MANUFACTURE AND PROPERTIES OF ULTRA-LOW DENSITY FIBREBOARD FROM WOOD FIBRE

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This study described a process of making ultra-low density fiberboard (ULDF) and investigated the properties of samples of ultra-low density fibreboard made from wood fiber using a liquid frothing approach. The fiberboard had a density of 56.3 kg/m^3 and a layered cross-linked interior structure. Density profiles showed a relatively high density in the surface layers and low density in the core layer. The results showed that the fiberboard had an internal bond strength of 0.15 MPa, a modulus of rupture of 0.70 MPa, a modulus of elasticity of 8.91 MPa, and a compressive strength of 0.17 MPa at 10% deformation. Thickness swelling after 24 hours water immersion was 0.57%. It had a low thermal conductivity of 0.035 W/mK, and a high sound reduction coefficient of 0.67. Resin was uniformly distributed on the fiber surface. The fiberboard can be used as buffer material for packaging and insulation material for building.

Keywords: Ultra-low density; Fibreboard; Liquid frothing; Physical and mechanical properties; Interior structure; Density profile

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INTRODUCTION

Since the 1960s, conventional dry-process fibreboard has been manufactured by applying both heat and pressure to consolidate the mat to a desired density and thickness and to cure the resin to provide bonding between the fibres (Youngquist 1999). This approach uses forest residues and small or low-quality wood as raw material. Fibreboard has excellent physical and mechanical properties and machinability. It has been widely used as a substitute for solid wood in the furniture industry. However, it has notorious issues such as high formaldehyde emission and relatively high density (Xie and Chen 2005).

Attempts have been made to lower panel density. One of the purposes of making low density panel is to reduce raw material consumption while maintaining panel properties. For example, some studies attempted to lower the density of fibreboard by using different compositions of raw materials of different species (different wood densities) (Huang et al. 2003). It is difficult to make fibreboard with density under 200 kg/m^3 using conventional processes because wood density is typically much higher than 300 kg/m^3. Xu et al. (2004) used kenaf core, a light material with density of 150 kg/m^3, to make binderless particleboard with density ranging from 100 to 300 kg/m^3. Since density of resin is normally higher than that of wood, and much higher than that of kenaf core, it is possible to make binderless low density panel using low density kenaf core. However,

the strength of particleboard with 100 kg/m^3 was still too poor to satisfy mechanical test requirements. In addition, the binderless approach is expensive because it requires high press temperature and long press time to degrade hemicellulose into sugars which can be repolymerized so that they function like a resin (Ernest W. Hsu, Hsu Consulting, personal communication, June 8, 2011). Kawasaki et al. (1998) applied steam injection in the manufacture of an ultra-low density fibreboard of 50 to 100 kg/m^3. The process used 10 and 30 percent of isocyanate resin solid to provide connection and bonding between carding-machine loosened fibres. The authors concluded that the limit of lowering density to which fibreboard can be made is 50 kg/m^3. These low density panels are suitable for the core layer in a sandwich construction. However, they may not be economically feasible.

A foaming approach was shown to be an efficient way to lower panel density (Dai and Dai 2004; Lawton et al. 1999; Matuana and Mengeloglu 2004). But it is an expensive approach because these panels are polymer-based composite foams in which plant fibre is used as reinforcement material. Xie et al. (2003) applied a liquid frothing principle to make foaming material from plant fibres, and its internal structure was further discussed in Xie et al. (2008a, 2008b). During the process, air was introduced into pulp solution to form a pulp froth. When liquid froths, interspaces (bubbles) are created inside the solution with fibres suspended in the solution being re-oriented around the bubbles (Xie et al. 2008a, 2008b). Under the effect of water bridging, along with the aid of resin, fibres become interconnected and form arches. When water drains out, fibres move closer together, but the arches in the structure are retained.

The objectives of this study are to demonstrate the feasibility of making ultra-low density fibreboard using a liquid frothing approach in a demonstration production line and to investigate whether it is potentially suitable for thermal insulation and noise reduction applications. The manufacturing process did not involve heat (except during drying) and pressure (Xie et al. 2003), and the manufactured fibreboard had a much lower density than the fibreboard of conventional definition. According to the definition of composites, the ultra-low density fibreboard is a kind of plant fibre-based, organic resin-enhanced composite.

