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Development of boards made from oil palm frond II: properties of binderless boards from steam-exploded fibers of oil palm frond

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Abstract Binderless boards were prepared from steam-exploded fiber of oil palm (*Elaeis guineensis* Jacq.) frond at six levels of explosion conditions. Their properties were investigated and evaluated. The mechanical properties (i.e., modulus of rupture, modulus of elasticity, and internal bonding strength) of the boards increased linearly with increasing board density as the usual hardboard. The boards made from fibers treated under a steam explosion condition of 25 kgf/cm^2 (steam pressure) and 5 min (digestion period) exhibited the maximum strength. These boards at a density of 1.2 g/cm^3 met the requirement of S-20 grade of JIS A 5905 – 1994 (fiberboard). Thickness swelling of the boards ranged from 6% to 14% under the JIS A 5908 – 1994 (particleboard) test condition and showed no significant changes with increasing board density. The main bonding strength of the board is believed to be due to a lignin–furfural linkage. Considering the chemical components of oil palm frond, which is rich in hemicellulose, there seems to be a good possibility for producing binderless boards using steam-exploded fibers of oil palm frond.

Key words Oil palm frond · Fiberboard · Binderless board · Steam explosion

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Introduction

Oil palm (*Elaeis guineensis* Jacq.) fronds are currently considered waste from oil palm plantations, and their biomass is not used completely.[1] In 1992 production from these plantations by pruning and replanting programs generated about 18 million tons of fronds a year all over the world.[2] Oil palm frond is considered one of the new sustainable lignocellulosic raw materials if we use it effectively.

Adhesive is generally accepted to be the most expensive raw material for making particleboard or dry fiberboard. Therefore, research on adhesive has long been a propelling force in the evolution of the forest products industry and has been an important aspect of technological development. Synthetic glues dominated during the 1950s and 1960s, but the oil embargo in 1973 and the following price increases of petrochemicals caused the forest products industry to focus its attention on the need for adhesive self-sufficiency and the development of adhesive from natural, renewable raw materials.

As reviewed by Sasaki,[3] it is effective to produce self-bonding board by means of activating chemical components of the board constituents. Johns and Woo[4] reported on the improvement of internal bonding of hardboard by treating fiber with hydrogen peroxide and furfuryl alcohol. It has been said that K.C. Shen of Canada submitted and has patents on nonconventional (binderless) board. However, we have not been able to get any information about the scientific discussions or results of the industrialization of the process.

The chemical composition of oil palm frond, as shown in a previous paper,[5] clearly indicates that it is 1.5–3.0 times richer in hemicelluloses than is wood. In addition, the lignin substance of oil palm frond can be removed easily from the cell wall to the fiber surface after steam-explosion treatment.[6] These chemical components treated by steam explosion can possibly create good bonding strength between fibers during the hot pressing process. Oil palm frond is therefore deemed to be an ideal material for manufacturing boards without the addition of any resin or adhesive. Considering these facts, the possibility of producing binderless boards from steam-explosion fibers of oil palm frond was investigated.

Materials and methods

Materials

Fronds attached to oil palm trees approximately 10–15 years old were harvested from a plantation in Krabi Province, southern Thailand. Leaflets were removed from the fronds, and the fronds were cut and chipped to 5 to 40-mm lengths. After sun-drying, these lengths were hammermilled and screened in the laboratory.

Furnish B or core furnish,[5] which are mixtures of three fractions of screened hammermilled particles (−5.5 to +8.6 mesh, −8.6 to +18.5 mesh, and −18.5 to +30 mesh and with compositions of 75%, 20%, and 5%, respectively) were used in this research. Minus (−) means that the particles passed through the mesh, and plus (+) means they were retained on the mesh. The moisture content of these particles was 12%.

