

THE STRUCTURAL PERFORMANCE OF MDF: RAW MATERIALS, REFINER PRESSURE, AND RESIN FORMULATION EFFECTS

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SUMMARY

Loblolly pine chips separated into 4 levels of juvenility, and chips from yellow-poplar peeler cores were refined and made into MDF panels in a 2-phase study. Phase I evaluated the effect of juvenility and refining on MDF mechanical properties. Phase II evaluated the effect of resin molecular weight in conjunction with juvenility and refining levels.

In Phase I, chips were refined from 2 to 18 bar at the BioComposites Centre and sent to the Southern Research Station for the manufacture of MDF panels. The MDF panels with the best mechanical properties were comprised of juvenile fibres, with the optimal refiner pressure between 7 and 8 bar. The mechanical properties of the panels decreased with increasing levels of maturity. The optimal refiner pressure with regards to the MDF mechanical properties increased with increasing raw material maturity.

MDF panels comprised of juvenile fibres again outperformed their mature counterparts in Phase II. Juvenility of the raw material was especially evident in the IB strength, with the IB of juvenile MDF panels approximately 50 percent greater than their mature counterparts. The resin molecular weight did not have an effect on the MDF panels in this portion of the study. However, the effect of resin molecular weight may prove significant with a more varied press schedule.

INTRODUCTION

The production of MDF is a simple process: disassemble solid wood into wood fibres via refining and then reassemble the fibres into a structural composite. The primary factors that govern the physical and mechanical properties of MDF are the fibre properties, fibre orientation, density, profile, and fibre-to-fibre adhesion. This paper presents the results of an on-going study that investigates the relationship between fibre generation, fibre-to-fibre adhesion, and MDF panel properties.

In traditional wood-based composites such as plywood and laminated veneer lumber, the structural performance of the composite is directly dependent on the mechanical properties of the wood components. This axiom does not apply to wood fibre-based composites. The mechanisms for transferring stresses amongst composite components are different. Clear wood and veneer composites have a finite number of transfer points with adequate adhesion. Wood strand composites have many more stress transfer locations with a lesser amount of adhesive coating the surfaces. As a result, wood strand components have diminished structural properties as compared to their clear wood and veneer-based counterparts. However, the strand components are still planar and generally oriented, resulting in a modulus of elasticity (MOE) that is less than half of the equivalent clear wood MOE.

The development of the mechanical properties of wood fibre-based composites differs from the previously discussed composites, relying on a near infinite number of 'spot welds'. These spot welds are dictated by the resin type, content, flow, and distribution on the fibre surfaces. These variables are selected both by the composite manufacturer and the resin manufacturer and are based on empirical observations. However, the choice of resin and its relationship with the fibre surface has remained largely unstudied because of the inability to adequately

determine resin location on the fibre surface. Recent advancements in microscopy and fluorescent staining techniques have allowed us to ascertain resin distribution on the fibre surface, and these techniques are being employed in this study.

The mechanical properties of individual wood fibres are equally important in the development of MDF structural properties. However, the relationship differs from clear wood, veneer, or strand composites: structural performance of MDF increases as the proportion of compliant fibres increases. This is supported by previous studies that show that the stiffness and strength of MDF panels increase with increasing proportions of compliant juvenile wood fibres (Groom et al. 1999; Groom et al. 2000).

The long-term goal of this on-going study is to ascertain the mechanisms that govern the physical and mechanical properties of structural fibreboards. These goals are achieved by studying the primary factors governing MDF: fibre properties, fibre-to-fibre stress transfer, density, density profile, and fibre orientation. Data presented in this paper are the compilation of several studies that address these factors. Specifically, the objectives of this paper are to: (1) determine the effect of refining on the mechanical properties of individual fibres and subsequently the properties of MDF; and (2) ascertain the resin distribution on and penetration of individual wood fibres during blending and pressing.

MATERIALS AND METHODS

The raw material for the construction of MDF panels was mature loblolly pine (*Pinus taeda* L.) harvested from a conventional plantation in southern Arkansas (USA) and yellow-poplar (*Liriodendron tulipifera* L.) peeler cores from North Carolina. The yellow-poplar peeler cores were chipped, dried and sent to the BioComposites Centre (Bangor, Gwynedd, UK) for subsequent refining. The felled loblolly pine logs were further subdivided into 4 zones: juvenile, juvenile-transition, mature-transition, and mature. The juvenile zone was the pith to growth ring 8, juvenile-transition was represented by growth rings 9 to 16, mature transition was from growth rings 17 to 24, and the mature zone was represented by growth rings 25 and beyond. The loblolly pine logs were segregated into these 4 zones by a portable sawmill as well as a series of rip saws at the Southern Research Station (SRS), Pineville, LA, USA. The wood generated from the saws was chipped, dried, and sent to the BioComposites Centre for refining.

The chipping and refining was done in two phases. In Phase I, all 5 chip types (yellow-poplar and 4 loblolly pine zones) were sent to the BioComposites Centre. Refining was done at the following pressures: 2, 4, 5, 6, 7, 8, 10, 12, 14, and 18 bar. Fibres were dried, bagged, and sent back to the SRS for analysis and MDF panel manufacture. Phase II was to investigate the effect of resin on panel properties, with all 5 chip types refined at 5.5, 7, 8.5, and 10 bar. Full-sized panels were made directly from the blowline using one of three different molecular weight resins. Finished panels were sanded and sent back to the SRS for property determination.

