The Effect of Fiber Morphological Properties and Composition on Fiberboard Performance

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Although much is known about the properties of fiberboard and its constituents as a composite material, their dependency on morphological properties of the fibers within remains relatively unstudied. Regardless of the exact defibration method used on wood, a certain range of fiber aspect ratios are produced. The influence of aspect ratio distribution on fiberboard performance has been studied in conjunction with its dependence on hardwood/softwood content. Fiber samples with a range of hardwood content were imaged using a digital microscope and measured using image analysis. Thin fiberboard made from the sampled wood fiber was subjected to a variety of performance tests. Testing of fiberboard was done according to ASTM Standard D1037-12 (2020). No significant difference in flexural performance was found between the samples, with strain at break being the only exception. It is concluded that while longer, softwood fibers may have more favorable properties in standard applications of fiberboard, shorter, hardwood fibers have comparable mechanical properties when made into thin fiberboard while exhibiting significantly higher performance in internal bonding and water resistance.

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INTRODUCTION

Fiberboard is a wood composite material produced by mixing and subsequent hot pressing of wood fibers and adhesive. In 1965, fiberboard production occurred alongside hardboard manufacturing in the United States, which was patented nearly 40 years prior, and a dry process was developed to avoid generating the large amount of wastewater produced by the earlier developed process (Mason 1924, Lubis *et al.* 2021). Fiberboard currently is being used in the construction of furniture, flooring, doors, cabinets, and moldings. The physical and mechanical properties of fiberboard have been of interest to material scientists and composite aficionados alike since its invention and consequent mass production in the 20th century. As fiberboard is inherently a composite material, the unique properties of both wood and adhesive come together to create a versatile product. Those properties, however, can be influenced by changing thermal, chemical, and/or biological factors such as temperature, humidity, pH, UV radiation, and biological degradation (Maloney 1993; Winandy and Rowell 2005). However, where much is known about how the properties of fiberboard and its composite constituents and what can influence them,

their relation to the morphological properties of the wood fibers within remains relatively unstudied.

Morphology can be defined simply as the study of structure or form (Webster 2025). In regard to wood fiber, morphology references the length, width, aspect ratio, and qualitative shape and/or form of those fibers (Horn 1978). The correlation of wood properties and the fibers that make them is not a new scientific concept. The properties of wood are attributed to the interesting polymeric fibers that wood is made of, including cellulose, hemicellulose and lignin. Just as their role in the strength of wood is still under study, so is the influence of wood fiber morphology in fiberboard properties (Winandy and Rowell 2005). Although there is still some uncertainty and occasional disagreement in the field of fiberboard's property dependence on fiber morphology, it is generally accepted that fiberboard properties are indeed affected by the morphology of their fibers (Park *et al.* 2001; Roffael *et al.* 2001; Roffael *et al.* 2009; Krug 2010; Aisyah *et al.* 2012a, b; Benthien *et al.* 2014; Nayeri *et al.* 2014; Benthien *et al*. 2017; Imken *et al.* 2021; Rockwood *et al.* 2022).

Roffael *et al.* (2001) published a prominent early study of the effect of fiber morphology on fiberboard properties. Studied variables included defibration temperature and steaming time. The studied effects included pulp properties and the consequent physical and mechanical properties of the fiberboard made from such pulp. Roffael and his team found that increased pulping temperatures led to a significant influence on water absorption and thickness swelling of fiberboard and a deterioration of the internal bond strength of the fiberboard. In other words, fiberboard produced from fibers refined at higher temperatures during the defibrating process generally saw increased water resistance and a decrease in internal bonding (Roffael *et al.* 2001). A later study (Roffael *et al.* 2009) focused on the morphological properties of thermomechanical pulp in relation to the pulping temperature. The researchers found that increasing the temperature during the thermomechanical pulping process decreased the length and width of the fibers produced (Benthien *et al.* 2017). Increasing the pulping temperatures led to shorter and thinner fibers. When they were made into MDF, water resistance was increased and internal bonding was decreased (Roffael *et al.* 2001, 2009).

