

MECHANICAL, PHYSICAL, AND MACHINING PROPERTIES OF BLACK WALNUT FROM INDIANA AND MISSOURI

David R. Schumann²

Forest Products Technologist, Forest Products Laboratory, Forest Service,
U.S. Department of Agriculture¹

(Received 19 January 1973)

ABSTRACT

The relationships of the anatomical characteristics and physical features of black walnut to the machining and mechanical properties were investigated. The influence of geographic location, site quality, and growth conditions on these properties was also examined. Machining properties of black walnut were satisfactory regardless of locality, site, growth rate, and anatomical characteristics.

Specific gravity influenced the machining and mechanical properties of black walnut more than any other feature. Specific gravity increased slightly with an increase in growth rate.

Indiana-grown black walnut heartwood contained less extractive material and consequently shrank more than Missouri-grown wood. Good sites, regardless of location, produced tougher wood than poor sites.

Additional keywords: *Juglans nigra*, wood quality, specific gravity, volumetric shrinkage, hardness, toughness.

Black walnut (*Juglans nigra* L.) is a preferred wood in the manufacture of furniture, musical instruments, novelties, fixtures, and architectural woodwork, mainly because of its appearance, machining characteristics, and strength.

Appearance depends on the texture, grain, figure, color, and luster of the wood. Texture denotes the relative size of the wood elements, while grain refers to their structural arrangement. Figure refers to the various patterns displayed when the wood is viewed at different angles of inclination to the light source; these patterns arise from the arrangement of the different types of tissue in the wood. The wood is usually chocolate brown, but may have a grayish, purplish, or reddish tinge, giving it a variegated cast. The amount and kind of extractives in the wood impart these characteristic colors. Luster is the manner in which light is reflected by the wood elements and their contents. Luster

has depth, whereas gloss from a surface finish is superficial.

In addition to pleasing appearance, black walnut has desirable physical characteristics with concomitant favorable machining and strength properties. Variation in these characteristics and properties may occur, however, because of site, geographic location, and growth rates. Black walnut log buyers often pay premium prices for logs from specific areas. For instance, black walnut from Indiana is high on the buyers' preference list, and that from Missouri is low. To try to quantify the basis for this, Nelson et al. (1969) used spectrophotometry to investigate the color of black walnut heartwood from Indiana and Missouri. The results indicated larger differences in heartwood luminance (brightness) than in dominant wavelength (hue) or purity (percentage of principal hue). Indiana-grown walnut heartwood had higher luminance than Missouri-grown. Moslemi (1967) also showed color variations from various locations within Illinois.

Hiller et al. (1972), using Nelson's sample, then investigated whether the differences in color observed by Nelson et al.

¹ The Laboratory is maintained at Madison, WI, in cooperation with the University of Wisconsin.

² Present address: Chugach National Forest, Anchorage, Alaska.

were related to specific gravity, structure, and the extractive content of the wood. Luminance was significantly related to extractive content and to the combination of extractive content and wood density. Trees from Indiana had lower extractive content, thinner walled fibrous tissue, and smaller vessel lumens than those from Missouri.

The present study is also based on wood specimens from the sample of Nelson et al. The objective was to determine whether the anatomical characteristics measured by Hiller et al., along with some additional physical features, were related to machining and mechanical properties of wood. In addition, the effect of site, locality, and growth conditions on these physical, mechanical, and machining properties was examined. Machining tests were conducted for planing, shaping, and turning. The mechanical properties included in the analysis were hardness and toughness. Three physical characteristics—volumetric shrinkage, slope of grain, and specific gravity—were also examined.

METHODS

A total of 32 trees represented the sample. Four trees were chosen at random within each site class (good and poor) and growth rate class (fast and slow) from each of the two states. One 4½-ft bolt was taken from each tree between 8 and 13 ft above the ground. Table 1 lists average bolt data in each of the eight classes.

