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Manufacture and properties of ultra-low-density fiberboard

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Abstract Low-density fiberboards with densities ranging from 0.05 to 0.50 g/cm^3 were manufactured with steam injection pressing. Bond-type and foam-type isocyanate compound resin adhesives were used separately at 10% and 30% resin content levels. Two types of different-size fibers from softwood were used. Mechanical, dimensional, thermal, and sound insulation properties of the fiberboards were tested. The results are as follows: (1) Bond-type isocyanate adhesive showed higher mechanical and dimensional properties of low-density fiberboards than the foam-type adhesive. (2) Fiberboards produced from small fibers have better mechanical and dimensional properties than those made from large fibers. (3) Thermal conductivity of fiberboards depends more on the board density than on the type of resin or fiber dimension. At a board density lower than 0.2 g/cm^3, the thermal conductivity is almost equivalent to those of thermal insulation materials such as polystyrene foam and rock wool. (4) Generally, the sound absorption coefficient of low-density fiberboards tends to increase at higher sound frequency. As the board thickness increases, low-frequency sounds are more readily absorbed by boards.

Key words Low-density fiberboard · Isocyanate resin · Physical property · Thermal insulation · Sound insulation

Introduction

The demand for a comfortable life in wooden houses requires them to be constructed from high-quality structural materials with good thermal and sound insulation performances and high-quality mechanical and dimensional properties. Lightweight structural panel material is imperative for the improvement of architectural quality. Low-density board can satisfy the aforementioned demands, because its porous structure and its low potential for swelling provide good thermal and sound insulation properties and good dimensional stability, respectively. This wood-based material can be produced from low-grade logs and wood wastes, and it be recycled for environmental conservation.

One of the drawbacks of using low-density boards is its mechanical property because of the poor contact among the elements. In this regard, isocyanate compound resin adhesive, which yields carbon dioxide gas by a chemical reaction with water, can provide foams that give rise to improved bondability in lightly compacted board. The formation of this adhesive foam can be accelerated by application of a steam injection press.

Isocyanate resins were applied as the most feasible adhesive with hot press on low-density particleboards[1–6] or fiberboards.[7] Lowering the density may be easier to achieve in fiberboards than in particleboards, as fiberboard density tends to depend less on the raw material density.[8] Only a few studies have been conducted on low-density fiberboards, and they are still not systematized.

This paper discusses the lower density limit of manufacturing fiberboards bonded with isocyanate resin using steam injection pressing. The effect of isocyanate resin type, resin content, and fiber type on the fundamental board properties, such as mechanical, dimensional, thermal, and sound insulation performances, was investigated.

Materials and methods

Fiber preparation

Two types of softwood fiber were prepared: small fibers (S-fibers) from radiata pine (*Pinus radiata* D. Don) using pressurized double disc refiner (PDDR) (Hokushin Co.) and large fibers (L-fibers) from yellow cedar (*Chamaecyparis*

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nootkatensis Spach) using pressurized single disc refiner (PSDR). The air-dried densities of radiata pine and yellow cedar are 0.49 and 0.50 g/cm^3, respectively[9,10]; and the densities of the two types of fiber are assumed to be the same. The moisture contents of the fibers at the air-dried condition are 11.6% for S-fibers and 10.5% for L-fibers.

Microphotographs of S-fibers and L-fibers after loosening with a sample-carding machine were taken at 19× and 3× magnifications, respectively. The lengths and widths of 100 randomly chosen fibers were measured using a caliper, and the aspect (length/width) ratios were calculated. The distance between the two ends of each fiber (end-to-end distance) was measured, and the end-to-end distance/length ratio (which indicates the straightness of the fibers) was calculated. The mats of S-fibers and L-fibers were formed without resin using a fibermat apparatus. The fibermat bulk densities of S-fibers and L-fibers were 0.034 and 0.030 g/cm^3, respectively.