Refining: Refining was conducted at the BioComposites Centre pilot plant using an Andritz Sprout-Bauer 12-inch pressurised refiner. The refiner consisted of an in-feed hopper leading to a modular screw device (i.e. plug feeder), which conveys the material from atmospheric pressure into the desired pressurised environment. Wood chips were fed through the modular screw device via a 2.6 meter long cooker to a 60 litre digester.

The material from the digester was fed by screw conveyor to the centre of the stationary refiner disc, and hence into the refining zone. In order to maintain a level of comparability, refiner feed screw settings and energy consumption were maintained for all fibre production using nominal refiner plate gaps that maintained the level of energy consumption. Target refiner feed screw rate was set to 30% maximum revolutions and target refiner energy consumption to 10 KW/hr.

Fibre was vented from the refiner housing via a blow valve into a 9-meter long stainless steel blowline, which in turn is connected to a continuous, 120-meter long flash drier. The internal diameter of the drier is 159 mm and the air for the drier is heated via a hot oil heat exchanger. The air velocity used was approximately 37 meters per second. These conditions gave a total residence time for fibres in the drier of 4-6 seconds. The drier inlet temperature was varied in order to achieve a target furnish moisture content of 8-10 percent.

MDF Panels – Phase I: 300-by 300- by 15-mm southern yellow pine and yellow-poplar MDF panels were constructed at the Dynea research facility located in Winnfield, LA, USA. Before blending, the moisture content was determined for each fibre type and refiner pressure. The appropriate quantity of water was then added with the resin to yield a target unblended fibre moisture content of 10%. The water was added to the resin prior to blending to ensure uniform distribution, of moisture. The appropriate amount of 65% non-volatile solids urea-formaldehyde resin (8% resin solids based on oven dry fibre) and the additional water was applied via spray atomisation in a rotary drum blender. MDF mattresses were then formed using a cyclone attached to a laboratory scale hammer mill with the screen removed. The mattresses were hot-pressed to thickness at 160°C for 270 seconds. The hot-press cycle does not reflect the 30 second close time and a 10 second decompress time. A target density of 780 kg/m³ was used for this study. A total of 220 test panels were manufactured.

MDF Panels – Phase II: 600- by 600- by 13.5-mm MDF panels were constructed on-line at the BioComposites Centre. Panels were constructed for each chip type (yellow-poplar and all 4 loblolly pine zones) and for fibres refined at 4 various pressures (5.5, 7, 8.5, and 10 bar). Each of these panels were constructed in triplicate using one of 3 UF resins varying in molecular weight and all with a solids content of 50%. The 3 resins varied in molecular weight and had viscosities of 233,325, and 589 centipoises. For all panels; resin was injected into the blowline at a point 1 meter from the blow valve. The target resin addition level was 10% resin solids based on the oven-dry weight of the fibres. A wax emulsion was also injected into the refiner at an addition level of 0.5%. Formed mattresses were cold pre-pressed and then transferred to the hot press. Panels were pressed at 160°C with a press cycle time of 250 seconds. The target density was 780 kg/m³.

Determination of Resin Distribution: Selected panels from Phase I and Phase II were constructed with a fluorescent dye to investigate resin distribution and cell wall penetration. For selected panels, a 1% by weight based on resin solids of Rhodamine B was added to the resin immediately prior to blending. The Rhodamine B enhanced resinated fibres were formed and pressed in accordance with standard techniques and settings. These samples were then observed with a confocal scanning laser microscope (CSLM).

RESULTS AND DISCUSSION

Fibre Physical Properties: The refining condition has a pronounced effect on the physical appearance of individual wood fibres. Figure 1 shows a montage of juvenile fibres refined in Phase I ranging from 2 to 18 bar. Shives were dominant in the furnish up to 4 bar and diminished quickly thereafter. Fibres appeared to begin physically breaking down at or above 10 bar pressure in the refiner. Fibre quality was greatly reduced at the extreme pressures, with significant damage present at 18 bar pressure.