Steam-explosion process

The particles were treated by means of a steam-explosion process. The prepared particles (350g dry basis per batch) were subjected to an explosion digester (21 volume; Nitto Koatsu Co., Japan) under various steam pressures and for various digestion periods. The conditions are as follows;

EC-1: 20kgf/cm^2, 5min
EC-2: 20kgf/cm^2, 10min
EC-3: 25kgf/cm^2, 5min
EC-4: 25kgf/cm^2, 10min
EC-5: 30kgf/cm^2, 5min
EC-6: 30kgf/cm^2, 10min

After reaching the desired duration of steam injection, the contents were released; and the pressure instantaneously fell to atmospheric pressure. All defibrated fibers and black liquor were collected for use in making the binderless boards.

Board preparation

Steam-exploded oil palm frond fibers were dried to a moisture content of 12% in an air-dried condition for several weeks. It should be noted that these fibers may form clumps during drying, so they were manually fluffed, separating and breaking up the clumps to achieve consistent forms.

The test boards were made on a laboratory scale by standard techniques and controlled conditions. In this research, 6 and 12mm thick binderless boards were manufactured at three levels of target board densities. For the 12-mm boards the target densities were set at 0.7, 0.8, and 0.9g/cm^3; and for 6-mm boards they were 0.7, 0.9, and 1.1g/cm^3. Dried fibers were formed-manually, using a forming box, into homogeneous single-layer mats 300 × 150mm. The mat moisture content was controlled at 12%.

After forming, the mat was prepressed by hand and Teflon sheets were used on both the top and bottom surfaces of the mat. The mat was then transferred to a single-opening hydraulic hot press with a platen temperature of 150°C and pressed for 10min for the 12-mm boards and at 125°C and 6min for the 6-mm boards. All the boards were pressed by means of a three-step-down method of pressing. Distance bars 6 or 12mm in thickness were inserted between the hot platens during hot pressing. Two replications were made for each combination of manufacturing conditions.

Board testing

All the boards were trimmed and cut into various test specimens and then conditioned at 20°C and 65% relative humidity (RH) prior to testing. Tests were carried out for moduli of rupture and elasticity (MOR, MOE) and internal bonding (IB) strength, thickness swelling (TS), and water absorption (WA) after water immersion for 24h in accordance with JIS A 5905 – 1994 and JIS A 5908 – 1994.

Results and discussions

Board appearance and others

All the binderless boards were dark brown and had peculiar sweet smells, especially boards made at high densities. Boards made from fibers treated under severe steam-explosion conditions were dark-colored and had a smell, which indicates a high degree of hydrolysis or modification of the chemical components during steam explosion and hot pressing.[6] It has been reported by Goring[7] that the softening temperature of lignin at 12% moisture content is around 120°C, so an unusually low temperature (125°C for the thinner 6-mm boards) was selected for hot pressing.

The boards (except EC-5 and EC-6) had smooth surfaces and tight edges, similar to those of medium-density fiberboard (MDF) or S2S hardboards, owing to the fineness of the steam-exploded fibers and the strong bonding strength generated by the chemical reaction of the fibers. In the EC-5 and EC-6 boards lignin was destroyed and became brittle as discussed below, so the surfaces and edges were quite rough.

Mechanical properties

The boards made from fibers treated at a steam pressure of 30kgf/cm^2 (EC-5, EC-6) were brittle, and some specimens broke during cutting. Hence there were not enough test pieces.

Relations between MOR and board density under different explosion conditions are shown in Figs. 1 and 2. In all cases the MOR linearly increased with the board density,

