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Relationship between Fiber Furnish Properties and the Structural Performance of MDF


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Abstract

The structural performance of medium density fiberboard (MDF) is attributable to three primary variables which are: physical and mechanical properties of individual wood fibers; fiber-to-fiber stress transfer; and fiber orientation. These origins of fiber properties and stress transfer can be traced to the fiber generation method wherein fiber orientation is associated with mat formation. This paper is part of an on-going study to determine the mechanisms governing the stiffness and strength of fiber-based composites. Preliminary data are presented in this paper focusing on the effect of juvenility and fiber generation on the mechanical properties of individual wood fibers and the subsequent properties of MDF panels. Development of panel stiffness and strength is also discussed with regards to fiber packing and stress transfer as determined by testing oriented and un-oriented panels as well as direct observation with microtomography.

Introduction

Over the past few decades, the need for improved use of this nation's natural resources, particularly forest products, has developed. One of the best ways to address this challenge is through an expansion of the reconstituted wood fiber philosophy. This philosophy began with rectangular dimension lumber cut from cylindrical logs and has evolved to the point of fiberboard. Breaking down wood into its constituent elements is not exceedingly difficult. The challenge lies in reassembling the elements to meet desired end specifications. The manner in which these elements are reassembled dictates the performance of the final product, which is the overall premise of engineering wood products.

This axiom is applicable to the production of medium density fiberboard (MDF) with improved performance. The stiffness and strength of MDF, like any other wood composite is dependent upon the properties of the individual wood components and the manner in which these components are combined. Most research efforts to improve the mechanical performance of MDF are proprietary in nature and have focused primarily on the binding system. Other variables commonly studied include particle orientation, board density, additives, sizing agents, species, and pressing variables (Maloney 1986). Due to technological limitations, studies correlating fiber properties and panel properties have only recently been possible.

The long-term goal of this on-going work is to ascertain the mechanisms that govern the physical and mechanical properties of structural fiberboard. These goals are achieved by studying the three factors governing MDF: physical and mechanical properties of individual wood fibers; fiber-to-fiber stress transfer; and fiber orientation. Data presented in this paper are the compilation of several studies that address these factors. Specifically, the objectives of this paper are to ascertain the relationship between fiber properties and the structural performance of MDF; determine the effect of refining on the mechanical properties of individual fibers, and subsequently the properties of MDF; and ascertain the in-situ physical characteristics of fibers in MDF.

Experimental Procedures

The experimental procedures can be divided into four main categories based on objectives and anticipated outcomes. In all cases, the raw material for the construction of MDF panels and mini panels was loblolly pine (*Pinus taeda*) harvested from a conventional plantation in southern Arkansas. The juvenile and mature portions of the bole were separated manually, The term "juvenile" in this study refers to wood up to the tenth growth ring whereas "mature" refers to wood beyond the 30th growth ring. The transition wood between these zones was discarded.

Effect of Fiber Properties

***Full-Size* Panels.** -Thirty 16- by 16- by 3/8-in. MDF panels were manufactured at the University of Maine to investigate the relationship between fiber furnish mechanical properties and MDF performance. The panels were comprised from furnishes with varying degrees of juvenile and mature fibers. Fibers were generated with a pressurized disc refiner at feed pressures of 10 and 40 psig. Fibers were air dried and bagged for panel manufacture. Panels were manufactured at a target density of 48 lbs./ft.^{3} and with a panel resin content of 8 percent urea formaldehyde (solid content = 65%). Panels were pressed for 3 minutes at 270°F, conditioned (70°F, 50% RH), and subsequently evaluated for mechanical properties, linear expansion (LE), density, and internal bond (IB) strength.

The mechanical properties of individual fibers were ascertained on the four fiber types (juvenile or mature, 10 psig or 40 psig). In addition, unrefined portions of juvenile and mature chips were macerated in acetic acid and hydrogen peroxide. Fibers were then tested in tension to determine the modulus of elasticity (MOE) and ultimate tensile stress (UTS) of the fiber furnish. A detailed explanation of the maceration technique can be found in Mott (1996), and a detailed explanation of the mechanical property determination can be found in Groom et al. (1996).

Mini Panels.-Miniature MDF panels measuring 4- by 5- by 1/8-in. were constructed to verify full-size panels and, subsequently, to investigate the effects of fines and fiber orientation. Mini panels were constructed with a press schedule and adhesive that were identical to full-size panels. Mini panel and fiber properties were determined similarly to the full-size panels.

Effect of Fiber Orientation

There exist two primary methods to achieve fiber alignment: electric field (Woodson 1977; Talbot 1974) and physical manipulation. This study used physical fiber alignment, consisting of a series of vibrating fins located approximately 1 mm above the forming mat. The degree of fiber orientation was controlled by the gaps between the steel fins. Gap spacings were chosen to be 2, 4, and 8 mm. Fibers passed through the vibrating fins and settled down onto a 4- by S-in. mat with fiber orientation locatetl in the S-in. direction. Mini panels were constructed with varying degrees of fiber orientation and varying degrees of juvenile and mature fibers. Panels were subsequently tested for mechanical properties, LE, density, and IB.

