Development of Compressive Molding Process of Wood by High-pressure Steam and Mechanism of Permanent Fixation for Transformed Shape

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Summary

The compressive-molding process of wood by high-pressure and high-temperature steam-treatment was developed in our laboratory a couple of years ago. The system comprises the following three steps: softening of the row wood with steaming at 120°C, compressing to transform the wood and fixation of the compressed shape with steaming at 180°C continuously in the same apparatus. By this process, physical properties of softwoods were improved to hardwood-like materials and extremely large transformations of wood were easily achieved. The transformed shape was permanently fixed by high-pressure steam-treatment. For these reasons, the compressive-molding method is a useful process for the improvement of softwood. The compressed wood possessed many useful characteristics such as higher Young's modulus, higher surface hardness, deeper color for furniture, finer grain pattern and easier transformation of wood to various shapes. Thus we attempted to apply this flexibility of transformation for the preparation of compiled-wood from small wasted logs.

We developed some new techniques for compiling small logs and branches by compressive moulding process under high-pressure steam with some adhesives, which we named 'aggregated-wood', and without any adhesives, 'assembled-wood'. The assembled-woods were made from only native materials without any chemicals as adhesives.

With this method, a large laminated lumber was constructed from small logs or squares grooved with new types of finger joints, hereby referred to as 'Side-finger joints'. The first type was compression parallel to the joint plane, and the other was compression perpendicular to the joint plane. As an improvement of these side-finger joints, we developed some new finger-shape joints, named 'cogged-joints', 'serrated-joints' and 'hooked-joints'. These forms of coupling joints ensured better results than normal finger joints for the compression perpendicular to the joint plane. The hooked-joint did not fit initially, but a very firm fitting occurred after the softening and the compressing process.

Also, the use of steam is enough to ensure a very solid bond for LVL prepared from veneers with the same fiber orientation without adhesives. Even under this orientation of

veneer, it is possible for 3-dimesionally processed items like trays to be physically bonded strongly. Furthermore branch-boards were made from branches pruned down from roadside trees.

These binding forces were mainly through physical adhesion caused by a permanent fixation of transformed shape. The mechanism of fixation is mainly the structural changes of cellulose crystals, namely, recrystallization following partial degradation of warped and strained amorphous domain and transformation of cellulose crystalline form by high-temperature steam.

SAWDUST BOARDS FABRICATED BY THE HIGH- PRESSURE STEAM PROCESS

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Abstract

Sawdust boards from three softwood species (Sugi, *Cryptomeria japonica* D. Don; Hinoki, *Chamaecyparis obtuse* Sieb. Et Zucc.; Karamatsu, *Larix leptolepis* Gordon) and three hardwood species (Rubber, *Hevea brasilensis*; Keyaki, *Zelkova serrata*; Shirakaba, *Betula platyphylla*) were fabricated in our laboratory by using a high-pressure steam apparatus previously designed to mold wood. This apparatus, developed in our laboratory a couple of years ago, uses high-pressure steam and a piston-like pressing component to improve the mechanical properties of low quality wood. All the boards were fabricated from locally available sawdust without using chemical adhesives. Mechanical properties such as thickness swelling, dimensional stability, modulus of elasticity, modulus of rupture, surface hardness and internal bond strength were determined. Results obtained indicated that very satisfactory properties were attained for the sawdust boards compared to boards previously fabricated from rice husk and straw. By varying the particle sizes, it was observed that most of the mechanical properties were further enhanced with the finest particles. Further discussion is also made on other practical uses of the boards including their use as moisture-retention materials or erosion control structures.

Keywords: Sawdust boards; High-pressure steam process; Mechanical properties

1 Introduction

With deforestation proceeding at alarming rates in many developing nations, many wood–based industries are gradually placing emphasis on the utilization of agricultural and forest residue in the production of composition panel. For example, rice husk and wheat which are quite fibrous and easy to handle, have been used widely in the manufacture of particleboards [4, 10]. Maize fibers [2] and palm fronds [6] are among some of the other raw materials under investigation. Forest residue has also been used in the particleboard industry [1], although it has been reported that the presence of large amounts of bark has a negative impact on board properties [3].

