Effect of Fiber Surface and Mechanical Properties on the Stiffness and Strength of Medium-Density Fiberboard

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INTRODUCTION

The mechanical properties of wood-based composites are dependent upon the properties of the wood components (e.g. wood fibers, wood strands) and the manner in which they are combined. The relationship between fiber mechanical properties and fiber-based composites has been discussed in several publications, but is best described in Page et al. (1977). This paper will focus primarily on the influence of fiber physical and mechanical properties on the structural performance of medium density fiberboard (MDF).

The effect of fiber mechanical properties on the stiffness and strength of MDF will be evaluated by making panels with varying levels of juvenile and mature wood in the fiber furnish. It has been well documented that juvenile wood does indeed alter the physical and mechanical properties of various types of wood-based composites (Pugel et al. 1990a, Pugel et al. 1990b, and Pugel et al. 1998). This study will attempt to quantify the relationship between component (i.e. individual wood fibers) properties and the subsequent wood fiber-based composite (i.e. MDF).

In previous wood fiber-based composite studies, fiber physical property data has generally been restricted to easy to measure variables such as fiber length, fiber curl, and various length classifications via fractionation. This study will measure traditional variables, but will also collect data on microfibril angle and surface morphology and roughness. Characterization of wood fiber surfaces has been difficult at best and has generally been accomplished qualitatively through microscopic observations. Suleman (1996) has recently showed that surface features of cellulosic fibers could be qualitatively and quantitatively assessed with the atomic force microscope (AFM). This study will use analogous techniques to assess fiber roughness and surface features with an AFM.

The Southern Research Station (Pineville, LA), University of Maine (Orone, ME), the BioComposites Centre (Bangor, Wales), and the University of Southwestern Louisiana have cooperatively developed methods to characterize the mechanical and physical properties of individual wood fibers. Surface properties are determined with the AFM; mechanical property data are ascertained from traces of

individual fibers in tension. This study utilized traditional and novel experimental techniques to characterize fiber mechanical and physical properties to achieve the following objective: *to determine the relationship between fiber furnish physical and mechanical properties and the structural performance of the MDF composite.*

EXPERIMENTAL PLAN

One loblolly pine (*Pinus taeda* L.) tree 51 years of age was harvested from a plantation stand in the Crockett Experimental Forest, Southern Arkansas. The tree was bucked into 18-inch bolts and transported to the Southern Research Station (SRS). The bolts were segregated into juvenile wood (defined in this study as wood within the tenth growth ring) and mature wood (wood beyond the thirtieth growth ring) portions. These segregated portions were transported to the University of Maine (UM) where they were chipped and then pulped in a pressurized disk refiner. The chips were divided into approximate halves, and mechanically pulped at ambient temperature and with a refiner pressure of either 10 or 40 psi. The resultant 4 pulp types consisted of (a) juvenile - 10 psi; (b) mature - 10 psi; (c) juvenile - 40 psi; and (d) mature - 40 psi. All fibers were air-dried and subsequently bagged for panel manufacturing. A small sample of each pulp type was extracted for determination of individual fiber properties.

Original, unrefined portions of juvenile and mature wood at the SRS were macerated to evaluate the effect of refining on fiber properties. A detailed explanation of the maceration technique can be found in Panshin and deZeeuw (1970) and is as follows: (1) matchstick-size wood samples were placed in a beaker with glacial acetic acid and hydrogen peroxide; (2) the beaker contents were warmed with continual, gentle agitation for 24-48 hours; and (3) the resulting pulp was washed thoroughly with distilled water.

Individual fiber properties.- Epoxy droplets were placed at the ends of dried pulp fibers. Fibers were then placed in a miniature tensile tester, with the epoxy droplets seated in ball-type socket grips (Fig. 1). Approximately 90 fibers of each type were tested in tension to failure at a crosshead rate of 80 microns/minute, resulting in a load-elongation trace. Failed fibers were stained with acridine orange and placed in a Biorad 600 Confocal Laser Scanning Microscope (CLSM) for cross-sectional area determination. The LSCM cross-sectional area was used to convert the load-elongation traces to stress-strain curves. In addition to cross-sectional area determination, the CLSM was used to classify fibers as either earlywood (EW) or latewood (LW) as well as to determine the microfibril angle of the S_2 layer. A detailed discussion of the tensile fiber testing technique used in this study can be found in Groom et al. (1996) and Mott (1996).

Qualitative fiber surface morphology was determined with an Electroscan Environmental Scanning Electron Microscope (ESEM); quantitative data were collected with a Digital Instruments Nanoscope III atomic force microscope.