The 4½-ft bolts were sawed into 1¼- by 4¼-inch boards, and from each bolt eight boards were randomly selected for the study. Each board was cut parallel to the bark to minimize diagonal grain, was lightly surfaced on both sides, and then cut into four 1-ft-long pieces and one 6-inch randomly selected section. The latter section provided the samples used by Hiller et al. (1972) for determining color, wood structure, volumetric shrinkage, and extractive content. The 12-inch-long pieces were dried to 12% moisture content and provided the samples for the machining and strength tests. In each board, shaping and hardness tests were conducted on two

TABLE 1. *Bolt characteristics of black walnut trees from Indiana and Missouri. Each value is the average of four trees*

Site quality	Growth rate	Diameter inside bark inch	Heartwood diameter inch	Number of rings per inch
INDIANA				
Good	Fast	13.0	10.6	7.2
	Slow	10.9	9.4	12.9
Poor	Fast	15.2	12.2	7.2
	Slow	12.0	10.4	10.5
MISSOURI				
Good	Fast	13.7	12.0	8.3
	Slow	11.6	9.8	10.6
Poor	Fast	12.7	11.1	9.1
	Slow	11.0	9.5	10.6

of the 12-inch pieces and toughness and turning tests on the other two pieces. Specific gravity and slope of grain were determined from the toughness specimens. The specific gravity was based on unextracted oven-dry weight and volume at 12% moisture content.

MACHINING TESTS

Planing

Planing is probably the most common and essential machining operation in the woodworking industry. A smooth surface is necessary for fine finishing and assembling. Planing defects are characterized as raised grain, fuzzy grain, chip marks, or chipped grain. Raised grain is common in softwoods where there is an abrupt transition between the earlywood and latewood. It also occurs in ring-porous hardwoods but rarely in diffuse- or semi-ring-porous woods such as black walnut. Fuzzy grain is caused by the tearing of fibers in the aberrant structure of tension wood in hardwoods and compression wood in softwoods. Chip marks are caused by shavings that have adhered to the knives rather than passing off in the exhaust. Chipped grain is associated with cross grain.

Low moisture content, sharp knives, small cutting angle, shallow cut, and a

large number of knife cuts per inch minimize the occurrence and severity of planing defects. The moisture content of the test specimens was 12%. The depth of cut was $\frac{1}{8}$ inch with 16 knife cuts per inch. This cut was deeper than normal to make the test more sensitive to borderline defects.

Planing quality was recorded in two ways, number of defect-free pieces and defect severity. Because depth of tearout, and not the amount, is the limiting factor in sanding, the most critical defect in the specimen was reported as defect severity. Six classes of defect ranging from a chip depth of $\frac{1}{64}$ to $\frac{1}{8}$ inch were included.

Two types of cross grain are recognized in black walnut, spiral and diagonal; a third type, interlocked, occurs rarely in this species. Chipped grain was due to grain distortions associated with knots. Without exception no planing defects occurred in the clear portion of the specimens; they always occurred in the distorted grain around knots.

Regression analysis was used to determine the relationship between planing defect severity class and specific gravity, rings per inch, and slope of grain, measured in this study and extractive content, per cent normal fibrous tissue, number of vessels per square millimeter, and average fiber diameter measured by Hiller et al. (1972). The independent variable that explained the largest amount of variation was specific gravity, but it still accounted for less than 9% of the variation in the planing defects. This is statistically significant at the 0.01 probability level but from a practical standpoint is negligible, since it reduces the standard deviation about the regression by only 4%.

The number of defect-free pieces and the defect severity were subjected to analyses of variance also to see whether there was any association with locality, site, or growth conditions. Neither analysis showed a statistically significant difference in any of the three categories. A comparison of defect-free pieces is summarized in Table 2 for source, site qual-

ity, and growth rate. The poor sites and slow-growing trees produced fewer defect-free pieces. This possibly could be associated with limbiness and a preponderance of knots. The grand mean of 63.1% defect-free pieces is very similar to the 62% reported by Davis (1962) for black walnut.

Shaping

The shaper is used to cut a curved pattern on the edge of boards and panels such as a table top. Chipped and torn grain are the most common defects in shaping, although some roughness on the end grain may occur in diffuse-porous woods. Raised grain may also occur in diagonal cuts across ring-porous woods.

A double spindle-type shaper operating at 7,200 rpm was used in this study. The spindles revolve in opposite directions, thus reducing the possibility of cutting against the grain. The test specimens were rough-sawn to shape, fastened to a jig, and hand-fed through the shaper. Two specimens from each of the eight boards per bolt were shaped.