In Japan, biomass residue of various forms including logging waste, weeded material along roads or river banks as well as agricultural residue are being generated in large volumes and their means of disposal is either too costly or poses a threat to the environment. [7]. It is against this backdrop that our research is focused on utilizing residue generated from the forest, saw mills and farms as raw materials to fabricate biomass boards. In our previous work [7], boards were fabricated from agricultural waste in the form of rice straw and rice husk as well as pruned branches and leaves from a Sugi (*cryptomeria japonica*) stand.

The purpose of our present study is to further investigate the possibility of using the compressive-moulding apparatus to fabricate boards from sawdust derived from softwood and hardwood tree species. This apparatus, developed in our laboratory a couple of years ago [5, 8], uses high-pressure steam and a piston-like pressing component to improve the physical properties of low quality wood. The method of fabricating the sawdust boards is briefly presented and the effect of particle size on some physical properties such as MOR, MOE, thickness swelling, internal bonding strength and dimensional stability of the boards in relation to water absorption and surface hardness is investigated. Board samples were also analysed for their total nitrogen and carbon contents.

2 Materials and methods

2.1 *Particle preparation*

Sawdust for the experiment was selected from three softwood species (Sugi, Cryptomeria japonica D. Don; Hinoki, Chamaecyparis obtuse Sieb. Et Zucc.; Karamatsu, Larix leptolepis Gordon) and three hardwood species (Rubber, Hevea brasilensis; Keyaki, Zelkova serrata; Shirakaba, Betula platyphylla). The sawdust particles for each species were separated into various particle size classes after screening them through sieves (Table 1). With the exception of Sugi and Rubber wood that had five particle size classes, the rest of the species were sorted into three particle class sizes.

2.2 *Board fabrication*

After oven drying at 105°C for about 3 hours, 600g of the mats (about 10% moisture content) prepared above were put inside metallic frames lined with Teflon sheets for fabrication. The compressive moulding apparatus consists of an airtight pressure chamber (Hisaka made HTP-60/250) with an internal diameter of 60 cm and a depth of 250 cm, a compressor, an intake valve and an exhaust valve. The fabrication processes involved are briefly introduced in the following stages:

(a) Softening stage: Hot steam is initially injected into the chamber to drive away air for 5 minutes. More steam is injected while the temperature gradually rises to 120°C in 5 minutes. The temperature is then held constant for 10 more minutes. All these processes are automated. (b) Compressing stage: The softened mats are compressed to a target density of about 1 g/cm3. (c) Fixation stage: In this compressed stage, more steam is injected while the temperature gradually rises to 180°C within a 10-minute duration and maintained for a further 10 minutes.

After forming, the boards are made to stay in the chamber for 24 hours. The fabricated homogeneous single-layer boards were of dimensions 200 x 300 mm and 10 mm thick.

2.3 *Sample preparation and testing*

All boards were trimmed and cut to various specifications for testing. Physical properties such as modulus of elasticity and modulus of rupture were conducted for Sugi and Rubber wood. Other tests conducted for all tree species included internal bond strength, thickness swelling, surface hardness and dimensional stability after immersing in water for 24 hours in accordance with JIS A 5908-1994. Samples were also prepared for the determination of total carbon and nitrogen contents of the raw materials and boards to see if there had been significant changes due to the compressive moulding process.

3 Results and discussion

3.1 *Board appearance*

Each type of board had a peculiar smell and all had different colours from their original materials. Removal from the metallic frames was relatively easier due to the Teflon linings. Boards made from fibres treated under severe steam-explosion usually have a smell, which is an indication of a high degree of hydrolysis or modification of the chemical components during steaming [6].

