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RESEARCH ARTICLE

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Structural mechanism and effect of hole compressibility on mechanical strength of MFLB

Abstract We have studied the structural mechanism of micron flaky wood fiber light density board (MFLB), of which voids are an important structural characteristic. A new parameter called hole compressibility (η) was added to study the characteristics of MFLB further, in order to produce various levels of hole compressibility. A set of hot pressures was applied, and uniform parts at cross-sections of MFLB were selected to study the effects of hole compressibility on the modulus of elasticity (MOE) and modulus of rupture (MOR) of MFLB by microscopic analyses. The results showed that MFLB (0.3 g/cm^3 in density) processed at various hot pressures (from 1.6 to 2.2 MPa) all meet the norms of the Japan Light Particleboard Industrial Standard JISA 5908, where $\eta \leqslant 0$ ranging from -0.0487 to -0.068. The critical value of hole compressibility at which the strength began to decrease was also obtained. We compared the void distribution, size and shape at different void contents and hole compressibility and discussed the effects of hole compressibility on MOE and MOR of MFLB as well. To a certain density of raw material and micro-fiber of a certain thickness, the strength of MFLB can be decreased with an increase in hole compressibility. When the hole compressibility of MLFB exceeds a certain critical value, loading at a lower level will decrease MOR and MOE of MFLB considerably.

Keywords micron flaky wood fiber light density board (MFLB), structural mechanism, hole compressibility, modulus of rupture (MOR), modulus of elasticity (MOE)

1 Introduction

The construction of composites relies on their microstructure characteristics and the development of their micro mechanics, the iconography of computer graphics and other advanced theories and technologies. When these are applied to wood science, the physical and mechanical characteristics of wood-based panels need almost to be studied at the level of their microstructure, which will gradually reveal the essentials that affecting these characteristics of wood-based panels (Gutowski, 1997; Cahn, 1999).

In our study, we have focused on a new wood-based panel called micron flaky wood fiber light density board (MFLB). The idea of constructing a composite is based on a new method of studying the relationship between microstructure and the characteristics of MFLB in an attempt to analyze the effects of hole compressibility in the composites on the modulus of elasticity (MOE) and modulus of rupture (MOR) of MFLB.

2 Structural mechanism of MFLB

MFLB as a construction material is proposed based on the theory of recombination of wood micro-fibers. Its manufacture uses mechanical micro-technology, which consists of cutting the wood cell of its hexagonal structure, thus forming a flocculent structure of these flaky wood micro-fibers, which is then processed into a new wood-based panel. In a traditional particle board, particles are isolated from each other, and if the raw material density is greater than 0.4 g/cm^3, adhesives and other materials are added, which, in the end, make it very difficult to form a wood-based panel with a density less than 0.4 g/cm^3 without developing blisters on the surface. In order to achieve this lower density, a new manufacturing method was adopted in the construction of MFLB, which breaks with the traditional method of relying on processing technology. With this new mechanical micro-technology, almost pure wood micro-fibers are obtained, and the density of

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the new board is barely affected by that of the raw material. Thus, at this point, raw wood material with a density of more than 0.3 g/cm^3 can be used to produce MFLB, which then becomes a new product manufactured by micro-technology.

Because the circular radius and cutting thickness of the slicer used in cutting wood is generally greater than the equivalent diameter of wood cells, this usually ends up with racking and splitting the wood. In this way, natural knots, worm channels and wounds can hardly ever be cut out in a suitable manner. The reason for this at the micro-level is that the cross-section of defects are much larger than that of the micro-fibers of the wood when the blade wedge angle, circular radius and cutting thickness are insufficient for wood cutting, as shown in Fig. 1. The original micro-defects can be largely removed, and the dish-spring effect for cell characteristics of hexagonal wood structures can also be eliminated when the essential contents of wood cells are extruded. These measures would decrease the power required in cutting wood and reduce the cost of wood-based panels at the same time. Then, long, flaky and soft wood fibers without any defects become the main construction units from which to form a new wood-based panel. This is the essential structural mechanism of MFLB (Ma, 2002a, 2002b, 2003, 2005).

