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How to Manufacture and Utilize Compressed Wood

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Mechanical properties of wood such as stiffness, strength, hardness and abrasion resistance can be improved by compression perpendicular to the grain, which also gives more uniform properties. However, the compressed wood is known to recover almost to its initial state under the influence of both moisture and heat. The deformation in wood is thought to be fixed by the following three kinds of methods; to make the wood inaccessible to water, to form crosslinks between the wood components, and to release the elastic energy stored by deformation. Treatment with a low molecular weight phenol or melamine-formaldehyde resin, heating, or steaming are all effective methods to permanently fix the compression in wood.

1. Introduction

In the future, fast-growing woods, which are soft and have a low density, will be a main supply for the wood industry. To utilize these woods for furniture and interior materials, it is necessary to improve their surface properties, such as hardness and abrasion resistance, since inadequate surface properties have restricted the markets for these kinds of soft wood products. Soft wood with useful surface properties can be obtained by compressing the wood in the direction perpendicular to the grain, resulting in a higher density (1). However, the compressed wood is known to recover almost to its initial state under the influence of both moisture and heat (2). Therefore, a permanent fixation is essential in order to utilize compressed wood as an engineering material.

This paper deals with the methods for compression and fixation of the deformation of wood, as well as with the practical process and utilization of compressed wood.

2. Compression perpendicular to the grain

The solid thick line in figure 1 shows stress-strain curve for wet sugi wood (*Cryptomeria japonica* D.Don) in radial compression at 20C. Like stress-strain curves for other cellular materials, it shows a linear elastic regime (A) at low stress followed by a long collapse plateau regime (B) with a roughly constant stress, leading into a final regime (C) with a steeply rising stress. When wood is compressed, the cell walls first bend, giving linear elasticity, but when a critical stress is reached the cells begin to collapse by elastic buckling. Eventually, at high strains, the cells have collapsed so much that opposing cell walls touch and further deformation compresses the cell wall material itself. This gives the final, steeply rising portion of the stress-strain curve labelled densification (D). When the deformation exceeds the densification, the wood specimen extends remarkably in the tangential direction damaging the structure in cell walls.

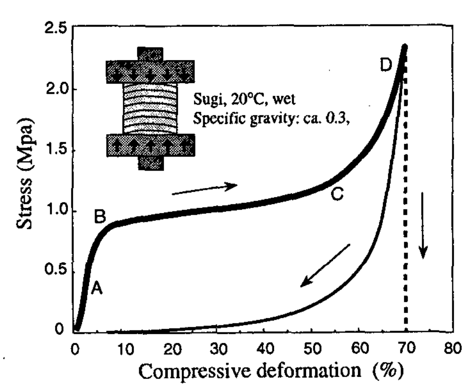

Figure 1. Stress-strain diagram for compression of wet wood.

As shown by the solid thin line in figure 1, most of the deformation is recovered when the wood is unloaded even after a strain of 70%. From this fact, wood differs considerably from other cellular materials. When the specimen is dried in the deformed state, the initial stress for the deformation is gradually decreased and finaly extinguished by shrinkage of the specimen, resulting in a temporary set of deformation which is called "drying set".

The cross-sections of an unloaded sugi specimen (A) and a compressed one (B, 67% of strain) are shown in figure 2. The annual ring width shows a marked decrease and it is mainly the early wood portion that is compressed. There is no visual rupture of cell walls observed. Expansion of the specimen perpendicular to the compressed direction is very small compared to solid materials, because wood is a cellular material. It has been observed by SEM (scanning electric microscope) that the cell walls are smoothly bent without any failure and lumens are almost extinguished.

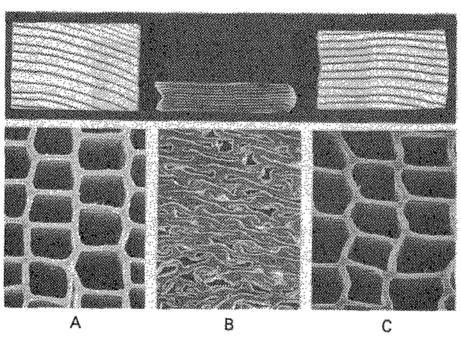

Figure 2.Original(A), compressed(B), and recovered wood(C).

3. Mechanical properties of compressed wood

The specific gravity increases with increasing compression set. At a compression set of 60%, the specific gravity increases to 1.0, which is more than twice the initial. Figure 3 shows the increase in moduli of elasticity and rupture for bending test, surface hardness and abrasion resistance. It is possible to obtain values larger than those of high density hardwoods. Furthermore, compression decreases the difference in properties between early- and late-wood, which results in more uniform properties. This is one of the characteristics of compressed wood which simplifies the processes of cutting, curving and overlay, in addition to improved mechanical properties,.