As explained by Benthien *et al.* (2017), the fact that thinner fibers result from defibration at high temperatures can be attributed to reaching the glass transition temperature of lignin at about 170 and 155 °C for softwoods and hardwoods, respectively. But when the moisture content is high, those temperatures have been seen to decrease (even to -10 °C), which results in the softening of the wood which makes defibration easier and "more intense" (Glasser *et al.* 1998; Benthien *et al.* 2017). Benthien *et al.* (2017) showed a noticeable decrease in panel properties with intensified steaming conditions during the defibration process. Higher values for internal bonding, thickness swelling, water absorption, MOE, MOR, and surface soundness were recorded for panels that had been made from longer fibers that had been produced under intensified steaming conditions (Schneider and Roffael 2000; Benthien *et al.* 2017). Interestingly, the reported higher values for thickness swelling and water sorption (TS and WS) tests agree with Roffael *et al.* (2001). The effects have been attributed to the thermal degradation of hemicellulose during the steaming process, which constitutes a loss of hydrophilic compounds in the structure of the wood fibers, thereby increasing hydrophobicity (Benthien *et al.* 2017). Benthien and his team concluded that changes in fiberboard properties can be seen as a

function of fiber morphology. Additional variables in the properties of wood fibers can be linked to the property changes observed. These changes may be due to changes in the chemical nature of the wood fibers that affect their wettability with water (TS and WS) and resin (mechanical properties) (Benthien *et al.* 2014, 2017). Other teams have reached similar conclusions in studies on the influence of thermo-mechanical refining of wood fiber on fiberboard properties (Xing *et al*. 2006, 2007; Aisyah *et al*. 2012a; Nayeri *et al*. 2014; Razali *et al*. 2018; Ismail *et al*. 2020; Rockwood *et al*. 2022).

As can be seen from discussing only a handful of the existing studies on the topic, the effects of wood fiber morphology and composition on fiberboard performance are considered influential albeit uncertain in both significance and characterization. Additional efforts are needed to determine the correlation of such effects to fiberboard performance and what factors determine their morphology during fiber processing. This study addresses these gaps by characterizing fiber bundle particle size distribution (PSD), length, width, and aspect ratio of varying mixtures of softwood/hardwood formulations refined into wood fiber and examining physical and/or mechanical performance changes that occur when that wood fiber is made into fiberboard. It is hypothesized that increasing the proportion of softwood will produce longer, thicker fibers, which in turn will yield MDF with improved physical properties compared to panels made from hardwood fibers (Roffael *et al.* 2001, 2009; Ross and US Department of Agriculture Forest Service 2010; Benthien *et al.* 2017).

EXPERIMENTAL

Materials

Softwood and hardwood chips used in this study were donated by Jeld-Wen Windows and Doors Co. (Charlotte, NC, USA). The softwood chips were a mixture of softwoods, including southern yellow pine (*Pinus echinata*), and the hardwood chips were a mixture of hardwoods, primarily containing species of oak (*Quercus*). As a non-formaldehyde resin was desirable for the laboratory, Rubinate® 1840, a polymeric methylene diphenyl diisocyanate (pMDI) resin from Huntsman (The Woodlands, Texas, United States) was used as a binder for fabricating the MDF panels.

Sample Preparation

Five batches of hardwood and softwood chips were mixed according to their dry weights: 100% softwood, 20% hardwood, 40% hardwood, 60% hardwood, and 100% hardwood. The wood chips were dried to a sub 10% moisture content and placed in an open metal container for steaming. Each chip formulation was primed with water and thoroughly drained, at which point steam was introduced to the container from the bottom, rising through the chips under atmospheric pressure at a temperature over 105 °C, for one hour. The chips were then immediately fed into a dual disk attrition mill (Bauer Bros. Co.) with Dura-Metal™ refining plates set at a separation distance of 0.305 mm. After refining, the fiber was dried to a moisture content between 7 and 8%, and a portion of the fiber was set aside for fiber geometry analysis.

For fiberboard fabrication, the wood fibers were resinated with pMDI at a loading percent of 2.4% in a drum mixer with a triple spray nozzle system. Resinated fibers were evenly added to a 38 cm x 30 cm forming box on top of a metal caul plate and release paper

for panel forming. Once each panel was formed, the forming box was removed, and an additional release paper and metal caul plate were placed on top. Although the curing temperature of pMDI has been observed to start at 20°C, the peak curing temperature of pMDI when mixed with wood has been determined to be between 115 and 120 °C. Therefore, the panel was then hot-pressed in a 100 cm x 75 cm hot press at 160 °C with a predetermined press schedule for 35 seconds at a target density of 865 kg/m^3 which was sufficient for the panels to reach the peak curing temperature (Wolcott 2003; Liu *et al*. 2022). Once hot pressing was complete, and the panels were allowed to cool, testing samples were cut from each panel with ASTM D1037-12 (2020) as a standard (ASTM-International, 2020).