Manufacture of low-density fiberboard

Fiberboards with densities ranging from 0.05 to 0.50 g/cm^3 were manufactured using two types of fiber prepared as above. Two types of prepolymerized methylene diphenyl diisocyanate resin adhesive were used: a bond-type UL-4811 (IC-B in this report) by Gun-ei Kagaku Co. and a foam-type HBN-003 (IC-F in this report) formulated for foam use by Nihon Polyurethane. The isocyanate group (NCO) contents of IC-B and IC-F are 25%–27% and 12%, respectively. IC-F includes a foam promoter. Only IC-B was used in the production of fiberboards from L-fibers. Resin contents were 10% and 30% resin solids of isocyanate based on oven-dried fiber weight. Acetone equal to 20% of the IC-B resin weight was added to the resin to obtain a suitable viscosity and quantity for efficient spraying. Similarly, acetone equal to 60% and 30% of the IC-F was added to the resin in the case of 10% and 30% resin contents, respectively. The fibers were loosened with a sample-carding machine and then sprayed with a corresponding amount of adhesive using a newly designed laboratory scale air-cyclic pipeline blender.[11] The glue-furnished fibers were formed into mats and then steam injection-pressed into boards (370 × 360 × 12 mm) with a steam pressure of 0.6 MPa at 160°C. Total pressing time was 3 min including 2.5 min of steam injection for all boards with the exception of boards bonded with 30% IC-F, which were pressed for 5.5 min including 5.0 min of steam injection to obtain improved board properties. The top and bottom surfaces of the fiber mats were covered with glass fiber-reinforced Teflon net sheets, which prevent sticking to press platens while allowing a free flow of steam; and the sides were sealed with a 12 mm thick stainless steel frame. All boards were stabilized to equilibrium conditions at ordinary room temperature and humidity.

Property testing

The mechanical properties of boards were tested according to the Japanese Industrial Standards for Fiberboards (JIS A 5905). A static bending test in dry condition was conducted on four 220 × 25 × 12 mm test pieces from each board at a test span of 180 mm. The bending modulus of rupture (MOR) and modulus of elasticity (MOE) were calculated. Internal bond (IB) tests were conducted on four 50 × 50 × 12 mm test specimens for each board.

The compressive MOE in the thickness direction was tested on an 84 mm diameter 12 mm thick specimen for each board by the vibration method[12] in accordance with JIS K 6394. Specimens were fixed with the double-side adhesive sheets to the vibrating plate propped on a vibration exciter. An iron disk 76 mm diameter and 3 mm thick was fixed on top of the specimen in the same manner. The accelerometer was attached with wax at the center of the iron disk. The compressive MOEs were determined from the resonance frequency with specimens and the mass material consisting of the iron disk, the accelerometer, and the specimen using an FFT analyzer. The compressive MOE of some commercial insulation materials were also measured. The fiberglass wool and rock wool samples were 76 mm in diameter and 13 mm in thickness, and those of polyurethane foam was 84 mm in diameter and 27 mm in thickness. The latter was using a 5 mm thick iron disk.

The dimensional stability under accelerated weathering condition was tested on four 50 × 50 × 12 mm specimens. The test order is as follows: air drying at 20°C and 60% relative humidity (RH), cold water soaking at 20°C for 24 h, oven drying at 60°C for 24 h, hot water soaking at 70°C for 24 h, oven drying at 60°C for 24 h, and air drying under the initial conditions. The thicknesses of boards after each stage were measured, and the thickness changes were calculated based on the board thickness at the initial air-dried condition.

To investigate moisture resistance, the linear expansion (LE), thickness swelling (TS), and equilibrium moisture content (EMC) of boards after moisture absorption and desorption processes were tested on four 220 × 25 × 12 mm specimens from each board. During the moisture absorption process oven-dried specimens were put in a desiccator at 20°C and exposed to circulating air at constant RH until the boards attained EMC. The RH in the desiccator was kept constant at 33%, 67%, and 98%, successively, by saturated solutions of $MgCl_2$, $CoCl_2$, and $CaSO_4$, respectively. The moisture desorption process was conducted using the solutions, the corresponding RH in reverse order, and finally oven drying.

The thermal conductivities of the fiberboards were tested on an air-dried 50 × 50 × 12 mm specimen from each board at 6%–7% moisture content in accordance with the American Society for Testing Materials (ASTM C 518-76, steady-state thermal transmission properties by means of the heat flow-meter). Two gauges were used for each specimen that were covered with polystyrene foam to prevent the escape of heat.

