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EFFECT OF DRYING TEMPERATURE ON THE MECHANICAL PROPERTIES OF BINDERLESS FIBERBOARD FROM BAGASSE: *STUDY OF FLEXURAL AND TENSILE STRENGTH*

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Abstract. Sugarcane remains to be one of the largest cash crops in the world. Despite its economic benefits, a large amount of bagasse generated from extraction processing ends up as an environmental issue. The utilization of bagasse as fiberboard is introduced as an alternative waste management. However, nowadays, fiberboard is commonly produced by adding chemical adhesive, such as Urea-formaldehyde resin, which is harmful to living things. The current research was conducted to study and produce environmentally friendly fiberboard by relying only on lignocellulose due to hydrogen bond formation. The methods used consisted of cutting, soaking, refining, concentration determination, and forming with various drying temperatures of 110ºC, 130ºC, 150ºC, 170ºC, and 190ºC. Characterizations of flexural and tensile strength were carried out to investigate the feasibility of fiberboard based on the standard of JIS A 5905 (2003). The calculations show that the increase in drying temperature from 110ºC to 190ºC increased the flexural and tensile fracture stress by 24.12-36.87 MPa and 12.89-19.77 MPa respectively with both maximum values obtained by fiberboard 190ºC. By considering the density and moisture content of fiberboards which ranged from 1.0210-1.0164 g/cm^3 and 6.19-4.19% respectively, the results indicate that only fiberboard 110ºC, 130ºC, and 150ºC meet the standard of JIS A 5905 (2003) for high-density fiberboard (HDF) with type of S20 and S25. HDF has applications for exterior siding, interior wall, paneling, and household furniture.

Keywords: bagasse, fiberboard, hydrogen bonding, drying temperature, mechanical strength

Abstrak. Tebu merupakan salah satu tanaman komersial terbesar di dunia. Terlepas dari manfaat ekonominya, sejumlah besar ampas tebu yang dihasilkan dari proses ekstraksi berakhir sebagai masalah lingkungan. Pemanfaatan ampas tebu menjadi papan serat diperkenalkan sebagai alternatif pengelolaan limbah. Namun, papan serat umumnya diproduksi dengan menambahkan perekat kimia, seperti Urea-formaldehid resin, yang berbahaya bagi makhluk hidup. Penelitian saat ini dilakukan untuk mempelajari dan memproduksi papan serat yang ramah lingkungan dengan hanya mengandalkan konten lignoselulosa melalui pembentukan ikatan hidrogen. Metode yang digunakan terdiri dari pemotongan, perendaman, pembuburan, penentuan konsentrasi, dan pembentukan (pengepresan dan pengeringan) dengan berbagai temperatur pengeringan sebagai variabel bebas, yaitu 110ºC, 130ºC, 150ºC, 170ºC, and 190ºC. Karakterisasi kekuatan lentur dan tarik dilakukan untuk menyelidiki kelayakan papan serat berdasarkan baku mutu JIS A 5905 (2003). Hasil penelitian menunjukan bahwa peningkatan temperatur pengeringan dari 110ºC sampai 190ºC meningkatkan tegangan putus lentur dan tarik sebesar 24,12-36,87 MPa dan 12,9-19,77 MPa dengan nilai maksimum keduanya

diperoleh oleh papan serat 190ºC. Dengan mempertimbangkan densitas dan kadar air papan serat yang berkisar 1,0210-1,0164 g/cm^3 dan 6,19-4,19%, hasil menunjukan bahwa hanya papan serat 110ºC, 130ºC, dan 150ºC memenuhi baku mutu JIS A 5905 (2003) untuk papan serat berdensitas tinggi (HDF) dengan tipe S20 dan S25. HDF memiliki aplikasi sebagai pelapis dinding eksterior, dinding interior, panel, dan furnitur rumah tangga.