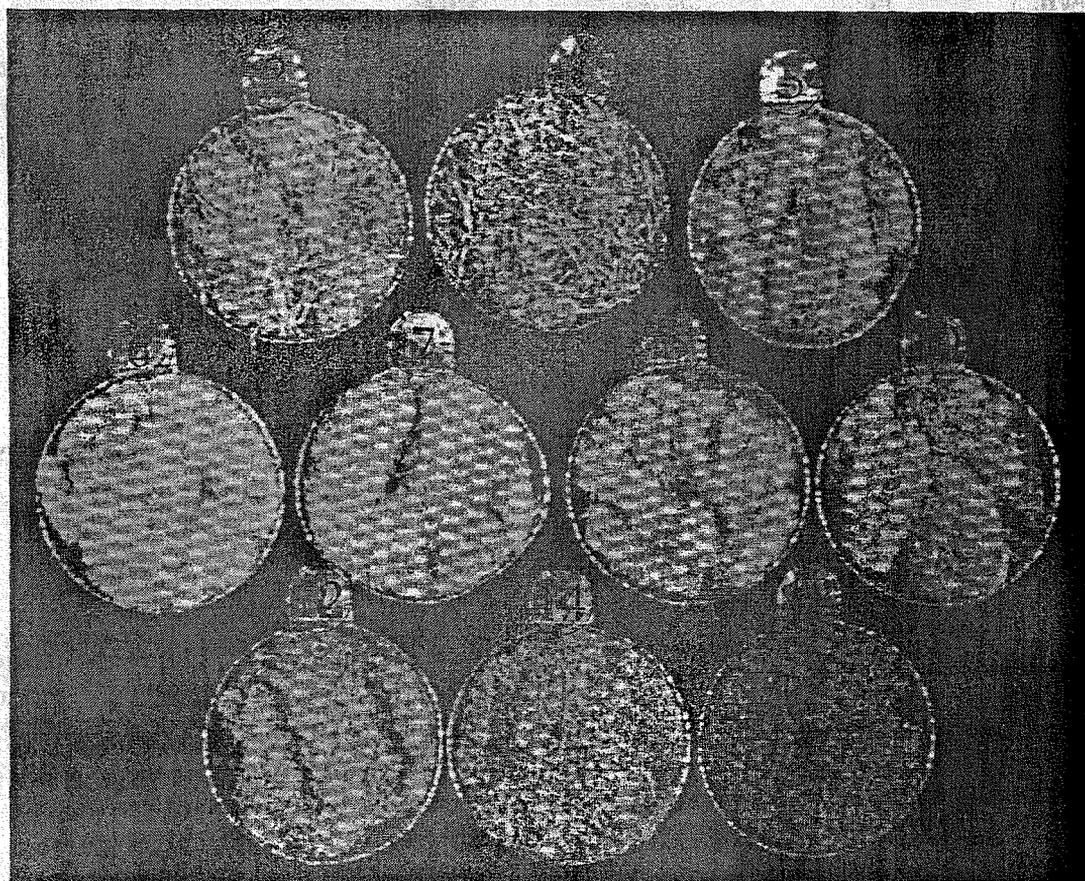


Figure 1. Juvenile loblolly pine fibres refined at various pressures.

Fibre damage is evident in the scanning electron microscope (SEM) images shown in Figures 2 - 4. Fibres refined at low pressures showed numerous interwall failures and often contained remnants of adjacent cell walls. As refiner pressure increased to the more conventional range of 5 to 1.0 bar, the cell wall structure and features increased in complexity. In addition to inter- and intrawall failures, these fibres generally had surfaces smoother than the lower pressure fibres. These relatively smooth surfaces often appeared coated, possibly the result of redeposition of constituents during the refining process. Fibres generated at 12 bar and above were generally fragmented resulting in predominantly fine fractions.

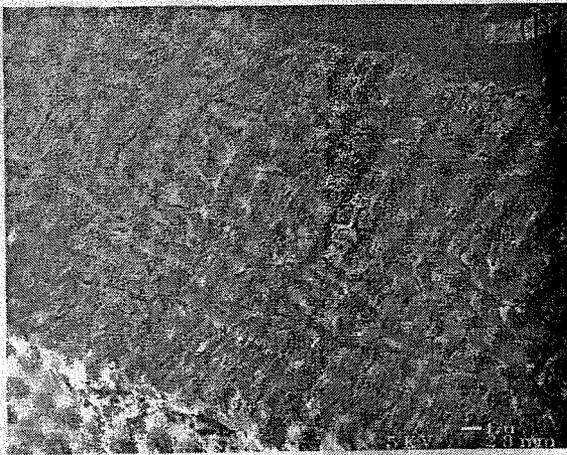


Figure 2. SEM micrographs of (a) juvenile and (b) mature loblolly pine fibres refined at a pressure of 2 bar.

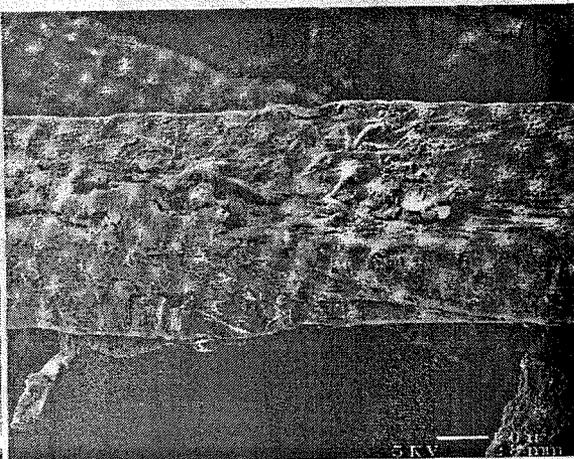
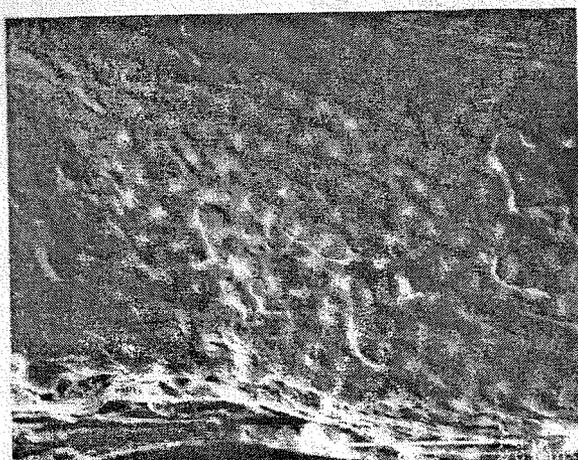


Figure 3. SEM micrographs of (a) juvenile and (b) mature loblolly pine fibres refined at a pressure of 6 bar

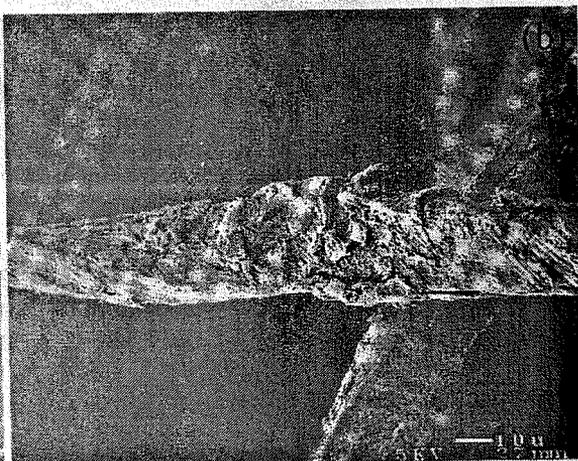


Figure 4. SEM micrographs of (a) juvenile and (b) mature loblolly pine fibres refined at a pressure of 18 bar.