Fiber Geometry Analysis

Fiber size distribution

Using U.S. Standard Sieves 10, 20, 40, 80, 100, 270, and pan in a Ro-Tap sieve shaker, average fiber size distribution was obtained for the 100% hardwood and 100% softwood fibers. Similarly to other teams, each trial was run for ten minutes before the sieves were disassembled and their collected fiber weighed and analyzed (Xing *et al*. 2006; Ding *et al.* 2020). The average percentage of fiber retained in each sieve is recorded.

Fiber bundle morphology

A manual method of measurement was decided upon rather than an automated measurement system. Hardwood and softwood fiber bundle samples were taken from the fiber refined in the Sample Preparation section above. The representative fiber bundles were lightly sprinkled onto microscope slides to minimize overlap and imaged with a digital microscope (Keyence VHX-600; Keyence, Osaka, Japan), capturing both colored and high-contrast images, rather than using electron microscopy (Ding *et al.* 2020). Using image J software, over 420 fiber bundles were identified from both the hardwood and softwood fiber samples. Using ImageJ software, more than 420 fiber bundles were identified from both the hardwood and softwood fiber samples. Each identified fiber bundle had its lengths and average widths measured using a predetermined set of procedures, outlined as followed. A main fiber branch is identified and measured as shown in Fig. 1a, followed by digitally cutting off and measuring of any secondary branches connected to the main branch, digital cut and measurement shown respectively in Fig. 1b in white and red. In the case of overlapping fibers/bundles, the high-contrast images were compared to the colored images taken to accurately distinguish and measure them. All frayed ends of a main branch were excluded from the measurements. An example of this is shown in Fig. 1c with red lines showing the sites of exclusion. The lengths were taken as the distance from one end of the fiber's/bundle's main branch, and the width was taken as an average between three measurements along its length. Following these measurements, the average aspect ratios of the fiber bundles were determined and plotted. Statistical analyses of the collected data were performed using Python in Jupyter Notebook (Project Jupyter, 7.2.2, Berkeley, CA, USA). Analysis of variance (ANOVA) was done with a 95% confidence interval and Tukey Honestly Significant Difference tests when significant differences were detected.

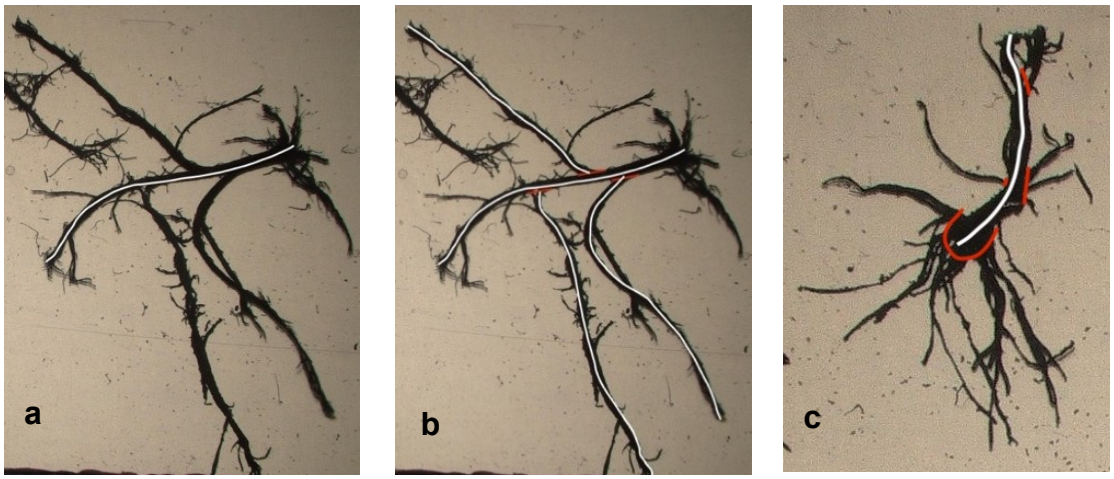

Fig. 1. High-contrast digital images depicting the measurement of a fiber bundle's (a) main and (b) secondary branches' lengths, as well as (c) an example of a bundle's frayed ends being excluded from the main branch length

Fiberboard Panel Mechanical and Physical Tests

Fiberboard samples were cut and tested in accordance with ASTM D1037-12 (2020) for flexural, water sorption, and internal bonding. For each of the five formulations of panels, 6 flexural, 10 internal bonding, and 2 water sorption samples were taken. The data collected in these tests were likewise run through ANOVA statistics using a 95% confidence interval, and Tukey HSD groups lettering were employed in the results when significant differences were identified.

