3.2. Bending test results

A review of the mechanical properties in this test is the amount of MOE, which indicates if the material has stiffness so that it can withstand the significant stresses imposed on it without deformation [11]. The results of the MOE data are shown in Figure 3.
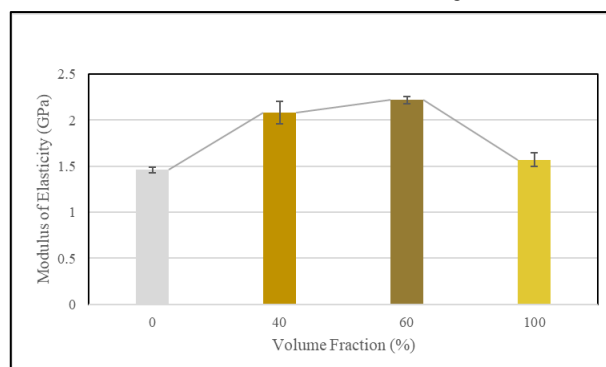

Figure 3. Bending test results graph for the various volume fraction of waste bangkirai wood-polyester matrices.

From Figure 3, the MOE results of 0%, 40%, 60%, and 100% volume filler fraction were 1.46 GPa, 2.08 GPa, 2.22 GPa, and 1.57 GPa, respectively. The data obtained that the MOE of the composite was higher than the forming material, namely in polyester (0% filler fraction) and in bangkirai wood (100% filler fraction). In this study, the particle size used was 40 mesh with a purpose to have the great surface area possessed by the composite. The more number of fillers in the composite, there will be more amplifiers that hold the load from the matrix before failure [12]. It can be seen that the filler fraction of 60% has the highest MOE. The addition of filler into the matrix aims to increase material stiffness through the effective distribution of pressure between fillers and matrices [13]. From pure polyester to 40% volume filler fraction composite can be seen that the addition of bangkirai wood powder waste filler increases the MOE value. It indicates that the filler particles have an influence on composite materials in dispersion ability and load distribution; thus, it can increase uniformity in load distribution.

Compared with previous the study, the composite reinforced pineapple fiber with polyester matrix at 40%, 50%, and 60% filler fraction has MOE value of 1.05 GPa, 1.16 GPa, and 1.43 GPa, respectively [14]. In addition, the sound-absorbing material conventionally, Rockwool, is under development using the fiber epoxy matrix. To expand Rockwool's application, it uses as a wall coating that has an average MOE of 1.13 GPa [15]. From these comparisons, it can be seen that the composite reinforced with bangkirai wood powder waste with a polyester matrix is better than previous studies because it meets the ASTM D 5319-97 standard criteria for panel walls and having a minimum value of MOE of 2.07 GPa. A previous study found that the category of the same material specimens with this research had a sound absorption coefficient class D with the range 0.30-0.55 based on ISO standard 11654. From the results, this composite material has the potential ability to absorb sound in controlling noise and possibility as a commercial sound absorber [16].

3.3. Fractography

3.3.1. Macro observation

The following is the result of the fracture from the composite bending test reinforced with bangkirai wood powder waste and polyester matrix for 40% and 60% filler fraction.
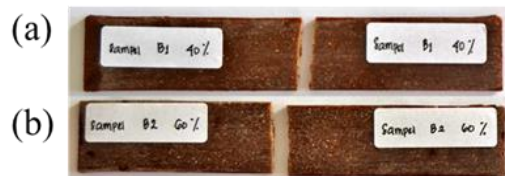

Figure 4. Filler fraction pattern of (a) 40% (b) 60%.

Figure 4 shows the results of a fractional bending test by macro observation using a mirrorless camera. Based on observation, the pattern of straight fracture is one of the fault characteristics of brittle material. Thus, the increasing filler fraction, the more brittle fracture. It was proven by the MOE value of 60% filler fraction, so that the higher the MOE, the more brittle becomes.
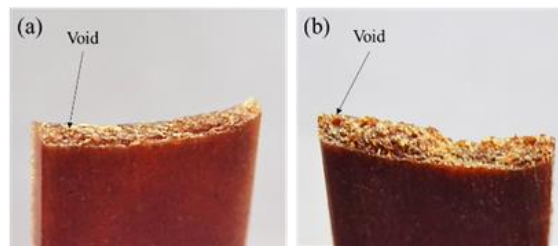

Figure 5. Fractography bending test results for (a) filler fraction 40% and (b) filler fraction 60%.

Figure 5 shows the results of fracture from bending testing. In the filler fraction of 40% and 60%, which is a brittle fracture, fine grains on the fracture surface of the specimens are seen beside the void. By increasing the number of filler fractions, the making of composites is relatively more difficult. As a result, it produces more and more voids. Voids are air bubbles that are trapped when making a composite process is one of the weaknesses of the hand lay-up method [17]. In other words, the fractographic discussion explains that the cavity that occurs will affect the decrease in flexural strength in composites. The existence of the cavity showed the stress concentration, which starts the crack initiation [18]. In failure modes of composite, crack propagation inevitably leads to abrupt brittle fracture for weak interface [19]. Further research needs to be done in the more advanced methods of hand lay-up, such as vacuum bagging process, vacuum infusion process, and compression molding.

