BENDING PROPERTIES OF WOOD FLAKES OF THREE SOUTHERN SPECIES

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ABSTRACT

This research focuses on experimental investigations of the bending properties of wood flakes of three southern species. Modulus of elasticity (MOE), modulus of rupture (MOR), and strength at proportional limit (SPL) of flakes were measured based on Methods of Testing Small Clear Specimens of Timber (ASTM D143-94; ASTM 1994a) using a miniature material tester. Effect of species, cutting direction, and temperature were evaluated. Bending properties were found to vary between and within the three species. Southern yellow pine had the lowest bending stiffness and strength followed by sweetgum, while yellow-poplar had the highest bending properties. Radially cut specimens (force applied on the tangential axis) were found to have lower MOE, MOR, and SPL than tangentially cut specimens (force applied on the radial axis). Drying temperature was also found to have a significant effect on bending stiffness and strength. A decreasing trend in bending properties was observed when drying temperature was increased.

Keywords: Bending properties, MOE, MOR, SPL, wood flakes, drying temperature.

INTRODUCTION

Quality of any wood composite product depends heavily upon the quality of the raw materials used. For example, strength of oriented strandboard (OSB) is a function of the mechanical properties of the flakes, and knowledge of mechanical properties of the flakes can lead to better strength and performance. Flakes used in manufacture of OSB are generally dried to very low moisture content using high temperature. When wood is dried below the fiber saturation point, its physical, chemical, and mechanical properties are affected. Drying temperature may also have an effect on the mechanical properties of wood. Generally, wood strength decreases when the wood is heated and increases when it is cooled. There is minimal permanent strength loss when temperature does not exceed 100°C, but exposure to high temperature for long periods can cause permanent strength loss (Haygreen and Bowyer 1996).

General discussions of the influence of temperature on mechanical properties of wood have been presented in the Wood Handbook (FPL 1999) and by Haygreen and Bowyer (1996). Research on the effect of temperature on various mechanical properties of wood specimens has been performed through the years. Gerhards (1982) summarizes the relevant studies on the immediate effects of moisture content and temperature on mechanical properties of clear wood.

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A detailed account is given by Salaman (1969) of changes in mechanical properties from thin boards to dimension lumber of softwoods and hardwoods dried at high temperature.

The only research found in the literature on the effect of temperature on wood flakes was that performed by Plagemann (1982). Red oak, white oak, and sweetgum flakes were dried at 20°, 150°, and 350°C and conditioned at 21.1°C (70°F) and 65% relative humidity. Small beams measuring 0.5 × 3.8 × 14.2 mm (0.02 × 0.15 × 0.56 in.) were tested for modulus of elasticity (MOE) and modulus of rupture (MOR). Plagemann's results indicated a general trend of decreased strength and stiffness with increased drying temperature. However, the trend toward decreasing bending properties associated with high temperature drying did not result in reduced board properties (i.e. MOR and MOE).

Because of the lack of information on the effect of temperature on wood flake properties, the objective of our study was to determine the bending properties of flakes dried at three different temperatures. Modulus of elasticity, modulus of rupture, and stress at proportional limit were measured using flakes of southern yellow pine, sweetgum, and yellow-poplar. The effects of species, cutting direction, and drying temperature on bending stiffness and strength were analyzed.

MATERIALS AND METHODS

Fresh green bolts, 1.5 m in length and averaging 30 cm in diameter, of southern yellow pine (Pinus spp.) and sweetgum *(Liquidambar styraciflua)* were obtained from Georgia Pacific OSB plant in Skippers, VA, and freshly cut yellow-poplar *(Liriodendron tulipifera)* boards 50 mm in thickness were obtained from a local sawmill. The logs were cut into 50-mm boards using a portable sawmill. Sound boards from the three species were segregated according to type of cut: flatsawn or quartersawn.

Radially and tangentially cut specimens were taken from the flatsawn and quartersawn boards, respectively (Fig. 1). Randomly selected blocks measuring 25 mm thick × 152 mm wide, crosscut into 300 mm in length were prepared for flaking and subsequent drying. Three flakes 0.6 mm in thickness were cut from each block using a CAE flaker. Flaking variables (i.e., rotation speed, depth of cut, and angle) were kept constant to minimize the influence of cutting on bending properties. Flakes were dried at three drying temperature levels (150°, 200°, and 250°C). Mean drying times of the specimens are presented in Table 1.

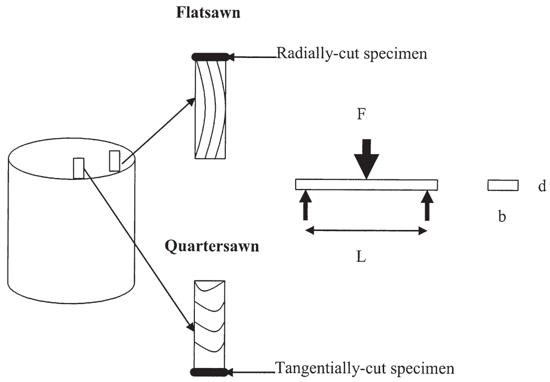

FIG. 1. Cutting diagram for flake bending specimens.