Effect of Fines Loading

Mini panels were constructed with varying proportions of long fibers and fines as well as fibers intermediate in length. Approximately 3 kg each of juvenile and mature wood fibers were placed on a series of shakers in which various fragment lengths were segregated. The shaker trays were chosen such that the largest to smallest segments consisted of:

Tray 1		
3-5%	Shives and bundles	*Discarded.*
Tray 2		
20-30%	Mostly fibers, with some bundles and broken fibers.	Designated *fibers.*
Tray 3		
30-50%	Mixture of fibers and fines.	Designated *intermediate.*
Tray 4		
20-30%	Comprised mostly of fines.	Designated *fines.*

A total of 24 oriented mini panels were constructed to investigate the effect of fiber packing and stress transfer on the mechanical properties of MDF. The 24 mini panels were composed of 12 juvenile and 12 mature mini panels, with three replicates each of:

- 100 percent fibers:0 percent fines.
- 50 percent fiber:50 percent fines.
- 0 percent fibers: 100 percent fines.
- 100 percent intermediates.

There were 24 corresponding mini panels constructed with random orientation.

Effect of Refining Levels

In addition to the full-size MDF panels described previously, mini panels were constructed to evaluate the effect of refining levels on fiber and MDF panel properties. Juvenile and mature wood fractions from a loblolly pine tree were chipped and refined at feed pressures of 4, 8, and 12 bar. These pressures are respectively, below, at, and above the glass transition temperature of lignin. Fibers from these six furnishes, as well as juvenile and mature chemically macerated fibers, were analyzed for mechanical properties. Mini panels were also constructed to evaluate the effect of refining on MDF mechanical properties, LE, and IB.

Microtomography of MDF panels

The in situ physical characteristics of fibers in MDF, including a three-dimensional fiber network and void structure, were investigated using microtomography and image analysis techniques. The state of individual fibers within the panel including lumen collapse (if present), fiber length, fiber curl, and orientation in three-dimensional space were evaluated.

Microtomography is a technique for nondestructively evaluating the internal three-dimensional structure of a material. The measurement principles (Deckman et al. 1991) and its application to cellulosic structures including solid wood and paper were previously described (Shaler 1997; Shaler et al. 1998).

The specific results reported are for an MDF specimen from 4 bar refined mature loblolly pine. The volume of the specimen scanned was 1.28 by 1.09 by 0.37 mm, with the 0.37-mm dimension corresponding to the panel z-direction. The specimen was excised approximately 5 mm from the top surface of the panel. A 10x-lens was used in the microtomography setup so that the individual voxel resolution was 2.4 μ. The x-ray energy was 8.5 keV. Information was collected at the X2B beam line built and run by Exxon Research &Engineering at the Department of Energy managed National Synchrotron Light Source (NSLS). Visualizations of the internal structure were developed through volumetric clipping, pseudo coloring, and opacity change techniques.

Results and Discussion

Panel density was determined on IB specimens prior to test and averaged 45.9 lb./ft.^{3} on full size specimens and 39.3 lb./ft.^{3} for mini panels. Average moisture content at time of testing was 7.5 percent. The average test duration for bending tests was six minutes. For mini panels, four bending specimens were tested for each panel. However, only the most interior parallel and perpendicular specimens were used in the analysis due to a significant edge effect.

Mean mini panel properties were comparable to the properties of full-size specimens. The coefficient of variation (COV) of the mini panel mechanical properties were generally less than 15 percent, especially for tests measuring in-plane properties. The lowest variability existed for the linear expansion specimens with an average COV of 12 percent. Bending properties' had a similar variability, with COV values for MOE and modulus of rupture (MOR) of approximately 14 percent. Internal bond stress values were extremely variable; average COV's were 36 percent with some samples having COV's over 80 percent. It appears as though the mini panels may be too thin to gather reliable IB data, with results being altered by the process of specimen attachment to the IB blocks.

Effect of Fiber Properties

***Full-Size* Panels.**-The most significant finding of this study is that there exists an inverse relationship between fiber properties and MDF mechanical properties (Figs. 1 and 2). The refined, juvenile wood fibers used to make the un-oriented MDF panels shown in Figures 1 and 2, had a MOE and ultimate tensile stress (UTS) of 500,000 psi and 29,700 psi, respectively. The corresponding mature fibers had MOE and UTS values of 970,000 psi and 62,800 psi. This seemingly paradoxical inverse relationship of stronger panels from weaker fibers must be explained based on something other than fiber mechanical properties. All panels in the study were randomly oriented, so orientation did not play a role.

If weaker fibers make stronger MDF panels, then it is probable that the governing strength mechanisms originate with fiber-to-fiber stress transfer. Stress transfer is encompassed by many peripheral variables such as adhesion, panel density, and fiber packing. Adhesive application and amount used in all panels were kept constant, although adhesive distributions may have been different due to the size and morphology differences between juvenile and mature fibers (Zobel 1961; Larson 1962). Panel density and density profiles were similar among panels. The juvenile wood fiber components in Figures 1 and 2 were shorter, and contained a higher percentage of fibers less than 0.5 mm, and a lower percentage of fibers greater than 2.5 mm.

One important note to consider is that the mechanical properties of MDF may not be governed so much by fiber orientation but rather by fibril orientation. Wood fibers are themselves cylindrical multi-laminate composites that derive their mechanical properties from the orientation of microfibrils. A wood fiber with a microfibril angle of 45” such as a juvenile fiber has in theory MOE values, which are equivalent parallel and perpendicular to the long axis of the fiber. The same condition does not exist for mature fibers with fibril angles of approximately 5 to 10°, where the longitudinal MOE is much greater than the transverse MOE. Thus, although the longitudinal modulus of mature fibers is greater in magnitude than juvenile fibers, the transverse modulus of juvenile fibers far exceeds the corresponding mature fibers. The transverse modulus of mature fibers provides a weak linkage in composite panels and thus may produce MDF panels with diminished mechanical properties.