Panel production and testing

Restrictions in the amount of fiber available limited panel size to 16- by 16- by 3/8-inches. Panels consisted of fibers refined at either 10 or 40 psi, and at 5 mixture levels of juvenile:mature fibers ranging from 100% juvenile:0% mature to 0% juvenile:100% mature. Three panels were produced for each panel type resulting in a total of 30 panels. The adhesive used was urea-formaldehyde (solids content = 65.16%). Panel resin content was 8%. Preliminary panels with thermocouples were manufactured so as to develop a core temperature of at least 210 °F for a minimum of 45 seconds. The press cycle used to

manufacture all panels in this study was as follows: 30 seconds from daylight to position; 2 min., 45 sec. press time at 270 °F; 0.1 sec. bump time; 15 sec. press time at 270 °F. Target density was 47 lbs/ft^3. Panels were allowed to condition at 72°F, 65% RH and cut into 2 specimens each for determination of bending mechanical properties.

RESULTS AND DISCUSSION

Properties of individual pulp fibers

Physical properties. – Confocal microscopy analyses of post-failure fibers were necessary for mechanical property determination. Although the CLSM images were used primarily to assess cell wall cross-sectional area for stress calculations, the images were for intrawall damage assessment as well as earlywood/latewood classification. Figure 2a shows representative samples from chemically macerated mature fibers and shows a rather even distribution of earlywood and latewood fibers. Figure 2b shows the comparative mature fiber samples refined at a pressure of 40 psi. Most noticeable is the absence of the earlywood fraction. This was also seen in the juvenile wood fibers (Fig. 3). This composition of EW and LW fiber ratios in the furnish indicates that refining drastically alters the ratio between the thin-walled, heavily-pitted EW fibers and the thick-walled, scarcely-pitted LW fibers. It should be noted that this LW/EW determination looked only at intact, single fibers and not at fragmented fibers. Of the 85-90 fibers for each fiber type, the refining process changed the juvenile fiber LW:EW ratios from approximately 1:1 to 9:1. Mature fibers behaved in an analogous manner with refining altering the LW:EW ratios from 6:4 to approximately 9.5:1. In essence, EW fibers become fragmented to such an extent during refining that they become the 'fine' fraction of the furnish whereas the LW fibers tend to remain intact and thus become the primary structural components.

Although refining did alter the physical properties of the fibers as compared to unrefined fibers, there was not a difference between refining levels. This was further confirmed by physical observations in the ESEM (Figure 4). The AFM is currently being used to determine quantitative differences in surface properties of fibers from the various furnishes (Figure 5). However, at the time of this writing, no digital technique has been established which statistically distinguishes the different pressure-refined fibers.

Mechanical properties. - Average stress-strain curves for individual wood fibers are shown in Figure 6. Mature fibers were found to be stiffer and stronger than their juvenile counterpart. This holds true for both macerated fibers and those generated by the refining process. This difference is due primarily to the differences in microfibril angle (Page et al. 1977). Individual fiber mechanical properties are summarized in Table 1. The stiffness and strength of individual wood fibers is approximately halved as a result of the refining process. Fiber damage may have been reduced had the refining conditions occurred above the glass-transition temperature of lignin, which in the refiner would have been approximately 95 °C (Rials 1989).

Panel properties

Stiffness and strength.- MDF panels produced in this study had an average density of 45.9 lbs/ft^3. The relationship between individual fiber stiffness on MDF modulus of elasticity (MOE) is shown in Figure 7. A similar trend exists for the fiber strength/MDF modulus of rupture, that being: The mechanical properties of MDF panels were inversely correlated to fiber properties. It has been well established by Page et al. (1972) and others that fiber mechanical properties increase with decreasing fibril angle, and that

fibril angle in softwoods decreases with cambial age (Panshin and deZeeuw 1970). Thus, the structural performance of wood-fiber based composites would be enhance by increasing the proportion of juvenile fibers in the furnish. It should be noted that these panels were made from fibers refined below the glass-transition temperature of lignin and there was no attempt to orient fibers in the composite. Current investigations are under way to investigate the effect of fiber orientation and refining temperature.

Panels comprised of fibers refined at 40 psi were stiffer and stronger than equivalent panels comprised of fibers refined at 10 psi (Figure 8). Although there was no difference in the mechanical properties of individual wood fibers refined at various pressures, the panel properties are significantly affected. Since the refining pressures did not affect fiber mechanical properties and orientation, then the difference in MDF mechanical properties can be attributed to altered fiber-to-fiber stress transfer mechanisms. The altered stress transfer mechanism is most likely due either to difference in fiber surface morphology (which was indiscernible with ESEM observations but is being investigated with the AFM) or a physical change in fine composition and distribution within the 3-dimensional composite network.