Ten replicates were used in the bending experiments. After drying, flakes were moisture-conditioned based on ASTM D 4933-91 (ASTM 1994d). Flakes were tested for bending properties when they reached EMC (temperature and relative humidity set at 20°C and 65%, respectively).

Bending tests based on Methods of Testing Small Clear Specimens of Timber ASTM D 143-94 (ASTM 1994a) were conducted. Modulus of elasticity (MOE), Modulus of Rupture (MOR), and Stress at Proportional Limit (SPL) were measured. Static bending tests on small specimens cut from each flake were performed.

TABLE 1. *Average drying times, moisture content, and specific gravity of flakes.*

Species	Drying time (seconds) Temperature (ºC) 150	200	250	Moisture content at test (%)	Specific gravity green
Southern yellow pine	210	150	115	10.3	0.58
Sweetgum	185	130	100	12.0	0.64
Yellow-poplar	165	115	85	9.5	0.58

A small specimen measuring 5.0-mm (width) × 25.0-mm (length) was cut using a guillotine razor blade cutter. Actual dimensions (length, width, and thickness) of each specimen were recorded using a caliper, and these values were used in the calculations. Bending tests were performed using a miniature material tester (Rheometric Scientific MiniMat 2000) at a cross-head speed of 2.54 mm/min. MOE, MOR, and SPL were calculated using the following equations (Bodig and Jayne 1982; Haygreen and Bowyer 1996):

$$MOE = P_{pl}L^3/4\Delta_{pl}bd^3 \quad (1)$$

$$MOR = 1.5\ P_{ult}L/bd^2 \quad (2)$$

$$SPL = 1.5\ P_{pl}L/bd^2 \quad (3)$$

where: P_{pl} is load at proportional limit (N)
L is span of the bending specimen (mm)
Δpl is the deflection of the bending specimen (mm)
b is the width of the bending specimen (mm)
d is the thickness of the bending specimen (mm)
P_{ult} is the ultimate load (N)

Excess material from the flake where the specimen was cut was used for moisture content and specific gravity determinations using the oven-dry (ASTM D 2395-93, 1994b) and water displacement (ASTM D 4442-92, 1994c) methods, respectively. Extreme care was taken to reduce the error in determining weight and volume of the specimens due to their size and geometry. Initial weight of the flake was measured right after cutting using a Mettler PR1203 balance. Green volume of the flake was determined by clipping one end of the flake using an alligator clip connected to a stand and immersing the flake inside a tube containing distilled water. The weight of the tube with water was determined using the same Mettler balance before and after immersing the flake. The difference in weight is converted into volume of the flake. Oven-dry weight of the flake was determined by placing the flake inside an oven at 102+3°C overnight. Moisture content for each flake was calculated using the oven-dry and initial weights. Oven-dry weight and green volume were used to calculate specific gravity.

Average moisture content and specific gravity of the flakes are given in Table 1. Values for specific gravity reported in Table 1 are all higher than average values reported in the Wood Handbook (FPL 1999). This most probably can be traced to specimen geometry and position within growth rings. For example, very thin flakes were used rather than the typical small clear ASTM specimens, which contain a range of wood structure with high and low specific gravity regions averaged together. Also, because thin flakes were used, many were cut entirely from latewood. If there were more latewood flakes than earlywood, this could also drive up specific gravity values. It should be noted, however, that flakes with a specific gravity more near handbook values might behave differently than the specimens used in this study.

Statistical analyses

Multiple comparisons of bending properties between species, cutting direction, and drying temperature were conducted using analysis of variance (ANOVA) and Tukey's test. MOE, MOR, and SPL were compared between species, cutting direction, and drying temperature using the split-plot design. Species represented the whole plots. Cutting direction and temperature represented the subplots. Means and Tukey's test were used in comparing the main parameters. Comparison of bending properties between cutting directions and drying temperature by species was analyzed using an analysis of covariance (ANACOVA) (Ott, 1992) with specific gravity as a covariate. Treatment levels were compared using the least squares means and Tukey's test. The data set was analyzed as a whole and then by species. Details of the analyses are presented in Deomano (2001).