***Mini* Panels.**-Mini panels were constructed to confirm full size panels as well as to evaluate the effectiveness of orientation. Stiffness and strength of mini panels are summarized in Figures 3 and 4, respectively. MOE and MOR show identical trends as was seen in full-size panels; panel stiffness and strength increase with increasing percentages of juvenile fibers. As expected, parallel and perpendicular properties were identical for un-oriented panels. There is a significant separation of parallel and perpendicular mechanical properties for the oriented panels, but both properties follow a similar trend of increased mechanical properties with increasing percentages of juvenile fibers.

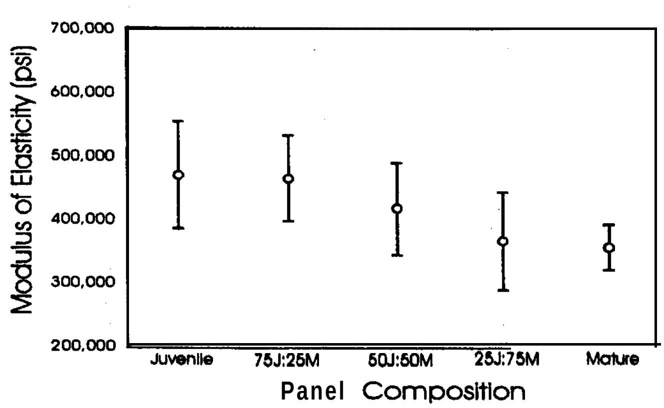

Figure 1.—Full-sized MDF panel MOE shown as a function of juvenile: mature wood ratios. Vertical bars represent one standard deviation.

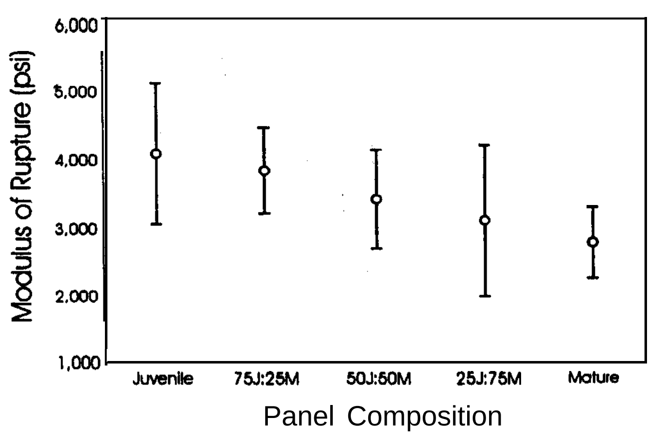

Figure Z.-Full-sized MDF panel MOR shown as a function of juvenile: mature wood ratios. Vertical bars represent one standard deviation.

Effect of Orientation

Results for the mechanical property testing of these varying levels of orientations are shown in Figures 5 and 6. It was anticipated that, according to traditional mechanics theory, improved orientation of the individual elements, i.e., fibers would increase mechanical properties in the alignment direction. As this orientation improved, the mechanical properties of the composites with the strongest elements would increase at a faster rate and surpass corresponding composites made of the weakest elements. Indeed, in-. creased orientation did improve the mechanical properties of both juvenile and mature panels. However, the data show some trends that were unanticipated. The parallel specimens for the juvenile panels increased at a faster rate than the mature panels. Although the mechanisms for this result have not yet been identified in this study, the answer most likely lies either individually or in concert, with altered bonding areas and the relative differences in stiffness between the mature and juvenile fibers. Mature fibers are generally much stiffer and stronger than their juvenile counterparts longitudinally. Although it may seem ideal, this longitudinal stiffness and strength make the mature fiber less flexible in a fiber mat. This diminished flexibility decreases the fiber-fiber con-

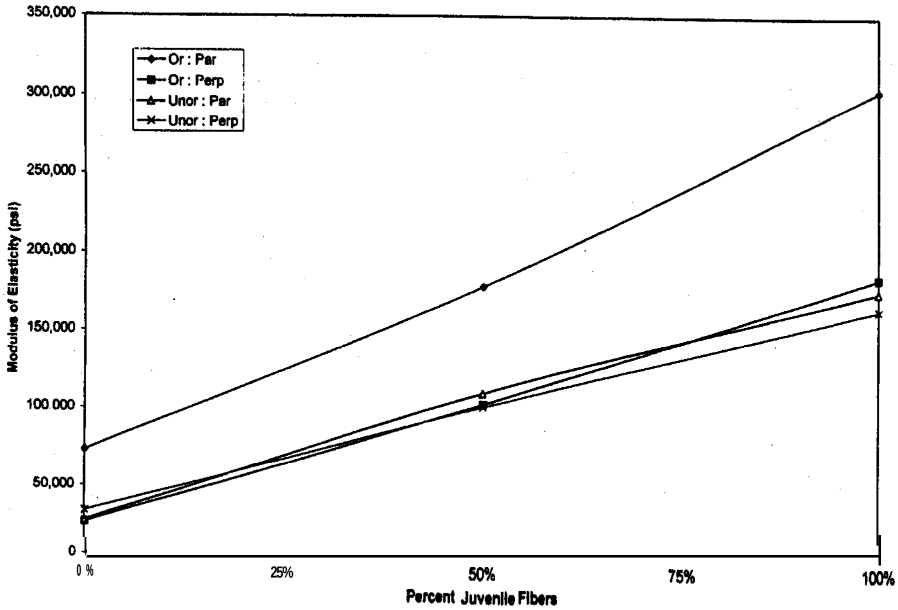

Figure 3.—MOE of un-oriented and oriented MDF mini-panels in relation to percent of juvenile fiber content.