RESULTS AND DISCUSSION

Fiber Geometry Analysis

Fiber size distribution

The particle size distribution of the fiber samples was collected in seven U.S. Standard sieves, which can be seen graphically in Fig. 2. A shift in size distribution can be observed between the soft and hardwood with softwood fibers being consistently larger in size and the hardwood having a significantly higher amount of fines. Although this test gave preliminary data supporting higher amounts of hardwood fibers retained in the smaller meshed sieves than softwood fibers, additional measurement data would be needed to make any definitive results on the fiber bundles' geometry.

Fiber bundle morphology

Figures 3, 4, and 5 depict the cumulative frequency of average fiber/bundle length, width, and aspect ratio in the 100% hardwood, 40% hardwood, and 100% softwood fiber formulations for over four hundred individual fiber bundles per formulation. The 100% hardwood fiber had higher amounts of shorter and thinner fiber bundles when compared to 100% softwood fibers. Likewise, the ANOVA results indicated that the 100% hardwood fibers had significantly smaller aspect ratios than the 100% softwood fibers, which agrees with previous literature (Ross 2010). It should also be noted that each fiber formulation

converges together in their cumulative widths around 20 µm (Fig. 4), meaning width only showed statistically significant differences between the formulations below that point, which amounted to more than 75% of the fibers. This same convergence in measurements occurred around 110 µm (Fig. 5) in length measurements, which make up over 80% of the fibers. A separate joining of measurements occurred in measured aspect ratios at 75 and at 95 for the joining of 40% and 100% softwood and 40% to 100% hardwood respectively, which totals up to more than 90% of the fibers measured.

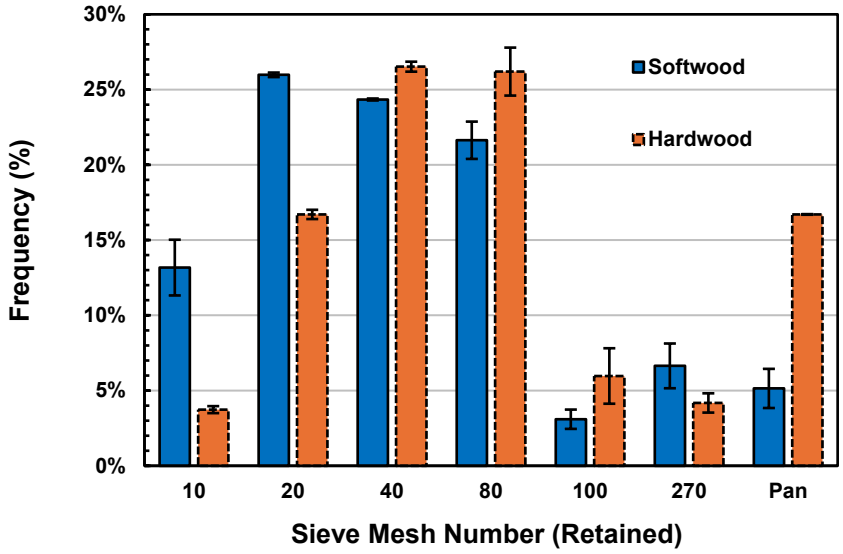

Fig. 2. Fiber size distribution results for 100% softwood and 100% hardwood fibers using U.S. Standard sieves

The 40% hardwood formulation of fibers was shown to have cumulative lengths and widths in between the averages of the 100% hardwood and softwood formulations. However, the cumulative aspect ratio for the 40% hardwood formulation was broader than the 100% formulations. This phenomenon can be explained as individual fiber's and fiber bundle's measurements of length and width are taken independently from one another and the ratio between the length and width are directly compared in respect to those fibers. In other words, the cumulative broadening in fiber aspect ratio is caused in part by the increased variety of aspect ratios being measured as a mixture of the hardwood and softwood fiber formulations. Likewise, no significant difference was observed between the 40% hardwood fibers' lengths when compared to the 100% softwood fibers, nor was there any significant difference between the 40% hardwood fibers' widths when compared to the 100% hardwood fibers.