Kata kunci: ampas tebu, papan serat, ikatan hidrogen, temperatur pengeringan, kekuatan mekanik

1. Introduction

Sugarcane is one of the largest crops in the world with a worldwide harvest of approximately 1.84 billion tons in 2017 [1]. Despite its economic benefits, a large amount of bagasse generated from extraction processing ends up as an environmental issue with estimated waste of 165.74 million tons corresponding to 9% of the total sugarcane mass, and the numbers keep growing 1.1% p.a in 2018 along with the grow of sugarcane production [1][2]. The most economical and ecofriendly way of managing bagasse shall be through enzymatic conversion, such as bioethanol, etc., but most factories prefer discarding them as agricultural waste or burning them for direct energy supply [3]. Based on environmental aspects, both practices are considered to have negative impacts by polluting air, water, and soil.

In this case, the other alternative management, which can be great solution, is by utilizing bagasse as a raw material in the making of bio-based product such as fiberboard. Fiberboard is widely known for its utility in various industries, but thus far fiberboard is commonly produced by adding chemical adhesive, such as Urea-formaldehyde resin ($(OCNHCN_2NH)_n$), to strengthen the structure. If the adhesive is heated, the vapor may occur and become harmful for the health of living things around [4]. Eventually, this will be considered as another environmental issue.

Recent studies show that fiberboard can be produced without adding adhesive through wet-forming process. The structural strength of fiberboard only relies on the role of lignocellulose, especially cellulose, by means of hydrogen bonding formation. There are several research papers studying the mechanical strength of binderless fiberboard with various biomass and forming conditions, such as rice straw with various drying temperatures (J. Zhang, 2016), corn straw with various pressures (T. Wu, 2015), and so on [5][6]. However, the study on bagasse as the raw material of fiberboard is relatively still few in number. Therefore, in current research, fiberboard is produced from bagasse to investigate the feasibility of its mechanical strength, specifically with drying temperature as the various forming conditions.

2. Methods

2.1 Forming Principle

Intra- and intermolecular hydrogen bond between neighboring celluloses occur between (1) the oxygen atom of hydroxyl group at C_6 and the hydrogen atom of hydroxyl group at C_2, (2) the hydrogen atom of hydroxyl group at C_3 and the oxygen atom of glucose ring, and (3) the oxygen atom of hydroxyl group at C_3 and the hydrogen atom of hydroxyl group at C_6. The bonds provide strength of 15 kcal/mol to the structure [7].

Wet-forming process is proposed because in dry state, hydrogen bond can only be formed between cellulose molecules in the range of 0.15-0.35 nm. These values are much smaller than the actual surface roughness of fiber ranging from 10-10,000 nm. Therefore, through wet-forming process, the presence of water can help cellulose molecules to extend outwards from fiber surfaces and reach the minimum required distance [8]. The mechanism is called molecular diffusion theory of Voiutskii in which cellulose molecules tend to interact more with water molecules before eventually water interference is reduced through pressing and drying to allow hydrogen bond occurs [9].

2.2 Fiberboard Making Methods

Fiberboard making consists of 5 processes, namely cutting, soaking, refining, concentration determination, and forming. Firstly, dried bagasse was broken down into chips with targeted length of 13-150 mm by using agricultural cutter machine, SU-16 Kowa. The bagasse chips were then soaked in water with ratio of chips to water of 1:70 for 96 hours in room temperature. Afterwards, beatfiner, Type-A Satomi, was used to break down chips into fibers (pulp) by pumping it through rotating blades repeatedly for 25 minutes before then being sifted with sieve mesh size of 4 mm. To assume the uniformity of fibers in all fiberboards, 5 samples of 100 ml of fibers were dried in laboratory oven under temperature of 110ºC for 24 hours. The fiber concentration was obtained at 0.035 gr/ml. Forming was then carried out by using hot-press machine, RH-50 Tsushima. 500 ml of fibers were poured into metal mold with holes of 2 mm in diameter, inter-hole matrixes of 7 mm, and dimension of 100x100x40 mm (in length, width, and depth) before being stacked with the rest of molding tools in. Afterwards, 5 MPa of loads were then applied to the stacked mold tools while being heated for 2 hours with various drying temperatures of 110ºC, 130ºC, 150ºC, 170ºC, and 190ºC.

