STRENGTH PROPERTIES OF JUVENILE AND MATURE WOOD IN BLACK LOCUST (*ROBINIA PSEUDOACACIA* L.)

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ABSTRACT

This study was undertaken to investigate the strength properties of juvenile and mature wood in black locust (*Robinia pseudoacacia* L.). Wood specimens were prepared from various stem heights, up to 9 m, of five naturally-grown black locust trees, 21–37 years old. Mechanical properties tested included moduli of rupture (MOR) and elasticity (MOE), and pure modulus of elasticity (PMOE) in static bending, stress wave modulus of elasticity (SWMOE) in dynamic strength, axial compression, and toughness. Comparisons between juvenile and mature wood specimens of similar densities (0.667–0.894 g/cm^3 and 0.682–0.892 g/cm^3, respectively) showed that juvenile wood had a statistically significant lower mean MOR (138.78 N/mm^2), MOE (13,936 N/mm^2), PMOE (18,125 N/mm^2), SWMOE (16,813 N/mm^2) and toughness strength (155.25 KJ/m^2) than the mature wood (148.29 N/mm^2, 14,747 N/mm^2, 19,498 N/mm^2, 17,635 N/mm^2 and 181.27 KJ/m^2, respectively). On the contrary, no statistically significant differences were found for the mean strength in axial compression among juvenile (63.75 N/mm^2) and mature wood (66.65 N/mm^2). Fractured surfaces of juvenile and mature wood specimens in static bending and toughness were classified into the "splintering tension" type of failure, while compression failures were of the "shearing type" according to ASTM D 143-83 standards. Lower strength of juvenile wood in most of the properties examined may be attributed to anatomical and chemical properties rather than density of wood specimens. The adverse influence of juvenile wood on strength properties should be considered for effective management (e.g. longer rotation age and other genetic and forest or plantation management measures that reduce juvenile wood content) and utilization of the species.

Keywords: Black locust, juvenile wood, mature wood, static bending, dynamic strength, compression, toughness.

INTRODUCTION

The concept of juvenile wood and its formation is documented in numerous publications (Rendle 1960; Thomas 1984; Zobel and Talbert 1984; Zobel and van Buijtenen 1989). The production of juvenile wood results from normal physiological processes and it cannot be avoided. The extent of juvenile wood can only be defined by arbitrary criteria. Nearly all wood properties undergo rapid and progressive

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changes from ring to ring within the juvenile zone. However, the rates of change are not the same either along different radii within a single stem cross-section or within cross-sections at corresponding heights from different trees. Cell length, cell diameter, and cell-wall thickness increase rapidly from the pith outwards. Juvenile wood is also characterized by faster growth rate, lower density, greater microfibril angles, higher lignin and hemi-cellulose content, and lower alpha cellulose than the mature wood (Boutelje 1968; Bendtsen 1978; Thomas 1984; Zobel and van Buijtenen 1989; Zobel and Sprague 1998). There is no absolute shift from juvenile to mature wood within one year, but the change occurs over several years. The age of transition from juvenile to mature wood varies among different species and properties (Heliñska-Raczkowska 1994; Heliñska-Raczkowska and Fabisiak 1999; Sauter et al. 1999; Evans et al. 2000; Bao et al. 2001; Passialis and Kiriazakos 2004) and depends upon genetic factors and silvicultural management (Oliver 1986; Rockwood et al. 1997; Saucier 1987).

Juvenile wood adversely influences the quality of most wood products. A significant content of juvenile wood is undesirable due to its worsening of wood quality, especially the strength of solid wood (Senft et al. 1985; Zobel and van Buijtenen 1989). For example, caution should be exercised in the utilization of juvenile wood in structural lumber as a result of lower strength properties of juvenile wood than those of mature wood (Thomas 1984). The degrading effect of juvenile wood on the mechanical properties is more pronounced in coniferous than in deciduous trees (Bendsten 1978; Bendsten and Senft 1986; Pearson and Gilmore 1971; Larson et al. 2001). However, less attention has been devoted so far to this problem in hardwoods (Nepveu 1981; Roos et al. 1990; Zhang et al. 1994).