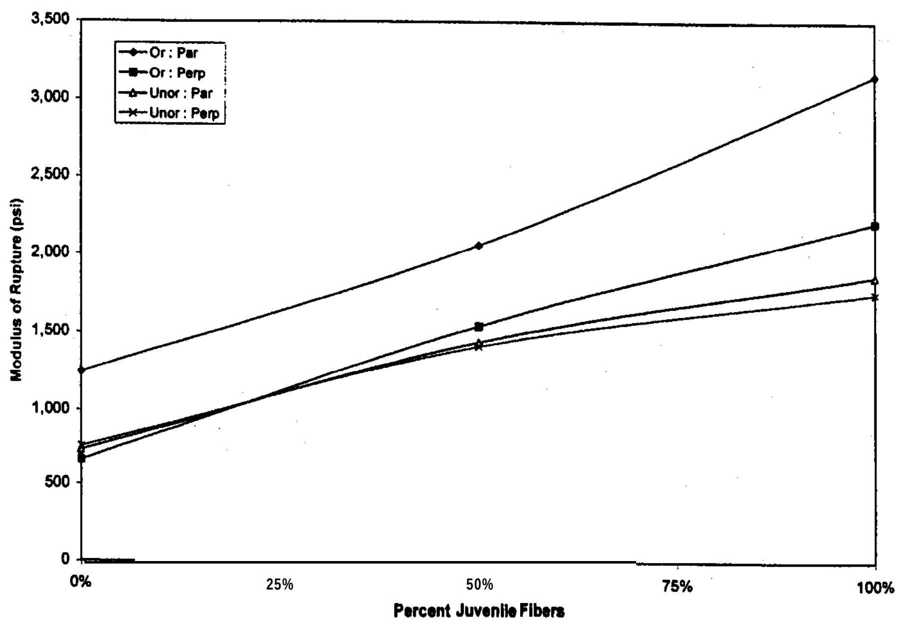

Figure 4.-MOR of un-oriented and oriented MDF mini-panels in relation to percent of juvenile fiber content.

tact area and thus the number of sites in which stresses can be transferred among the fibers.

Effect of Fines

Shaker trays for separation of fiber fractions varied depending on fiber type.

Juvenile fibers were separated as follows:

- Long fibers passed through a 20 mesh (0.0394 in.), but were retained on a 45 mesh (0.0139 in.) tray.
- Fines were the fraction that passed through a 140 mesh (0.0041 in.) tray.

Juvenile long and fine fiber fractions, respectively, comprised 23 and 26 percent of the total.

Mature fibers were separated as follows:

- Long fibers passed through a 10 mesh (0.0787 in.), but were retained on an 18 mesh (0.0394 in.) tray.
- Fines were the fraction that passed through a 50 mesh (0.0117 in.) tray.

Mature long and fine fiber fractions, respectively, comprised 20 and 36 percent of the total.

The effect of tines loading on the stiffness and strength of MDF mini panels is shown in Figures 7 and 8, respectively. The mechanical properties are inversely correlated to fines loading, regardless of orientation or fiber type. The compliance and weak-

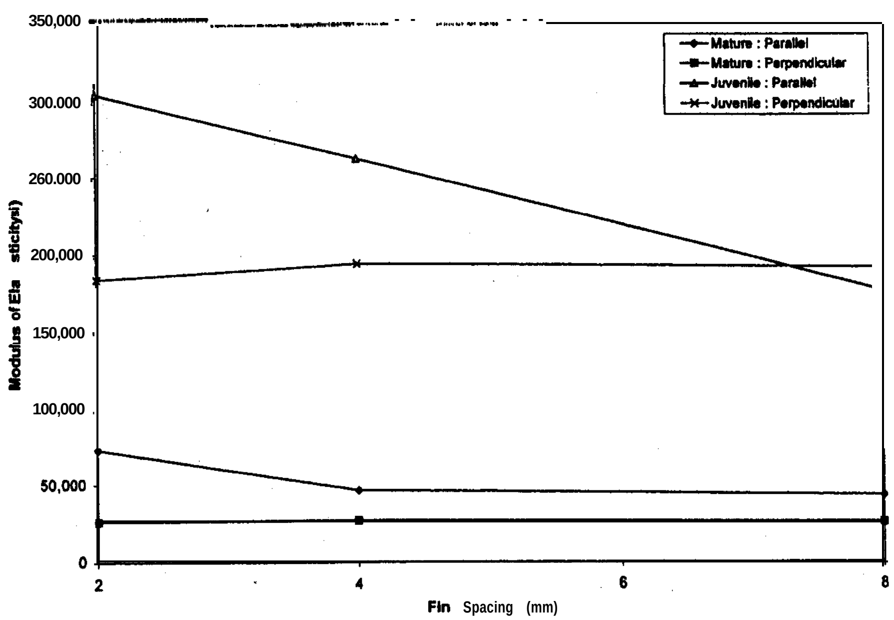

Figure S.-Effect of orientation of MDF mini-panel bending stiffness. The smaller fin spacings equate to increased fiber orientation.