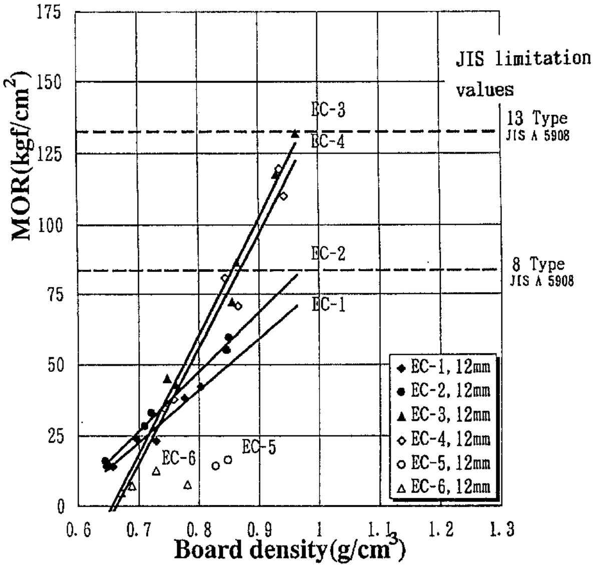

Fig. 1. Effect of board density on modulus of rupture (MOR) of 12 mm thickness binderless board made from fibers treated under different steam explosion conditions. *EC*, explosion condition; *EC-1*, 20 kgf/cm², 5 min; *EC-2*, 20 kgf/cm², 10 min; *EC-3*, 25 kgf/cm², 5 min; *EC-4*, 25 kgf/cm², 10 min; *EC-5*, 30 kgf/cm², 5 min; *EC-6*, 30 kgf/cm², 10 min

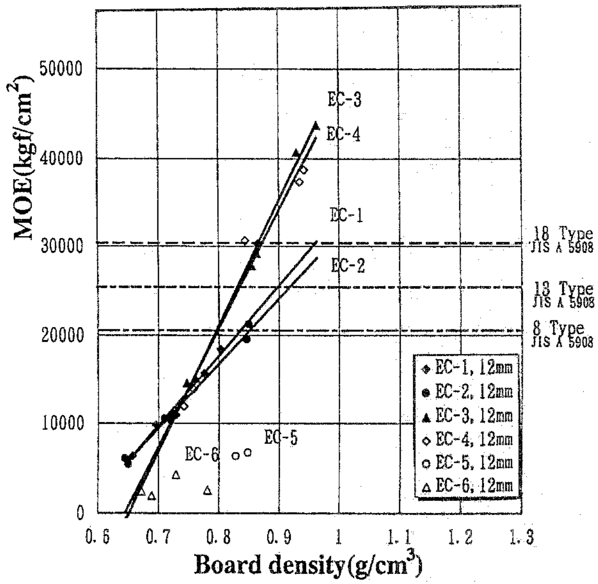

Fig. 3. Effect of board density on modulus of elasticity (*MOE*) of 12 mm thickness binderless board made from fibers treated under different steam explosion conditions

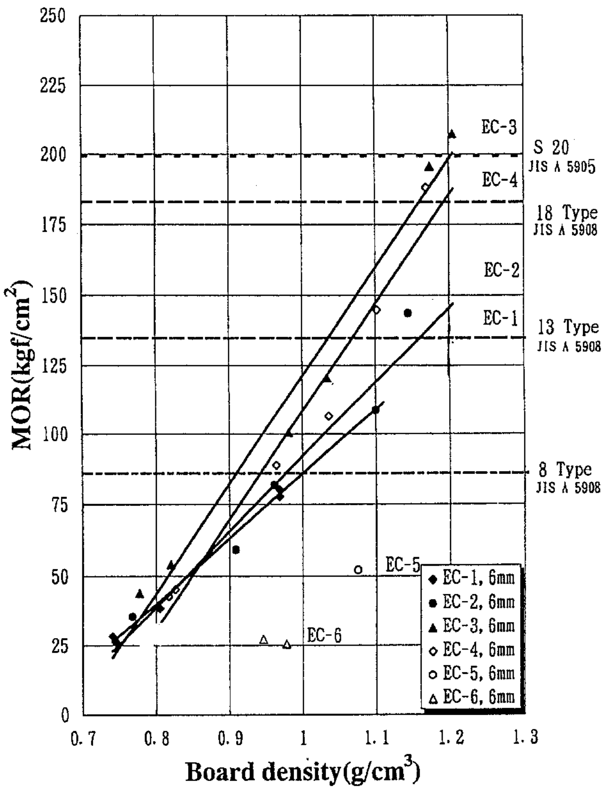

Fig. 2. Effect of board density on MOR of 6 mm thickness binderless board made from fibers treated under different steam explosion conditions

similar to the usual fiber-boards and particleboards. Shearing failure could not be seen in any broken specimens.