Panel Properties – Phase I: The mechanical properties of MDF panels constructed in Phase I are summarised in Figure 5. The stiffness and strength of MDF panels made from loblolly pine fibres validate earlier research that shows performance was increased with juvenile fibres (Groom *et al.* 1999; Groom *et al.* 2000). Juvenile loblolly pine fibres generated at 7 to 8 bar pressure produced the stiffest and strongest MDF panels. The optimal refiner pressure for MDF panels made with juvenile-transition fibres appears to be between 8 and 9 bar, The optimal refiner pressure for more mature loblolly pine appears to be at or slightly above 10 bar.

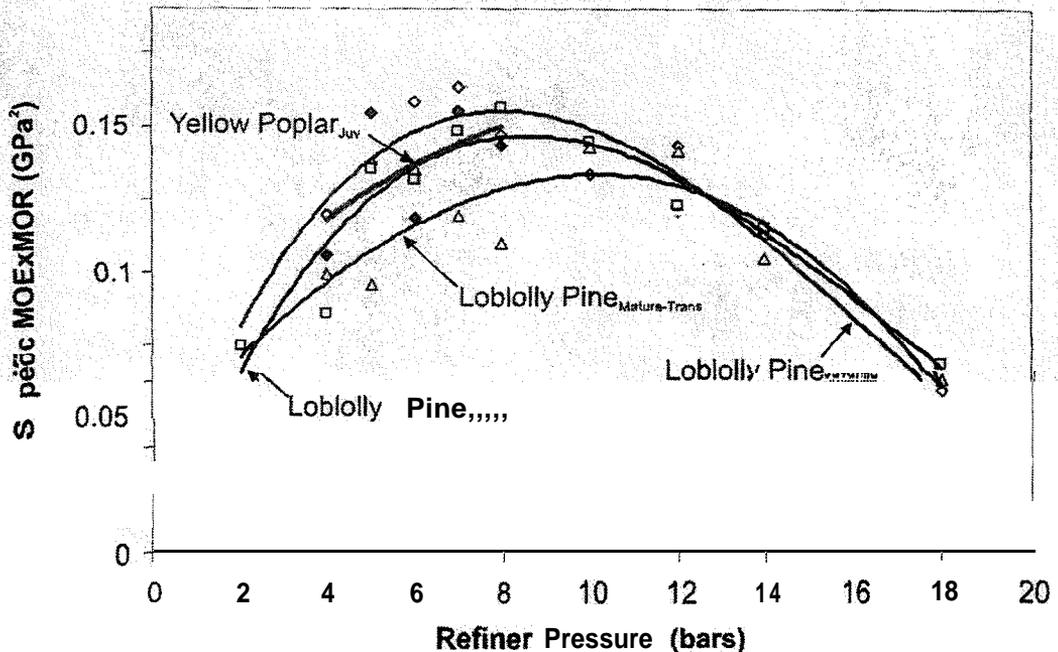


Figure 5. Product of loblolly pine and yellow-poplar MOE and MOR, normalised against MDF panel specific gravity, as a function of refiner pressure.

The inverse correlation between fibre maturity and MDF performance appears to be counterintuitive. Mature fibres have been shown to be longer (Bendtsen and Senft 1986) and mechanically superior (Mott *et al.* 2001) to their juvenile fibre counterpart. However, the compliant behaviour of juvenile fibres allows for maximum out-of-plane flexure, increases the fibre-to-fibre bonding and ultimately increases the stress transfer mechanisms within the fibre matrix.

Panel Properties – Phase II: The relationships established in Phase I determined the refiner settings for Phase II. Mature-transition fibres were not produced at the various pressures due to a lack of chips. Phase II was designed to investigate the relationship between fibre generation and fibre adhesion.

Figure 6 shows that fibres generated from juvenile loblolly pine produce MDF panels that are stiffer than panels made comparable mature fibres. The relationship is not as well defined as in Phase I due in part to the fewer number of panels constructed. An unexpected dip in stiffness occurred at approximately 7-7.5 bar across all fibre maturity levels. An analysis is currently underway to explain this dip.