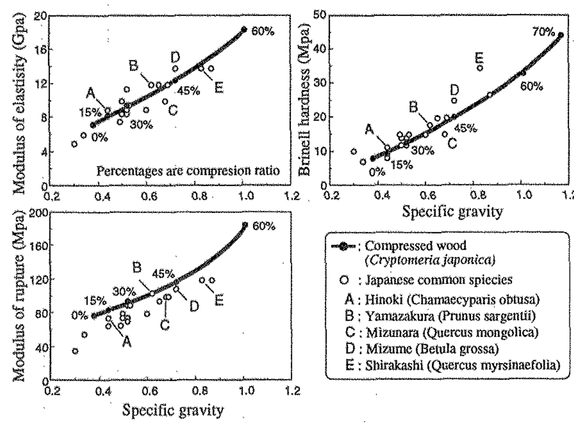

Figure 3. Mechanical properties of compressed wood.

4. Recovery of compressive deformation by moisture and heat

Drying set of deformation is stable in the dry state, but it is recovered under the influence of both moisture and heat. Picture C in figure 2 is the cross section of the recovered specimen which was obtained by boiling specimen B. There is a little residual strain observed by SEM, but the deformation is recovered almost to its original state.

Figure 4 shows the relationship between recovery of set (percentage of the recovery to the deformation) and compression set. Recovery of set is about 85% irrespective of compression set if the strain is less than about 75% and the specimen is without marked fractures.

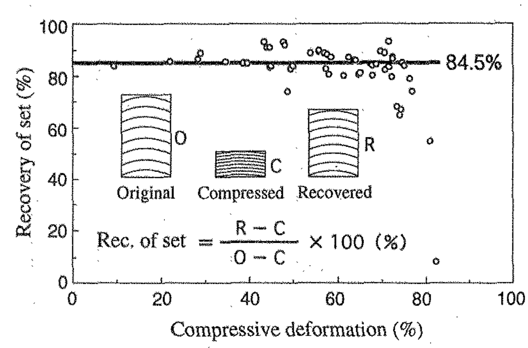

Figure 4. Recovery of set by boiling.

5. Mechanisms of softening, drying set, recovery of set, and permanent fixation of deformation

The wood cell wall is composed of cellulose microfibrils embedded in a matrix of lignin and hemicelluloses. Increasing the temperature of wood in a wet condition causes softening of the matrix components, but the crystalline parts of the cellulose microfibrils remain in the glassy state. On the basis of this fact, the mechanism of the drying set of the deformation and its recovery by moisture and heat can be simplified as shown in figures 5-a, b, and c. Softening of the matrix portion enables the relative displacement of the microfibrils, which are represented by a spring in the figure. The matrix component does not flow by the deformation, since lignin has a three-dimensional crosslinked structure.

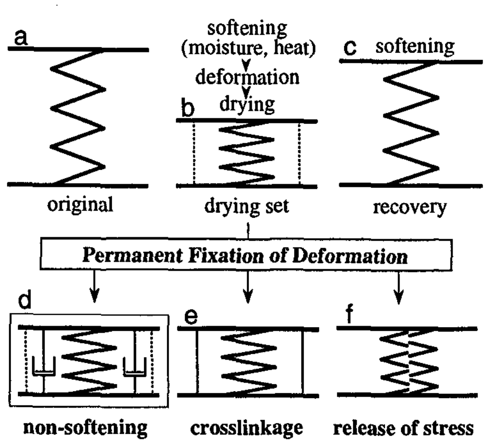

Figure 5. Mechanisms for drying set of compressive deformation in wood and its recovery, along with the methods for fixation of deformation.

The departure of water molecules due to drying induces the re-formation of hydrogen bonds between the molecules of the matrix constituents as shown by broken lines in figure 5-b. Together with the temperature decrease, this process leads to the return to the glassy state, where the elastic deformations are frozen. However, when the matrix is softened again through re-moistening and heating, the set will be recovered owing to the release of the energy-elastic strain stored in the microfibrils and entropy-elastic molecular movements in the matrix as shown in figure 5-c.

In order to fix the deformation permanently, we propose three kinds of methods shown in figures 5-d, e, and f. The first method is through preventing the re-softening of wood by conversion of wood to water-inaccessible material, since the set does not recover unless re-softening of the matrix occurs. The second method is to form covalent crosslinks between the wood components in the deformed state. The third method is to release the elastic stresses and strains stored in microfibrils and matrix.