MATERIALS AND METHODS

Manufacture

Four ultra-low density fiberboards of $1200 \times 300 \times 50$ mm ($L \times W \times T$) were manufactured separately using the same parameters in a demonstration production line with target bulk density of 55 kg/m^3. This demonstration line was built as the result of the project "Key Technologies for Manufacture of Degradable Bamboo-Based Composites" supported by the National Science and Technology Support Program under the Eleventh-Five-Year Guideline in China. It has 1000 metric tonnes annual capacity for producing ultra-low density foaming products from natural fibre. It consists of a fibre dissociator (ZFC), a refiner (ZDP12A), a foaming tank (ZMA) with blending vanes, a forming mould (ZCA), a 20 m^3 dry kiln, and a bandsaw (MQ433).

Fiber used in this study was a mixture (6:3:1 dry weight) of mechanical pine (*Pinus massoniana*) pulp, kraft pulp (spruce-pine-fir from Canada), and fibre for medium

density fibreboard (MDF) (3:7 of *Pinus massoniana* : mixture of hardwoods). The fibre mixture was dissociated in the dissociator at 15% consistency, then refined in the refiner at 10% consistency until the pulp reached a beating degree of 32°SR. The refined pulp was adjusted to 6% concentration and transferred to the foaming tank. Based on chemical solid /dry fiber mass, approximately 6.8, 3.4, 2.3, and 1.7 percent of polyacrylamide resin, polyurethane, water repellent (alkyl ketene dimer), and surface active agent (sodium dodecylbenzene sulfonate), respectively, were added at different manufacturing stages, as shown in Fig. 1. Fibre quality analysis was performed with a MorFi Compact device for the 3 types of fibres before being mixed and the mixture after refining (Table 1).

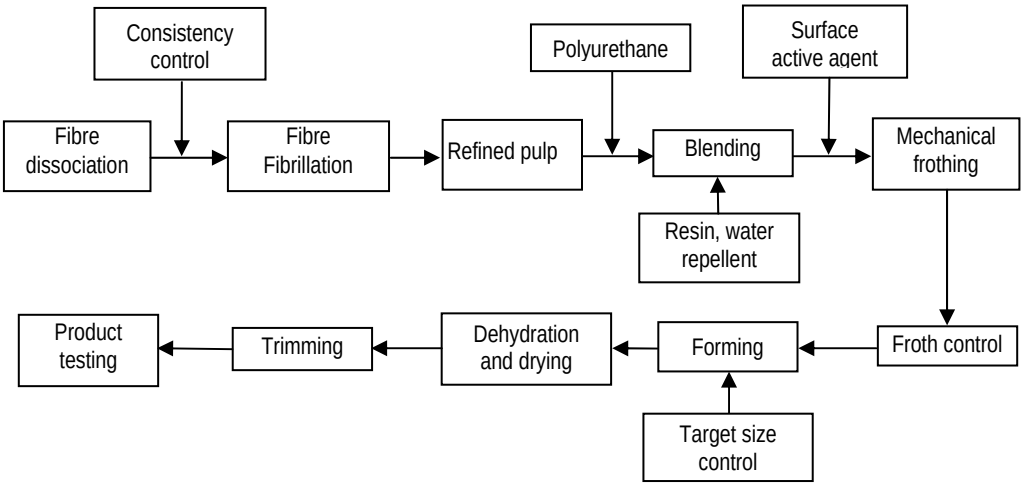

Fig. 1. Flow chart of the process of manufacturing ultra-low density fiberboard

Table 1. Morphology of Three Types of Fbers and their Mixture after Refining

Fibre characteristics	Fibre type			
	Mechanical pulp	Kraft pulp	MDF [2)]	Mixture [3)]
Number of fibres (million/g)	11.99	7.41	3.158	23.50
Length arithmetic average (mm)	0.55	1.38	0.735	0.594
Length weighted average in length (mm)	0.837	2.14	1.041	0.994
Width (μm)	32.3	33.6	29.0	32.5
Coarseness (mg/m)	0.1423	0.1054	0.429	0.0675
Fine elements (% in length) [1)]	65.1	20.8	48.6	58.5

1) Length percentage shown by fines or debris, versus the total length of all objects, i.e., the total length of fibers and fines.
2) Fibre for medium density fiberboard.
3) Mixture of three types of fibres after refining.