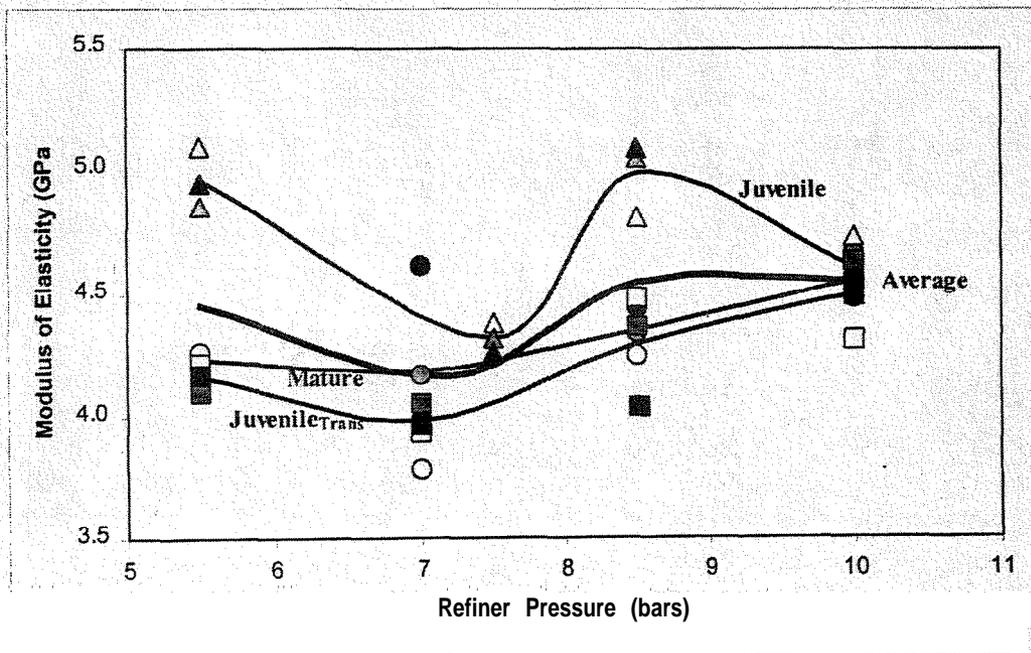


Figure 6. MOE of MDF panels constructed from fibres varying in maturity and refining pressure. Data points have been adjusted for panel specific gravity

There was little if any effect of resin molecular weight on the mechanical properties of the MDF panels constructed in this study. Figure 7 shows the effect of resin molecular weight on panel stiffness and Figure 8 demonstrates a similar response with internal bond stress (IB). These results do not mean that resin molecular weight does not play a significant role in bond development and thus stress transfer. Differences in resin molecular weight are reflected in the resin viscosity and thus should affect the distribution on and penetration of the cell wall. This will be discussed in the next section.

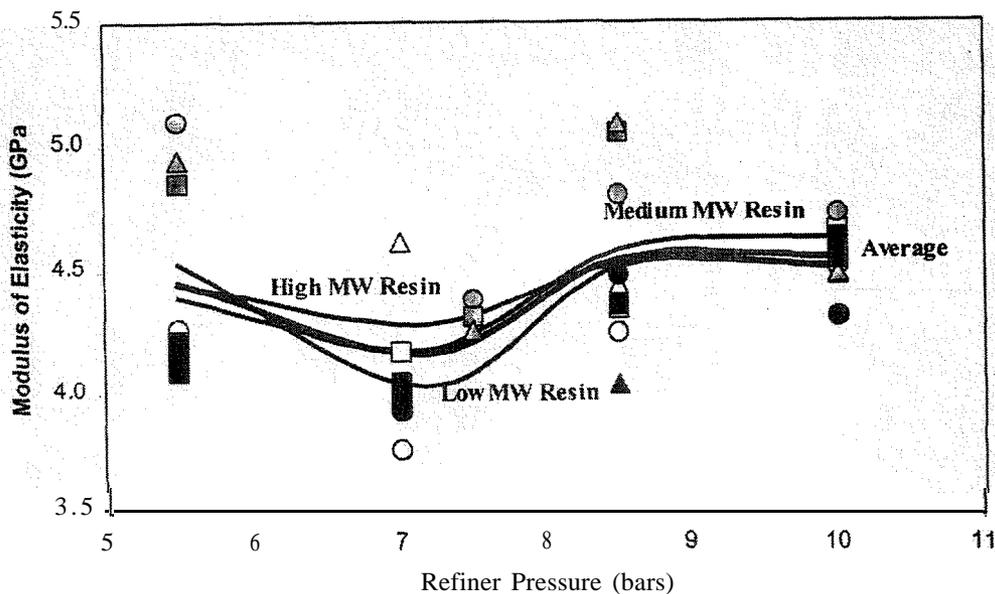


Figure 7. MOE of MDF panels constructed using various molecular weight resins and refining pressure. Data points have been adjusted for panel specific gravity.