6. Fixation of compressed wood

There are some useful treatments to fix the compressed wood. In practice, it is necessary to select or combine these treatments considering service conditions.

Fixation by resin treatment

High dimensionally stabilized compressed wood can be prepared by using phenol- (2) or melamine-formaldehyde (3) resin with low molecular weight (200 - 600). When specimens are impregnated with a phenol or melamine-formaldehyde resin solution with more than 15 or 25% concentrations, respectively, and then compressed in the radial direction by a hot press at 130 C, the deformation of the specimens is almost completely fixed. The surface hardness of the products increase with increasing compression sets and resin concentrations, and it is possible to obtain larger values than those of high-density hardwoods without any failures. The moduli of elasticity and rupture of the products increase with increasing resin concentrations except at low resin concentration. Resin treatments also give wood an improved biological resistance and a high dimensional stability, therefore resin treated compressed wood has great potential in use as exterior materials.

Fixation by heat or steam treatment

Table 1 shows the characteristics of conventional steam and heat treatments to fix the deformation in wood. With steaming (4), compressive deformation is perfectly fixed in 8 minutes at 180C or less than 1 minute at 200C. Changes in mechanical properties and color are relatively small, however, the apparatus is very expensive and its operation and control are complicated. There is a specimen size limit and it is difficult to treat the specimens uniformly, because the steam is introduced from the outside of the wood. On the other hand, heat treatment is easily done using a regular hot press (5). The size of the product is not limited, and it is possible to treat the wood uniformly. However, compared to steam treatment, heat treatment takes a considerably longer time. For example, permanent fixation can be achieved in 20 hours at 180C, or 5 hours at 200C. These conditions result in dramatically change of mechanical properties, color, and moisture content.

Table 1. Characteristics of heating and steaming

	Heating	Steaming
Condition of fixation (Temperature and time)	180C, 20hs 200C, 5hs	180C, 10min 200C, 1min
Mechanical properties (MOE and MOR)	-5%, -36%	-7%, -5%
Color change	29%	12%
Sizing limit	Not limited	Limited
Uniformity	Uniform	Not uniform
Operation	Simple and easy Hot press	Complicated Special apparatus

Fixation by airtight heating

To overcome the drawbacks previously mentioned, we developed a new process to permanently fix the compressive deformation of wood (6). In this process, a hygro-thermal treatment using the moisture in the wood in a closed system was applied. As shown in figure 6, the wood specimens are compressed in the radial direction and heated in a hot press equipped with an air-tight O-ring seal. Following the treatment, the specimens are rapidly quenched in the press. The recovery of the compression set after boiling in water decreased with the increase of heating time and temperature. A permanent fixation of the set was achieved when specimens with a moisture content of 17% were compressed for 8 minutes at 180C. For dry specimens, however, the treatment was not effective, so we conclude that the moisture in the wood acted on the fixation of the deformation in wood.

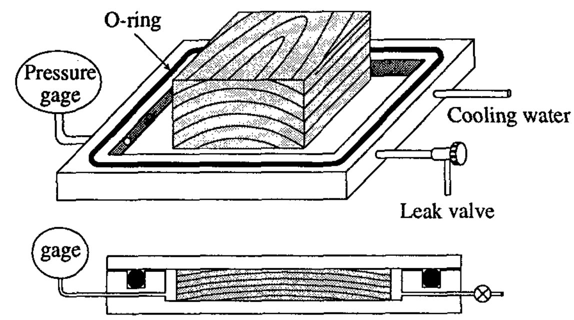

Figure 6. Sealed system for the airtight heating

7. Utilization of compressed wood

Excellent surface properties can be obtained by compression in radial direction which makes possible to utilize the fast growing soft wood as a substitute for hardwood. Compressed woods are especially suited for table tops, flooring, sills, steps, and top rails where hardness and high abrasion resistance are needed. Strength properties of compressed wood are also very high, so which is available for handrails, window sashes, and fine frameworks of highly designed cabinets or chairs.

In addition, compressed wood can be used as a substitute for rare wood species, such as ebony or rose wood, for high-grade furniture and craft articles, because of its heavy, hard, uniform properties, and darker color.

The methods of the fixation of compressed wood can be applied for the dimensional stabilization of wood based materials, such as laminated veneer lumber(LVL), particle boards, etc. We are trying to make reinforced (compressed) LVL as the joint materials for timber constructions(7). This new joint system has advanced properties in operation efficiency of the execution, the accuracy of joints, the fire resistance, the dew condensation and the aesthetic quality, compare with conventional steel plates joints system.

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