The EC-5 and EC-6 boards gave low MOR values. Suzuki and coworkers suggested that the reason may be due to the chemical structures, especially the aromatic nuclei of lignin, being destroyed[6] based on the structural analysis of lignin using wet chemistry and spectroscopic measurements: Significant differences in structural characteristics of lignin isolated from steam-exploded pulps digested at 25 kgf/cm² (EC-3, EC-4) and 30 kgf/cm² (EC-5, EC-6) pressure were detected by ^{13}C and ^{1}H nuclear magnetic resonance (NMR) spectroscopy and Fourier transform infrared (FTIR) spectra. However, no significant difference was observed for the different steam-explosion periods under the same steam-explosion pressure.[6]

The maximum value of MOR for the 6-mm board was 228 kgf/cm² at board density 1.2 g/cm³ and 138 kgf/cm² for 12-mm board at board density 1.0 g/cm³, both of which were obtained from the EC-3 board. Only EC-3 and EC-4 of 6-mm boards at a density of 1.2 g/cm³ exceeded the minimum requirements of 204 kgf/cm² set forth for grade S-20 by JIS A 5905 – 1994. The results of the MOE tests for the 6-mm board are shown in Fig. 3, which indicates the same trend as the MOR. The MOE of EC-3 and EC-4 boards at densities of more than 1.0 g/cm³ exceeded the minimum values of 30 600 kgf/cm² set forth for grade 18 type particleboard by JIS A 5908 – 1994.

For IB strength, as shown in Figs. 4 and 5, the orders of regression lines under EC-1 to EC-4 explosion conditions were similar to those for MOR. However, the values for 12-mm board were much smaller than those for 6-mm boards owing to the greater density gradient in the thickness direction, which means lower density at the core layer. The values of EC-5 and EC-6 boards in Figs. 4 and 5 are not as low as those for MOR or MOE, although the number of the specimens was small. Some chemical structures were destroyed by the severe steam-explosion treatment, as mentioned above; but bonding strength was activated during the

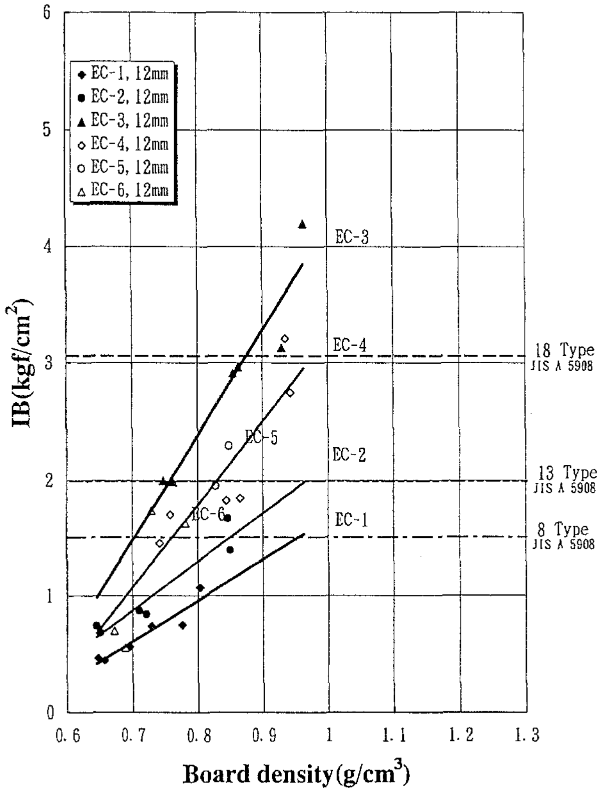

Fig. 4. Effect of board density on internal bond (*IB*) strength of 12 mm thickness binderless board made from fibers treated under different steam explosion conditions