The final mixture was transferred to the forming mould of 1200×300 mm dimension with target thickness of 50 mm for dehydration for 30 minutes. The resulting mats were dried at 105°C until they reached approximately 12% moisture content. The

moisture content was measured with a paper moisture meter (SFY-20A). All four ULDF boards had smooth surfaces but somewhat uneven thickness (Fig. 2a)). Each board was sliced and trimmed into two $1200 \times 300 \times 20$ mm boards with a MQ-433 bandsaw equipped with a toothless saw blade. The boards were further cut into different sizes of specimens for evaluation of various properties. Unless otherwise specified, all specimens had a thickness of 20 mm.

Evaluation of Mechanical and Physical Properties

Four specimens from each of the 4 boards were tested for each property. Prior to the evaluation, the specimens were stored in a conditioning chamber (20 ^{o}C, 65% RH) until constant weight was reached. Mechanical properties were tested in accordance with GB/T 17657-1999 (SFAC 1999). Internal bond strength and thickness swelling after 24 h water immersion were tested on 50×50 mm specimens. Static bending was conducted flat-wise with three-point loading on 450×50 mm specimens over an effective span of 400 mm to determine the modulus of elasticity (MOE) and modulus of rupture (MOR). The compressive strength at 10% deformation was tested on 100×100 mm specimens following GB/T 8813-2008/ ISO 844:2004 (CNLIC 2008).

The bulk density at 12% moisture content was measured on 300×300 mm specimens following GB/T 17657-1999 (SFAC 1999). In accordance with GB/T 10294-2008/ ISO 8302:1991 (CBMIA 2008), the same specimens were used to measure thermal conductivity under steady-state conditions using a guarded hot plate apparatus (KY-DRX-PB2). The noise reduction coefficient (NRC) was determined as the average of sound absorption coefficients measured at 250, 500, 1000, and 2000 Hz frequencies. The sound absorption coefficients for each board at the four frequencies were measured on four 20-mm-thick circular specimens of 60 mm in diameter using impedance tube method in accordance with GB/T 18696.1-2004 (CAS 2004).

Vertical density profile (along thickness direction) was measured on 50×50 mm specimens with a densitometer from Carl Schenck (DA22X) equipped with a Denserob EWS System based on the relationship between the density of material and the attenuation of gamma radiation. The Denserob EWS System converts the values of gamma attenuation into the values of density at 0.1 mm intervals and reports the maximum, minimum, and average density in the outer layers (the first 3 mm in each side) and inner layer of the measuring direction. Because the densitometer is capable of measuring density over 100 kg/m^3, in order to measure the density profiles of the specimens (density < 100 kg/m^3), a special calibration was made by using an inflated specimen weight (used by the densitometer to calculate density) such that the density readings would fall within the measuring range of the densitometer. This calibration affected only the values of density readings but not the variation of the density. The density profiles were then corrected using the actual specimen weights.

Microscopic and Surface Chemical Analysis

Specimens were also prepared for microscopic and surface chemical analyses according to the protocols specified by each apparatus. Microscopic images were obtained with stereo microscope (XGL-2I) and digital microscope (Motic DMB5) for board surfaces and interior structure along fibreboard thickness, and environmental

scanning electronic microscope (Philips XL-30 TMP) for resin distribution on fibre surface. Both fiber samples attained before and after liquid frothing process were prepared for chemical states on fiber surface using X-ray photoelectron microscopy (XPS) (PHI-5000 VersaProbe). A typical XPS spectrum is a plot of the number of electrons detected per unit time versus the binding energy of the electrons detected. Each element produces a characteristic set of XPS peaks at characteristic binding energy values that directly identify each element that is present on the surface of the material being analyzed. XPS is able to produce chemical state information from the topmost 1 to 12 nm of any surface, including the presence or absence of the chemical states of carbon known as: carbide (C^{2-}), hydrocarbon (C-C), alcohol (C-OH), ketone (C=O), organic ester (COOR), etc.

The mechanical and physical properties of the ULDF were compared with those of wood-based composites of similar density found in the literature and product technical data published. Although technical data for commercial products might not be directly comparable because of different standards or test methods that followed, it may still serve as a reference. Technical data published in the websites of two building insulation products from wood, NBT Pavadentro (http://www.natural-building.co.uk) (density 180 kg/m^3) and Gutex (http://www.gutex-insulation.com) (density 110 kg/m^3), were used in this study only for rough comparisons.