Normal incident sound absorption coefficients of boards were tested on an 84 mm diameter 12 mm thick specimen for each board in accordance with JIS A 1405 (test for sound absorption of materials by the tube method). The standard sound frequency range (100–2000 Hz) was used for the

Table 1. Configurations of fibers used in the experiment

	S-fibers of radiata pine (*Pinus radiata* D. Don) defibrated with pressurized double disc refiner				L-fibers of yellow cedar (*Chamaecyparis nootkatensis* Spach) defibrated with pressurized single disc refiner			
	Width (mm)	Length (mm)	Aspect ratio (length/width)	End-to-end distance/length	Width (mm)	Length (mm)	Aspect ratio (length/width)	End-to-end distance/length
Average	0.047	0.83	17	0.95	0.253	14.0	81	0.70
Standard deviation	0.017	0.82	13	0.07	0.208	6.0	46	0.22
Maximum	0.115	3.89	60	1.0	1.052	32.3	198	1.0
Minimum	0.016	0.11	3	0.68	0.058	3.4	8	0.08
Tracheid size[14]	0.044	3.0			0.027	3.2		

test.[13] The specimens investigated for the effect of board thickness on sound absorption were two or three of 12-mm samples piled on top of one another without intersample bonding.

Results and discussion

Fiber dimensions

The average widths of the single softwood tracheid were 20–60 μm and 5–20 μm in the early and late wood, respectively, and 2–4 mm in length.[14] As shown in Table 1, single tracheid dimensions of species used in this experiment were almost the same and within the average size range of softwood. Compared with these single tracheids, the S-fibers used in this experiment are equal to the single tracheid width, but the length is only one-fourth that of the single tracheid length. In contrast, the width and length of L-fibers are nine and four times that of the single tracheid, respectively. Therefore, L-fibers can be regarded as the large tracheid bundles. The aspect ratio of S-fibers was smaller than that for L-fibers. The end-to-end distance/length ratio of S-fibers was closer to 1 than that of L-fibers. This indicates that S-fibers were straighter than L-fibers. Many splits and more curves and twists were observed in fiber bundles of L-fibers. These differences in the dimensions and shapes of the fibers slightly reflected on the fibermat density.

Mechanical properties of low-density fiberboard

Figure 1 shows the MOR, MOE, and IB of fiberboards in relation to board density. Ultra-low-density fiberboards (density 0.05 g/cm^3) could be produced effectively. By increasing the resin content, the mechanical strength of fiberboards was improved even at low densities. The specific mechanical strength of these boards is much superior to that of the commercial low-density fiberboards. For example, the MOR of fiberboards of 0.2 g/cm^3 density from radiata pine bonded with 30% IC-B was three and five times as much as those of class A insulation board and straw-mat board (JIS 5905), respectively. Considering the mechanical properties, the limit of lowering the density to which fiberboards can be produced is 0.05 g/cm^3 under these conditions. The mechanical strength of low-density fiberboards can be improved while retaining their low density by sandwich construction.

In respect to the effect of resin type, the bond-type IC-B recorded mechanical strength superior to that of the foam-type IC-F at the same board density and resin content level. This is probably due to the fact that the isocyanate NCO group of IC-B is twice that of IC-F, which caused harder bonding in IC-B fiberboards. Further details of the foaming mechanism of these resins under the high pressure steam condition remain to be investigated.

On the other hand, in respect to the effect of fiber type on fiberboards bonded with IC-B, the L-fibers recorded somewhat less mechanical strength in fiberboards than S-fibers at the same board density and resin content. This finding is contrary to the tendency in particleboards, where longer particles have a higher MOR.[3] The mechanical properties of fiberboards are affected by the various characteristics of fibers with resin, as discussed below.

Single tracheid tensile strength depends on the ratio of the cell wall to the lumen cross section. It can be assumed that the single tracheid tensile strength of the two fibers used are similar, as this ratio is also the same owing to their almost equal densities. Corresponding to the general tendency that the tensile strength of fiber or fiber bundles decreases as its length and width increase,[15] the boards from L-fibers had less strength (despite its better twisting effect) than those from S-fibers in this experiment.

The resin distribution in S-fibers might be better, although theoretically there is less resin per unit surface area. On the other hand, the rough surface of L-fibers caused uneven resin distribution. It is also difficult for the resin to penetrate the inner side of the bent fibers or fiber cracks owing to the damage to fibers during the refining process. There are fewer bonding points in L-fibers than in S-fibers, although the contact area per point is larger. Moreover, the surface of S-fibers may be smoother and more suitable to the foam of the resin in relation to its surface tension strength and radian of contact.