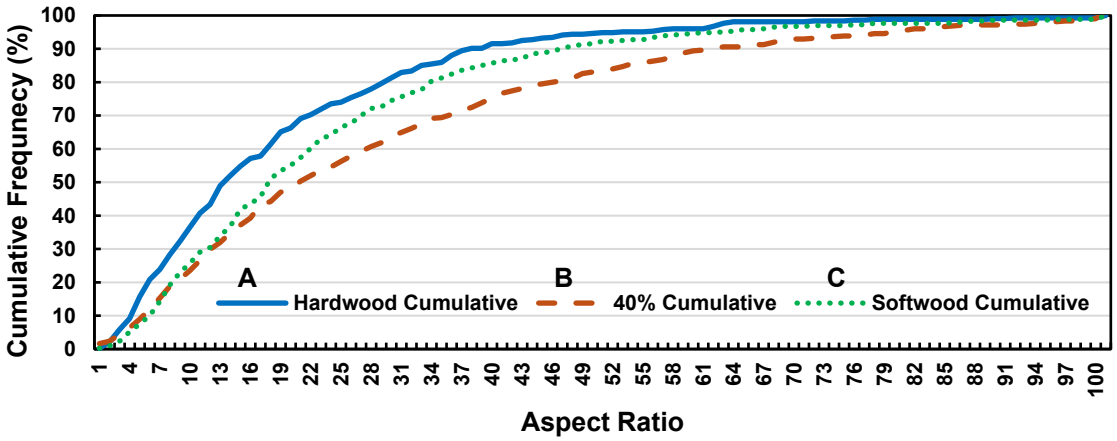

Fig. 3. The cumulative frequency of fiber aspect ratios from 100% hardwood, 40% hardwood, and 100% softwood fiber formulations with Tukey HSD group lettering above the legend

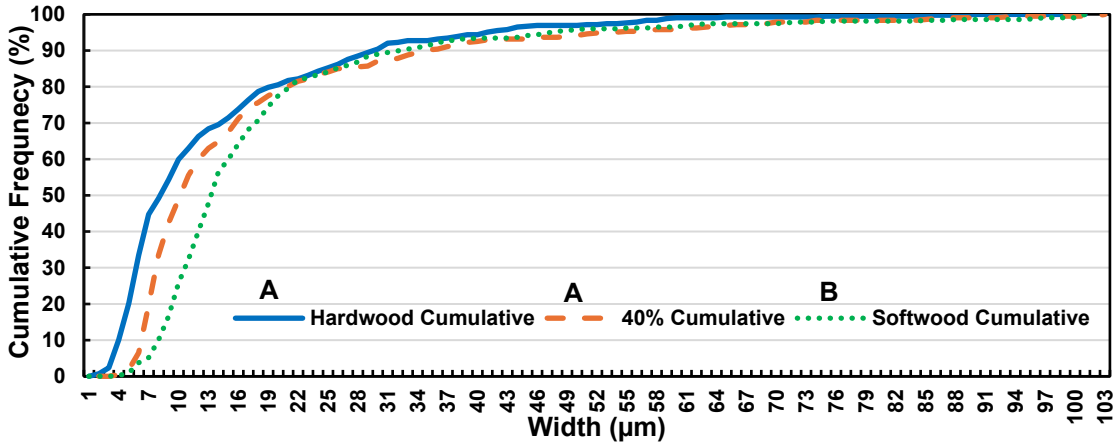

Fig. 4. The cumulative frequency of fiber widths from 100% hardwood, 40% hardwood, and 100% softwood fiber formulations with Tukey HSD group lettering above the legend

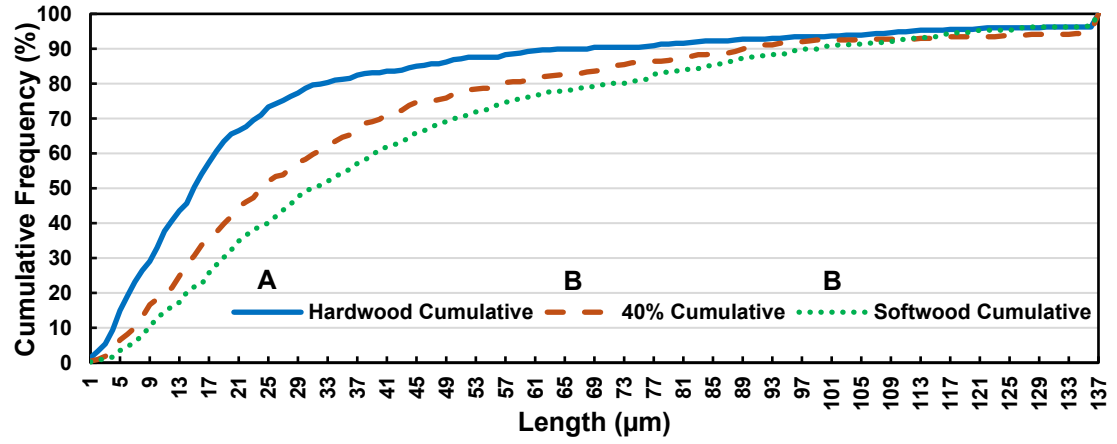

Fig. 5. The cumulative frequency of fiber lengths from 100% hardwood, 40% hardwood, and 100% softwood fiber formulations with Tukey HSD group lettering above the legend