RESULTS AND DISCUSSION

Exterior, Interior and Micro Characteristics

The ULDF had smooth surfaces with fibres randomly scattered over the surface, featuring porous structure (Fig. 2a)). Fibres were covered with resin and bonded together at inter-crossing nodes. Unlike the conventional MDF in which fibres are distributed uniformly across the thickness, fibres in the ULDF tended to form cross-linked layers across the thickness (Fig. 2b)). The distance between layers ranged from 0.2 to 0.5 mm.

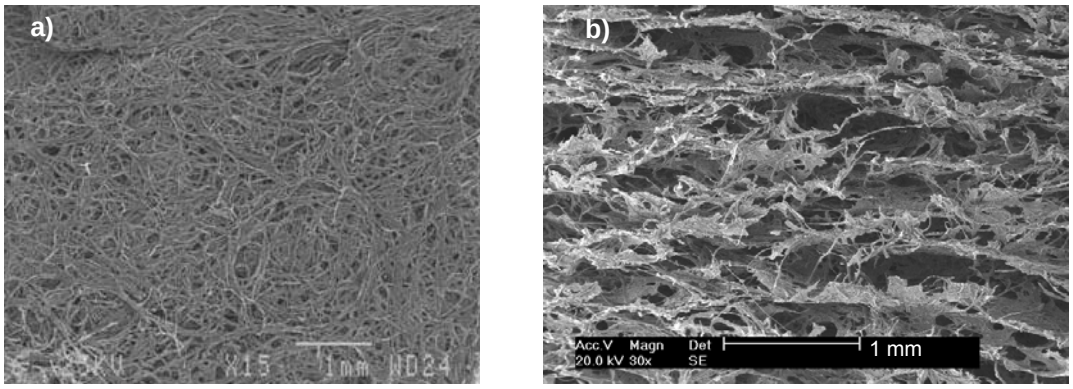

Fig. 2. Microscopic images showing: a) the surface (Motic DMB5 digital microscope) and b) cross section along thickness (XGL 2I stereo microscope) of ultra-low density fiberboard.

As expected, liquid frothing created a large amount of bubbles, which grew and "pushed" fibres away. Meanwhile, neighbouring bubbles merged, adopting the shape

with the smallest possible surface area (Isenberg 1992). The common wall of the merged bubbles was either bulged into larger bubbles or flat in case of equal bubble size. Since every bubble, except those on the surface, was surrounded by the others, the merged bubbles tended to reshape themselves into cubes or polyhedrons with fibres rearranged in the meeting lines of the common walls. The polyhedrons closely lined up such that the fibres formed a layered structure of arches (Fig. 2a)). The interior structure of the ULDF, and the shape, size and formation of the arches are therefore, to a great extend, determined by the size, size distribution and arrangement of the bubbles (Xie et al. 2008a, 2008b). When bubbles burst and water drained, the support from the bubbles disappeared, the arches tended to collapse and fibres to move closer or stack together. It is believed that with the mutual effects of froth control (i.e., control of bubble generation, growth, and bursting), hydrogen bond and resin, the layered structure and interspaces were retained after bubbles burst and water drained. The voids shown in Fig. 2 reflect the size, size distribution, and arrangement of the bubbles, which in turn determined the bulk density and density profile of the ULDF.

With dissociation and refining process, fibers were separated and sufficiently fibrillized (Table 1 and Fig. 3), getting more hydroxyl groups activated and exposed. Theoretically, the hydroxyl groups readily get connected with each other through hydrogen bonding. However, this connection is not strong enough to keep the arches from collapsing during burst of bubbles or draining of water, nor for some applications like packaging. The addition of resin may have enhanced the connection between fibers (Fig. 3) and helped to retain the final structure after water drained.

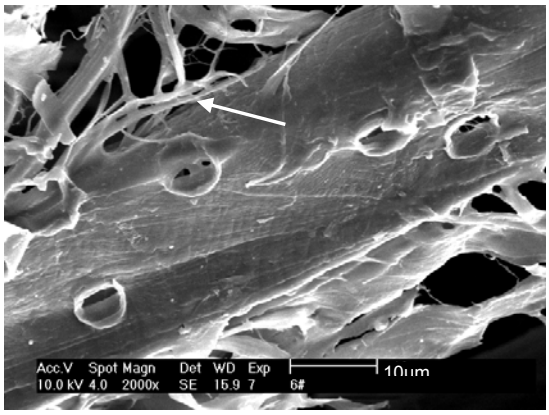

Fig. 3. Microscopic image showing connections between fibres. Fibres were sufficiently fibrillated.