Failure Mechanisms

There does exist a strong relationship between the physical and mechanical properties of wood fibers and the structural behavior of panels made from them. The most significant finding of this study is that MDF panel stiffness and strength are inversely related to fiber stiffness and strength. There exists a myriad of explanations including differences in fiber lengths, altered fiber packing in the composite network, and varying degrees of fiber collapse in the various fiber types. However, the most logical explanation goes back to the basics of secondary cell wall morphology and the fact that the complexity of a 3-dimensional composite cannot be fully explained with 1-dimensional data. Juvenile wood fibers possess thin walls, are severely pitted (natural stress concentrations), and possess a flat microfibril angle. Although the flat microfibril angle gives them exceedingly poor longitudinal stiffness and strength, it also provides exceptional radial mechanical properties (in theory as no data empirical data exists). Mature fibers have an ideal microfibril angle for longitudinal properties, theoretically possessing extremely low radial UTS and MOE values. Thus, the weak link in the composite is achieved earlier in panels comprised of mature fibers as compared to their juvenile counterpart. This explanation holds true only in this study as the MDF panels were unoriented. Oriented panels will most likely behave differently, with the longitudinal properties of the fiber playing a more significant role.

CONCLUSIONS

The most significant conclusions from this study are:

* Refining degrades the mechanical properties of individual wood fibers. However, the level of refining does not alter fiber mechanical properties.

* Refining alters the LW and EW composition. Refining disintegrates EW fibers into 'fine' fragments whereas LW fibers remain intact and act as the structural component of the MDF panel.

* Panel stiffness and strength are inversely correlated to individual fiber longitudinal mechanical properties. Thus, the mechanical properties of unoriented MDF panels increase with increasing proportions of juvenile wood.

* Increasing levels of refining increases the MOE and MOR of unoriented MDF panels.

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Table 1. Mechanical properties of individual wood fibers.

Figure 1. Individual wood fiber prepared and mounted for tensile testing.

Figure 2. Cross-sectional profiles of individual mature wood fibers immediately after tensile testing. Images were gathered with a confocal laser scanning microscope and are segregated into (a) macerated, and (b) refined (40 psi) fibers.

Figure 3. Microfibril angles and earlywood/latewood fractions of various fiber types.

Figure 4. Environmental scanning electron microscope images of: (a) juvenile fibers refined at 10 psi, (b) mature fibers refined at 10 psi, (c) juvenile fibers refined at 40 psi, and (d) mature fibers refined at 10 psi.

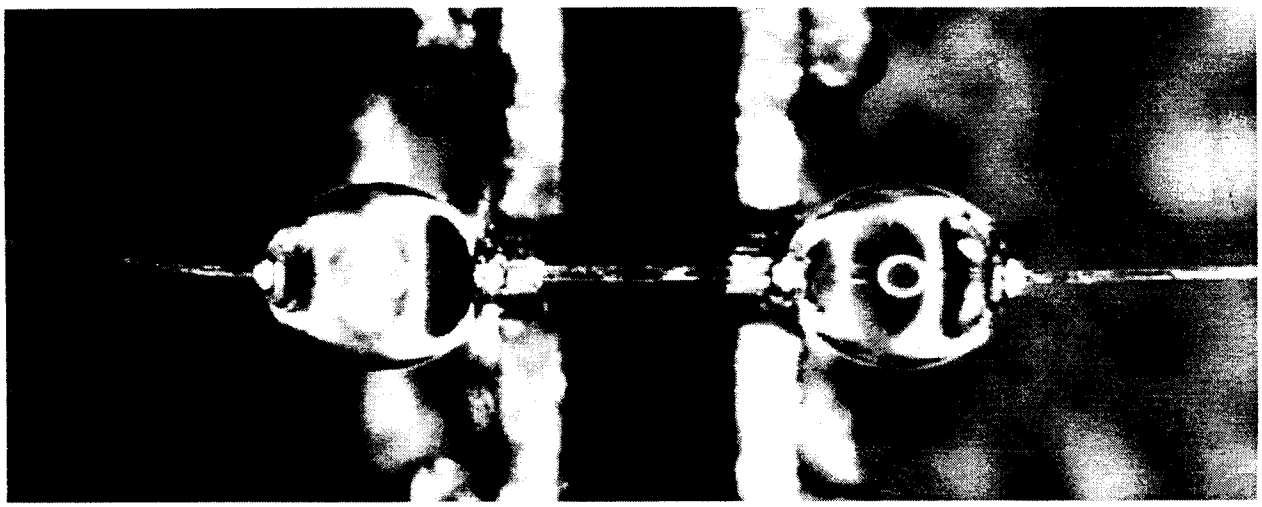
Figure 5. Atomic force microscope images of loblolly pine fibers: (a) macerated with glacial acetic acid and hydrogen peroxide, (b) refined at 10 psi; and (c) refined at 40 psi.

