Physical and Mechanical Properties of Binderless Particleboard Made from Steam-Pretreated Oil Palm Trunk Particles

Jia Geng Boon 1,*, Rokiah Hashim 2, Mohammed Danish 3 and Wan Noor Aidawati Wan Nadhari 3

1 Faculty of Bioengineering and Technology, Universiti Malaysia Kelantan, Jeli 17600, Kelantan, Malaysia
2 School of Industrial Technology, Universiti Sains Malaysia, Minden 11800, Pulau Pinang, Malaysia; hrokiah@usm.my
3 Malaysian Institute of Chemical and Bio-Engineering Technology, Universiti Kuala Lumpur, Alor Gajah 78000, Melaka, Malaysia; mdkanish@unikl.edu.my (M.D.); wan.noor.aidawati@unikl.edu.my (W.N.A.W.N.)

* Correspondence: jia.geng@umk.edu.my; Tel.: +60-99-477-922

Received: 24 February 2019; Accepted: 26 April 2019; Published: 2 May 2019

Abstract: Formaldehyde emissions from conventional particleboards raise issues of health and safety. One of the potential solutions is binderless particleboards made without using synthetic adhesives. However, the physical and mechanical properties of untreated binderless particleboards are relatively poor compared to conventional particleboards. This research aims to reveal the potential of using steam pretreatment to improve binderless particleboard properties made from oil palm trunk. The oil palm trunk particles were treated with steam pretreatment for different durations of time (20, 40, 60 min). The chemical constituents of the treated and untreated particles were evaluated. The binderless particleboards were made from treated and untreated particles. In addition, panels using untreated oil palm trunk particles with 10% urea–formaldehyde resin were made and used as a comparison. The boards were evaluated according to European Standards. The results indicated that the hemicellulose and starch content gradually reduced with the progression of steam pretreatment. The physical and mechanical properties were improved by increasing steam pretreatment duration. The steam pretreatment was able to improve the properties of binderless particleboards made from oil palm trunk. However, the performance of steam-pretreated binderless particleboard in this study is not compatible with the particleboards made using 10% urea–formaldehyde.

Keywords: binderless particleboard; steam pretreatment; oil palm trunk; self-bonding

1. Introduction

The public health concern regarding formaldehyde emissions from particleboard manufacturing using formaldehyde-based adhesives has increased since the end of the 20th century [1,2]. Many countries, especially in Europe, have strictly controlled the formaldehyde emission of wood-based products. Many researchers have begun to investigate alternative methods to overcome this issue. Throughout their efforts, besides the research on environmentally friendly adhesives such as starch-based adhesives [3–5], some researchers have proposed a new technique for making particleboards. This involves forming particleboards without using the addition of any adhesives, which are known as binderless particleboards.

The manufacture of binderless particleboards is dependent on the self-bonding properties of lignocellulosic wood particles. The self-bonding phenomenon of lignocellulosic material is due to the chemical constituents contained in the lignocellulosic material, such as sugar and lignin, that can
provide adhesive properties. Besides, the self-bonding properties of the lignocellulosic material can be formed by hydrogen bonding [6]. Since binderless particleboards are made without using any synthetic adhesives, they are theoretically safer for the end user. However, their strength could be relatively low compared to conventional particleboards.

From the scholarly journal database, oil palm trunk is revealed to be one of the popular biomass materials for binderless particleboards [7–9]. To improve the strength of oil palm trunk binderless particleboards, many fundamental studies have been carried out to reveal the factors that can influence their strength. Lamaming et al. [10] discovered the influence of sugar content on binderless particleboard formation. Boon et al. [11] discovered the influence of lignin on binderless particleboard formation. Boon et al. [12] have also revealed the effect of a few parameters, including heat, duration, and pressure, in forming coarse binderless particleboards. However, there is limited information on the effect of steam pretreatment on the formation of oil palm trunk binderless particleboards.

Steam pretreatment is a common pretreatment for biomass material. The hot steam combined with pressure alters the biomass of the material, providing changes to the wood such as (a) allowing the fibers to be opened up; (b) promoting the flow out of lignin; and (c) hydrolyzing hemicelluloses to become sugar [13]. This research proposes a new study on binderless particleboards by revealing the potential of steam pretreatment in improving the properties of binderless particleboards.