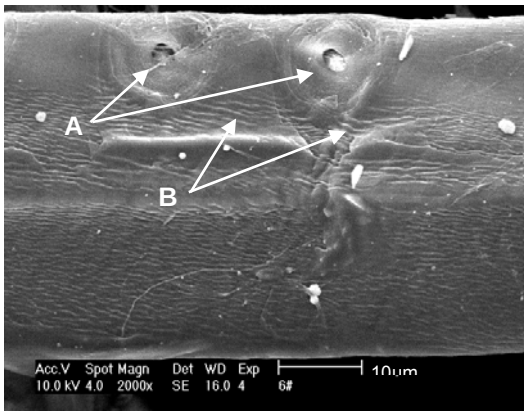

Fig. 4. Microscopic image showing a fibre covered with resin. A: resin films within pits; B: resin film crease

Figure 4 indicates that after liquid frothing process, the fibre surface was uniformly covered with resin and the pits are also covered with a thin resin film. The film creases were in good agreement with the direction of microfibril, suggesting a good integration of resin and fibre.

The different compositions of carbon states on fibres before and after liquid frothing process, as shown in X-ray photoelectron spectra (Fig. 5), further confirmed the presence of resin on the fibre surface.

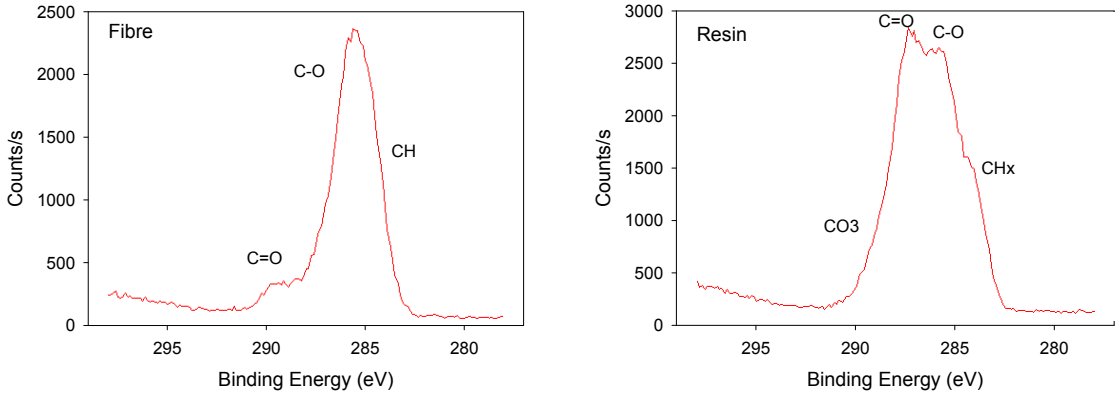

Fig. 5. X-ray photoelectron spectra of fibre before manufacture (left) and fibre after liquid frothing process (right), showing different chemical states of carbon on fibre surface (1-12 nm).

During the process, resin was fully blended, thus uniformly dispersed in the pulp solution. Therefore, resin had an equal chance to be adsorbed on the fibre surface. In addition, more resin was directed towards fibre ends because of the more intensive hydroxyl groups activated at the ends of fibres during fibrillation. Such resin distribution on fibre surface is critical to the porous structure (thus low density) and mechanical and physical properties of the ULDF because it determines whether arches and inter-connections are retained after water drains, and how strong fibre and the connection are.

Mechanical Properties

The ULDF exhibited a very low bulk density of 56.3 kg/m^3 (Table 2) compared to conventional MDF (500-1000 kg/m^3). The bulk density was in between Styrofoam LB (30 kg/m^3) (www.dow.com) and rock wool (78 kg/m^3) (Kawasaki et al. 1998).

The mechanical properties (Table 2) of the ULDF were very low due to its extremely low density, compared with MDF (e.g., 2000 to 3000 MPa in MOE). The MOE was lower than that (40 MPa) of the fiberboard of similar density (50 to 100 kg/m^3) (Kawasaki et al. 1998). The primary reason is likely that the fibreboard that Kawasaki et al. (1998) contained 10% and 30% resin solid of isocyanate, compared with 6.8% and 3.4% solid content of polyacrylamide resin and polyurethane, respectively, in this study. In addition, the actual resin content in the ULDF may be lower than the nominal value of 6.8% for polyacrylamide and 3.4% for polyurethane because part of the resin may have been lost in the drained water. In contrast, both bending MOR and IB were higher than those in Kawasaki et al. (1998) (Table 2). This suggested that the liquid frothing approach is able to produce fiberboards of similar density with higher IB and MOR than the conventional process. The compressive strength at 10% deformation (0.16MPa) was about a half of the value for Styrofoam (0.3MPa) (www.dow.com), but much higher than that of Gutex (0.02MPa) and NBT Pavadentro (0.07). This suggests that the ULDF can have the same applications as the commercial products for building insulation.