RESULTS AND DISCUSSION

Statistical analysis of the data set as a whole (the three species combined) indicates that there were

TABLE 2. *Average flake bending properties of the three species, two cutting directions, and three drying temperatures.*

Parameter	MOE (N/mm^2)	MOR (N/mm^2)	SPL (N/mm^2)
Species			
Southern yellow pine	4,086.9 a	66.0 a	48.1 a
Sweetgum	4,430.6 a	78.6 b	56.5 b
Yellow-poplar	5,829.4 b	89.0 c	66.0 c
Cutting Direction			
Radial	4,308.0 a	69.1 a	48.3 a
Tangential	5,256.6 b	86.7 b	65.5 b
Temperature (ºC)			
150	5,401.6 a	87.7 a	64.3 a
200	4,665.4 b	77.6 b	56.5 b
250	4,280.3 c	68.3 c	49.6 c

Means with the same letter are not significantly different at p = 0.05.

highly significant differences in flake MOE, MOR, and SPL between specimens (Table 2). There was also a highly significant difference between radially and tangentially cut specimens in terms of bending properties. Interaction of species and cutting direction was not significant for bending stiffness and strength. This means that the effect of cutting direction on flake MOE, MOR, and SPL was the same for the three species.

There were highly significant differences in flake bending properties between drying temperature. However, interaction of temperature with species and with cutting direction was not significant at $p = 0.05$. This implies that the difference in bending properties caused by temperature did not depend on the species or on cutting direction. Three-way interaction among species, cutting direction, and drying temperature was also not significant.

Among the three species, southern yellow pine had the lowest average bending properties (Table 2). Sweetgum had higher bending strength and stiffness than southern yellow pine except for MOE, which was not significantly different. Yellow-poplar had the highest MOR, MOE, and SPL. This is somewhat unexpected since southern pine would typically exhibit higher values than sweetgum and yellow-poplar. This discrepancy is probably traceable to high average specific gravity values for the yellow-poplar and sweetgum specimens. Evaluation of results shown in Table 2 might also indicate that high temperature drying has a greater effect on the bending properties of southern yellow pine than on yellow-poplar.

Radially cut specimens have lower bending properties than tangentially cut specimens (Table 2). For radially cut specimens, the force was applied on the tangential axis. On the other hand, for tangentially cut specimens, the force was applied on the radial axis.

The effect of temperature on bending properties is also shown in Table 2. A decreasing trend in flake bending strength and stiffness with increased temperature was observed. The same trend was observed by Plagemann (1982); however, statistical analysis indicated that only MOE of flakes was significantly affected by temperature in his tests. In our experiment, the effect of temperature on MOE, MOR, and SPL was highly significant. Specimens dried at 150°C had higher mean bending properties than specimens dried at 200°C. Specimens dried at 250°C had the lowest mean bending stiffness and strength.

Analysis of the data by species was conducted using ANACOVA with specific gravity as a covariate. Analyses of this nature allow comparisons while taking into account the influence of specific gravity. Table 3 lists results for each species studied. Because using specific gravity as a covariate provided a significant reduction in experimental error, the observed means were replaced with an estimated adjusted mean as shown in Table 3. This led to a slight change in least square means of the MOE, MOR, and SPL of all three species. The significance of cutting direction and temperature was then determined on the basis of the adjusted means and not on the experimentally observed means. Equation (4) was used as the general linear model to calculate adjusted mean.

$$y_{ijk} = m + C_i + e^{(A)}_{ij} + T_k + CT_{ik} + bG_{ijk} + e^{(B)}_{ijk} \tag{4}$$

where: y_{ijk} is bending property (MOE, MOR, or SPL)
m is mean
C_i is effect of cutting direction

TABLE 3. *Adjusted means of bending stiffness and strength.*

Parameter	Specific gravity	MOE (N/mm^2) Mean	MOE (N/mm^2) Adj	MOR (N/mm^2) Mean	MOR (N/mm^2) Adj	SPL (N/mm^2) Mean	SPL (N/mm^2) Adj
Southern Yellow Pine							
Cutting Direction							
Radial	0.61	3,469.9	3,030.2 a	55.2	47.4 a	36.7	30.5 a
Tangential	0.54	4,710.8	5,143.6 b	76.9	84.6 b	59.5	65.7 b
Temperature (ºC)							
150	0.60	5,206.9	4,940.1 a	79.3	74.5 a	55.3	51.4 a
200	0.56	3,772.6	3,959.6 ab	65.4	68.7 a	49.0	51.6 a
250	0.57	3,281.1	3,360.9 b	53.4	54.8 a	40.0	41.2 a
Sweetgum							
Cutting Direction							
Radial	0.64	4,153.4	4,135.2 a	67.9	67.6 a	47.4	47.3 a
Tangential	0.63	4,707.9	4,726.1 b	89.2	89.6 b	65.6	65.8 b
Temperature (ºC)							
150	0.61	4,912.2	5,012.2 a	90.7	92.6 a	69.4	70.1 a
200	0.66	4,205.0	4,144.6 b	75.9	74.7 b	52.2	51.8 b
250	0.65	4,174.7	4,135.1 b	69.2	68.4 b	48.0	47.7 b
Yellow-poplar							
Cutting Direction							
Radial	0.60	5,307.8	5,365.3 a	84.1	85.3 a	60.8	61.6 a
Tangential	0.55	6,351.0	6,293.5 a	94.0	92.8 a	71.2	70.5 a
Temperature (ºC)							
150	0.58	6,085.6	6,080.0 a	93.2	93.1 a	69.2	69.2 a
200	0.58	6,017.6	6,043.1 a	91.6	92.1 a	68.3	68.6 a
250	0.59	5,385.1	5,364.4 a	82.4	82.0 b	60.6	60.4 a