MDF Panel Mechanical and Physical Tests

Flexural

The MDF flexure tests showed no statistically significant differences in density, modulus of elasticity, modulus of rupture, or specific strengths between the hardwood/softwood panels (Figs. 6 to 8). The only significant difference was in strain at break, where the 100% softwood differed from all other formulations. This contrasts with Benthien *et al.* (2017), who reported that shorter, thinner fibers generally reduce mechanical properties. In the present study, the absence of such reductions may result from the way fiber morphology was controlled. Fiber refining conditions were kept constant, and only the hardwood-to-softwood ratio was varied, rather than using different steaming conditions (Xing *et al.* 2007; Roffael *et al.* 2009; Aisyah *et al.* 2012a).

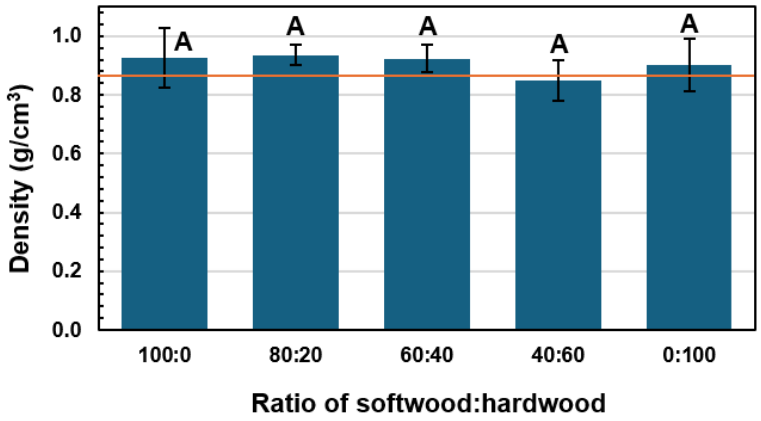

Fig. 6. The average density values of the fiberboard with different ratios of softwood and hardwood with a line representing the target density of 0.865 g/cm^3 and with Tukey HSD group lettering

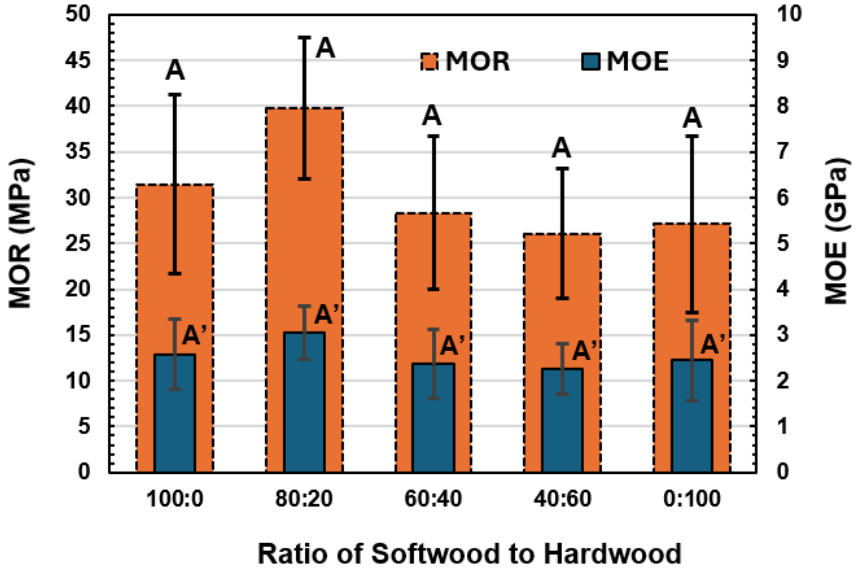

Fig. 7. The average MOR and MOE of the fiberboard flexural specimens and with Tukey HSD group lettering with MOE's groups having an apostrophe (') notation