Table 2. Physical and Mechanical Properties of Ultra-Low Density Fiberboard (ULDF) and Similar Density Products from wood in the Literature and Commercial Market

Property	This study	Literature		Product technical data	
	ULDF	Fibreboard [5]	Particleboard [7]	NBTPavadentro	Gutex
Bulk density (kg/m^3)	56.3 (4.38) [4]	50/100 [6]	100 [6]	180	110
Internal bond strength (MPa)	0.15 (0.007)	0.063 (0.022)	-	-	-
Bending MOE (MPa)	8.91 (0.28)	40.0 (-)	-	-	-
Bending MOR (MPa)	0.70 (0.06)	0.5 (-)	-	-	-
Compressive strength (MPa) [1]	0.16 (0.002)	-	-	0.07	0.02
Thickness swelling (%) [2]	0.57 (0.06)	-	1.41 (0.99)	-	-
Noise reduction coefficient [3]	0.67 (0.035)	0.134 (-)	-	-	-
Thermal conductivity (W/mK)	0.035 (0.001)	0.039 (0.001)	0.043 (0.0006)	0.042	0.037

1) Value at 10% deformation
2) 24 h cold water immersion
3) Average of sound absorption coefficients at 250, 500, 1000 and 2000 Hz
4) Figures in brackets: standard deviation
5) Figures in column: average of all samples with density ≤100 kg/m^3 (Kawasaki et al. 1998)
6) Target density
7) Figures in column: average of all samples with density ≤100 kg/m^3 (Xu et al. 2004) Mechanical properties were too poor to be tested.

Mechanical properties of a composite material depend on both the inherent nature and the spatial arrangement of its components. To improve the mechanical properties of the ULDF, one way is to improve the performance of wood fibre, by making fibres stiffer and stronger. The other way is to improve the connection between fibres. Increasing resin content may be a straightforward approach to improve both stiffness of and connection between fibres. Since resin is normally much more expensive than fibre, further studies are necessary to explore possible substitutes.

Physical Properties

The ULDF produced had a low thermal conductivity of 0.035 W/mK, which was similar to or slightly lower than that of similar products reported in the literature (0.039 W/mK for fiberboard in Kawasaki et al. 1998 and 0.043 for kenaf particleboard in Xu et al. 2004) (Table 2). It was also similar to that of rock wool (0.036 W/mK) (Kawasaki et al. 1998), a common thermal insulation material, and that of NBT Pavadentro (0.042) and Gutex (0.037), building insulation materials in the market. Heat transfer through porous materials consists of conduction, convection, and radiation. For lightweight materials, heat conduction through the solid portion of the matrix (the fibers) is negligible (Gibson and Lee 2006). Since porous materials contain a large number of voids, primary heat

transfer is conduction through the still air trapped within the material and natural convection of the air (heated air rising through the material). Therefore, its thermal conductivity is primarily determined by the size of voids and the inherent nature of air. For material of the same density, the smaller the void size, the more difficult the air flows, thus the lower thermal conductivity. Low fibre content (low density) and small void size (< 0.5 mm in diameter) make the ULDF a good thermal insulation material.

The NRC of the ULDF was 0.67. This is comparable with the NRC values of heavy carpet on foam and acoustic plaster that are 0.55 and 0.56, respectively (Cox and D'Antonio 2009). This means that the ULDF may have a high noise reduction ability. It is commonly accepted that materials with a sound absorption coefficient ≥ 0.3 are considered as sound absorption materials. Porous sound absorption materials normally have a large number of small continuous open pores. When a sound wave strikes on a material surface, it excites air vibration in the pores. Because of the friction, thermal interaction, and the viscous resistance offered to small vibratory movements of air, acoustic energy is dissipated and converted to heat. The amount of acoustic energy attenuated depends partly on the acoustic frequency. Since NRC reflects only the overall noise reduction ability and sound absorption coefficient increases with increasing frequency, a high NRC does not necessarily imply high noise reduction ability at all frequencies. In fact, sound absorption coefficient (0.132) of the ULDF, like the other porous materials, was very low at 250 Hz. This requires significant thickness (compared to operating sound wavelength) to be an efficient sound barrier. This means that the ULDF is an inefficient and impractical sound absorber at low frequencies.