When wood is cut at a given micro-level, the flocculent structure of flaky wood micro-fibers is obtained, shown as in Fig. 2. The original state of wood micro-fibers is shown in Fig. 3.

Compared with the natural structure of wood, it can be clearly seen that the knitting action of this flocculent structure is just like the bonding action of lignin between the intercellular layers of wood. For example, in an experiment we conducted where the adhesive was not effective when MFLB was submerged in water, the panels were kept intact and did not become loose.

While forming long and flaky wood micro-fibers into a flocculent structure, they are mixed with large amounts of air, and during the hot-pressing period, steam and some other volatiles as well as uniformly distributed and varied voids are formed. The number of these voids considerably increases the porosity of the raw material, and in this way, the new panel can be formed to a density below 0.4 g/cm^3. Thus, when processing MFLB, the number of voids is an important micro-structural characteristic which ensures that MLFB will have a lower density ($<$ 0.4 g/cm^3). In the end, it is also an important factor which affects the physical and mechanical properties of the panel where the number of voids, their size, shape, and distribution play key roles in forming MFLB. This part can be studied with a computerized, digital micro-graphical processing technique, which we did not present in this paper.

Just like in any other wood or non-wood based panels, voids are regarded as defects, but in the case of MFLB, uniform voids are its basic structure, of which advantage is taken in its formation. In contrast, non-uniform voids will weaken the mechanical strength in terms of MOR and MOE, for example.

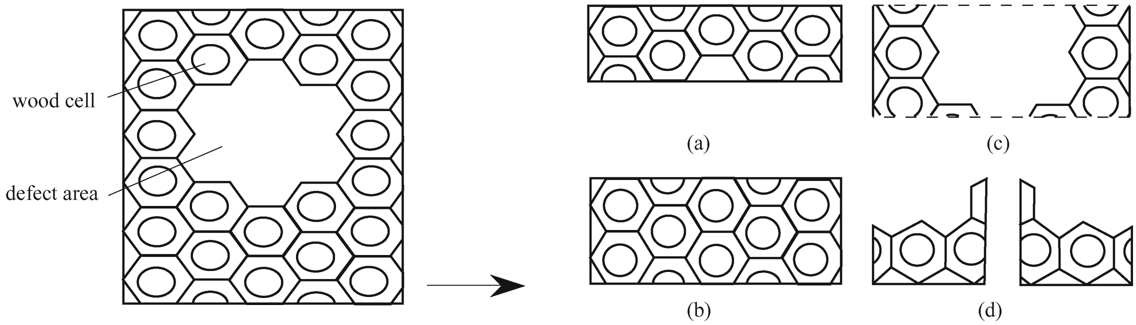


Fig. 1 Cells structure in defects and changed structure by micro-machining technology

Fig. 2 Flocculent structure of flaky wood micro-fibers

Fig. 3 Original state of flaky wood micro-fibers

3 Effects of compressibility of holes on mechanical strength of MLFB

We have introduced a new parameter, called hole compressibility (η), to study MFLB. When cutting wood to micro-fibers, different tree species and different cutting thickness and blade parameters would obtain wood micro-fibers with varied cell structures, i.e., we end up with a variety of micro-fibers differing in thickness and density, and in an interlaced state instead of a flocculent state. All these factors can determine the critical density and inner structure of a panel, as well as the final physical and mechanical properties of the panel. At this stage, we introduce this parameter because it can not only reflect the number of voids, but also the extent of variation in cell structures and the degree or size, at the micron level, to which the wood was cut.