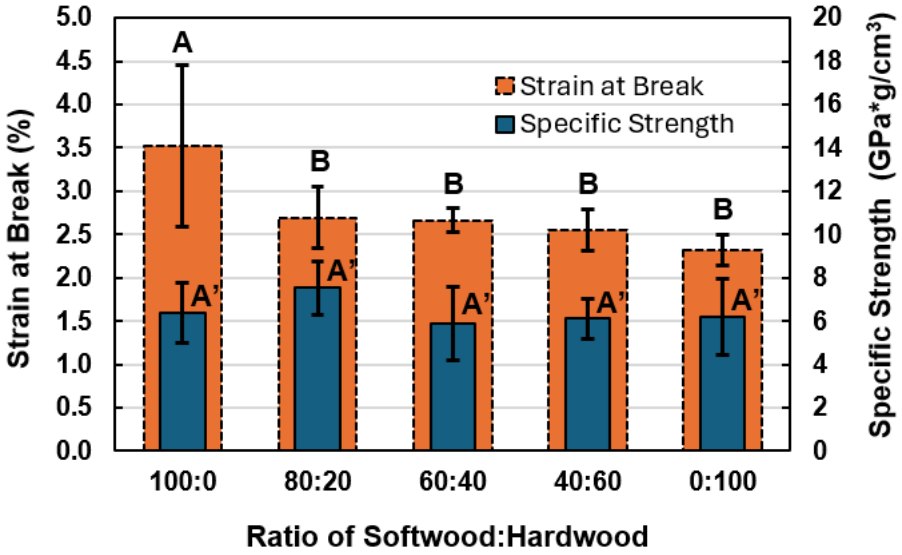

Fig. 8. The average Strain at Break and Specific Strength of the fiberboard specimens with different ratios of softwood and hardwood with Tukey HSD group lettering with Specific Strength's groups having an apostrophe (') notation

Water sorption (WS)

The WS tests on the fiberboard panels showed a statistically significant decrease in both water sorption and thickness swelling as the ratio of hardwood in the formulations was increased, as shown in Figs. 9 and 10. This result is supported by Benthien *et al.* (2014, 2017), who found that fiberboard made from hardwood fibers have increased water resistance (Benthien *et al.* 2014, 2017).

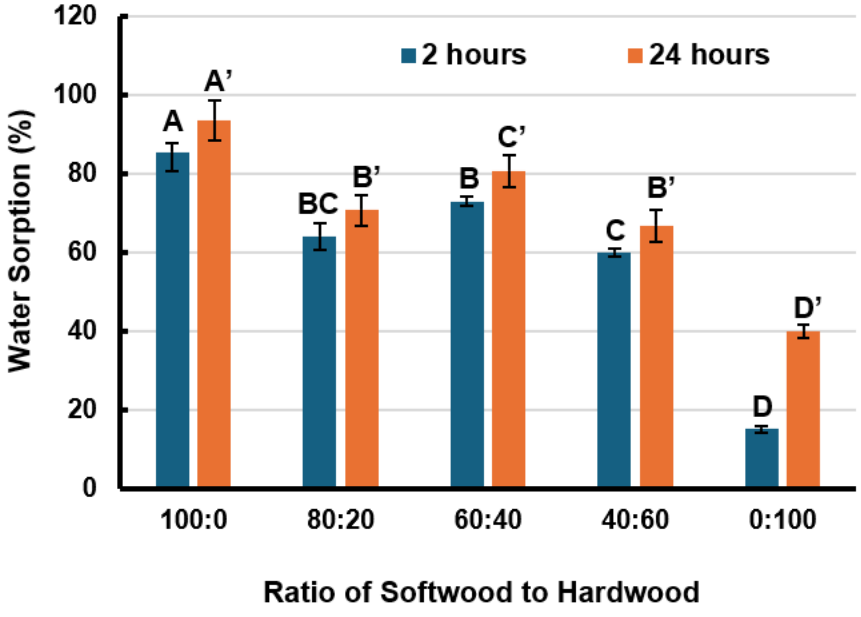

Fig. 9. The average water sorption sustained after 2 and 24 hours for each fiberboard softwood:hardwood ratio formulation with Tukey HSD group lettering with 24 hours' groups having an apostrophe (') notation

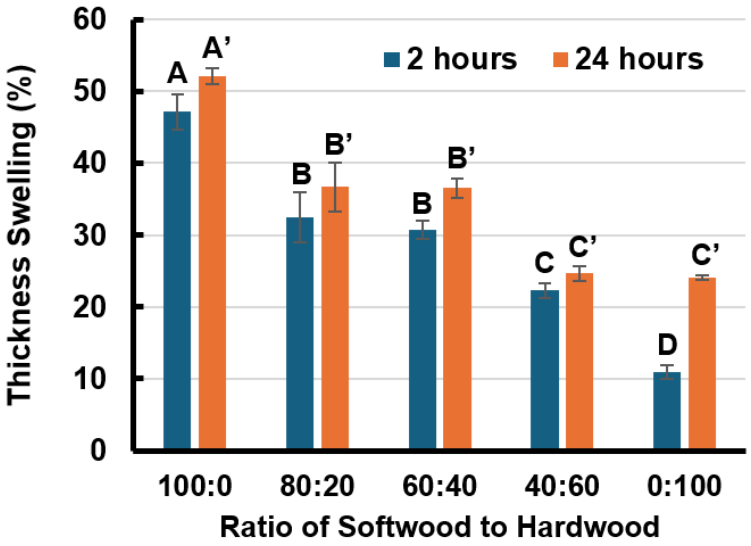

Fig. 10. The average thickness swelling sustained after 2 and 24 hours for each fiberboard softwood:hardwood ratio formulation with Tukey HSD group lettering with 24 hours' groups having an apostrophe (') notation