3.2 *Mean density and thickness swelling (TS)*

Mean densities for all the various board species and particle class sizes are shown in Table 1. None of the board densities was exactly equivalent to the target density of 1 g/cm3 possibly due to the fact that the boards underwent slight expansions when the press was immediately released. Nevertheless, the mean densities all exceeded the air-dry density of the original materials before fabrication. Generally, the boards with finer particle sizes tended to have the highest densities. Results of the percentage increases in thickness (thickness swelling) when samples were immersed in cold water for 24 hours are also shown in Table 1. Generally, boards with finer particles had lower values of thickness swelling and most of the selected conifer boards had TS values within the JIS specification of below 12%. Larger particle size boards have a porous structure, which may allow a quicker water uptake and in turn cause the boards to swell. In our previous report on boards fabricated from agricultural residues, TS values of 56.93% and 46.98% were obtained for rice husk and straw respectively [7].

3.3 *Dimensional stability*

In order to determine their dimensional stability, board samples were subjected to cyclic conditions of oven-drying/wetting, after which a permanent increase in thickness was attained. Dimensionally stable samples are those with low values of percentage changes in thickness after being subjected repeated drying and wetting. After the fifth oven drying treatment D5, the samples were boiled and finally oven-dried. The total thickness swelling of a board sample after immersion in water is attributed to the release of the compressive stresses, hygroscopic swelling of the fibres, and the deterioration of the inter-particle bonding [9]). As shown in Figure 1, the effect of particle size on changes in thickness was hard to see though the softwood boards exhibited more stability than the selected hardwood species. Even after boiling and finally drying, very low changes were seen in all the three size classes of Karamatsu (*Larix leptolepis*) boards (less than 10%), a very strong indication that structures made of such materials would be able to withstand external conditions subject to repeated wetting and drying.

Table 1. Mean density and thickness swelling after soaking samples in water for 24 hours

Type of Sawdust Board (Particle size class, mm)	Mean density (g/cm^3)	Air-dry density of original material (g/cm^3)	Thickness swelling (TS, %)	Internal bond strength (IB, KPa)	Surface hardness (SH, MPa Top (Bottom surface)
Sugi 1 (2.00-4.70)	0.83	0.38	11.2	64.1	5.46 (6.44)
Sugi 2 (0.84-2.00)	0.79		11.1	109.8	4.42 (5.78)
Sugi 3 (0.42-0.84)	0.78		18.5	170.3	4.50 (6.81)
Sugi 4 (0.25-0.42)	0.81		14.3	332.0	6.07 (7.62)
Sugi 5 (< 0.25)	0.95		12.2	875.5	8.86 (8.95)
Hinoki 1 (0.84-2.00)	0.70	0.41	16.5	73.4	4.73 (4.91)
Hinoki 2 (0.355-0.84)	0.85		14.7	189.4	5.43 (6.36)
Hinoki 3 (< 0.355)	0.93		10.3	1061.0	6.68 (8.21)
Karamatsu 1 (0.84-2.00)	0.87	0.53	9.4	162.3	6.08 (6.39)
Karamatsu 2 (0.355-0.84)	0.86		9.0	237.2	4.94 (5.77)
Karamatsu 3 (< 0.355)	0.97		7.4	476.4	7.37 (7.71)
Rubber 1 (2.00-4.70)	0.74	0.56-0.64	23.2	30.1	6.45 (6.26)
Rubber 2 (0.84-2.00)	0.75		20.8	32.4	5.87 (5.80)
Rubber 3 (0.42-0.84)	0.80		16.8	34.3	5.44 (6.64)
Rubber 4 (0.25-0.42)	0.81		20.4	14.7	5.75 (7.11)
Rubber 5 (< 0.25)	0.80		12.7	235.5	7.78 (8.95)
Keyaki 1 (0.84-2.00)	0.65	0.62	19.2	1479.4	4.85 (6.09)
Keyaki 2 (0.355-0.84)	0.70		19.7	869.3	5.76 (8.14)
Keyaki 3 (< 0.355)	0.83		19.9	1824.4	7.26 (8.10)
Shirakaba 1 (0.84-2.00)	0.87	0.60	10.8	166.4	4.94 (8.00)
Shirakaba 2 (0.355-0.84)	0.78		10.4	144.6	4.19 (6.45)
Shirakaba 3 (< 0.355)	0.88		9.7	282.6	5.41 (7.98)

Note: Particle class size 2.00-4.70 refers to particles that passed through the 4.70 mm sieve but could not pass through the 2.00 mm sieve.