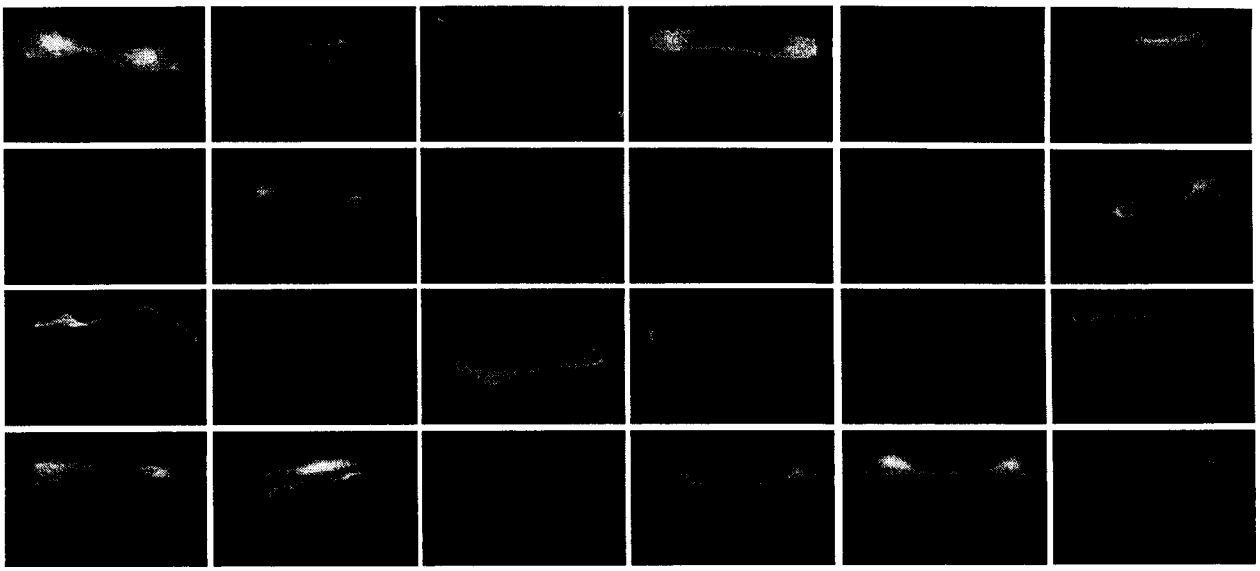
Figure 6. Average stress-strain curves for refined and macerated fibers.

Figure 7. Panel MOE shown as a function of fiber longitudinal MOE. Vertical bars represent one standard deviation.

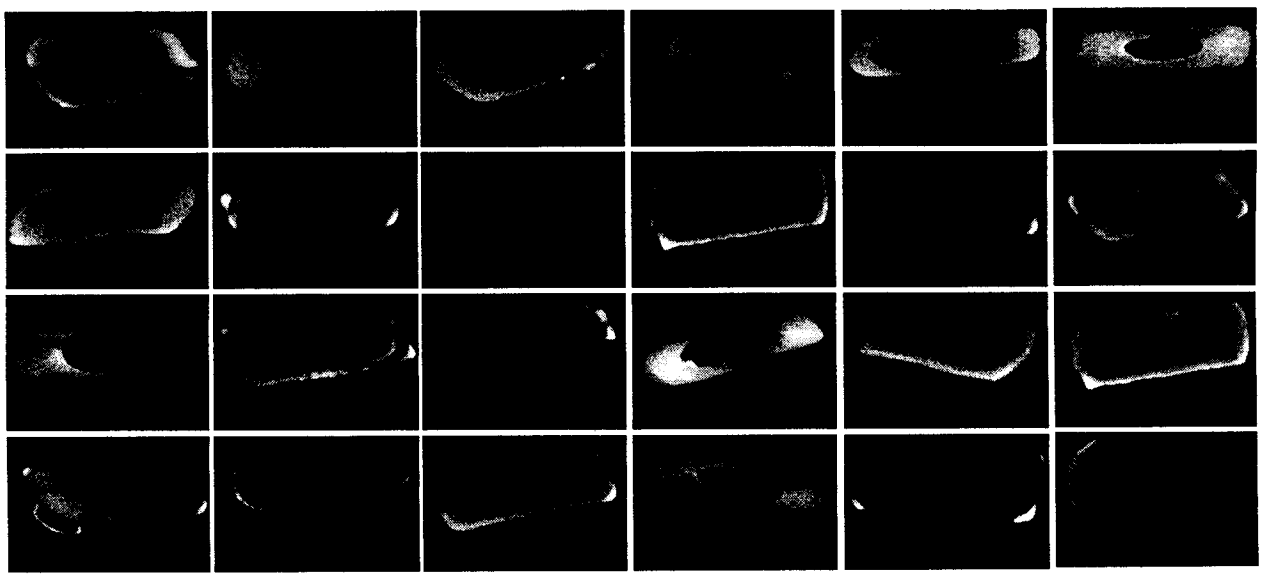
Figure 8. Effect of refining levels on panel MOR and MOE. Vertical bars represent one standard deviation.