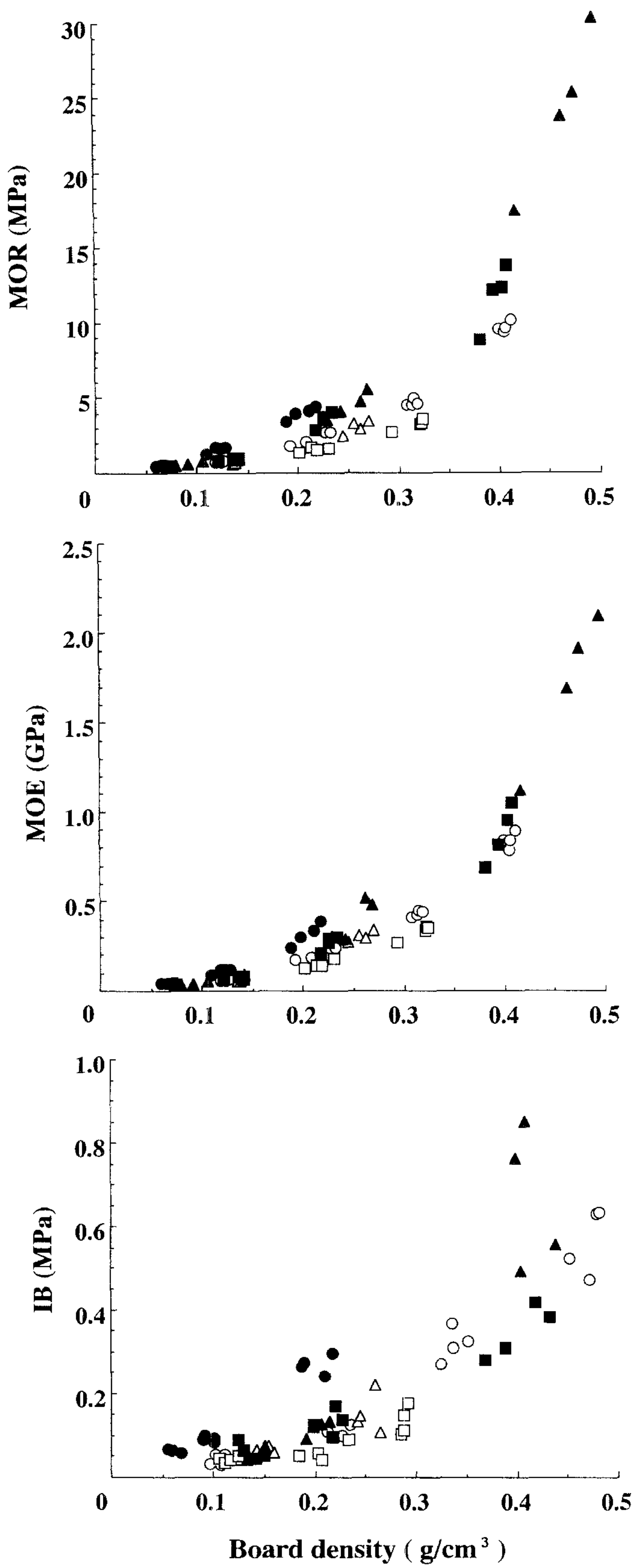

Fig. 1. Modulus of rupture (MOR), modulus of elasticity (MOE), and internal bond strength (IB) of fiberboard in relation to board density. Fiberboard made from S-fibers bonded with IC-B (*circles*) and IC-F (*squares*), and that made from L-fibers bonded with IC-B (*triangles*). Resin contents were 10% (*open symbols*) and 30% (*filled symbols*)

Thus, many factors influence the mechanical property of fiberboards in a complicated fashion, which is contrary to previous results regarding the mechanical property of fiberboards without resin adhesive, which was affected only by the fiber shapes.[16] Further details on the effects of fiber and resin on fiberboards must be investigated.

Figure 2 shows the compressive MOE in the thickness direction of fiberboards and other insulation materials. Generally, the compressive MOEs of various fiber types do not differ much from each other, although the fiberboards from S-fibers with 30% resin content had a slightly higher compressive MOE. The specific compressive MOEs of low-density fiberboards were much higher than those of fiberglass wool and rock wool. Therefore, these low-density fiberboards may be used as the core material for the sandwich panels.