2. Materials and Methods

2.1. Material Preparation

Oil palm trunks were collected from Kampung Gajah Perak Malaysia. Trunks were left to air dry, chipped, and grounded into particles with a 2 mm aperture mesh size. Steam pretreatment on particles was performed according to Shamsudin et al. [14]. The particles were steamed using an autoclave at 160 °C and 35 psi for 20, 40, 60 min, respectively. The steamed particles were air dried to approximately 10% moisture content.

2.2. Chemical Constituent

Oil palm trunk particles with and without acid pretreatment were grounded and sieved with 40 mesh size. Sample preparation was performed according to TAPPI T 264 cm-97. Extractive composition was conducted according to TAPPI T 204 cm-97. The holocellulose composition was carried out based on the method of Wise et al. [15]. The cellulose composition was determined by dissolving hemicelluloses with 17.5% sodium hydroxide. The hemicellulose composition was also determined by the weight reduction of cellulose composition from the holocellulose. Additionally, lignin composition was measured according to TAPPI T 222 om-02. Starch was extracted and the yield was determined according to the method conducted by H’ng et al. [16].

2.3. Panel Manufacture

Particles corresponding to each of the different treatment durations (20, 40, 60 min), as well as untreated particles (control) were used to form binderless boards with dimensions of 20 cm × 20 cm × 0.5 cm, in triplicate. A total of 12 single layer binderless particleboards at a target density of 0.60 g/cm³ were produced. The mat layout of each binderless particleboard was performed manually into a mold and compressed under a digitally controlled hot-press machine at a pressure of 10 MPa with a temperature of 200 °C for 20 min [12]. Particleboard with 10% urea–formaldehyde resins using untreated oil palm trunk particles were made as a comparison. The particleboards made with 10% urea–formaldehyde were formed with hot-pressing at a pressure of 10 MPa, with a temperature of 160 °C for 8 min. These boards were conditioned in conditioning rooms with a temperature of 20 ± 2 °C and a relative humidity of 65% ± 5%. The density of the boards was determined according to EN 323. The thickness of the boards was determined according to
EN 324. Boards that fulfilled the density and thickness tolerance assigned by EN 312 were cut into test specimens.

2.4. Physical and Mechanical Strength Tests of the Samples

Physical properties and mechanical properties of test specimens were tested according to the British Standard and the European Standard. Thickness swelling, dimensional changes with changes of relative humidity, bending strength and internal bond strength were tested according to EN 317, EN 318, EN 310 and EN 319, respectively.

2.5. Statistical Analysis: Tukey Test (Significant Difference Test)

The comparison of the means was performed with Tukey HSD at an alpha value < 0.05. Results of evaluation with replication were expressed as mean ± standard error.

3. Results

3.1. Chemical Constituents

From Table 1, the results show that the chemical composition of the particles has changed with the increase of steam pretreatment duration.

| Component   | Chemical Composition of Particles after Steam Pretreatment (%) |
|-------------|---------------------------------------------------------------|
|             | Untreated  | 20 min  | 40 min  | 60 min  |
| Extractives | 14.51 ± 0.74 | 13.53 ± 0.83 | 12.84 ± 0.53 | 11.20 ± 1.09 |
| α-Cellulose | 41.55 ± 0.96 | 42.83 ± 2.06 | 45.77 ± 1.18 | 50.58 ± 1.43 |
| Hemicellulose| 22.11 ± 1.63 | 19.63 ± 0.69 | 17.15 ± 0.35 | 15.89 ± 0.28 |
| Lignin      | 18.87 ± 1.59 | 23.16 ± 1.37 | 22.78 ± 0.47 | 21.62 ± 0.63 |
| Starch      | 11.56 ± 1.78 | 8.72 ± 0.54  | 7.21 ± 0.12  | 4.38 ± 0.48  |