Density Profile

The density across thickness of the ULDF was relatively uniform, except there was relatively high density in the outer layers than in the inner layer. Shown in Fig. 6 is a typical density profile of the ULDF of 20 mm thickness. The average density of the specimen was 66.5 kg/m^3. The inner layer had an average density of 62.4kg/m^3 with standard deviation of 7.8 kg/m^3. The periodically fluctuated density across thickness partly reflects the cross-linked layered structure of fibre distribution across thickness (Fig. 2b)). High density on the outer layers of the specimen is very likely the result of slicing and trimming with the toothless saw blade. The pressure that the saw blade applied on the specimen during slicing and trimming may have densified the cutting surface. The densification will be greater when cutting speed of the blade and feeding speed of the specimen are mismatched. The right side of the density profile in Fig. 6 shows an example of such densification. Another possible explanation for the higher density in the outer layers might be the higher level of resin content on the dried mat surface. During drying of the mat, it is possible that water and resin together moved towards the mat surface. When water reached the surface, moisture vaporized and escaped while resin was captured by the fibres and cured. Since resin normally has a higher density (~1000 kg/m^3) than that of wood fiber, a higher resin content on board surface implies a higher density in the outer layer of the board. The left side of the density profile in Fig. 6 is a typical example of outer layer density variation.

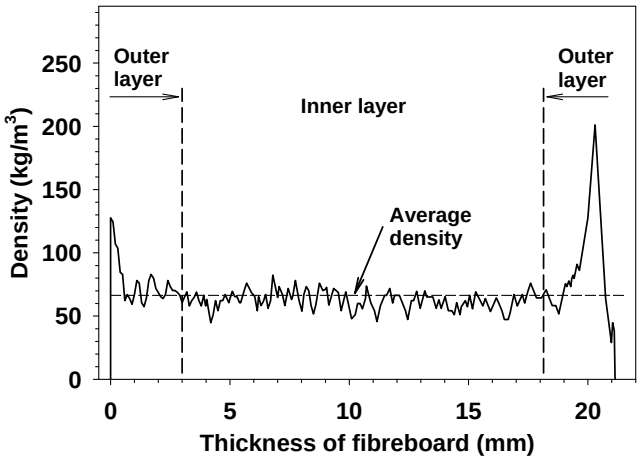

Fig. 6. Typical density profile of the ultra-low density fiberboard (bulk density 66.5 kg/m^3)

Dimensional Stability

Thickness swelling after 24h water immersion was only 0.57%, demonstrating high dimensional stability. Dimensional stability of wood-based composites depends on the factors such as compaction ratio, treatment temperature, resin content, and swelling or shrinkage of wood itself. A high compaction ratio may result in a high thickness swelling due to spring-back (Vun 2003). The manufacture process of the ULDF did not involve heating and pressing; therefore, swelling of wood itself was the primary cause for thickness swelling. The swelling of fiber was small because water repellant and resin film prevented water from reaching the fiber. In addition, most of the swelling would have filled in the voids, thus providing little contribution to the swelling of entire thickness. In contrast, water absorption was very high (582%) due to high porosity.

CONCLUSIONS AND RECOMMENDATIONS

The main conclusion of this study is that the liquid frothing approach is suitable for making ultra-low density fiberboard (ULDF). Other conclusions can be drawn as follows:

1. Liquid frothing creates a large quantity of small bubbles, forms cross-linked layers in thickness and makes possible to manufacture ULDF with low fiber content but with a lot of small voids.
2. Ultra-low density fiberboard can provide low thermal conductivity (0.035W/mK) and thus be a good candidate as a building insulation material.
3. ULDF has a high noise reduction coefficient (0.67) and thus has high noise reduction ability.
4. ULDF contains a lot of voids and thus can be an alternative of buffering materials for packaging.
5. ULDF has excellent dimensional stability in terms of thickness swelling (e.g. 0.57% after 24h water immersion).

To increase the applications for ULDF, future work is highly recommended to improve its mechanical and physical properties and evaluate its fire resistance, as well as investigate the impact of various materials and processing factors on fiberboard performances.