With diminishing harvest of old-growth forests due to environmental pressure and associated regulations (FAO 2001), new opportunities arise for use of nontraditional species. Black locust (*Robinia pseudoacacia* L.) is an alternative species that could potentially fill some of the market opportunities created by decreased harvest or partially substitute for traditional softwood and hardwood species. Black locust is indigenous to North America, and since its introduction to Europe in the seventeenth century it has become an important natural resource in eastern Europe (e.g., Hungary) and during the last ten years in Mediterranean countries, as well (Arabatzis 2005). Nowadays, black locust is the third widely planted broadleaf tree species in the world, after *Eucalyptus* and *Populus*, in total hectares established (Keresztesi 1988). Black locust is a ring-porous hardwood with pores blocked, in general, by tyloses. Rays are 1 to 5 seriate. Paratracheal and marginal parenchyma are present. Heartwood has a dark greenish-yellowish, brownish color, and sapwood is light yellow and restricted to 4–6 annual rings. Wood is dense (d = 0.72 g/cm^3 on average), hard and durable (Rendle 1972; Panshin and DeZeeuw 1980). Wood of black locust, well known for its good technological properties (Barrett et al. 1990; Stringer 1992), has various uses such as sawnwood, glue-laminated structures, window frames, doors, parquets, furniture components, and agricultural implements (Rendle 1972; Keresztesi 1981; Molnar 1995). However, it is still not used on a large scale as a raw material by the wood-processing industries. One of the main reasons is the insufficient knowledge of its properties. For example, there is not adequate information about the influence of juvenile wood on wood quality of black locust.

To satisfy the increasing demand for forest products, much of the future timber supply will be from trees grown in managed plantations. This is also the case for black locust. This fast-grown resource will tend to be harvested in short age rotations and will contain higher proportions of juvenile wood than that of current harvests. In anticipation of this resource and in order for black locust to compete with traditional softwoods and other hardwoods, definitive information is needed on the influence of juvenile wood on strength properties. In contrast to research related to anatomical and physico-chemical properties, detailed within-tree variability has not been determined so far for mechanical properties of black locust wood (Stringer 1992; Adamopoulos and Voulgaridis 2002; Adamopoulos et al. 2005). Reported mechanical property data, although establishing basic information for the species, represent, in general, mean tree values without questioning variations between juvenile and mature wood (So et al. 1980; Ahn 1985; Shukla et al. 1986; Forest Products Laboratory 1987; Keresztesi 1988; Kopitovič et al. 1989; Stringer 1992; Molnar 1995).

The present study reports on the intrinsic differences in strength properties between juvenile and mature wood of naturally grown black locust trees. A better understanding of juvenile effects on black locust will help utilize this resource more efficiently. This knowledge will also help in the managing of existing, as well as future plantation stands for high-quality timber required by different end uses.

MATERIALS AND METHODS

Five mature black locust trees (*Robinia pseudoacacia* L.) were felled from the University Forest of Taxiarchis, Chalkidiki, Greece. The trees were 21–37 years old and had a height ranging between 15.5–21.0 m (the height of branch-free stem was up to 9 m) and a diameter at stump level (0.25 m above ground level) between 24.9–27.7 cm. The forest is located at latitude 40°23′–40°28′, longitude 23°28′–23°34′, and elevation from 320 m to 1,165 m. The climate is characterized by large temperature variations with cold winters (mean temperature of coldest month +1.7°C) and relatively warm summers (mean temperature of warmest month +20.6°C). Annual rainfall is 740 mm with an additional 72 mm of snow.