3.2. Physical Properties

Tables 2–4 show the dimensional changes with when relative humidity was changed either from 65% to 85% or 65% to 35%, along with the thickness swelling of specimens. The specimens made with 60 min steam-pretreated particles showed the least change with changes of relative humidity in both the 65% to 85% and 65% to 35% samples. Also, specimens made with 60 min steam-pretreated particles showed the lowest swelling rate in the thickness swelling evaluation after 24 h immersion. The specimens demonstrated a gradual decrease in the change rate when there was an increase of steam pretreatment duration, against changes of relative humidity and thickness swelling. Through the Tukey test, it was shown that the dimensional stability and thickness swelling of specimens was significantly improved with steam pretreatment. However, the strength of steam-pretreated specimens against water is still relatively poor compared to specimens formed with 10% urea–formaldehyde.
Table 2. Dimensional changes with changes in relative humidity from 65% to 85% of particleboards made without synthetic adhesives and with steam-pretreated particles.

| Steam Pretreatment (min) | Dimensional Changes with Changes in Relative Humidity from 65% to 85% | Length (%) | Thickness (%) | Weight (%) |
|--------------------------|---------------------------------------------------------------|-------------|---------------|------------|
| 20                       |                                                               | 0.20 ± 0.04a| 2.95 ± 0.10a  | 0.77 ± 0.00a|
| 40                       |                                                               | 0.18 ± 0.02a| 2.76 ± 0.09ab | 0.69 ± 0.02b|
| 60                       |                                                               | 0.17 ± 0.02a| 2.56 ± 0.13b  | 0.62 ± 0.02c|
| Control                  |                                                               | 0.23 ± 0.01a| 2.94 ± 0.07a  | 0.77 ± 0.02d|
| 10% Urea–Formaldehyde    |                                                               | 0.09 ± 0.02b| 1.23 ± 0.08b  | 0.47 ± 0.01b|

Different letters within the same column have statistically significant differences at $\alpha = 0.05$.

Table 3. Dimensional changes with changes in relative humidity from 65% to 35% of particleboards made without synthetic adhesive with steam-pretreated particles.

| Steam Pretreatment (min) | Dimensional Changes with Changes in Relative Humidity from 65% to 35% | Length (%) | Thickness (%) | Weight (%) |
|--------------------------|---------------------------------------------------------------|-------------|---------------|------------|
| 20                       |                                                               | −0.04 ± 0.00ab| −0.14 ± 0.01a | −0.84 ± 0.02ab|
| 40                       |                                                               | −0.04 ± 0.00ab| −0.11 ± 0.00b | −0.80 ± 0.02bc|
| 60                       |                                                               | −0.03 ± 0.02a| −0.09 ± 0.00b | −0.76 ± 0.01c|
| Control                  |                                                               | −0.07 ± 0.01b| −0.16 ± 0.01a | −0.88 ± 0.02a|
| 10% Urea–Formaldehyde    |                                                               | 0.00 ± 0.00a | −0.04 ± 0.01c | −0.60 ± 0.03d|

Different letters within the same column have statistically significant differences at $\alpha = 0.05$.

Table 4. Thickness swelling of particleboard made without synthetic adhesive with steam-pretreated particles.

| Steam Pretreatment (min) | Thickness Swelling |
|--------------------------|--------------------|
| 20                       | 24.80 ± 0.29ab     |
| 40                       | 24.38 ± 1.09b      |
| 60                       | 21.83 ± 1.38c      |
| Control                  | 26.00 ± 0.66ab     |
| 10% Urea–Formaldehyde    | 15.35 ± 1.38d      |

Different letters within the same column have statistically significant differences at $\alpha = 0.05$.

3.3. Mechanical Strength Properties

Table 5 shows the mechanical strength properties of specimens. Specimens made with 60 min steam-pretreated particles showed the highest mechanical strength among steam-pretreated specimens, in terms of both internal bond strength and modulus of rupture. The specimens made with 60 min steam-pretreated particles were significantly stronger than untreated specimens. However, the strength is relatively poor when compared to panels made with 10% urea–formaldehyde.

Table 5. Mechanical strength properties of particleboard made without synthetic adhesive with steam-pretreated particles.

| Steam Pretreatment (min) | Internal Bond Strength (N/mm²) | Modulus of Rupture (MPa) |
|--------------------------|--------------------------------|--------------------------|
| 20                       | 0.68 ± 0.01a                  | 16.51 ± 0.37a            |
| 40                       | 0.71 ± 0.01b                  | 17.43 ± 0.32a            |
| 60                       | 0.75 ± 0.01c                  | 18.73 ± 0.52b            |
| Control                  | 0.66 ± 0.01d                  | 15.41 ± 0.23c            |
| 10% Urea–Formaldehyde    | 0.86 ± 0.01e                  | 20.36 ± 0.43d            |

Different letters within the same column have a statistically significant difference of $\alpha = 0.05$. 
4. Discussion

Acid is released from lignocellulosic materials during steam pretreatment [14]. This acid can partially hydrolyze the cell wall components, especially the short chain carbohydrates, such as hemicelluloses and starch. The hemicellulose and starch content decrease with the increase of steam pretreatment. Hence, steam pretreatment helps in increasing the ratio of cellulose and lignin.