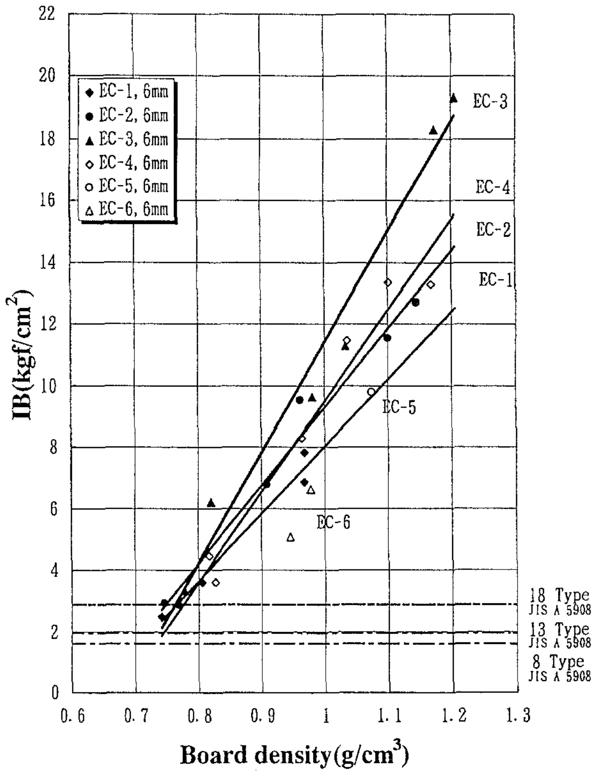

Fig. 5. Effect of board density on IB strength of 6 mm thickness binderless board made from fibers treated under different steam explosion conditions

steam-explosion process and possibly exhibited extra strength. The IB strength of the binderless board made of steam-exploded fibers satisfied the minimum requirements of the relevant standards specifications of JIS A 5908 – 1994 (particleboard).

Dimensional stability

The effect of board density on TS in the 12-mm board after water-soaking tests for 24 h at ambient conditions is shown in Fig. 6. The plotted values are scattered, showing low correlation. However, it can be seen clearly that EC-5 and EC-6 boards showed greater stability against water in contrast to the brittleness of the boards. This may be due to the existence of sufficient bonding strength together with the decrease in internal force generated by water. Fiber loses elasticity through destruction of the aromatic nuclei of lignin during the severe steam-explosion treatment, as mentioned above.[6]

In addition, no significant changes were observed for EC-1 to EC-4 boards, and all the test values were stable when compared to those of particle boards made from oil palm frond.[5] This stability could be due to a strong bonding strength generated between fibers treated with steam explosion. During steam explosion, polysaccharides are partially hydrolyzed under acidic conditions by acetic acid originating from acetyl groups on noncellulosic polysaccharides (hemicellulose), which are then modified to furfural derivatives.[6] Lignin could be released from the cell wall polymers (probably polysaccharides),[6] melted[7] and partially modified.[6]

The results of WA in the 6-mm board after 24 h of water soaking are shown in Fig. 7. The results indicated that the WA decreased with increasing board density because of the decrease of spaces in the board with the increase of the density. For all the explosion conditions, the 6-mm boards with densities higher than 1.1 g/cm^3 satisfied the maximum requirement of the relevant standards (30%) for the grade S-20 hardboards set force by JIS A 5905 –1994.

Conclusions

Binderless boards were made from steam-exploded oil palm frond and their properties examined. Based on the results, the conclusions are summarized as follows.

1. The mechanical properties (MOR, MOE, IB strength) of the boards increased linearly with increasing board density. Boards made from fibers exploded under severe conditions (EC-5, EC-6) were brittle and showed low MOR and MOE. In all cases, EC-3 and EC-4 boards (treated at a pressure of 25 kgf/cm^2) showed superior mechanical properties and met the requirements of S-20 grade according to JIS A 5905 – 1994 at a density of 1.2 g/cm^3 for the 6-mm board. Higher IB was obtained in 6-mm board