Only 13 of the 512 specimens exhibited some torn grain. In each instance this occurred in distorted grain in the vicinity of knots. All other specimens shaped satisfactorily and for this reason were not subjected to statistical analysis.

Turning

The turning tests were made at 3,200 rpm with a milled-to-pattern knife that made a bead, cove, and fillet with cuts at different angles to the grain. The finished specimen was 5 inches long and $\frac{3}{8}$ inch wide at the smallest diameter. A total of 512 specimens were turned.

No discernible differences in turning quality could be detected. This confirms the results of Davis where the variation in turning quality was the least of any machining property (1962). In comparing 34 native hardwood species, Davis also demonstrated that the highest percentage (91%) of "fair to excellent turning," was obtained from black walnut.

TABLE 2. Means and differences of mechanical, physical, and machining properties of black walnut by state of origin, site, and growth rate. Each value is the average of 16 trees

Classification	Extractive content ^a %	Volumetric shrinkage ^b %	Specific gravity ^c	Planing defect-free pieces %	Hardness lb.	Toughness In.-lb.	Slope of grain %
State:							
Indiana	5.3	5.14	0.556	62.9	1,154	251.9	6.7
Missouri	6.6	4.75	0.560	63.4	1,131	239.9	4.3
Difference	1.3*	0.39**	0.004	0.5	23	12.0	2.4**
Site quality:							
Good	5.5	5.05	0.563	65.7	1,172	272.7	5.1
Poor	6.5	4.84	0.554	60.5	1,113	219.0	5.9
Difference	1.0	0.21	0.009	5.2	59	53.7**	0.8
Growth rate:							
Fast	6.2	5.00	0.565	64.5	1,170	247.7	5.4
Slow	5.7	4.90	0.551	61.7	1,115	244.0	5.6
Difference	0.5	0.10	0.014	2.8	55	3.7	0.2
All	6.0	4.94	0.558	63.1	1,143	245.9	5.5

^a From C.H. Hiller et al., *Wood Fiber* 4(1): 41, Table 2 (1972).

^b Based on dimension when green and dried to 12 pct. moisture content.

^c Based on volume at 12 pct. moisture content and oven-dry weight.

* Difference significant at 0.05 level.

** Difference significant at 0.01 level.

MECHANICAL PROPERTIES

Hardness

Hardness indicates the resistance of wood to abrasion and indentation. The hardness test consists of measuring the load required to embed a 0.444-inch ball to one-half its diameter (ASTM 1970). Averages of the six tests on each of the two samples per board were used in the analysis. To avoid cross grain, hidden knots, and other defects, all tests were conducted on the tangential face.

The analysis of variance did not indicate any statistically significant differences between states, sites, or growth rates. Although specimens from Indiana averaged slightly harder than those from Missouri, good sites produced harder wood than poor sites, and harder specimens were obtained from fast-grown than from slow-grown trees (Table 2), none of the differences were statistically different at the 0.05 level. The latter comparison concurs with the results shown by Paul (1963).

The mean for all specimens, 1,143 pounds, is 13% higher than that shown for side hardness in the Wood Handbook (1955).

Hardness was significantly correlated (0.01 level) with only three of the seven independent variables considered: specific gravity ($r^2 = 0.45$), rings per inch ($r^2 = 0.19$), and fiber diameter ($r^2 = 0.12$). The nonsignificant variables were extractive content, per cent normal fibrous tissue, and number of vessels per square millimeter. Since cross grain was intentionally avoided in making tests, slope of grain also showed no correlation with hardness.

Toughness

Toughness is the ability of the wood to absorb shock or impact loads. It is an important property for such uses as chair and table legs, gunstocks, and novelties. Two specimens from each of the eight boards per tree were tested by standard procedures (ASTM 1970). The specimens measured 2 cm square by 28 cm long.

Specimens from good sites were substantially tougher than those from poorer sites (Table 2). Fast-grown specimens were slightly tougher than slow-grown ones, in agreement with the observations of Englerth (1966). This difference, like that between states, is not large enough to be statistically significant. The overall mean of 245.9 inch-pounds agrees fairly well with Englerth's mean of 254.0 inch-pounds.