Figure 1. Process of making binderless fiberboard

2.3 Fiberboard Testing Methods

Density of fiberboard was determined with JIS A 5905 using 2 samples from each drying temperature with dimension of 10x10 cm in length, as seen in Figure 2. The mass, thickness, and length of samples were measured. The result was then calculated using Equation 1 [10]:

$$\rho = \frac{m}{V} \quad (1)$$

where ρ is density (g/cm^3), m is mass (g), and V is volume (cm^3).

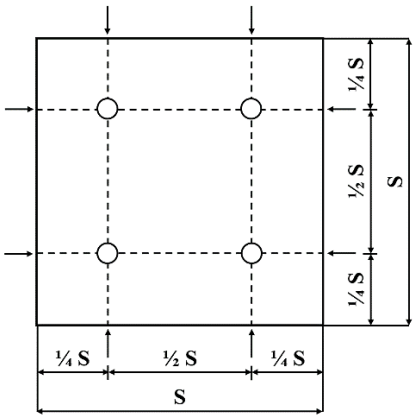

Figure 2. Appearance of test sample for density, water absorption, swelling, and absorption kinetic and its measurement point

Moisture content of fiberboard was determined using 2 samples of used flexural and tensile test samples from each drying temperature. The mass of samples was measured both before and after drying under temperature of 103ºC for 24 hours. The result was then calculated using Equation 2:

$$MC = \frac{m_1 - m_2}{m_1 - m_0} \tag{2}$$

where MC is moisture content (%), m_0 is mass of container (g), m_1 is mass of container and sample before drying (g), and m_2 is mass of container and sample after drying (g).

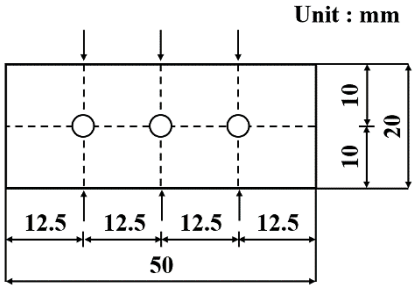

Figure 3. Appearance of flexural test sample with ratio modification and its measurement point

Flexural and tensile strength of fiberboard were determined with JIS A 5905 using 4 samples and 3 samples respectively from each drying temperature with the condition shown in Figure 3 and 4. Firstly, the initial width and thickness of samples were measured. Then, the applied load and displacement of samples were measured into data logger during testing. UTM, SVZ-200NB, was used and set with support span of 4 cm (only for flexural test), maximum load of 500 N, and load speed of 10 mm/min. The result was then calculated using Equation 3, 4, 5, and 6 [10]:

$$\sigma_f = \frac{3PL}{2bT^2} \tag{3}$$

$$\epsilon_f = \frac{6DT}{L^2} \tag{4}$$

$$\sigma_t = \frac{P}{bT} \tag{5}$$

$$\epsilon_t = \frac{\Delta l}{l} \tag{6}$$

where σ_f is flexural stress (MPa), ϵ_f is flexural strain (%), σ_t is tensile stress (MPa), ϵ_t is tensile strain (%), P is applied load (N), D is maximum displacement of the center of sample (cm), L is support span (cm), b is width of sample (cm), T is thickness of sample (cm), Δl is displacement of gauge length (cm), and l is initial gauge length (cm).