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REFERENCES CITED

CAS, Chinese Academy of Science (2004). *GB/T 18696.1-2004 Acoustics - Determination of Sound Absorption Coefficient and Impedance in Impedance Tubes - Part 1: Method Using Standing Wave Ratio,* Standard Press of China, Beijing, China.

CBMIA, China Building Material Industry Association (2008). *GB/T 10294-2008/ISO 8302: 1991 Thermal Insulation - Determination of Steady-State Thermal Resistance and Related Properties - Guarded Hot Plate Apparatus*, Standard Press of China, Beijing, China.

CNLIC, China National Light Industry Council (2008). *GB/T 8813-2008/ISO 844:2004 Rigid Cellular Plastics - Determination of Compression Properties*, Standard Press of China, Beijing, China.

Cox, T. J., and D'Antonio, P. (2009). *Acoustic Absorbers and Diffusers: Theory, Design and Application*, 2nd Ed., Taylors & Francis, New York.

Dai, H. M., and Dai, P.H. (2004). "Study on the key technologies of products of foaming plant fibre," (in Chinese with English abstract). *Packing Engineering* 25(2), 9-11.

Gibson, P., and Lee, C. (2006). "Application of nanofiber technology to nonwoven thermal insulation," *Report OMB No. 0704-0188*, U.S. Army Soldier Systems Center Natick, Massachusetts 01760-5020. Pp.8. http://www.dtic.mil/dtic/.

Huang, Y. T., Wang, X., and Jiang, F. C. (2003). "Experimental production of ultra-light medium density fibreboard from chinese fir," (in Chinese with English abstract). *China Forest Products Industry* 30(3), 15-17.

Isenberg, C. (1992). *The Science of Soap Films and Soap Bubbles*, Dover edition, General Publishing Company, Ltd., Toronto, Ontario, Canada.

Kawasaki, T., Zhang, M., and Kawai, S. (1998). "Manufacture and properties of ultra-low-density fiberboard," *Journal of Wood Sci.* 44, 354-360.

Lawton, J. W., Shogren, R. L., and Tiefenbacher, K. F. (1999). "Effect of batter solids and starch type on the structure of baked starch foams," *Cereal Chem.* 76(5), 682-687.

Matuana, L. M., and Mengeloglu, F. (2004). "Manufacture of rigid PVC/wood-flour composite foams using moisture contained in wood as foaming agent," *Journal of Vinyl and Additive Technology* 8(4), 264-270.

SFAC, State Forestry Administration of P.R. China. (1999). *GB/T 17657-1999 Test Methods for Evaluating the Properties of Wood-based Panels and Surface Decorated Wood-based Panels*, Standard Press of China, Beijing, China.

Vun, R.Y. (2003). *Ultrasonic Characterization of Engineering Performance of Oriented Strandboard*, Dissertation, Sch. of Renewable Natural Res., Louisiana State Univ. (http://etd.lsu.edu/docs/available/etd-0708103-163628/unrestricted/Vun_dis.pdf)

Xie, L. S., and Chen, Z. X. (2005). "Study on heat-conduction of dry-process low density fiberboard by conventional hot-pressing methods," (in Chinese with English abstract), *Forestry Science and Technology* (1), 23-25.

Xie, Y. Q., Chen, Y., and Wei, Q. H. (2008a). "Study on forming a truss-like reticular structure made from nature fibre under the effect of liquid frothing," (in Chinese with English abstract), *Journal of Fujian College of Forestry* 28(3), 203-207.

Xie, Y. Q., Chen, Y., and Zhang, B. G. (2003). "Study on a foamed material from plant fibres," (in Chinese with English abstract), *China Wood Industry* 18(2), 30-33.

Xie, Y. Q., Tong, Q. J., and Chen, Y. (2008b). "Construction mechanism of reticular structure of plant fibre," *Journal of Korea Furniture Society* 19(2), 106-110.

Xu, J., Sugawara, R., Widyorini, R., Han, G., and Kawai, S. (2004). "Manufacture and properties of low-density binderless particleboard from kenaf core," *Journal of Wood Sci.* 50, 62-67.

Youngquist, J. A. (1999). "Wood-based Composites and Panel Products," Chapter 10, in *Wood Handbook - Wood as an Engineering Material*, Gen. Tech. Rep. FPL–GTR–113. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 463 pp.

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