Fiber Type	Modulus of Elasticity ($x\ 10^6$ psi)	Ultimate Tensile Stress (psi)
Juvenile, 10 psi	0.46	29,400
Juvenile, 40 psi	0.53	30,100
Juvenile, macerated	1.37	80,100
Mature, 10 psi	0.99	59,900
Mature, 40 psi	0.95	65,600
Mature, macerated	1.87	89,100





(a)



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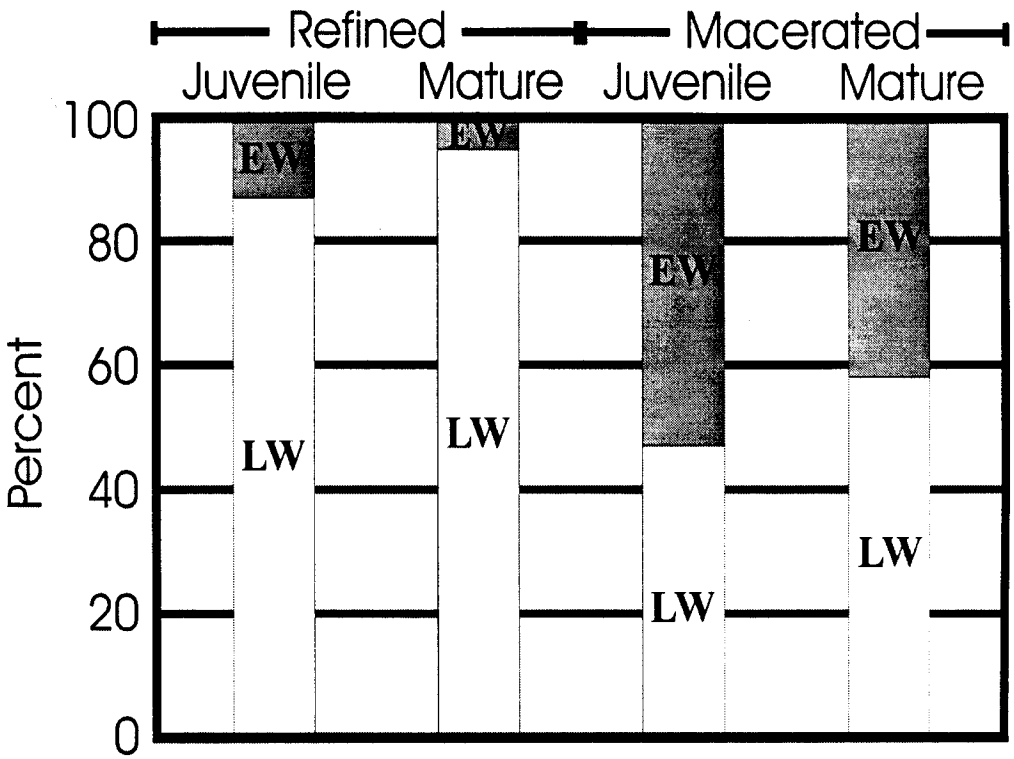