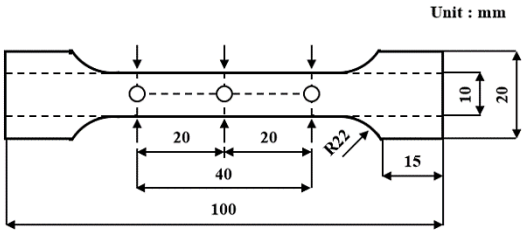

Figure 4. Appearance of tensile test sample and its measurement point

3. Results and Discussion

3.1 Density

The calculation results show that the increase in drying temperature from 110ºC to 190ºC slightly decreased the density of fiberboards by 1.0210 g/cm^3 to 1.0164 g/cm^3 (see Figure 5). The results indicate that the relationship between drying temperature and density is inversely proportional, and all fiberboards are high-density fiberboard (HDF) and meet all classifications of standard board, namely S20 (≥0.80 g/cm^3); S25 (≥0.80 g/cm^3); and S35 (≥0.80 g/cm^3), based on JIS A 5905 [10]. This typical density of fiberboard has applications for exterior siding, interior wall, paneling, and household furniture [11].

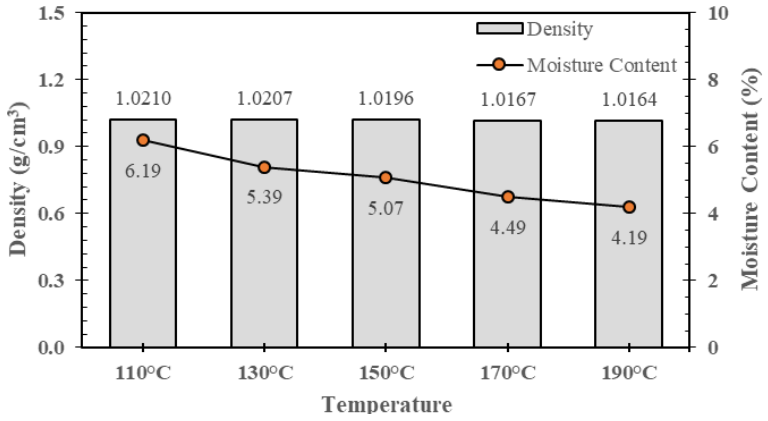

Figure 5. Effect of various drying temperatures on density and moisture content

According to Basu (2013), the drying process leads to mass loss of biomass material through moisture removal and slight decomposition at temperature of 100-200ºC [12]. Meanwhile, according to Dinwoodie (2000), if woody material loses its moisture below fiber saturation point (FSP) (≤27%; bound water region), shrinkage will occur [13]. From the theories, it implies that the outcome is caused by mass loss and volume shrinkage. Their contradictory mathematical relationship are expected to make the rate of change in density insignificant.

3.2 Moisture Content

From the calculations, the increase in drying temperature from 110ºC to 190ºC decreased the moisture content of fiberboards by 6.19% to 4.19% (see Figure 5). The results indicate that drying temperature has inversely proportional relationship with moisture content, and only fiberboard 110ºC, 130ºC, and 150ºC meet all classifications of standard board for HDF, namely S20; S25; and S35, with required moisture between 5% and 13% based on JIS A 5905 [10].

The decrease trend of moisture content is caused by the gradual evaporation. According to Basu (2013), moisture content evaporates highly in drying process taking place at 70ºC constantly until all free water in fiber cavities is driven off. After the critical temperature is reached at 110ºC, bound water within cell walls starts to evaporate [12]. In this case, the characteristic of moisture content has important role to define the other properties. As stated by Rowell (2005), the change of moisture content below FSP, which is related to bound water, can affect dimension stability and structural strength due to interference in hydrogen bond formation between organic polymers [11].

3.3 Flexural and Tensile Strength

Fracture stress and strain were investigated to represent both mechanical strengths. They were calculated from fracture points or the highest peaks in each stress-strain curve (see Figure 6). The calculation results show that the increase in temperature from 110ºC to 190ºC increased the flexural and tensile fracture stress by 24.12-36.87 MPa and 12.89-19.77 MPa respectively with both maximum values obtained by fiberboard 190ºC. Meanwhile, the flexural fracture strain increased by 1.62-1.72% from 110ºC to 150ºC and decreased by 1.72-1.63% from 150ºC to 190ºC with maximum value obtained by fiberboard 150ºC, whereas the tensile fracture strain increased by 1.30-1.77% from 110ºC to 190ºC with maximum value obtained by fiberboard 190ºC (see Figure 7 and 8). Majorly, the results indicate that drying temperature has directly proportional relationship with flexural and tensile strength. This imply that the trends of mechanical strength, as opposed to the trend of moisture content, support the influence of drying temperature which is by means of changes in water content.