When constructing MFLB, the density of the panel is less than that of the raw wood material, i.e., $\eta \leqslant 0$, meaning that voids between the wood micro-fibers are larger than those of raw wood material. For a given density panel, this is a critical value which ensures that the physical and mechanical properties of a panel meet minimum standards. In order to evaluate the integrity of the panel, we studied the micro- and nano-properties of the material. It should be pointed out that this specific value is more comprehensive and scientific than the void content or density alone.

We have carried out an experiment with the new method to study the relationship between the microstructure and properties of wood micro-products. We varied the hot pressures to gain different η values in this experiment and then studied the effects of hole compressibility on the mechanical properties such as MOR and MOE. We also calculated this critical value for a given density panel, in order to ensure that the MLFB measures up to the Japan Light Particleboard Industrial Standard JISA5908.

4 Materials and methods

4.1 Materials

Pinus koraiensis trees, which abound in the woodlands of Xiaoxing'anling Mountain, northeastern China, were left exposed to the air with moisture content between 12%–15% and a density of 0.44 g/cm^3. We used urea-formaldehyde (UF) (53.6% solid content) as an adhesive and ammonium chloride (added in 1.5%) as a hardener.

In order to measure up to the desired thickness, woodblocks, with dimensions of 80 mm × 80 mm × 80 mm were cut along the grain with a chipper designed and manufactured by the Forestry and Woodworking Mechanical Engineering Technology Center. The desired width was achieved with a hogging machine. The distribution of the geometric dimension of the flaky wood micro-fibers is shown in Fig. 4, where it can be seen that the thickness of the micro-fibers ranges from 50 to 150 μm, mainly from 60 to 100 μm, about 72% (Fig. 4c). The width of the micro-fibers mainly ranges from 5 to 8 mm, about 75% (Fig. 4b), and the length from 65 to 75 mm mainly about 78% (Fig. 4a).

4.2 Manufacture of MLFB

The nominal density of MLFB was 0.3 g/cm^3, the size of the mat was 500 mm × 250 mm × 10 mm and processed at different hot pressures of 1.4, 1.6, 1.8, 2.0 and 2.2 MPa, all at 130°C for 4 min. This was repeated once for each condition.

4.3 Micrographs collected at cross-sections

Two specimens of size 200 mm × 50 mm × 10 mm from each MLFB, pressed flat and with a burnished finish, were then subjected to optical microscopy (type: XYH—3A) in order to analyze the location, size and shape of the voids. We collected a total of ten micro-digital pictures at each different position of the specimens. The micro-digital pictures of the cross-sections were used to study the void distribution and density of MLFB, and then we computed the hole compressibility of MLFB as well. Micrographs collected from the cross-section are shown in Fig. 6.

4.4 Measuring hole compressibility at cross-sections

From the micro-digital pictures of the cross-sections, we selected five test specimens at those areas where the voids were distributed uniformly. Then, according to the Particleboard Standard GB/T4897-92, we measured the density of every specimen, determined the UF adhesive content, calculated the average number of voids (β) of every specimen, computed the porosity (C) of the solid wood of *P. koraiensis* and finally determined the hole compressibility (η). The results are presented in Table 1.

We used the following formulae:

$$\beta = 100\% - \gamma\left|\frac{w_r}{\rho_r} + \frac{w_f}{\rho_f}\right| \tag{1}$$

$$\beta = 100\% - V_f - V_r \tag{2}$$

$$V_r = \frac{\gamma}{\rho_r}\cdot w_r \tag{3}$$

$$V_f = \frac{\gamma}{\rho_f}\cdot w_f \tag{4}$$

where β is the average number of voids (%), γ is the density of MLFB, w_r is weight percentage and ρ_r density of the UF adhesive, w_f is weight percentage of wood fibers and ρ_f is density of wood fibers.