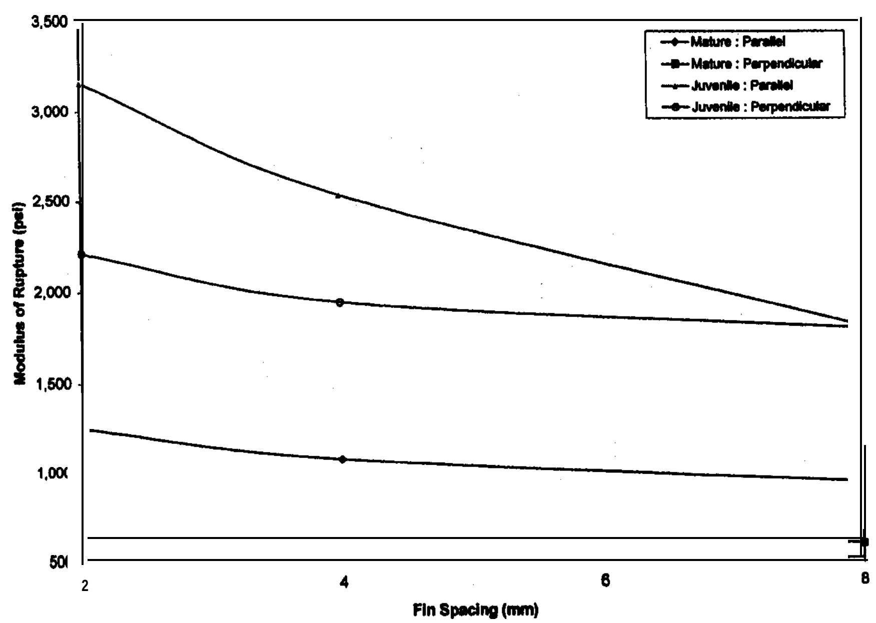

Figure 6.-Effect of orientation of MDF mini-panel bending strength. The smaller fin spacings equate to increased fiber orientation.

ness of the panels comprised of fines was due primarily to the lack of fiber length, resulting in low fiber aspect ratios and ultimately poor physical interlocking and fiber-fiber contact. It should be noted that the mini-panel specimens made up of juvenile fibers outperformed the panels comprised entirely of mature fibers. In addition, the stiffness ofjuvenile mini panels was less susceptible to fiber loading effects as compared to mature mini panels due to the shorter initial fiber length.

The effect of fines loading on LE is shown in Figure 9, which shows that the ideal furnish for minimal LE would be some combination of long fibers and fines. The data are insufficient to specify the optimal ratio, but it appears to exist between 0 and 50 percent fines loading. Moss and Retulainen (1995) found that addition of fines to kraft paper increases strength properties by filling in voids and thus providing a greater degree of bonding. A similar effect may be occurring in the MDF samples. Figure 9 also shows that perpendicular specimens exhibit greater LE than parallel specimens; juvenile specimens generally have a greater LE than their mature counterparts; and in all cases, mini panels comprised of only intermediate fiber lengths have the lowest LE values.

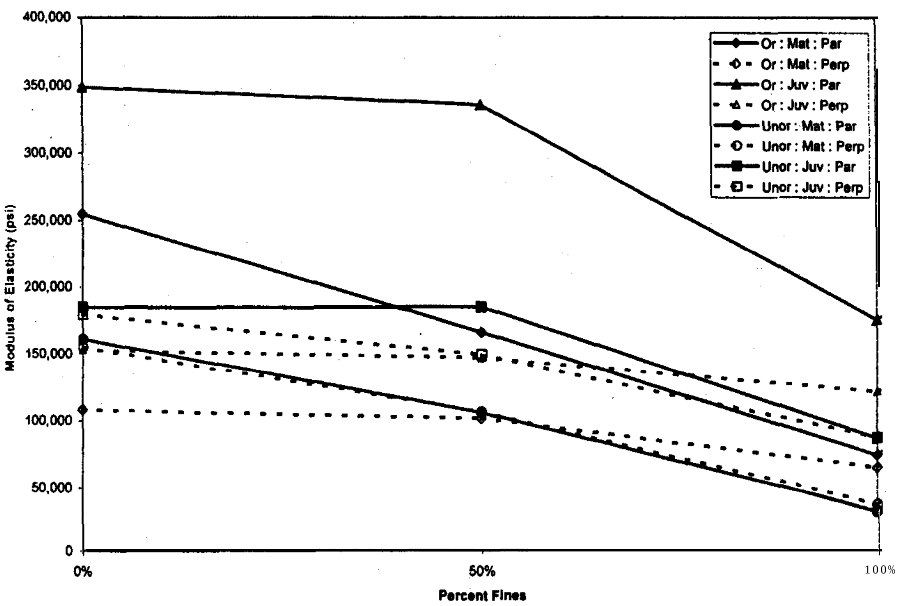

Figure 'I.-Effect of fines loading on the MOE of oriented and un-oriented MDF mini-panels.