Regarding to the fracture stress of flexural strength, the results indicate that all fiberboards meet all classifications of standard boards for HDF, namely S20 (≥20 MPa); S25 (≥25 MPa); and S35 (≥35 MPa), based on JIS A 5905, whereas the fracture stress of tensile strength is not used to determine the classification [10]. The fracture stress of both mechanical strengths imply the capability of fiberboard to withstand particular bending and stretching forces that is perpendicular and parallel to the longitudinal axis of fiberboard. Meanwhile, the fracture strain results of both mechanical strengths indicate that all fiberboards meet the classification of

brittle material with fracture strain less than 5% [14]. Brittle material implies that fiberboards do not deform significantly under stress before fracture due to relatively less energy absorbed. Less significant deformation occurs at low strain value. Thus, for brittle material, there is no difference between the ultimate point and the fracture point in stress-strain curve [15].

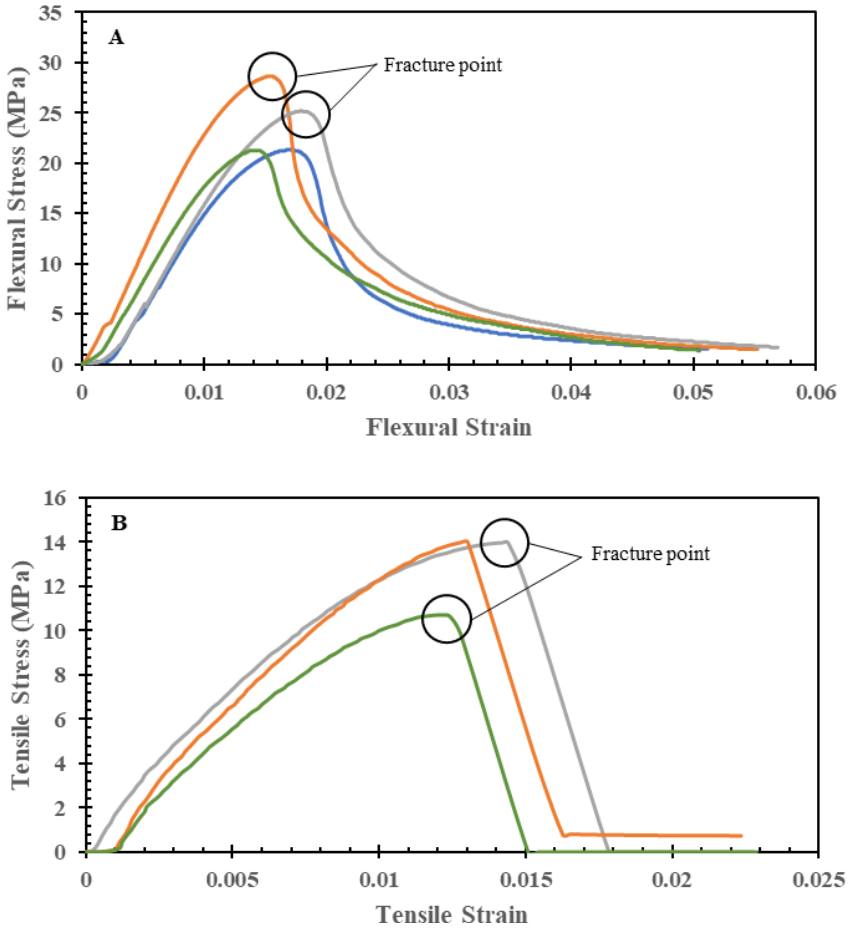

Figure 6. Stress-strain curve for fiberboard 110ºC; A). Flexural test; B). Tensile test