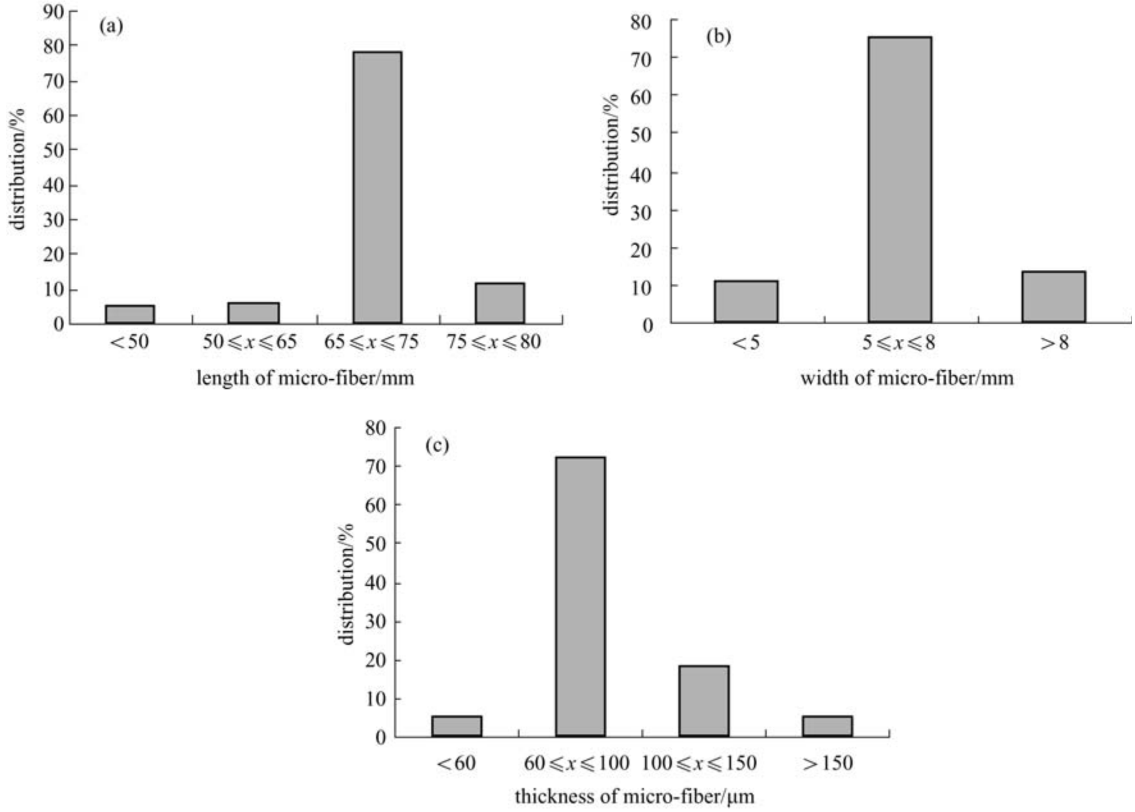


Fig. 4 Distribution of geometric morphology of micro-fibers

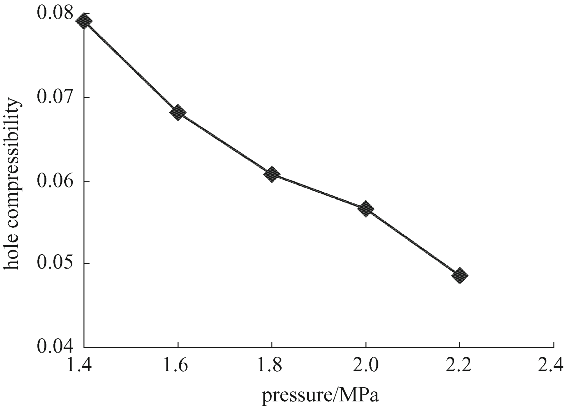


Fig. 5 Plot of hole compressibility and hot pressure

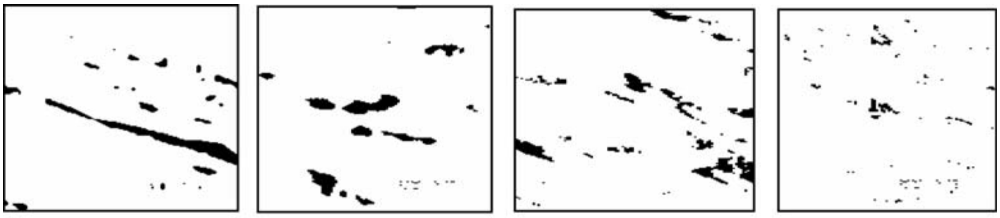
$$\rho_0 = \rho_q \cdot \frac{1 + 0.01 \times K_v \times W_q}{1 + 0.01 \times W_q} \tag{5}$$

$$\mathrm{C} = 100\left(1 - \frac{\rho_0}{\rho_{cw}}\right) \tag{6}$$

$$\eta = \frac{C - \beta}{\beta} \tag{7}$$

where ρ_q is air-dry density of *P. koraiensis*, ρ_0 is its oven-dry density, ρ_{cw} is the density of cell wall substances, K_v is volume shrinkage coefficient of the species, W_q the air-dry moisture content, C the porosity, and η the hole compressibility of MLFB, made from *P. koraiensis*.

The following values were obtained from (Cheng, 1985): $\rho_q = 0.44$ g/cm^3, $K_v = 0.459$ (Cheng, 1985). We



(a) 1.6 MPa (40×) (b) 1.8 MPa (40×) (c) 2.0 MPa (40×) (d) 2.2 MPa (40×)

Fig. 6 Micrographs at various hot pressures disposed determined by mathematical binarization assume: $W_q = 12\%$, $\rho_{cw} = 1.53$ g/cm^3. These values were entered into Eqs. (5) and (6) and we obtained: $\rho_0 = 0.4397$ g/cm^3, $C = 71.26\%$.

4.5 Performance tests

We tested the panel for its MOR according to Particleboard Standard GB/T4897-92, by a universal testing device for mechanical properties (type: Y005). Sample size was: 200 mm × 50 mm × thickness (mm) and the loading ratio was 0.125 ± 0.063 mm/s.

Modulus of elasticity (MOE) was tested according to the same standard and also by the universal testing device for mechanical properties (type: Y005). The conditions were the same as before.

The properties were also tested against the norms of the Japan Light Particleboard Industrial Standard JISA5908.

5 Results and discussion

5.1 Effect of hot pressure on hole compressibility of MLFB