From each tree, 2.25-m-long logs from stem heights of 0.25 to 2.25 m (A), 2.25 to 4.50 m (B), 4.50 to 6.75 m (C), and 6.75 to 9.00 m (D) provided material for the tests of mechanical properties. The demarcation zone between juvenile and mature wood was based on the radial variation pattern of fiber length in three trees and was determined to occur in the first 7–11 growth rings (Adamopoulos and Voulgaridis 2002). These three trees were included in the total sample of five trees of the present study. The samples of juvenile wood were taken from the inner side of the 11th annual ring. Information on the average width and proportion of juvenile wood (up to the 11th annual ring) at each stem height of the sample trees is given in Table 1. Juvenile wood comprised a significant part of the total stem area and averaged between 19.88–37.14% at the various sampling heights. The actual fiber length measurements for each of the above three trees and for different heights have been thoroughly presented by Adamopoulos and Voulgaridis (2002).

Wood specimens, straight-grained and free from any visible defects, 2 × 2 cm in cross-section, with true radial and tangential surfaces, were prepared separately from juvenile and mature wood for the investigation of bending strength (static and dynamic), compression, and toughness strength. For comparison purposes, specimens of similar densities between juvenile and mature wood were selected. The specimens were taken from the pith to bark direction and from the total part either of juvenile or mature wood. These air-dry densities ranged between 0.667–0.894 g/cm^3 for juvenile wood and between 0.682–0.892 g/cm^3 for mature wood and are shown in Tables 2–4 for each mechanical property. Only a few specimens, usually near the pith, were excluded from the test material due to lower density values from the above range. The density was determined by dividing the air-dry weight to volume calculated from the three dimensions of orthogonal wood specimens. Stem size and available testing material with absolute straight grain and lack of defects limited sample set size and, thus statistical arguments between

TABLE 1. *Average proportion of juvenile wood in different stem heights.*

Stem height, m	Juvenile wood radius,[a] mm	Stem radius,[b] mm	Juvenile wood proportion of the total stem area, %
0.25	50.38	112.96	19.88
2.25	48.47	96.88	25.03
4.50	42.60	86.18	24.43
6.75	43.29	74.35	33.89
9.00	36.89	60.54	37.14

[a] Up to the 11th growth ring.
[b] Excluding bark.

TABLE 2. *Bending strength of juvenile and mature wood in different stem heights.*

		Air-dry density*, g/cm^3		Static bending strength, N/mm^2						Dynamic strength, N/mm^2	
				MOR		MOE		PMOE		SWMOE	
Stem height, m		JW	MW	JW	MW	JW	MW	JW	MW	JW	MW
A	$\bar{x}$	0.76	0.77	140.95	149.71	13,507	14,595	17,133	19,538	16,626	17,526
0.25–2.25	s±	0.05	0.06	16.8	15.4	1,573	1,398	1,782	3,208	1,193	1,068
	n	17	15	17	15	17	15	17	15	17	15
B	$\bar{x}$	0.74	0.76	137.95	147.00	14,081	15,256	19,249	20,725	20,370	21,006
2.25–4.50	s±	0.06	0.08	19.7	12.5	1,482	737	3,390	3,993	1,027	982
	n	7	7	7	7	7	7	7	7	7	7
C	$\bar{x}$	0.73	0.75	153.54	156.75	15,416	15,117	20,257	19,194	17,254	20,580
4.50–6.75	s±	0.01	0.08	5.9	20.9	786	1,059	1,562	1,852	1,062	1,190
	n	5	5	5	5	5	5	5	5	5	5
D	$\bar{x}$	0.73	0.72	128.30	142.84	13,827	14,437	18,199	19,002	16,300	17,116
6.75–9.00	s±	0.01	0.02	24.3	16.4	1,561	1,214	3,745	2,364	1,649	736
	n	10	10	10	10	10	10	10	10	10	10
Total	$\bar{x}$	0.75	0.75	138.78	148.29	13,936	14,747	18,125	19,498	16,813	17,635
	s±	0.05	0.06	19.6	16.0	1,552	1,203	2,885	2,932	1,624	1,296
	n	39	37	39	37	39	37	39	37	39	37
	t	0.632^{ns}		2.315^{s}		2.536^{s}		2.711^{s}		2.136^{s}	

* Range: 0.667–0.894 g/cm^3 and 0.682–0.892 g/cm^3 for juvenile and mature wood specimens, respectively.
JW: juvenile wood, MW: mature wood.
^{s} Statistically significant differences at P = 5% (t-test).
^{ns} Not statistically significant differences.