Dimensional stability of low-density fiberboard

The thicknesses of all boards with densities ranging from 0.05 to 0.50 g/cm^3 recovered to near their original thickness after the accelerated weathering conditioning cycle; that is, the final springbacks of the boards were almost negligible. Generally, lower-density boards had a lower degree of TS. This is an advantage of low-density fiberboards, indicating the achievement of satisfactory interfiber bonding, despite the low compaction ratio. Figure 3 shows the thickness changes of boards at a density of 0.2 g/cm^3 under accelerated weathering conditions, where thickness changes were computed based on the thickness of the boards after the first air-dry conditioning. The TS of these steam injection pressed boards after 24 h of water soaking is less than or similar to that of 10% isocyanate-bonded low-density fiberboard produced from untreated, acetylated, or steam-treated fibers

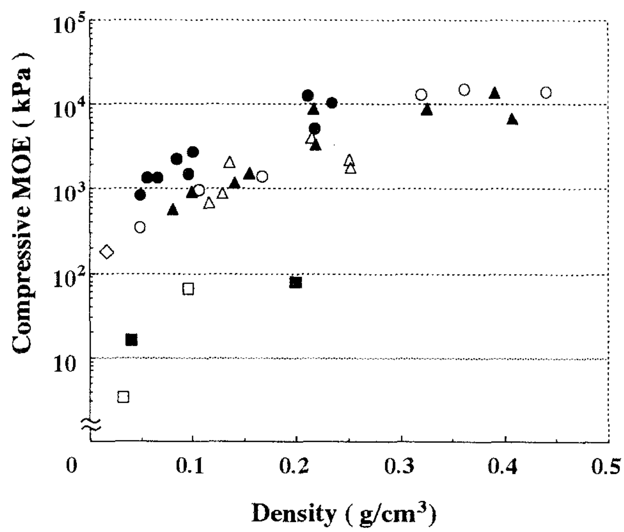

Fig. 2. Compressive MOE in thickness direction of fiberboards and other insulation materials. Fiberboard made from S-fibers bonded with IC-B (*circles*) and that made from L-fibers bonded with IC-B (*triangles*). Resin contents were 10% (*open symbols*) and 30% (*filled symbols*). *Open squares*, fiberglass wool; *filled squares*, rock wool; *lozenge*, polyurethane foam

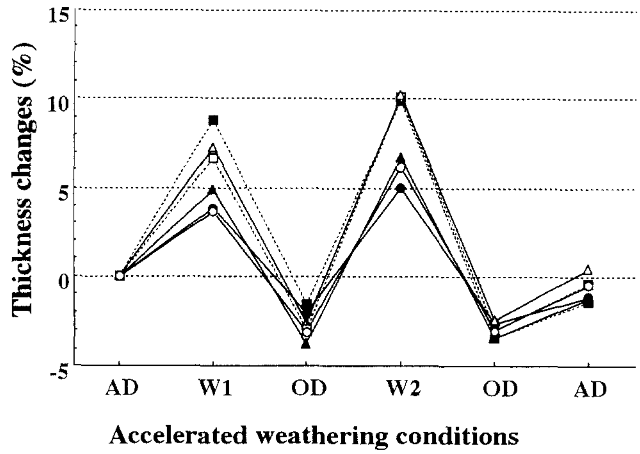

Fig. 3. Thickness changes of fiberboards at a density of 0.2 g/cm^3 under accelerated weathering conditions. Fiberboards made from S-fibers bonded with IC-B (*circles*) and IC-F (*squares*), and those made from L-fibers bonded with IC-B (*triangles*). Resin contents were 10% (*open symbols*) and 30% (*filled symbols*). *AD*, air drying at 20°C and 60% relative humidity (RH); *W1*, cold water soaking at 20°C for 24 h; *OD*, oven drying at 60°C for 24 h; *W2*, hot water soaking at 70°C for 24 h

using hot pressing at 160°C for 4 min.[7] The combination of isocyanate resin adhesive and steam injection pressing contributed effectively to the good dimensional stability of boards.

Boards bonded with IC-B have better dimensional stability (i.e., lower TS) than those bonded with IC-F. The TS values of boards bonded with IC-B after water immersion at 20° and 70°C were less than 7% and 10%, respectively.

Although the TS of fiberboards from L-fibers were greatly improved (lower TS) by increasing the resin content, their dimensional stability is somewhat inferior to that of S-fibers.