The improvement of the dimensional stability of panels against changes of relative humidity and thickness swelling with steam pretreatment could be due to the changes of chemical composition during steam pretreatment. Steam pretreatment resulted in degradation of hemicellulose and starch compounds via hydrolysis, where these compounds are crucial in water uptake of lignocellulosic material, hence increasing the hydrophobicity of the particles [17]. Furthermore, these compounds were hydrolyzed into simple sugar compounds and furan, in which these compounds were also one of the potential chemical constituents in promoting self-bonding in between particles [18].

During the process of steam pretreatment, the hot-steaming together with pressure results in the softening of the lignin and allowing the lignin to be redeposited in the cell wall. The redeposition of lignin made the lignin more accessible to fiber during the hot-pressing process. The function of lignin is to improve particle bonding. Furthermore, the process of steaming under pressure could destroy the cell wall structure on the fiber surface, which becomes defibrillated [19,20]. This structural change of the fibers created a larger surface area on the fibers and promoted particle bonding. The mechanical strength, resistance to the moisture, and water uptake of the panels was improved as a result of the bonding between particles and the hydrophobic properties of lignin. However, extensive steam pretreatment could bring about the drawback of fibers encountering severe damage.

5. Conclusions

The use of steam pretreatment was successful in improving the physical and mechanical properties of binderless particleboards made from oil palm trunk. With the incremental increase of steam pretreatment duration, the self-bonding of oil palm trunk particles became stronger due to the physical and chemical changes. However, the physical and mechanical properties of the steam-pretreated binderless particleboard are still not compatible with the physical and mechanical properties of particleboard made from 10% urea-formaldehyde.

Author Contributions: Conceptualization, J.G.B. and R.H.; methodology, J.G.B.; writing—original draft preparation, J.G.B., W.N.A.W.N., and M.D.; writing—review and editing, J.G.B.; supervision, R.H.; project administration, J.G.B.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Marutzky, R. Release of Formaldehyde by Wood Products. In Wood Adhesives: Chemistry and Technology; Pizzi, A., Ed.; Marcel Dekker: New York, NY, USA, 1989; Volume 2, pp. 307–387.
2. Yu, C.W.F.; Crump, D.R. Testing for Formaldehyde Emission from Wood-Based Products—A Review. Indoor Built Environ. 1999, 8, 280–286. [CrossRef]
3. Sulaiman, N.S.; Hashim, R.; Sulaiman, O.; Nasir, M.; Amini, M.H.M.; Hiziroglu, S. Partial Replacement of Urea-Formaldehyde with Modified Oil Palm Starch Based Adhesive to Fabricate Particleboard. Int. J. Adhes. Adhes. 2018, 84, 1–8. [CrossRef]
4. Wang, Z.; Li, Z.; Gu, Z.; Hong, Y.; Cheng, L. Preparation, Characterization and Properties of Starch-based Wood Adhesive. Carbohydr. Polym. 2012, 88, 699–706. [CrossRef]
5. Moubarik, A.; Charrier, B.; Allal, A.; Charrier, F.; Pizzi, A. Development and Optimization of a New Formaldehyde-free Cornstarch and Tannin Wood Adhesive. Eur. J. Wood Wood Prod. 2010, 68, 167–177. [CrossRef]
6. Nitu, I.R.; Shams, M.I.; Islam, M.N.; Ratul, S.B.; Ashaduzzaman, M. Development of Binderless Composites from Different Nonwood Lignocellulosic Materials: Overview. In *Handbook of Ecomaterials*; Martinez, L.M.T., Ed.; Springer International Publishing: Cham, Switzerland, 2019; Volume 3, pp. 1395–1409.