Specific gravity was not highly correlated with toughness and accounted for only about 8% of the variation observed in the toughness values. This coefficient of determination is statistically significant at the 0.01 level but reduces the standard deviation about the regression by only 4%.

Of the 10 independent variables regressed against toughness, extractive content was significant at the 0.01 level ($r^2 = 0.09$) and reduced the standard deviation about the regression from 63 to 60 inch-pounds, or 5%. Slope of grain accounted for a negligible amount of the variation since the specimens were cut parallel to the bark, which minimized the amount of cross grain. The other seven variables measured by Hiller et al. (1972)—distance from pith, rings per inch, per cent of normal fibrous tissue, number of vessels per square millimeter, average fiber diameter, vessel lumen area, and single wall thickness—did not explain any appreciable part of the variation in the toughness values.

Each test specimen was identified as to the type of break: typical fibrous splintering, brash and brittle, or obviously cross-grained and split. Regression analyses were run for each category and resulted in the coefficients of determination (all significant at the 0.01 level) shown in Table 3.

As expected, the correlation of specific gravity and toughness was greater in those specimens that broke normally. Specific gravity is a much better index of toughness in clear, straight-grained material where defects such as cross grain are excluded. The number of rings per inch was negatively correlated with toughness

TABLE 3. *Coefficients of determination obtained from regression analysis of toughness specimens. All coefficients are significant at the 0.01 level*

Independent variable	Type of Break		
	Normal	Brash	Split
Specific gravity	0.18	0.09	0.02
Rings per inch	--	0.04	--
Slope of grain	--	--	0.08
Distance from pith	--	--	0.02

in brash specimens as wide rings produced abrupt breaks. Cross grain, as stated earlier, was avoided where possible. However, it could not be entirely eliminated, and as expected, splitting was correlated with slope of grain. Distance from pith was a negligible factor except in split specimens, explained by the fact that cross grain was more predominant in specimens closest to the pith.

PHYSICAL CHARACTERISTICS

Shrinkage

Hiller et al. refer to the well-known inverse relationship of shrinkage to extractive content (1972). They suggest that shrinkage characteristics of walnut might be controlled by cultural practices. Table 2 illustrates the effect of origin, site, and growth rate on these two characteristics. Indiana specimens contained fewer extractives and consequently exhibited greater shrinkage. The difference in extractive content was significant at the 0.05 level and in shrinkage at the 0.01 level.

When the data were classified according to growth rate, the above relationship of shrinkage to extractive content did not follow. The apparent explanation is that the positive effect of growth rate on shrinkage probably masked the negative effect of extractive content on shrinkage.

Regression analysis showed that 13% of the variation in shrinkage was attributed to extractive content. Of the seven independent variables regressed against shrink-

age specific gravity accounted for the second largest share of the variation, 6%. Both these coefficients of determination were significant at the 0.01 level. Rings per inch, number of vessels per square millimeter, and fiber diameter each had an r^2 of 0.02, statistically significant at the 0.05 level but obviously not very significant from a practical standpoint. Slope of grain and per cent normal fibrous tissue showed absolutely no correlation with shrinkage.

The 4.94% volumetric shrinkage mean is substantially lower than that reported for the interpolated 12% level in the Wood Handbook (1955). This is probably due to the fact that these specimens were all heartwood, but the reported mean for the species in the Wood Handbook probably represents both sapwood and heartwood. Sapwood shrinks more than heartwood (Paul 1963).

Slope of grain

As mentioned during the discussion of the planing tests, spiral and aberrant grain were the types of cross grain exhibited in these samples. Cutting each board tangentially minimized diagonal grain. The 5.5% average slope of grain is similar to that of 5.7% reported by Davis (1962).

Indiana specimens had significantly more pronounced degrees of cross grain than those from Missouri (Table 2). This did not seem to affect appreciably any of the machining characteristics. The only mechanical property affected was hardness, which was not reflected in site of origin. Cross grain was a factor ($r^2 = 0.08$) in those individual specimens that split during the toughness test rather than breaking normally.