The resin type made no significant difference on the LE and TS of fiberboards during the moisture absorption and desorption processes. Figure 4 shows the LE and TS of fiberboards bonded with IC-B with density of 0.2 g/cm^3 during the moisture absorption and desorption processes in relation to the RH. The LE and TS of fiberboards from L-fibers were higher than those from S-fibers. The hysteresis was more obvious, and the residual LE after the cycle was higher in fiberboard made from L-fibers. Fiberboards made from L-fibers have more potential to swelling in the length and thickness directions because twist or bent fibers are included. In contrast to the general tendency in particleboards, where longer particles improve plane dimensional stability, fiber dimensions do not always directly affect the fiberboard dimensional properties, because fibers are softer than particles. The EMCs of all fiberboards within this density range were 5%, 8%, and 18% under 33%, 67%, and 98% RH, respectively.

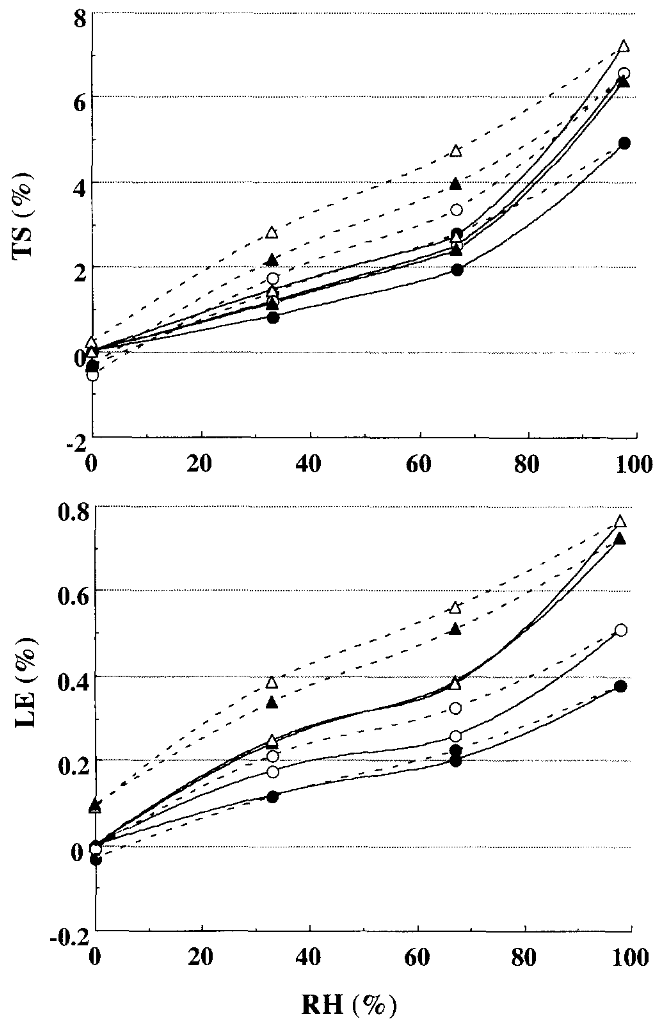

Fig. 4. Linear expansion (*LE*) and thickness swelling (*TS*) of fiberboard bonded with IC-B at a density of 0.2 g/cm^3 in relation to the RH. Fiberboard made from S-fibers bonded with IC-B (*circles*) and IC-F (*squares*), and that made from L-fibers bonded with IC-B (*triangles*). Resin contents were 10% (*open symbols*) and 30% (*filled symbols*). *Solid lines*, absorption; *dotted lines*, desorption

Thermal insulation properties of low-density fiberboard

Thermal conductivity (λ) is an indicator of the value of a material as a heat insulator. Generally, the λ of a wood-composite material is less than that of wood at the same density. Especially in fiberboard, the pore spaces within the board are equiaxed, and their distribution profile is more constant than that in wood, such that λ is less affected by air circulation. The λ values for low-density fiberboard are shown in Fig. 5. The results show that λ of the fiberboard is strongly influenced by the board density and hardly at all by fiber type or resin content. For lower-density fiberboard λ approaches 0.02 kcal/m h°C of dried air at 20°C and is much lower than that of wood substance at a density of 1.5 g/cm^3, which is 5.62 and 0.362 kcal/m h°C in the parallel and perpendicular directions of tracheid,[17] respectively. At a density range of 0.05–0.20 g/cm^3, the λ of fiberboard ranges from 0.03 to 0.04 kcal/m h°C, which is much lower than that of other wood-based materials[18] and almost the same as that for other insulation materials, such as rock wool, fiberglass wool, polystyrene foam, and rigid polyurethane foam.[19]