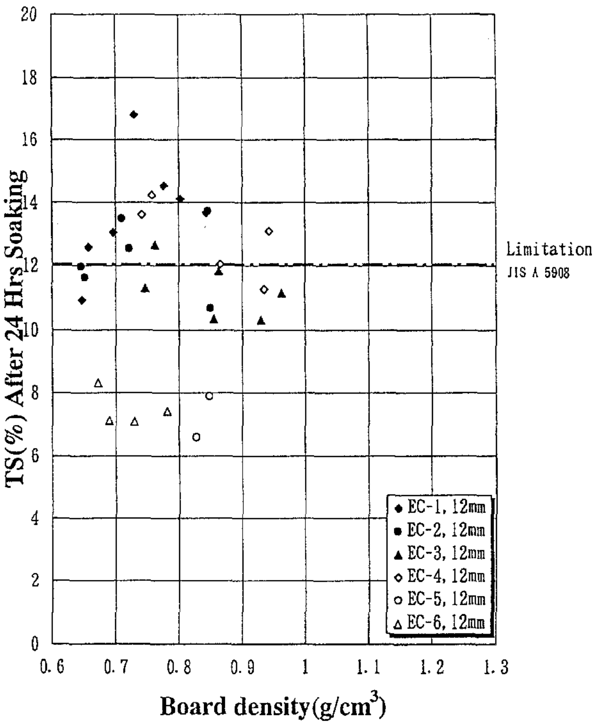

Fig. 6. Effect of board density on tensile strength (*TS*) of 12 mm thickness binderless board made from fibers treated under different steam explosion conditions

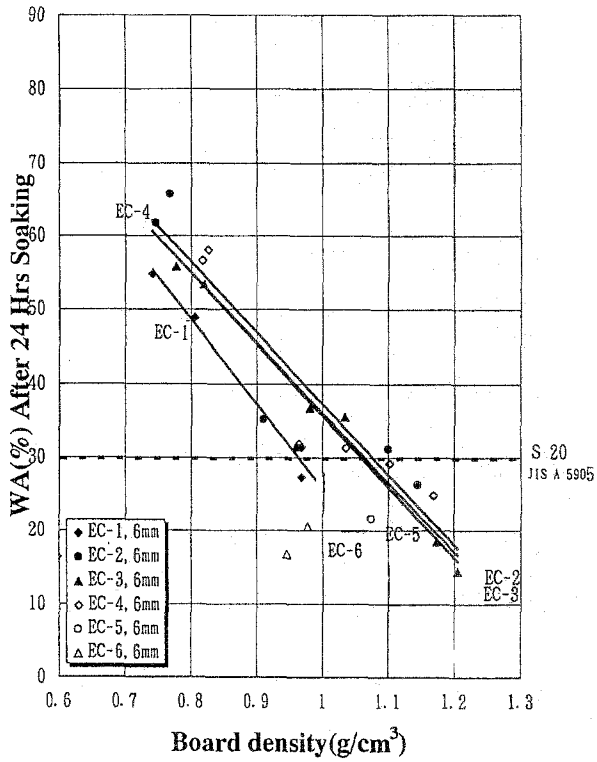

Fig. 7. Effect of board density on water absorption (*WA*) of 6 mm thickness binderless board made from fibers treated under different steam explosion conditions

than in 12-mm board, which could be due to the lower density gradient in the thickness direction of the 6-mm board.

2. Boards tested for TS at ambient temperature exhibited no significant changes with increasing board density. EC-5 and EC-6 boards showed the greatest stability against water in contrast to the brittleness of the board.

3. For WA, values decreased with increasing board density, and the values for 6-mm board at densities higher than 1.1 g/cm^3 satisfied the maximum requirement of the relevant standards (30%) for the grade S-20 hardboards set force by JIS A 5905 - 1994.

4. Based on the results of previous studies,[5,6] the main bonding strength of the boards is believed to be due to lignin–furfural linkages, generated during the hot-pressing process of steam-exploded fibers.

5. Severe steam-explosion conditions (treated at a pressure of 30 kgf/cm^2) resulted in stronger IB strength among fibers, which gave the high stability against water; but the boards' chemical components were seriously modified, including cleavage of aromatic nuclei of lignin, so the mechanical strength of the board was very poor. It was concluded that within the range of this study the optimum conditions of steam explosion to give boards excellent mechanical strength was 5–10 min of digestion period at a steam pressure of 25 kgf/cm^2.

6. It is suggested that boards satisfying the requirements of the relevant standards can be produced from oil palm fronds (which are waste material from tropical plantations) without using any binders. This would be a significantly important process in developing countries.

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