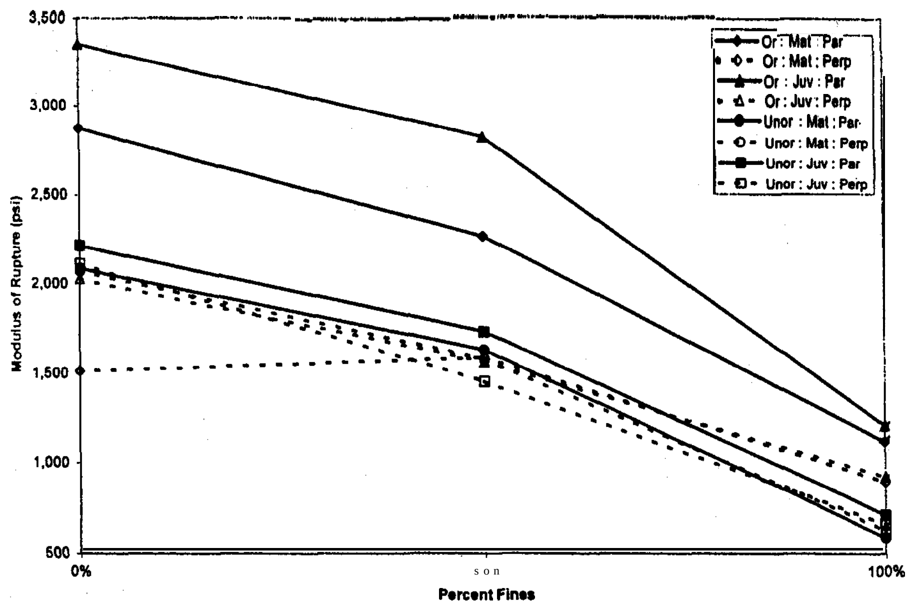

Figure S.-Effect of fines loading on the MOR of oriented and un-oriented MDF mini-panels.

The IB data for the fines loading mini panels are summarized in Figure 10. Fines are detrimental to the IB strength of MDF mini panels. The deleterious effect of decreased IB strength as a function of fines loading is equally applicable to all panel types, regardless of orientation or juvenile fiber content.

Microtomography

Microtomography successfully imaged the structure of the MDF material. A perspective view of the three-dimensional volume (1.28 by 1.09 by 0.37 mm) is given in Figure 11. The grid lines superimposed upon the volume are spaced 0.12 mm apart. Additional detail is visible from observing a representative side of the specimen (Fig. 12), which represents a digitally obtained 2.4 μ thick slice in the interior of the specimen, 391 μ from one end. The identifiable fibers clearly show a lack of collapse in the lumens of thick walled cells, which is in contrast to a fully collapsed fiber structure that has been observed in commercial kraft liner board material prepared from loblolly pine. Some fibers are oriented parallel with the field of view and exhibit a ribbon-like snake structure. This can also be observed from a top-view of the same specimen (Fig. 13). The white regions represent void structure with the dark regions corresponding to the cell walls. The hazy/milky regions may represent fines, which absorb the x-ray energy but whose structure is undefined or size is so low it is not discernible.

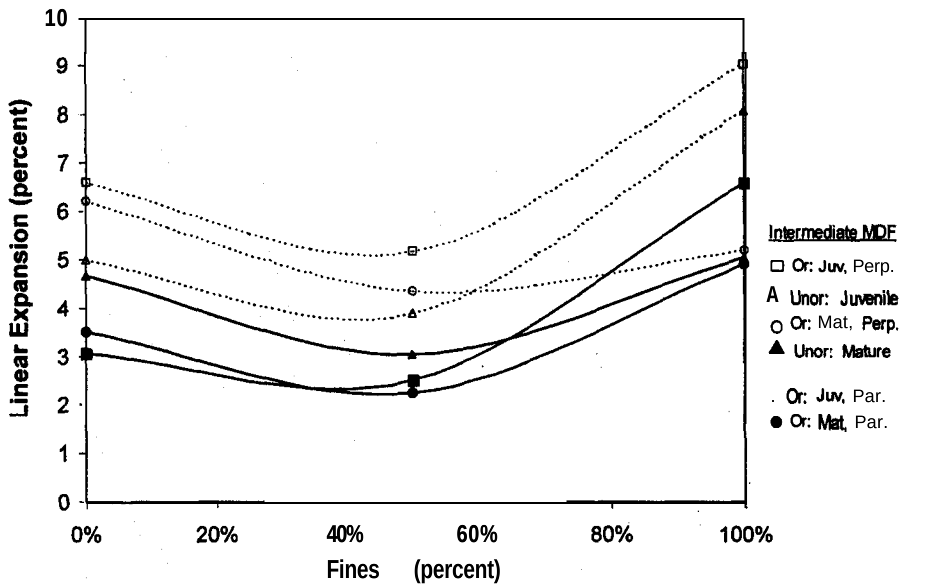

Figure 9.-Effect of fines loading on the linear expansion of MDF mini-panels. Six main traces represent fines loading for 0 percent to 100 percent. Six points to the right of the main graph represent values of linear expansion for mini-panels comprised solely of intermediate fibers.

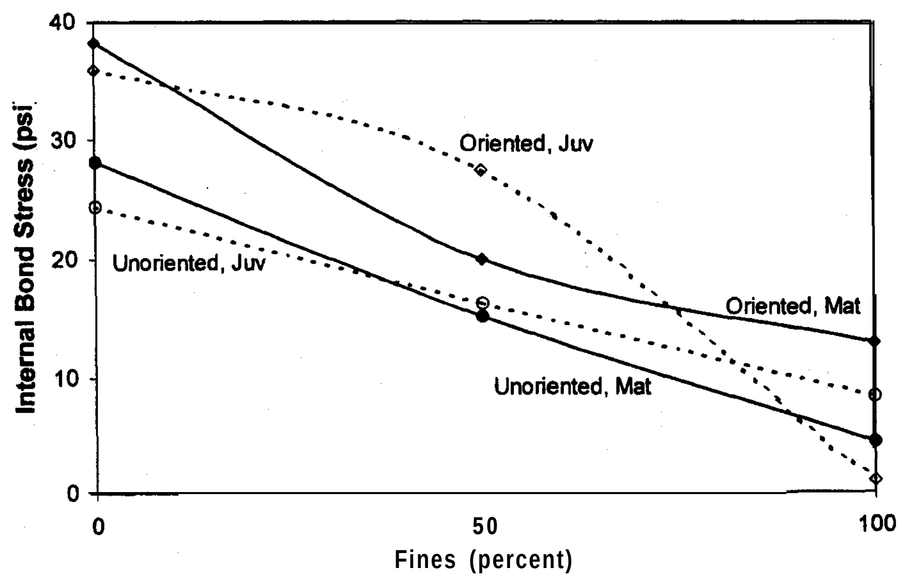

Figure 10.-Effect of fines loading on the internal bond strength of MDF mini-panels.