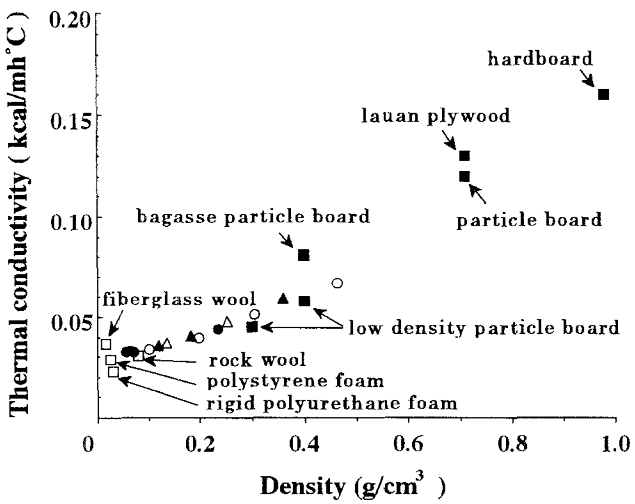

Fig. 5. Thermal conductivity of low-density fiberboard and other materials. Fiberboard made from S-fibers (*circles*) and that made from L-fibers bonded with IC-B (*triangles*). Resin contents were 10% (*open symbols*) and 30% (*filled symbols*). *Open squares*, insulation materials; *filled squares*, wood-based materials

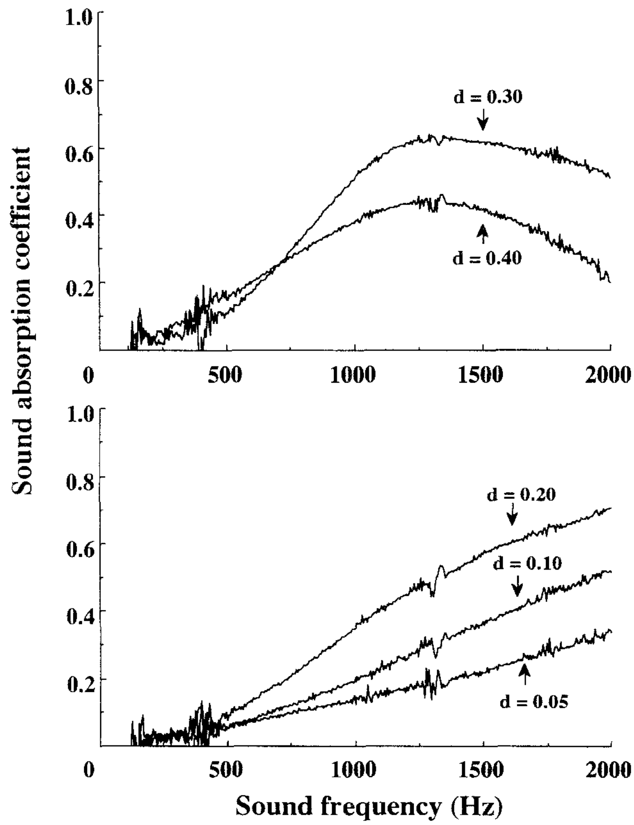

Fig. 6. Normal incident sound absorption coefficients of low-density fiberboard made from S-fibers bonded with 10% IC-B. *d*, density (g/cm^3)

Thermal conductivity of wood composites is also affected by moisture content, as the λ of water at a temperature range of 0°–20°C is about 0.50 kcal/m h°C. In a previous experiment on the relation between λ and the moisture content of wood within a density range of 0.20–0.50 g/cm^3, the variation in λ is only about 0.01 kcal/m h°C when the moisture content changes from 0 to 10%[17]. In the case of particleboards with density ranging from 0.4 to 0.9 g/cm^3, λ is almost constant when the moisture content changes from 0 to 20%[20]. Because the densities of fiberboards in this experiment are even lower and their moisture contents were 6%–7%, moisture content has a minimal effect on λ. The effects of material temperature and resin content on λ are less significant than that of moisture content.[20,21]