3.3.2. Optical microscope observation

The following are observations using a 350 times magnification optical microscope on composite reinforced bangkirai wood waste with the polyester matrix, as seen in Figure 6.
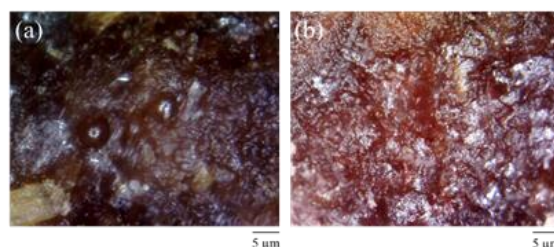

Figure 6. Observation results of microscopy after fracturing in filler fraction of (a) 40% and (b) 60%.

Micro-observation was carried out for the morphology of the material that had undergone bending testing. The results of micro-observations show the effect of fillers on the MOE of composite materials. Bangkirai wood waste is more likely to have a more even distribution of the highest filler fraction, which is 60%, causing a high MOE. The bonding of the polyester matrix also results in higher MOE in composite materials.

3.3.3. SEM observation

The following are the micro-observation results using a Scanning Electron Microscope (SEM) with 1,500 times magnification on composite reinforced bangkirai wood waste with a polyester matrix.
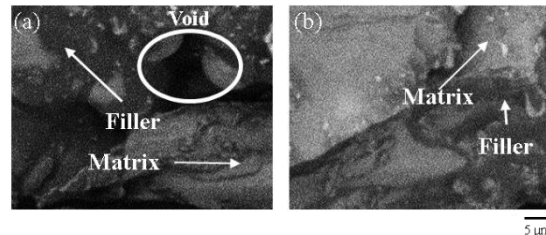

Figure 7. SEM observations after bending tests on filler fraction (a) 40% and (b) 60%.

SEM observations show that there is a void in the 40% and 60% filler fraction, which indicates that air bubbles were trapped, thereby as a cavity in a polyester composite reinforced with bangkirai wood powder waste. Figure 7(b) shows that the filler fraction of 60% has no void than the 40% filler fraction. It assumed that the higher the filler fraction, the lower the void formed. Thereby the MOE value obtained will increase. From this, it can be known that voids affect mechanical properties, especially their stiffness. The void is an unavoidable thing in making composites, mainly if you use the hand lay-up method because it interacts directly with open air. However, it can minimize its formation because the matrix does not bound the filler in the void part. While the matrix will always transfer the load to the reinforce. If the composite receives a load, the stress area will move to the void area and cause cracks so that the composite will be failure early. In addition, void content depends on the degree of fiber orientation [20]. In this case, the orientation of the composite direction was random and probably affected the configuration of voids. To analyze the number of voids that were seen in the fracture pattern, smaller magnifications were needed. In SEM observation, void areas appear in darker colors, which means areas that have depth, so it's less for reflecting light. Based on quantitative analysis with the calculation of the number of voids, the filler fraction of 40% has more voids than the filler fraction of 60%, as seen in Figure 8.
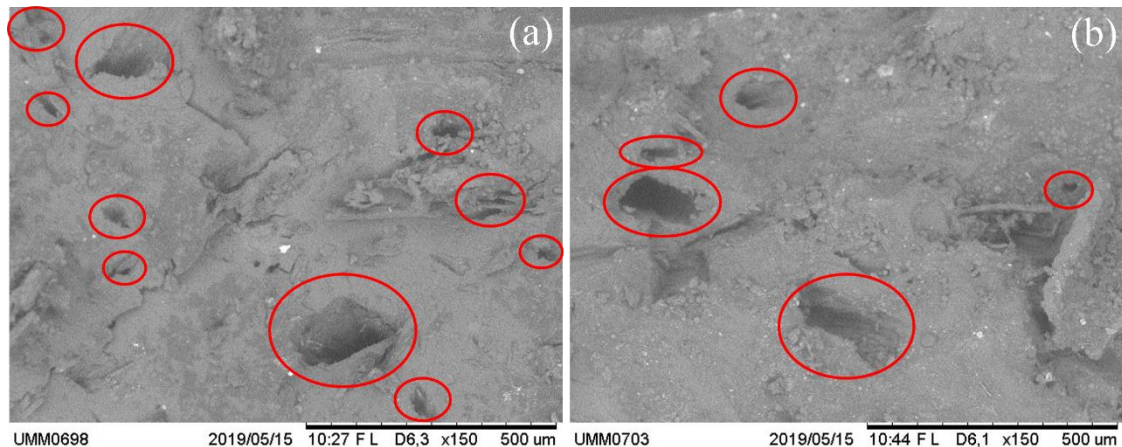

Figure 8. Observation of SEM at 150x magnification for the void mark on the red circle mark on (a) 40% and (b) 60%.

4. Conclusion

Utilization of bangkirai sawdust waste as new material needs to be optimized. With enhance new composite technology, the right combination of matrix and reinforced, and volume fraction needs to be further developed. The combination of unsaturated polyester matrices with bangkirai wood powder can increase the MOE to bending using the hand lay-up method. In this study, the highest average MOE of the composite bending test reinforced with bangkirai wood, powder waste with polyester matrix was 2.22 GPa at 60% filler fraction. The results of the bending fracture of bangkirai composites, according to SEM observations, shown the voids formation. It can be concluded that an increase in the volume of filler fraction results in an increase in the MOE to bending and a decrease in the number of voids. In addition, 60% volume fraction composites already meet the requirements for the MOE based on ASTM D 5319-97 wall panel applications. Thus, the bangkirai wood powder waste composite in terms of mechanical properties can be used as useful objects, such as absorbent material wall panels and, of course, needs to be supported by sound absorption testing.

Acknowledgments

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