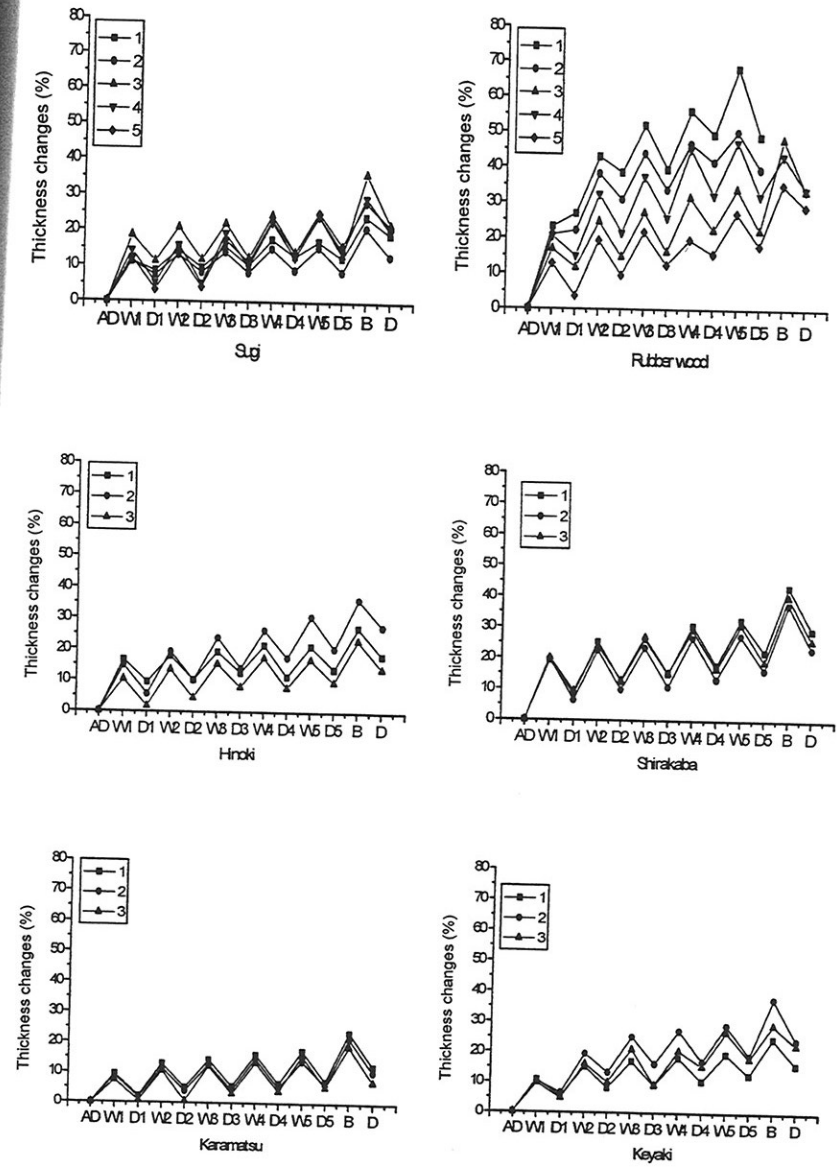

Figure 1. Changes in the thickness of the sample as a result of repeated wetting and oven drying. AD = air dry; W1, W2, W3, W4 and W5 = 24 hour immersion in cold water; D1, D2, D3, D4, D5 and D = Oven dry at 105°C; B = Boiling.