On the other hand, the thermal diffusivity of a material is characterized by the ratio of heat transport within the material, which is calculated from the thermal conductivity divided by the volumetric specific heat. The specific heat of wood or fiberboard with density ranges of 0.40–0.80 g/cm^3 is 0.42.[17] The thermal diffusivity of the board is 0.0015 m^2/h at 0.05 g/cm^3 density and 0.00048 m^2/h at 0.20 g/cm^3 density. These figures are only 0.04–0.8 times as much as those of fiberglass wool, polystyrene foam, rigid polyurethane foam, and rock wool, whose thermal diffusivities are 0.012, 0.0039, 0.0026, and 0.0019 m^2/h, respectively.[19] It can be concluded that low-density fiberboards are excellent materials for thermal insulation materials, apart from their superior strength, compared to common insulation materials such as fiberglass wool or polystyrene foam.

Sound absorption properties of low-density fiberboard

Normal incident sound absorption coefficient (α) of low-density fiberboards was highly dependent on the board density and sound frequency. Figure 6 shows an α for 10% IC-B bonded fiberboards. In lower-density boards (0.05–0.2 g/cm^3), the α increased gradually with sound frequency and board density. In higher-density boards (0.30 g/cm^3 and above), the α increased with sound frequency up to about 1250 Hz and then slightly decreased with a further increase in sound frequency. This change is due to the amount of fibers being lower in the low-density board, resulting in less friction between air and fibers and hence reducing the vibration of fibers caused by sound waves. Consequently, less sound energy is absorbed or converted into heat energy. On the other hand, at a higher board density some of the sound waves are reflected owing to increased board resistance to airflow (i.e., flow resistance) and decreased material porosity. Generally, in the other low-density fiberboards in the experiment, α tended to increase with sound frequency and density.

In the tube, the sound velocity is zero near the surface of the wall and maximum one-fourth of a wavelength away from the surface. In an insulation material used to cover a wall, for example, sound is not absorbed effectively if its thickness is less than one-fourth of a wavelength. For it to be effective, it is necessary to increase the thickness of the insulation material or place an air layer between it and the wall to improve absorption of lower sound frequencies. Figure 7 shows the effect of board thickness on α for 0.25 g/cm^3 fiberboards produced from L-fibers bonded with 10% IC-B.

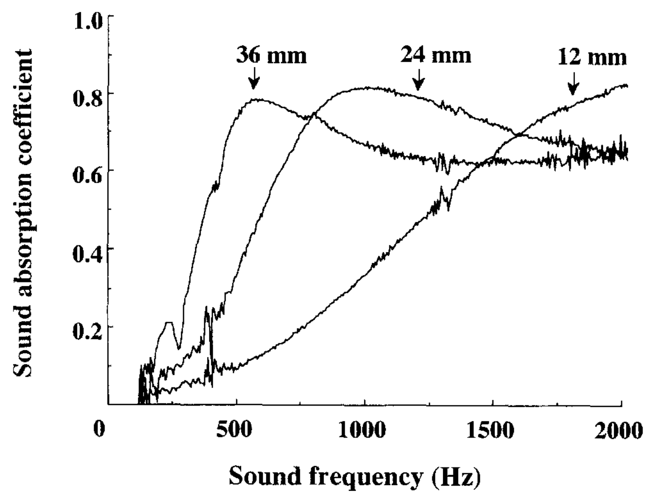

Fig. 7. Effect of board thickness on normal incident sound absorption coefficients of fiberboard at a density of 0.25 g/cm³ made from L-fibers with 10% IC-B. Numbers in the figure indicate board thickness

It is found that low-frequency sounds are more readily absorbed by boards as the board thickness increases from 12 to 36 mm. A similar trend was observed in fiberboard made from S-fibers.

These effects of the density and thickness of low-density fiberboard on sound absorption correspond to general porous-type absorption. The density and thickness of low-density fiberboard can be adjusted to suit the intended application and environmental conditions.

Conclusions

Ultra-low-density fiberboard (0.05–0.50 g/cm³) can be manufactured using isocyanate resin adhesives and steam injection pressing technology. These low-density fiberboards are multifunctional with good dimensional stability, improved specific mechanical properties, and superior thermal and sound insulation properties. Low-density fiberboard may also be used as the core material for sandwich panels.

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