TABLE 3. *Compressive strength of juvenile and mature wood in different stem heights.*

		Air-dry density*, g/cm^3		Compression, N/mm^2	
Stem height, m		JW	MW	JW	MW
A	$\bar{x}$	0.78	0.75	64.51	65.04
0.25–2.25	s±	0.05	0.03	5.7	4.9
	n	12	11	12	11
B	$\bar{x}$	0.74	0.81	61.57	71.02
2.25–4.50	s±	0.04	0.09	3.9	11.5
	n	6	6	6	6
C	$\bar{x}$	0.75	0.74	65.56	64.48
4.50–6.75	s±	0.01	0.03	1.9	1.8
	n	3	3	3	3
D	$\bar{x}$	0.73	0.71	63.48	66.31
6.75–9.00	s±	0.02	0.03	3.4	3.7
	n	6	6	6	6
Total	$\bar{x}$	0.76	0.76	63.75	66.65
	s±	0.05	0.06	4.6	6.7
	n	27	26	27	26
	t	0.330^{ns}		1.843^{ns}	

* Range: 0.695–0.870 g/cm^3 and 0.683–0.890 g/cm^3 for juvenile and mature wood specimens, respectively.
JW: juvenile wood, MW: mature wood.
^{ns} Not statistically significant differences.

juvenile and mature wood were not possible for each stem height and between sampling heights. Before testing, all specimens were conditioned at 20 ± 1°C and 65 ± 3% relative humidity until constant weight was achieved. Moisture content values of wood specimens ranged between 11.30–11.52%.

Moduli of rupture (MOR) and elasticity (MOE) in static bending were determined by load application on radial surfaces of specimens

TABLE 4. *Toughness strength of juvenile and mature wood in different stem heights.*

		Air-dry density*, g/cm^3		Toughness, KJ/m^2	
Stem height, m		JW	MW	JW	MW
A	$\bar{x}$	0.78	0.78	170.50	195.63
0.25–2.25	s±	0.06	0.05	44.7	49.4
	n	14	10	14	10
B	$\bar{x}$	0.72	0.78	139.83	174.83
2.25–4.50	s±	0.03	0.10	49.7	71.6
	n	6	7	6	7
C	$\bar{x}$	0.74	0.79	152.27	186.42
4.50–6.75	s±	0.02	0.09	31.0	54.1
	n	4	10	4	10
D	$\bar{x}$	0.75	0.74	133.44	164.60
6.75–9.00	s±	0.03	0.03	52.1	39.6
	n	5	9	5	9
Total	$\bar{x}$	0.76	0.77	155.25	181.27
	s±	0.05	0.07	46.0	52.6
	n	29	36	29	36
	t	0.886^{ns}		2.096^{s}	

* Range: 0.688–0.889 g/cm^3 and 0.689–0.889 g/cm^3 for juvenile and mature wood specimens, respectively.

JW: juvenile wood, MW: mature wood.

^{s} Statistically significant differences at P = 5% (t-test).

^{ns} Not statistically significant differences.

at 15:1 span to depth ratio according to DIN 52186 (DIN 1992) standards.