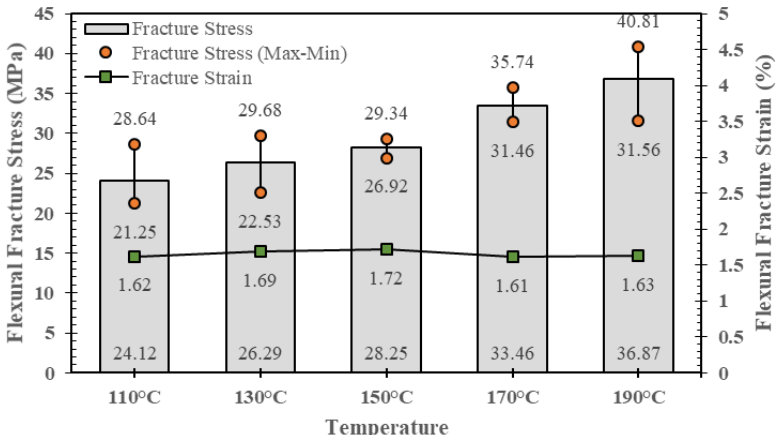

Figure 7. Effect of various drying temperatures on flexural fracture stress and strain

As previously identified, the increase trend of mechanical strength is related to the decrease of moisture content in fiberboard. As stated by Rowell (2005), thermal treatment affects strength associated with moisture loss, especially in bound water region or below FSP. Heat helps to reduce bound water interference in the formation of hydrogen bond between organic polymers, in which one of them is cellulose [11]. In addition, the increase in mechanical strength is also caused by lignin softening. According to Boon (2019), thermal treatment at certain temperature promotes the softening of lignin and allows lignin to surround fiber matrixes. Hardened lignin helps to strengthen the mechanical interlocking of the nearest fibers [16]. This is supported by Basu (2013) that lignin starts to soften at 80-90ºC and serves as binder prominently at 120-150ºC [12].

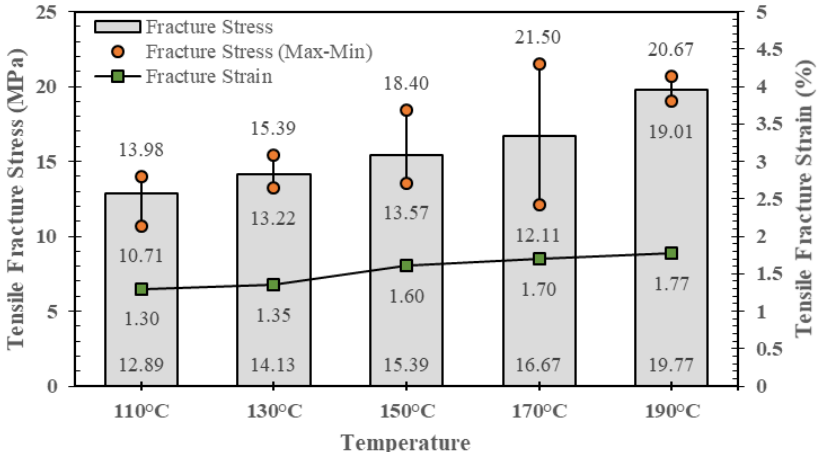

Figure 8. Effect of various drying temperatures on tensile fracture stress and strain

4. Conclusions

Fiberboards have been produced successfully by utilizing bagasse without using chemical adhesive. The properties of binderless fiberboards have also been investigated. From the results obtained, the following conclusions are drawn:

- The utilization of bagasse as binderless fiberboard with drying temperature of 110ºC, 130ºC, and 150ºC meets the standard of JIS A 5905 (2003) for high-density fiberboard with type of S20 and S25
- The most optimum drying temperature in the research is 150ºC. In average, the fiberboard has density of 1.0196 g/cm^3, moisture content of 5.07%, and flexural fracture stress of 28.25 MPa
- Regardless its significance, drying temperature has directly proportional relationship with flexural and tensile strength. On the other hand, drying temperature also has inversely proportional relationship with density and moisture content

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