Although difficult to communicate through two-dimensional images, the three-dimensional orientation and length of a sample fiber was obtained from the volume. This was accomplished using manual digital image interpretation of the volume. The ends of a fiber within the volume were identified and their coordinates (x, y, and z) recorded. The length of a straight line between the fiber ends was designated as the secant length. The curved nature of fibers was evaluated through defining the perimeter of fiber cross sections at 12 to 24 μ intervals in a principal direction (x or y) of the MDF volume. The length of each of the individual fiber was then calculated from the distance between the (x, y, and z) coordinate of adjacent slice centroids. The length of the individual segment was then summed and defined as the total fiber segment length. This fiber segment length is a truer measure of fiber length than the Secant length. While many descriptions of fiber curvatures have been made in the literature (Nguyen and Jordan 1994; Trepanier 1998), one particular measure was selected for description of the MDF fiber due to its simplicity and ease of calculation. The curl index (%) is defined as:

$$\frac{\text{Fiber secant length}}{\text{Fiber segment length}} \times 100 \qquad [1]$$

A perfectly straight fiber would have an index of 100 while a fiber bent in half would have an index of 50. The curl index was measured on 7 1 fibers. A summary of the fiber secant and segment lengths as well as curl index is given in Table 1.

The distribution of fiber lengths was not normal although free fibers have been identified to have such a distribution (Wang and Shaler 1998). The reason for this distribution is that in most cases the entire fiber length was not contained within the sample volume measured. This phenomenon leads to a fiber length distribution that is skewed to short lengths.

While the fibers measured by either the segment or secant method were underestimated, the curl index as defined as Equation [1] should still be valid. The mean and median curl index was 94.7 and 96.0 percent, respectively, with a range of 70.6 to 100.0

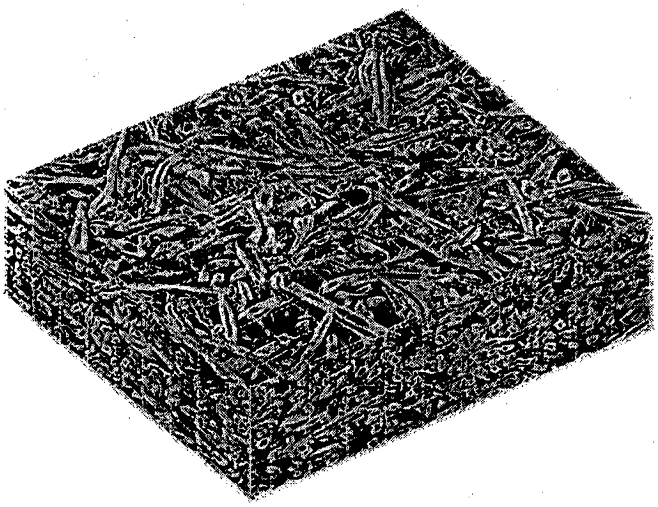

Figure 11.—Isometric **view of 1.28 by 1.09 by 0.37 mm MDF specimen imaged with microtomography.**

Figure 12.—Edge **view (0.92 by 0.81 mm) of internal fiber structure** 391 μ **from a specimen end.**

Figure 13.—Plain view of internal fiber structure (0.2 **by 0.81 mm).**

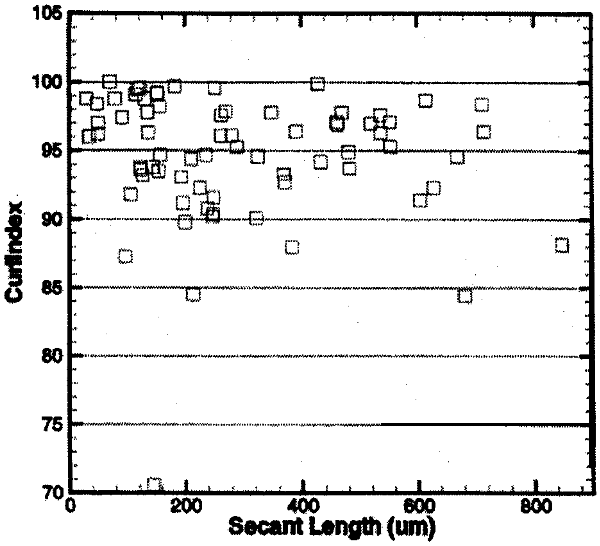

Figure 14.-Fiber **curl index vs. fiber secant length of 71 fibers from interior of MDF specimen.**

Table l.-Summary of length and orientation of 71 fiber segments from within a 1.28 by 1.09 **by 0.37 mm volume of MDF.**

	Mean	Median	Range
Fiber segment length (pm)	314.2	**262.6**	**30.1** to 961.3
Fiber secant length (pm)	296.0	**247.8**	29.7 to 847.6
Curl index (%)	94.7	96.0	**70.6** to 100.0
dyldx	**-0.3**	**3.5**	**-87.8** to 89.8
dz/dx	**7.7**	**7.5**	**-73.8** to 82.9
dzldv	**0.2**	**-2.9**	**-77.0 to 74.1**

percent (Tab. 1). Curl index as a function of fiber secant length (Figs. 13 and **14)** indicates that the amount of fiber curl was independent of fiber length. It is important to note that the observed fiber curl is impacted by the fiber latency of the pulp prior to consolidation as well as additional fiber distortions introduced by the hot pressing operation.