3.4 *Modulus of elasticity (MOE) and modulus of rupture (MOR)*
As no adhesives and clean fibres were used in the fabrication process, the boards were not expected to exhibit any extreme qualities in bending strength. Nevertheless, MOE and values for the finest particle size classes of Rubber wood and Sugi (Figure 2) were within acceptable JIS standards (MDF type 5). As already reported by many authors, the MOE and MOR values (Figure 2) for both Rubber and Sugi were found to be dependent on density.

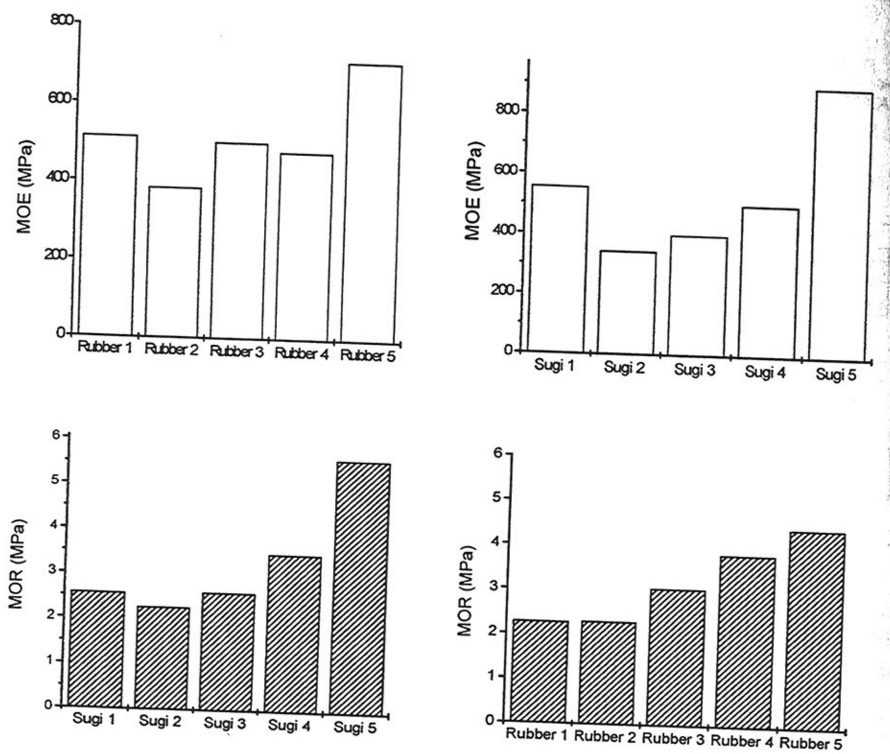

Figure 2. Modulus of Elasticity and Modulus of Rupture for particleboards of various particle size classes fabricated from Sugi and Rubber wood sawdust.

3.5 *Internal bond strength (IB) and Surface hardness (SH)*
In the determination of internal bond strength, failure occurred in the core of most of the samples, indicating that the particles were more loosely packed in the core than areas near the surface. It was observed for all the species that internal board strength (IB) increased as the particle became finer (Table 1). Boards fabricated from Keyaki had the highest IB values while Rubber wood boards had the lowest values with the exception of the finest class size board. Generally, most of the finer board types and all the Rubber wood boards satisfied the JIS MDF standards. The extremely low IB values for Rubber wood provides a possible explanation for the high values of thickness change in the dimensional stability analysis. Considering the fact that no adhesive resins were used, the results for IB were very satisfactory compared to IB values of 18.72 KPa and 1.91KPa obtained for rice husk and straw respectively in our previous work. Results of the surface hardness tests indicates that the SH values generally increased with particle size though the trends varied among the species. Tests were performed on both surfaces (top and bottom) of all the samples. During the compression phase of the fabrication process, many finer particles escaped to the bottom, thus resulting in a higher concentration of finer particles and hence a higher top SH values than the corresponding bottom values. This was quite visible when longitudinal sections were made through the samples. The highest SH values of 8.86 MPa (top surface) and 8.95 MPa (bottom surface) recorded were for the finest class size Sugi board. In general, no significant differences in SH values existed between the softwood and hard wood species. From Table 1, SH values for all the species ranged from 4.42 MPa to 8.86 MPa (top surface) and 4.91 MPa to 8.86 MPa (bottom surface).