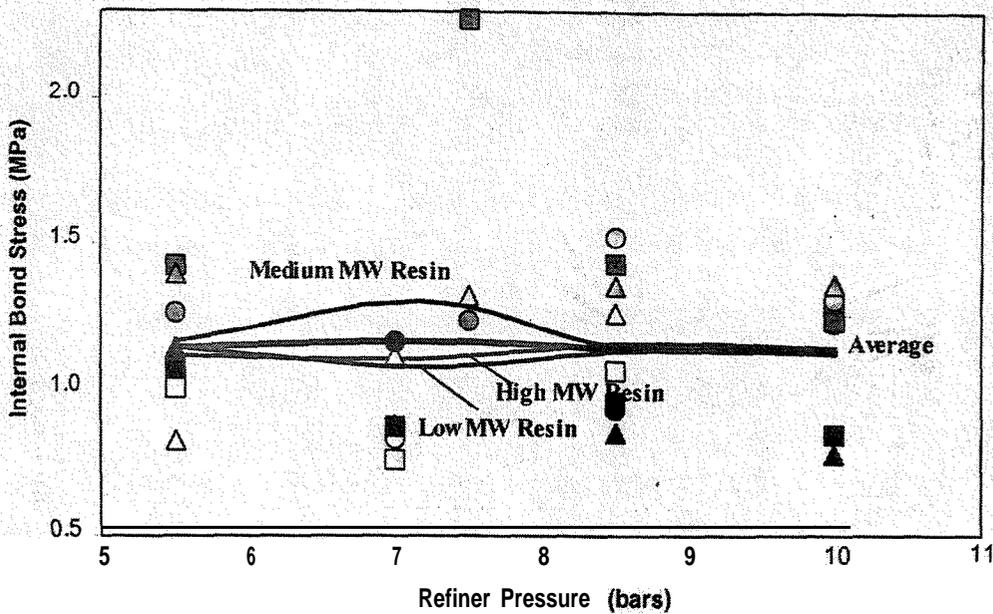


Figure 8. Internal Bond Stress of MDF panels constructed using various molecular weight resins and refining pressure. Data points have been adjusted for panel specific gravity.

The resin molecular weight will alter the cure rate. This effect could have been investigated by altering the press schedules. This will most likely be done in future studies of this type. Another factor may also have been hydrolysis. The press schedules chosen for this study allowed for ample polymerisation of the resin, but also may have resulted in excessive bond degradation. All of these variables may have combined to mask any molecular weight effect.

The relationship between refining pressures and resin molecular weight on the mechanical properties of MDF are shown in Figures 9 and 10. The refiner pressure had a greater effect on MDF stiffness than the corresponding IB values. Fibres refined at 7 bar resulted in panels with the lowest MOE regardless of the resin molecular weight. The panels with the best MOE values were constructed with fibres refined at higher pressures. These trends were not evident for the IB values, with IB values independent of either refiner pressure or resin molecular weight.

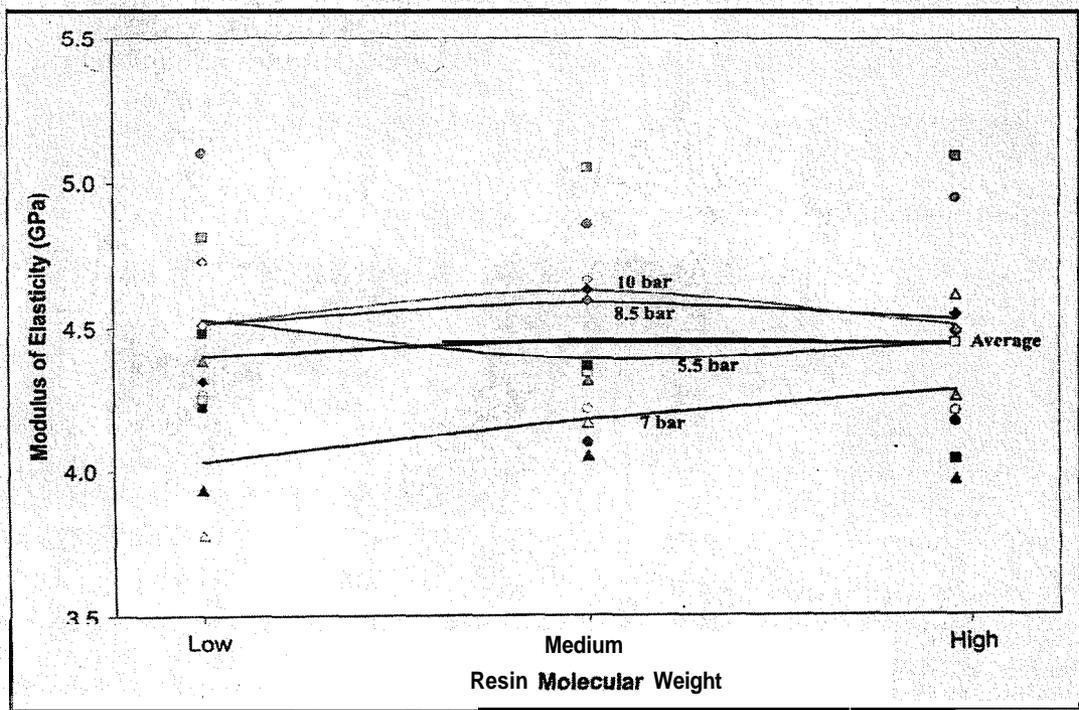


Figure 9. Modulus of elasticity of MDF panels constructed using various molecular weight resins and refining pressure. Data points have been adjusted for panel specific gravity.