At a given density of MFLB, a set of five levels of hot pressure was applied to produce various percentages of voids and hole compressibility, shown in Table 1. From this table, it can be seen that with an increase in hot pressure, the percentage of voids decreased, and the hole compressibility decreased as well.

Given that we are dealing with a light material for heat insulation, it is shown that the percentage of voids and the hole compressibility at higher levels of MLFB are acceptable on the basis of certain mechanical properties, i.e., we need to find a critical value against which to measure exactly the lowest acceptable density (Fig. 5). Therefore, a set of suitable hot pressures should be determined based on a desired hole compressibility or mechanical properties. Other technological parameters could do the same. Thus, it was practical to relax the quality requirements in order to lower manufacturing costs in light of specific application requirements. Our study was only at the level of research methodology. Further and more extensive research should be carried out with much more experiments in the future.

5.2 Analysis of microscopic variation of hole compressibility

Micrographs at various hot pressures, obtained by mathematical binarization, are shown in Fig. 6. The distribution and shapes of various voids at different hot pressures, i.e., at 1.6, 1.8, 2.0 and 2.2 MPa, are respectively shown in Figs. 6a–d. From Fig. 6, it can be seen that the higher the hot pressure, the lower the percentage of voids and hole compressibility, which leads to voids with larger width-length ratio, more nearly-round shapes, smaller sizes and not located close to each other. However, with an increase in the percentage of voids and hole compressibility, the voids have much smaller width-length ratio, are slighter in shape and larger in size, and are distributed close to each other, nearly connected together.