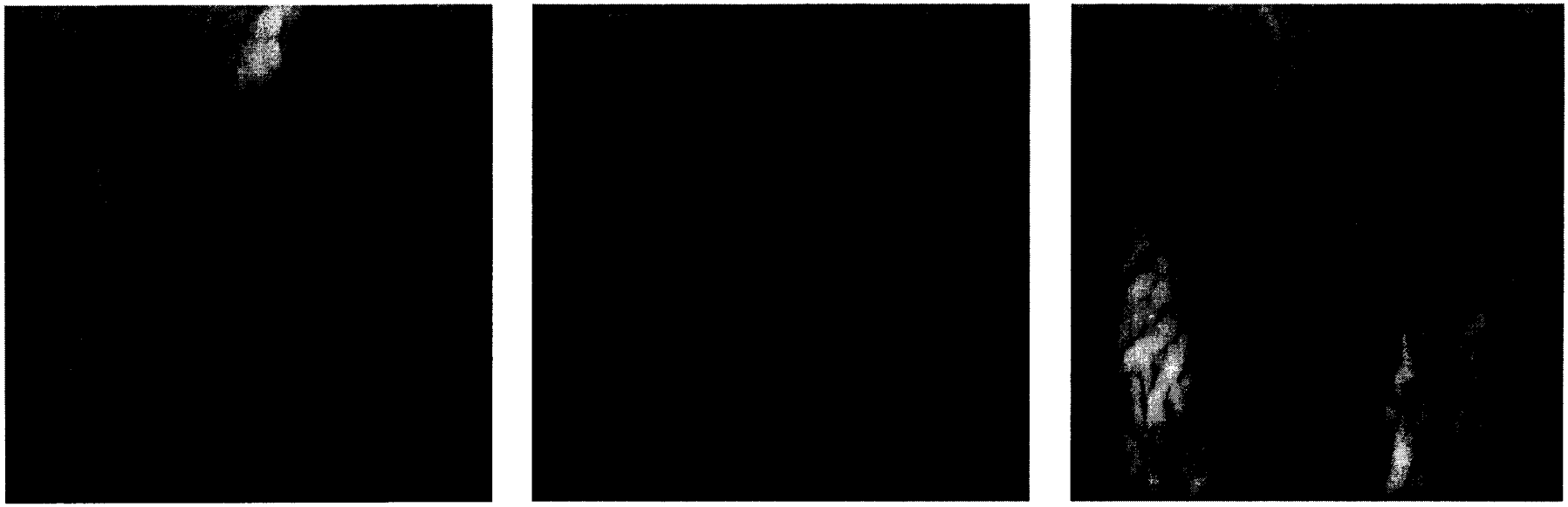
Fibril Angle	**25**	**10**	**25**	**9**

(a)

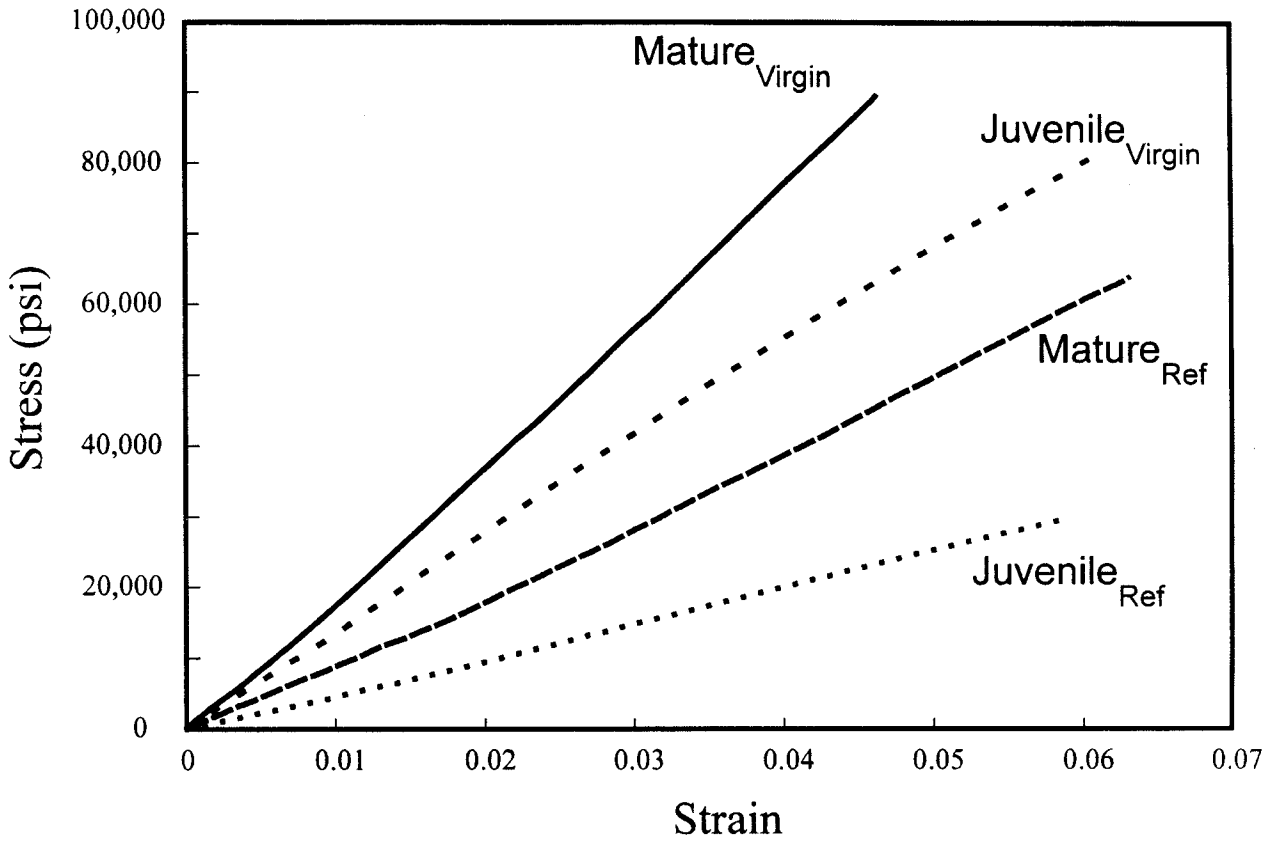
(b)