Specific gravity

Of all the anatomical and physical characteristics observed in this study, specific gravity was the most important. It accounted for 45% of the variation in hardness values. Specific gravity also produced the following coefficients of determination for some of the other properties: plan-

ing 0.09, toughness 0.08, shrinkage 0.06, and slope of grain 0.06; all significant at the 0.01 level. The only characteristic not correlated with specific gravity was extractive content.

The analysis of variance of data in Table 2 did not indicate any significant differences in specific gravity associated with locality, site, or growth conditions. The small difference between states concurs with Paul's statement that geographic location does not seem to be a controlling influence on specific gravity (1963). Hiller et al. show about the same magnitude of difference in extractive-free specific gravity due to locality but in the opposite direction (1972). The present study, along with studies by Englerth (1966), Hiller et al. (1972), and Paul (1963), shows that fast-growing trees are slightly heavier than slow-growing trees.

The species mean of 0.558 is very similar to that shown in the Wood Handbook, 0.55 (1955). A 0.55 value determined on a 12% moisture content volume basis corresponds to a 0.51 value calculated on a green volume as shown by the Wood Handbook. This converted value of 0.51 then is identical to that shown by Davis (1962). This would seem to indicate that the specimens used in this study were not atypical for the species.

SUMMARY

Indiana-grown black walnut heartwood shrank more than Missouri-grown. Extractive content and volumetric shrinkage were significantly and negatively correlated.

Slope of grain was greater in Indiana specimens, but the average for both states (5.5%) is similar to that reported by Davis (1962). This amount of spiral grain did not appreciably affect any of the machining and mechanical properties.

In both Indiana and Missouri, good sites produced tougher wood. Toughness was correlated with specific gravity and extractive content. An increase in specific gravity and extractive content will correspondingly reflect an increase in toughness.

Shaping and turning tests indicated that geographic location, site quality, and growth conditions did not influence the quality of the specimens, nor was it possible to evaluate the effect of any anatomical or physical characteristics on these specimens. All specimens machined well. Specific gravity, on the other hand, was correlated ($r = 0.29$) with the planing characteristics. The overall mean of 63% defect-free pieces corresponded very closely with that of Davis.

Specific gravity proved to be the one most important characteristic in evaluating machining and mechanical properties of black walnut. It accounted for 45% of the variation observed in the hardness values and 8% in toughness values. Nine per cent of the variation in planing was explained by specific gravity. Specific gravity was also correlated with volumetric shrinkage and slope of grain, $r = 0.24$ in both instances.

Why black walnut from one area is preferred to that from another area may be partially explained by the intrinsic characteristics measured in this study. Knowledge of what causes the changes in these intrinsic characteristics should be an es-

sential part of studies to improve the species by either genetic or cultural means.

REFERENCES

- AMERICAN SOCIETY FOR TESTING AND MATERIALS. 1970. Standard methods of testing small clear specimens of timber. ASTM D 143-52. Philadelphia, Pa.
- DAVIS, E. M. 1962. Machining and related characteristics of United States hardwoods. USDA Tech. Bull. 1267. 68 pp., illus.
- ENGLERTH, G. H. 1966. Machining and other properties of fast versus slow grown trees. Pages 77-82, in *Black walnut culture*, USDA For. Serv., No. Cent. For. Exp. Sta., St. Paul, Minn.
- HILLER, C. H., F. FREESE, AND D. M. SMITH. 1972. Relationships in black walnut heartwood between color and other physical and anatomical characteristics. *Wood Fiber* 4(1): 38-42.
- MOSLEMI, A. A. 1967. Quantitative color measurement for black walnut wood. USDA For. Serv. Res. Paper NC-17 No. Cent. For. Exp. Sta., St. Paul, Minn.
- NELSON, N. D., R. R. MAEGLIN, AND H. E. WAHLGREN. 1969. Relationship of black walnut wood color to soil properties and site. *Wood Fiber* 1(1):29-37.
- PAUL, B. H. 1963. The application of silviculture in controlling the specific gravity of wood. USDA Tech. Bull. 1288. 97 pp., illus.
- WOOD HANDBOOK. 1955. Forest Products Laboratory, USDA Agric. Handb. 72. 528 pp., illus.