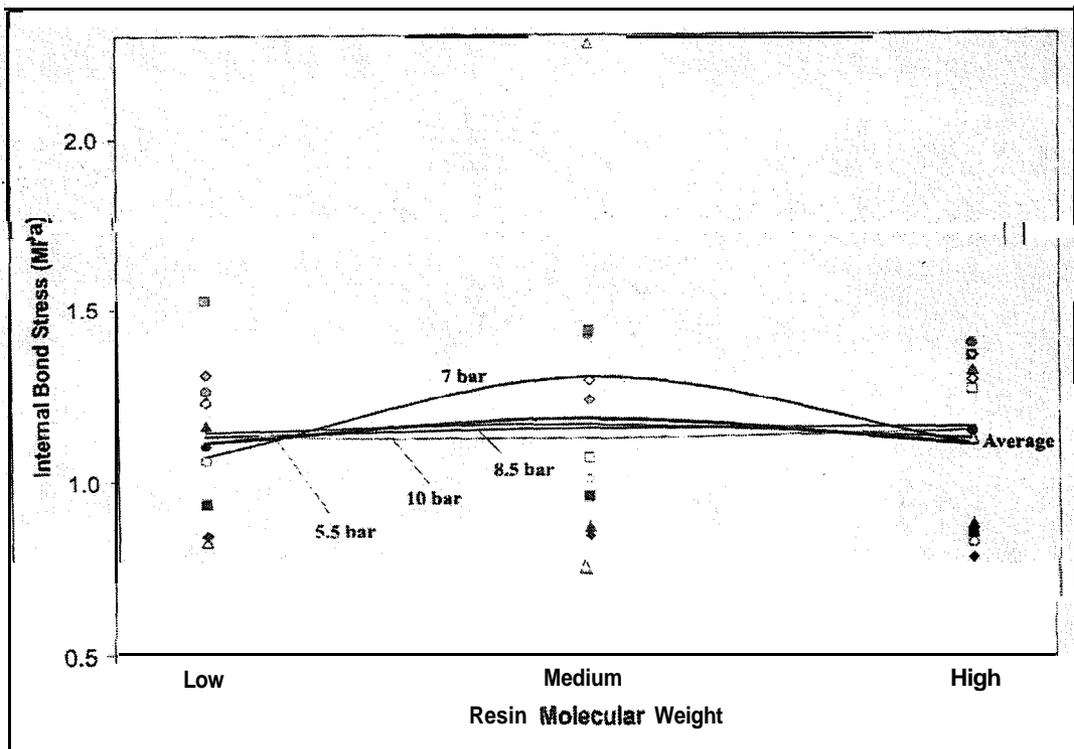
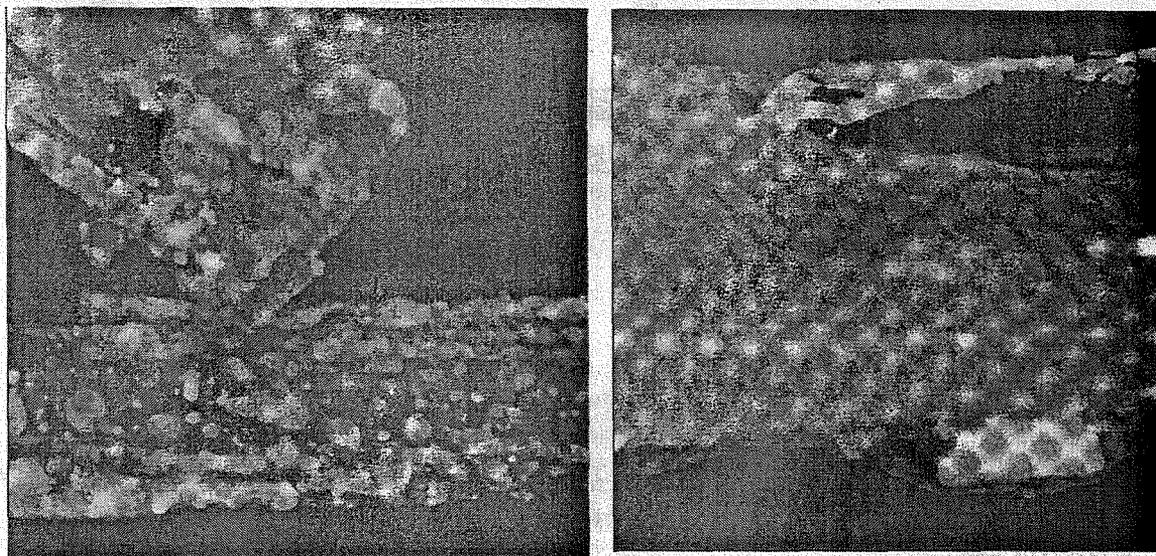


Figure 10. Internal Bond Stress of MDF panels constructed using various molecular weight resins and refining pressure. Data points have been adjusted for panel specific gravity.

Resin Distribution and Penetration: To evaluate the feasibility of the proposed method of evaluating resin distribution and penetration, several drum-blended MDF panels from Phase I were observed with the CSLM. Figure 11 shows individual fibres removed from a finished MDF panel. The fibre located in the squeeze out zone during pressing and not subjected to intense temperatures and pressures shows a spotty but even resin distribution. A similar fibre located at the face of the panel in the immediate vicinity of a platen shows the flow of the resin along the fibre surface.

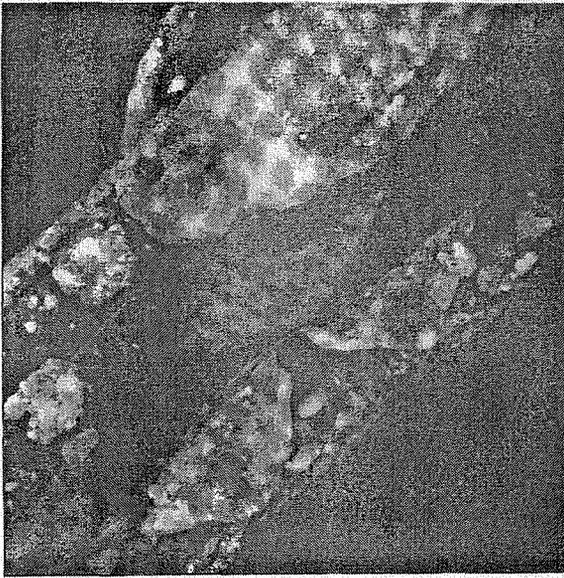


(a)