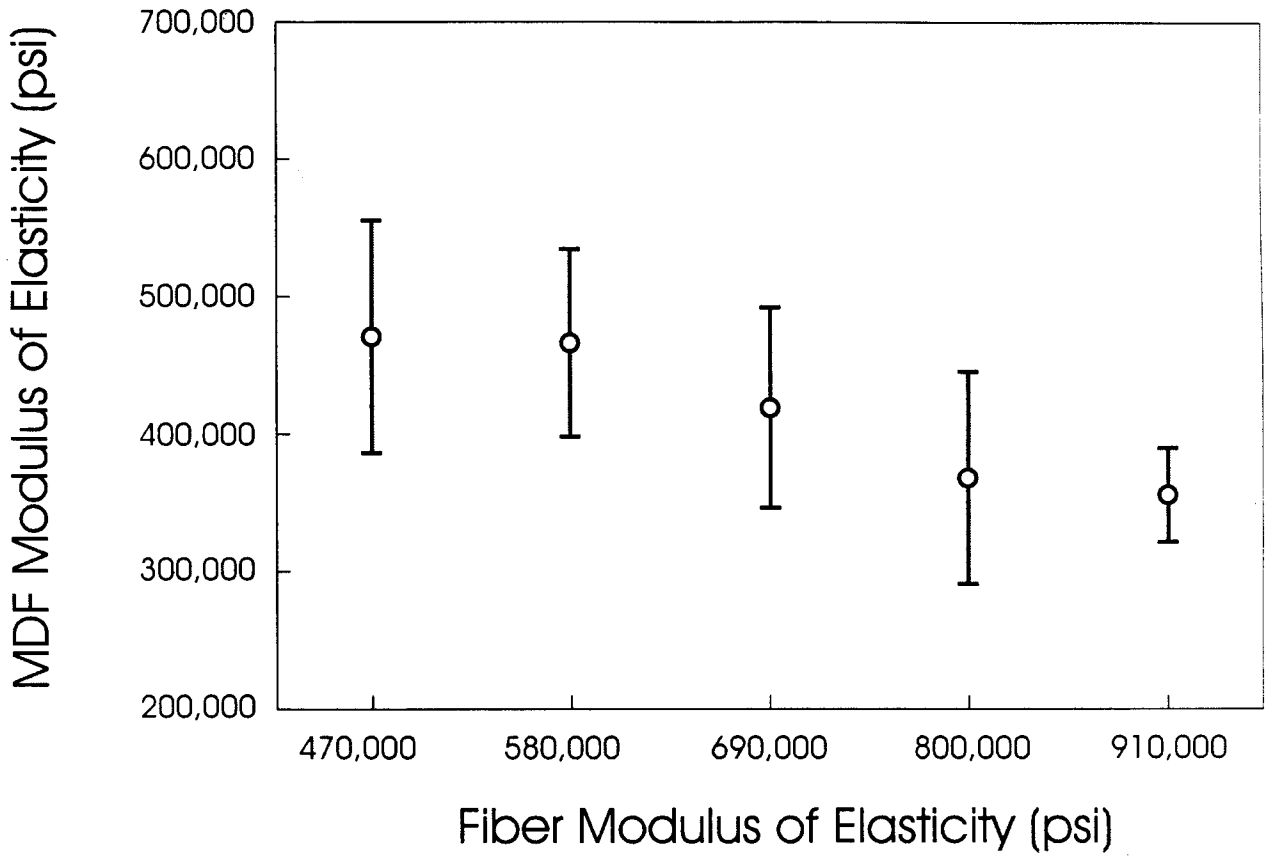
(c)