7. Baskaran, M.; Hashim, R.; Said, N.; Raffi, S.M.; Balakrishnan, K.; Sudesh, K.; Sulaiman, O.; Arai, T.; Kosugi, A.; Mori, Y.; et al. Properties of Binderless Particleboard from Oil Palm Trunk with Addition of Polyhydroxyalkanoates. *Compos. Part B* 2012, 43, 1109–1116. [CrossRef]

8. Hashim, R.; Nadhari, W.N.A.W.; Sulaiman, O.; Kawamura, F.; Hiziroglu, S.; Sato, M.; Sugimoto, T.; Tay, G.S.; Tanaka, R. Characterization of Raw Materials and Manufactured Binderless Particleboard from Oil Palm Biomass. *Mater. Des.* 2011, 32, 246–254. [CrossRef]

9. Laemsak, N.; Okuma, M. Development of Boards Made from Oil Palm Frond II: Properties of Binderless Boards from Steam-exploded Fibers of Oil Palm Frond. *J. Wood Sci.* 2000, 46, 322–326. [CrossRef]

10. Lamaming, J.; Sulaiman, O.; Sugimoto, T.; Hashim, R.; Said, N.; Sato, M. Influence of Chemical Components of Oil Palm on Properties of Binderless Particleboard. *Bioresources* 2013, 8, 3358–3371. [CrossRef]

11. Boon, J.G.; Hashim, R.; Sulaiman, O.; Sugimoto, T.; Sato, M.; Salim, N.; Amini, M.H.M. Importance of Lignin on the Properties of Binderless Particleboard Made from Oil Palm Trunk. *Arpn J. Eng. Appl. Sci.* 2017, 12, 33–40.

12. Boon, J.G.; Hashim, R.; Sulaiman, O.; Hiziroglu, S.; Sugimoto, T.; Sato, M. Influence of Processing Parameters on Some Properties of Oil Palm Trunk Binderless Particleboard. *Eur. J. Wood Wood Prod.* 2013, 71, 583–589. [CrossRef]

13. Glasser, W.G.; Wright, R.S. Steam Assisted Biomass Fractionation. II. Fractionation Behavior of Various Biomass Resources. *Biomass Bioenergy* 1998, 14, 219–235. [CrossRef]

14. Shamsudin, S.; Shah Md, U.K.; Zainudin, H.; Abd-Aziz, S.; Mustapa Kamal, S.M.; Shirai, Y.; Ali Hassan, M. Effect of Steam Pretreatment on Oil Palm Empty Fruit Bunch for the Production of Sugars. *Biomass Bioenergy* 2012, 36, 280–288. [CrossRef]

15. Wise, L.E.; Murphy, M.; Daddieco, A.A. Chlorite Hidocellulose, Its Fractionation and Bearing on Summative Wood Analysis and Studies on the Hemicelluloses. *Pap. Trade J.* 1946, 122, 35–43.

16. H'ng, P.S.; Wong, L.J.; Chin, K.L.; Tor, E.S.; Tan, S.E.; Tey, B.T.; Maminski, M. Oil Palm (*Elais guineensis*) Trunk as a Resource of Starch and Other Sugars. *J. Appl. Sci.* 2011, 11, 3053–3057.

17. Zhang, L.; Hou, J.; Bi, X. Triboelectric Charing Behavior of Wood Particles during Pellet Handling Process. *J. Loss Prev. Proc. Ind.* 2013, 26, 1328–1334. [CrossRef]

18. Widyorini, R.; Xu, J.; Watanabe, T. Chemical Changes in Steam Pressed Kenaf Core Binderless Particleboard. *J. Wood Sci.* 2005, 51, 26–32. [CrossRef]

19. Hsu, W.E.; Schwald, W.; Shields, J.A. Chemical and Physical Changes Required for Producing Dimensionally Stable Wood Based Composites. Part 1: Steam Pretreatment. *Wood Sci. Technol.* 1988, 22, 281–289. [CrossRef]

20. Avella, M.; Martuscelli, E.; Pascucci, B.; Raimo, M.; Focher, B.; Marzatti, A. A New Class of Biodegradable Material: Poly-3-hydroxybutyrate/Steam Exploded Straw Fiber Composites. I. Thermal and Impact Behavior. *J. Appl. Polym. Sci.* 1993, 49, 2091–2103. [CrossRef]