The fiber orientation in three-space was measured from the ends of **71** fibers (Tab. 1). Three angles were identified including:

- dy/dx = the angle of the projection of fiber length in the x-y plane relative to the x-axis;
- dz/dx = the angle of the projection of fiber length in the x-zplane relative to the y-axis; and
- dz/dy = the angle of the projection of fiber length in the y-z plane relative to the x-axis.

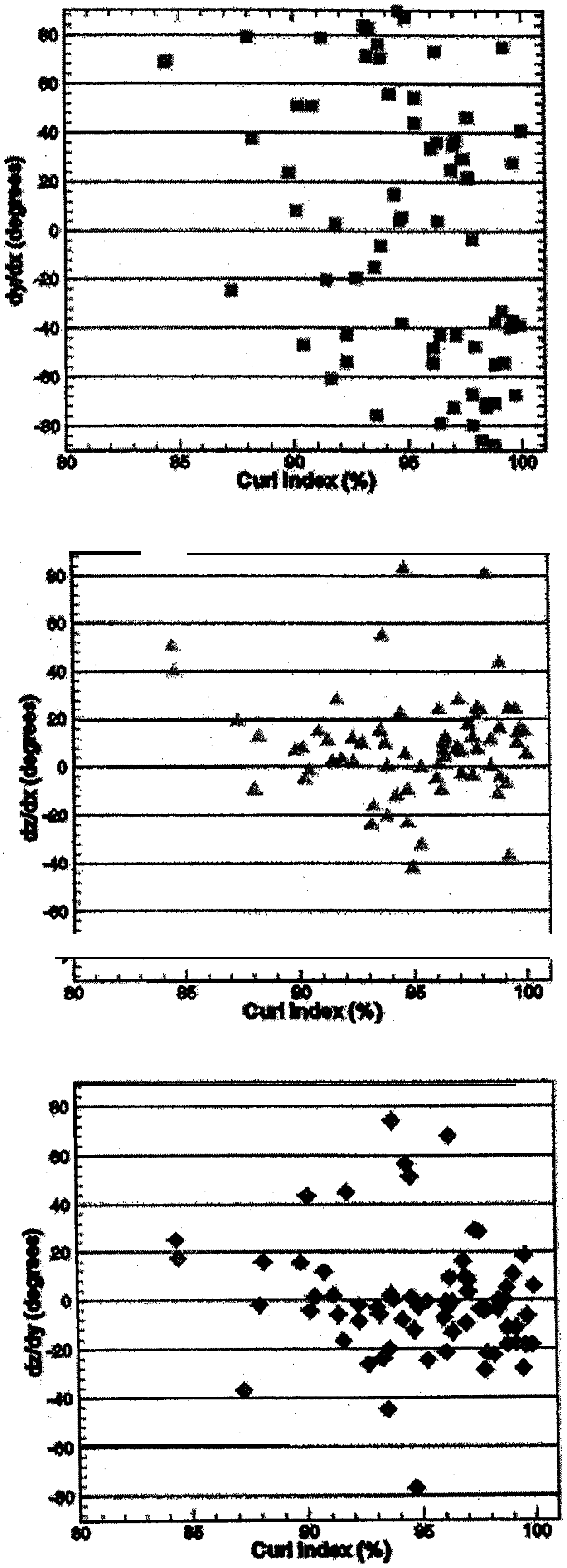

Figure 15.-Fiber **orientation vs. curl index of 71 fibers measured in the xy, xz, and yz specimen planes.**

The *dy/dx* angle corresponds to in-plane fiber orientation. The degree of alignment has been traditionally described in oriented strandboard (OSB) using either percent flake alignment or the von Mises distribution (Shaler 1991). The mean angle was near zero with a range of angles from ± 90" (Table 1). The expected random nature of fiber orientation is apparent from Figure 15. The vertical component of fiber orientation as defined by the *dz/dx* and *dz/dy* angles indicate that most fibers have an orientation with ± 25" of the x-y plane, but that an appreciable percentage of fibers exhibit orientations up to 85" out of plane. This significant vertical orientation of fibers is not typically described in MDF material. The presence of out-of-plane fiber alignment (Hermanson et al. 1997) impacts the mechanical properties of MDF and merits further investigation. The influence of fiber handling and forming operations on the three-dimensional fiber orientation within MDF offers potential to control and improve panel properties.

Conclusions

Miniature MDF panels are indicative of full-size panel stiffness and strength. Specific inferences that can be extracted from this study are:

1. MDF stiffness and strength increase with increasing percentages of juvenile wood fibers.
2. LE values are greater perpendicular to the direction of fiber orientation.
3. Orientation increases MDF stiffness and strength.
    a. MDF mini panels comprised of juvenile fibers have a greater benefit from fiber orientation than do the mature counterparts.
    b. Increase in stiffness and strength was increased both parallel and perpendicular to the direction of fiber orientation, which is most likely due to improved efficiency in fiber packing.

Inclusion of fines in the fiber furnish decrease the stiffness, strength, and IB strength of MDF panels. Fines do appear to restrict LE between packing levels of 0 to 50 percent. However, insufficient numbers of samples were manufactured to pinpoint the optimal level of fines loading with regards to LE.

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