3.6 *Total carbon and total nitrogen*

Table 2. Total nitrogen and carbon contents of the raw materials before and after fabricating boards

Board Type	Total Nitrogen (%)	Total Carbon (%)	C/N
Rubber wood (sawdust)	0.14	44.06	308.97
Rubber wood (board)	0.14	43.31	300.82
Shirakaba (sawdust)	0.06	43.33	769.68
Shirakaba (board)	0.09	46.53	499.10
Keyaki (sawdust)	0.12	44.51	391.47
Keyaki (board)	0.16	43.35	273.53
Sugi (sawdust)	0.06	46.15	936.90
Sugi (board)	0.06	46.37	781.48
Hinoki (sawdust)	0.09	49.40	551.52
Hinoki (board)	0.09	49.87	548.46
Karamatsu (sawdust)	0.01	41.24	3179.96
Karamatsu (board)	0.05	52.16	969.20

The essence of conducting this test was to verify if any changes had occurred in the total carbon and nitrogen constituents of the original material after fabrication (Table 2). Obviously, the total nitrogen contents were so low and hardly showed any differences. With the exception of Karamatsu, the total carbon contents for all the species did not vary considerably between the sawdust and boards.

4 Conclusions

All the boards were produced from sawdust, which is usually considered as milling waste in many countries and thus burnt to produce carbon dioxide. In effect, the fabrication rocess can contribute positively towards the fixation of carbon. Without using any dhesives, very satisfactory physical and mechanical properties of the sawdust boards vere obtained with the selected softwood and hardwood species. By varying particle size nd wood species, particleboards of various physical properties can be fabricated by this nethod for different end uses. As mentioned in our previous work, boards that do not neet JIS MDF requirements and may not be suitable as construction materials may be sed for other purposes such as weed suppressers or erosion control structures. As they re biodegradable, the boards can disintegrate with time and its constituents returned into ne soil without posing any environmental threat. Further studies are required to etermine other chemical constituents of the boards and to further explore the possibility f enhancing their characteristics. The fabrication process is an environmentally clean one as it utilizes only steam and a compression apparatus. Continuation of the studies can go a long way to contribute significantly towards the reduction of agricultural and forestry waste in particular and biomass waste in general.

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Load Bearing Behaviour of Textile Reinforced and Densified Timber Joints

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Abstract

Embedding, shear and cleavage strengths of wood are low and lead to poor structural behaviour especially of connections or require additional reinforcement techniques. This paper shows how the densification of wood under heat and pressure as well as the use of technical textiles provide substantial improvement of the load bearing behaviour [3].

The paper summarizes results from embedding tests on densified and textile reinforced wood with single dowel type fasteners (DTF) loaded parallel and perpendicular to grain [4,5]. Textile structures varied with respect to type of fibre (glass, aramid, carbon), fibre orientation and their manufacturing process. Apart from commercial glass fibre fabrics, multi-axial bonded fabric and tailor-made textiles were investigated. Load bearing behaviour of joints was found to be influenced in a wide range by densification as well as kind and ratio of the textile reinforcement [6,7].

1 Material

1.1 Densified wood

Densified wood was made of sawn, kiln dried spruce laminations of good quality. A grading according to knots, grain deviation and other characteristics was not done. The geometry of the section was 2500 x 140 x 100 mm. Moisture content before and after densification was 12 to 15% and 7 to 9% respectively. Initial density ranged from 380 to 530 kg/m^3.
The densification procedure took place in a conventional hot press in the laboratory (figure 1 (a)) and in industry (figure 1 (b)).
The manufacturing of compressed wood was realized in three steps: heating, densification and cooling (figure 2). In the first phase, the warming up of the specimen was done between the hotplates at a low pressure of 0.2 - 0.3 MPa. The heating time can be estimated roughly at 1 minute per mm thickness of the section. After having reached the necessary temperature throughout the section the plastification of the wood starts.