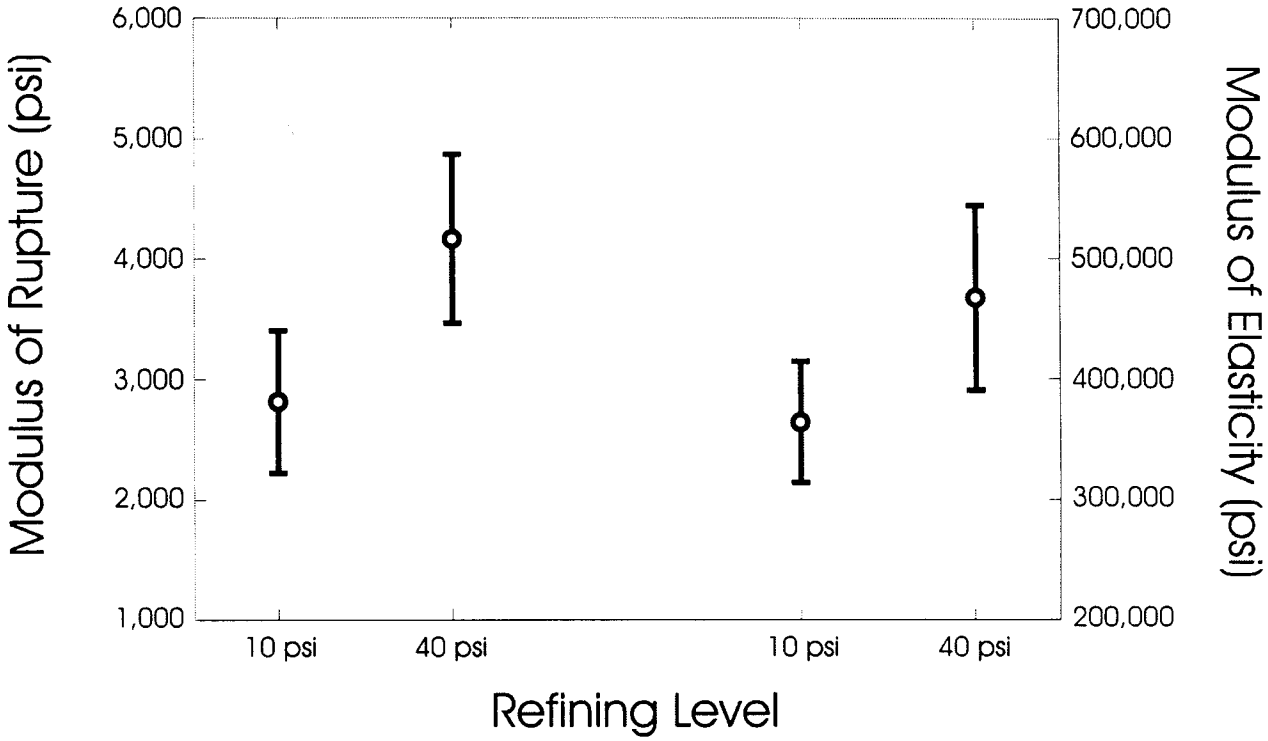
(d)



(a) (b) (c)


100,000
80,000
60,000
40,000
20,000
0
Stress (psi)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
Strain
Mature Virgin
Juvenile Virgin
Mature Ref
Juvenile Ref


MDF Modulus of Elasticity (psi)
700,000
600,000
500,000
400,000
300,000
200,000
470,000
580,000
690,000
800,000
910,000
Fiber Modulus of Elasticity (psi)


Modulus of Rupture (psi)
6,000
5,000
4,000
3,000
2,000
1,000
Modulus of Elasticity (psi)
700,000
600,000
500,000
400,000
300,000
200,000
10 psi
40 psi
10 psi
40 psi
Refining Level