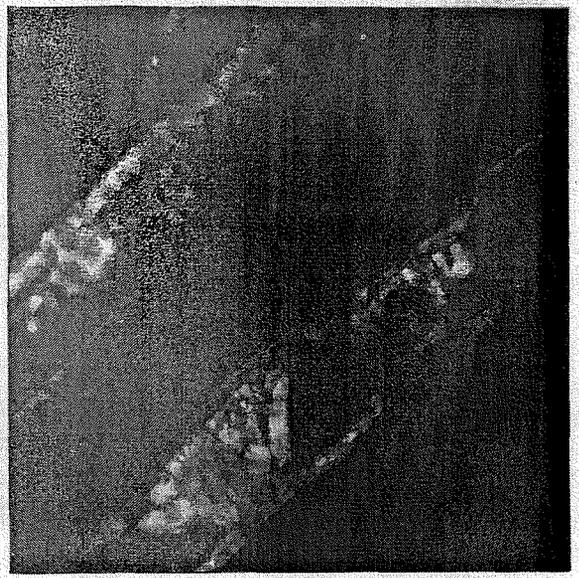
(b)

Figure 11. Loblolly pine fibres with Rhodamine B-enhance UF resin. The furnish was drum-blended and shows resin distribution on fibres (a) in the squeeze out portion of the pressed panel and (b) in the face layer in the immediate vicinity of the pressed panel.

The technique can also be used to investigate 3-dimensional distribution of resin on individual fibres. Figures 12a & b show the penetration of resin into the lumen through pit apertures. Penetration of resin into the lumen is also shown in Figure 13, but the resin travels through an intrawall crack. This same technique will be used to investigate the effect of various molecular weight resins on distribution patterns on the surface of fibres in this study as well as their penetration into the cell wall and lumen.



(a)



(b)

Figure 12. An individual loblolly pine fibre with Rhodamine B-enhance UF resin. This fibre was drum blended and removed from a pressed MDF panel. The images were taken at (a) fibre uppermost plane and (b) the fibre centre plane showing the lumen. Note the penetration of the resin in the 2 pits on the lower right portion of the fibre.

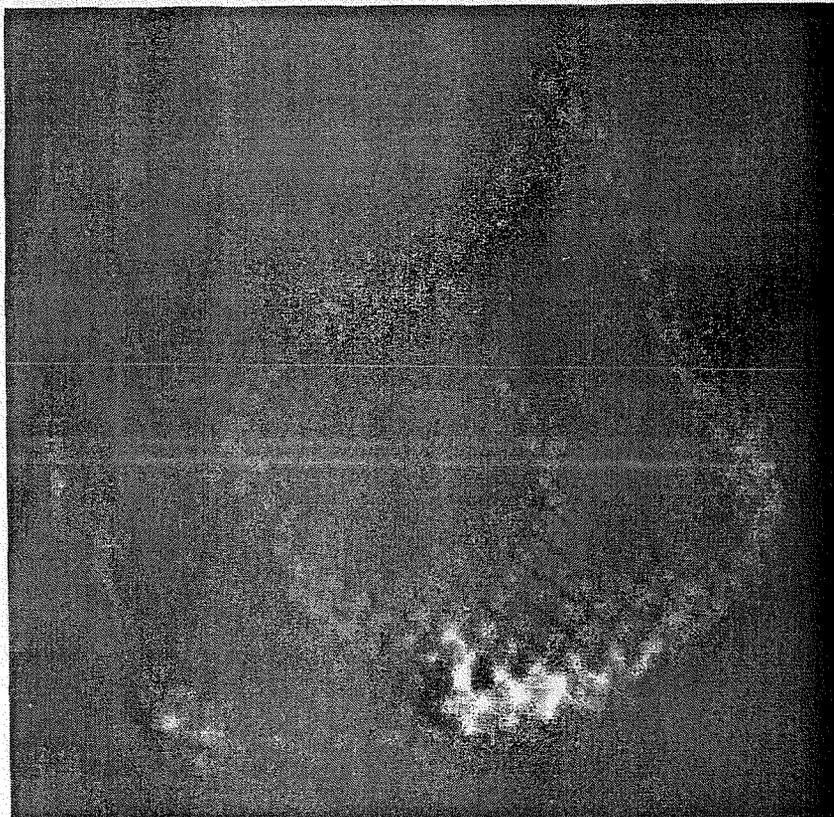


Figure 13. An individual loblolly pine fibre with Rhodamine B-enhance UF resin. This fibre was drum blended and removed from a pressed MDF panel. This image shows migration of resin from the fibre surface into the lumen by way of an intrawall crack.

CONCLUSIONS AND RECOMMENDATIONS

The refining levels commonly used for the manufacture of fibres for the structural fibreboard industry have a significant effect on the mechanical properties of the wood fibre furnish and the corresponding MDF mechanical properties. In all, the most influential property in relation to the structural performance of MDF is refiner pressure. However, the juvenility of the wood chips has a significant effect on the structural performance of MDF panels when refined at a constant refiner pressure. In all cases, the mechanical properties were greater for MDF panels comprised of juvenile fibres as compared to their mature fibre counterparts. The variable that most affected internal bond strength in this study was juvenility.

The molecular weight of the adhesive had little to no effect on the mechanical properties of MDF panels in this study. However, these findings may have been different under a wider range of press schedule variables. Studies are now underway to ascertain the effect of molecular weight on resin distribution and penetration. Preliminary results on drum-blended MDF panels show that a 3-dimensional spatial resin analysis will be possible with the confocal scanning laser microscope.

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