Differences in wood chemical composition have been proposed as a reason for this change, as hardwoods have higher percentages of hemicellulose, which is thought to degrade during steaming operations. Such degradation leaves the fibers with less hydrophilic components, likely including the relatively hydrophobic furfural, causing higher water resistance (Winandy and Rowell 2005; Werner *et al*. 2014; Benthien *et al.* 2017). However, fiber morphology has been seen to significantly influence the porosity of fiberboard panels, with larger, coarse fibers resulting in higher panel porosity, which increased porosity leads to higher absorption of water (Rebolledo *et al*. 2018; De Ligne *et al*. 2022). This increase in water resistance could very likely be caused by any number of other variables, and therefore a reason for the increased water resistance cannot be determined in this study. It can be stated, however, that a decrease in both water sorption and thickness swelling can be expected based on the literature, in fiberboard made from smaller, thinner fibers, especially including fines.

Internal bonding (IB)

As shown graphically in Fig. 11, the IB strengths for fiberboard made from 100% softwood, 20% hardwood, 40% hardwood, 60% hardwood, and 100% hardwood were 0.54 ± 0.21 MPa, 1.48 ± 0.38 MPa, 1.53 ± 0.63 MPa, 1.78 ± 0.39 MPa, and 2.17 ± 0.41 MPa, respectively. The IB tests showed a statistically significant difference between 100% softwood and 100% hardwood, with the 100% hardwood panels' internal bonding resulting in nearly four times that of the 100% softwood panels. This could stem from the hardwood fiber bundles being smaller and connecting the internal structure of the board more effectively than with larger bundles in softwood panels. When evaluating the varying densities of the IB specimens, there was no significant difference in density between the 100% softwood and 100% hardwood fiberboard panels, eliminating the influence of density on IB properties. The increase in IB performance for increasing amounts of

hardwood content was possibly due to the thickness of the fiberboard panels produced in the study, but further study needs to be done to confirm this.

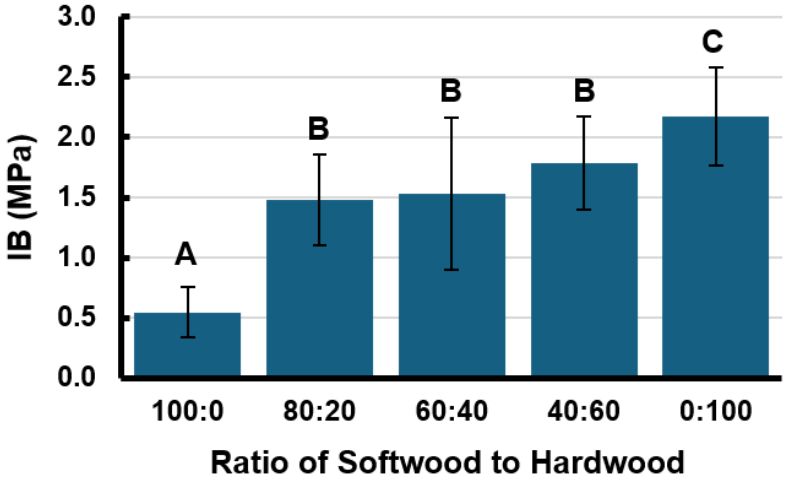

Fig. 11. The average internal bonding for each fiberboard softwood: hardwood formulation with Tukey HSD group lettering

CONCLUSIONS

1. The softwood and hardwood fibers, used in this study to manufacture fiberboard, were significantly different in length, width, and aspect ratio.
2. No significant difference was seen in fiberboard bending performance as a function of fiber morphological properties nor softwood to hardwood ratio, including modulus of elasticity, modulus of rupture, and specific strength, with the only exception being the significant difference in strain at break of the panels made from the 100% softwood formulation.
3. Significant differences in fiberboard performance were recorded in water sorption and internal bonding tests, including an increase in water resistance and internal bonding as the amount of hardwood increased. Further study is needed to identify the cause of these behaviors.
4. While longer softwood fibers may have more favorable properties in standard applications of fiberboard, shorter, hardwood fibers have comparable mechanical properties when made into thin fiberboard while exhibiting significantly higher performance in internal bonding and water resistance.

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