Means with the same letter are not significantly different at $p = 0.05$.

$e_{ij}^{(A)}$ is error
T_k is temperature effect
CT_{ik} is interaction effect of cutting direction and temperature
b is regression coefficient
G_{ijk} is covariate (specific gravity)
$e_{ijk}^{(B)}$ is error

Evaluation of Table 3 indicates that cutting direction had a statistically significant effect on bending properties of wood flakes made from southern yellow pine and sweetgum but not on yellow-poplar. For all species, radially cut specimens consistently had lower MOE, MOR, and SPL than tangentially cut specimens, but the impact was less significant in yellow-poplar. As illustrated in Fig. 1, force applied on radially cut specimens was directed along the tangential axis of the flake specimens, while force applied on tangentially cut specimens is directed along the radial axis. For force directed along the tangential axis (radially cut specimens), the stress is lower due to fewer cells involved in buckling. The strong latewood and weak earlywood are arranged parallel to each other or in columns resulting in equal strain but higher stress in the stiffer latewood portion. For force directed along the radial axis (tangentially cut specimens), stress is higher because the cells are arranged in series or in a row and so there are more cells and the cells buckle in a domino fashion. This also results in equal stress among latewood and earlywood, but most of the strain occurs in the earlywood.

A general trend of decreasing bending properties for increasing drying temperature was observed. Although significant differences were detected only in the MOE of southern yellow pine, MOE, MOR, and SPL of sweetgum, and

MOR of yellow-poplar, the trend was consistently observed on all bending properties of the three species. Plagemann (1982) observed the same trend in his flake bending tests; however, only MOE was found to be affected by dryer temperature, while MOR was not affected. The decrease in bending properties as influenced by dryer temperature can be attributed to thermal degradation of the wood components when exposed to high temperature. Haygreen and Bowyer (1996) stated that wood subjected to high temperature led to permanent strength loss. The strength loss is a permanent effect due to degradation of the wood.

In addition to cutting direction and temperature, other factors not studied in this research may have influenced the bending properties. These factors include processes that damage the flakes. For example, Geimer et al. (1986) studied the effect of flaking on the strength of flake and flakeboards. They observed visible damage in the flakes caused by machining in the form of end splits, tears in the earlywood zones, and cell-wall fibrillation; however, no internal damage was observed in the flakes. Because of this finding, flaking variables such as rotation speed, depth of cut, and angle were kept constant in our study to eliminate their influence on the bending properties. Noticeably damaged flakes were rejected. However, flakes were not closely examined for internal processing damage, and the influence of other, uncontrolled processing variables is undetermined. Other factors may also be considered like undetected anatomical differences and moisture content variability, among others to account for the differences in bending properties between species.

CONCLUSIONS AND RECOMMENDATIONS

Our results clearly indicate that bending properties of flakes differed between and within the three species. Yellow-poplar had the highest bending properties followed by sweetgum and southern yellow pine had the lowest bending stiffness and strength. The effect of cutting direction was similar on the three species. Radially cut specimens were found to have lower MOE, MOR, and SPL than tangentially cut specimens. Drying temperature was also found to have a significant effect on the bending properties of flakes. Effect of temperature was similar for the three species and did not depend on the cutting direction. A decreasing trend was observed for flakes dried at higher temperature.

Drying of flakes at high temperature resulted in a dramatic decrease in bending properties when compared to clear wood specimens dried conventionally. MOE and MOR decreased by as much as 67% in the case of southern yellow pine. The reduction of flake bending stiffness and strength was attributed to the thermal degradation. Subjecting wood flakes to high temperature can lead to permanent strength loss, and this loss is a permanent effect due to degradation of the wood substance.

Relative to OSB production, it may be ideal to use high specific gravity yellow-poplar or more of it in combination with other species and lower dryer temperature due to better bending properties as seen from the results of our flake bending experiments. Since southern yellow pine is the species predominantly used in OSB production in the south, it may be an advantage to cut more flakes in the tangential direction to have flakes with higher bending properties but this is not yet practical. This idea may lead to better panels due to better bending properties of raw materials.

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