When we focused on the effects of hole compressibility on the mechanical strength of MLFB, we found that with an increase in the hole compressibility, the relationship between the mechanical strength of MLFB and hole compressibility was not linear. We speculate that the reason is that hole compressibility is a ratio which emphasizes mechanical strength. However, the percentage, distribution, size and shape of the voids should be considered. Consequently, additional microscopic analyses could aid in analyzing the effects of hole compressibility on the mechanical strength of MLFB. Further study of this aspect should be carried out by identifying voids with computerized video-detection in the future.

5.3 Analysis of mechanical strength varying with hole compressibility

Because the voids were often irregular in shape or distribution, it was theoretically difficult to predict the effects of voids on the mechanical strength of MLFB. Generally, voids can increase the stress concentration in a limited region around itself, but MLFB might accept this stress concentration for a special application. As a consequence, a local region with a high hole compressibility has little effect on the strength of MLFB.

Moreover, when the hole compressibility of MLFB was below a certain critical value, the mechanical strength did not decrease very much by increasing the percentage of voids. In contrast, when the hole compressibility of

Table 1 Measurement of hole compressibility and strength of MFLB

number	pressure/MPa	void content/%	hole compressibility	MOE/MPa	MOR/MPa
1	1.4	76.89	−0.079	585 (disqualification)	2.12 (disqualification)
2	1.6	76.17	−0.068	978.87	4.53
3	1.8	75.59	−0.061	1105.37	6.47
4	2.0	75.30	−0.057	1140.14	7.73
5	2.2	74.73	−0.049	1173.55	8.82

Note: "−" means the number of cell holes of raw material is less than the number of voids in MFLB.

MLFB exceeded a certain critical value, loading at a lower level decreased MOR considerably. Therefore, hole compressibility of MLFB should be measured over a given region, not at any one point, i.e., the effect of hole compressibility on the mechanical strength of MLFB relies on the size of the local region where voids are found (He et al., 2000).

6 Conclusions

In our experiment, wood (*P. koraiensis*) with a density of 0.44 g/cm^3, was cut to the size of micro-fibers and then manufactured into MFLB at different percentages of voids and hole compressibility. These two variables were controlled by the level of hot pressure. The results show that the mechanical properties of MFLB (0.3 g/cm^3 in density) measured up to the norms of the Japan Light Particleboard Standard JISA5908, which were obtained with hot pressures ranging from 1.6 to 2.2 MPa, where $\eta \leqslant 0$, ranging from -0.049 to -0.068. The relationship between hot pressure and hole compressibility is not linear, an important inference in the prediction of the relationship between the strength and hole compressibility of MFLB and of vital theoretical importance in studying mechanical properties of MFLB.

By controlling the hot pressure to obtain different percentages of voids and hole compressibility and then further connecting other process parameters with mechanical properties, the process parameters can be optimized and manufacturing costs can be lowered.

The critical value of hole compressibility was -0.068, which ensures that the mechanical properties of MLFB (at 0.3 g/cm^3 in density) will meet required standards. The results provide a foundation for subsequent quantitative analyses on the strength and rigidity of MLFB by theoretical calculations.

Micrographs at various hot pressures obtained by mathematical binarization show that, the lower the percentage of voids and hole compressibility, the larger the width-length ratio of the voids, leading to voids more nearly round in shape and dispersed widely. With the void content and hole compressibility increased, the width-length ratio of the voids was much smaller, the voids were slightly smaller in shape and were distributed more closely to each other, almost being connected together.

Given the density of a raw material and its micro-fibers of a certain thickness, the strength of MFLB can be decreased with an increase in hole compressibility. When the hole compressibility of MLFB is over a given critical value, loading at a lower level will decrease the MOR and MOE of MFLB considerably.

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