Pure, shear-free modulus of elasticity (PMOE) in static bending was determined by a non-destructive method described by Wangaard (1964) according to the following equation:

$$(L/2d)^2/E' = 0.3/G + (L/2d)^2/E$$

where

E′ = modulus of elasticity (MOE) at a specified span/depth ratio (L/d), N/mm^2 by the equation $E' = PL^3/4bd^3y$

E = pure, shear-free modulus of elasticity (PMOE), N/mm^2

G = modulus of rigidity, N/mm^2

P = load in the region of proportionality, N

L = length between beam supports, mm

b = width of beam, mm

d = height of beam, mm

y = mid span deflection of beam at load P, mm

The static bending specimens were centrally loaded on radial surfaces. Approximately ⅓ of the proportional limit load (estimated in preliminary tests) was applied. Two span to depth ratios were used (8:1 and 15:1). The specimens were tested on a Shimadzu Universal testing machine. Deflection at middle span was measured with an electric linear motion potentiometer and recorded simultaneously with the corresponding load on the chart of an X-Y recorder. When data for E′ determined at two span to depth ratios are plotted on coordinates, the intercept of the above-estimated linear function on the Y axis is equal to 0.3/G and the slope of the line is equal to 1/E. The modulus of elasticity (E′) at 15:1 ratio corresponds to MOE determined according to DIN 52186 (DIN 1992) standards.

The stress wave modulus of elasticity (SWMOE) was computed by a non-destructive method according to the following equation (Gerhards 1975):

$$SWMOE = c^2r(1/g)\ 98 \times 10^{-6},\ N/mm^2$$

where

c = stress wave velocity (distance between transducers/stress wave propagation time, cm/sec

r = air-dry density, g/cm^3

g = acceleration due to gravity, 981 cm/sec^2

A commercial stress wave timer device (Metriguard 239A) was used to measure the time required for a longitudinal stress to propagate parallel to the grain over the 30 cm span of each specimen. "Start" and "stop" transducers were clamped alternately on each specimen's radial and tangential surfaces at constant pressure. A pendulum released from a fixed height induced a longitudinal stress wave in each specimen and wave propagation times were measured to 0.1 microseconds.

MOR, MOE, PMOE, and SWMOE were determined on the same wood specimens 34 cm long.

Axial compression and toughness strength were determined according to ISO Standard 3787 (ISO 1976) and DIN 52189 (DIN 1992) standards, respectively.

Failures of juvenile and mature wood specimens for static bending, axial compression and toughness and failures were classified according to ASTM D 143-83 (ASTM 1988).

RESULTS AND DISCUSSION

Statistical analysis (t-test, 95% probability level) showed that the juvenile wood of black locust has on average a significantly lower modulus of rupture (MOR), modulus of elasticity (MOE), pure modulus of elasticity (PMOE), and stress wave modulus of elasticity (SWMOE) than the mature wood (Table 2). This tendency was also observed in almost all stem heights although not defensible in the strictest statistical sense. Static bending strength (MOR, MOE, PMOE) as well as dynamic strength values (SWMOE) did not show a clear relationship with height. In most cases, slightly greater mean values were obtained in stem heights B and C (see Table 2).

The lower bending strength properties of juvenile wood could not be explained by wood density as no statistically significant differences existed between juvenile and mature wood specimens (see Table 2). Lower bending strength of juvenile wood specimens may be due to shorter fibers, larger microfibril angle, higher lignin and hemi-cellulose content, and/or lower crystallinity index (Zobel and van Buijtenen 1989).

As shown in Table 3, the mean strength in axial compression was slightly lower in juvenile (63.75 N/mm^2) than in mature wood (66.65 N/mm^2). However, this difference was not statistically significant (t-test, probability $P = 5\%$) and that was also true for the density of the specimens (0.76 g/cm^3). Small differences in compression strength between juvenile and mature wood were noted at most stem heights (A, C, D) where density differences were also small. The noticeably lower strength of juvenile wood than mature wood in stem height B was probably due to lower density of juvenile wood specimens. Compressive strength appeared to be more or less constant with height in juvenile wood and in most heights (A, B, C) of mature wood.

According to Table 4, mean toughness was found to differ significantly (t-test, probability $P = 5\%$) between juvenile (155.25 KJ/m^2) and mature wood specimens (181.27 KJ/m^2) while a significant difference was not observed for air-dry density. At all sampling heights, toughness was by far greater in mature wood than in juvenile wood. Toughness appeared to be decreased with height in both juvenile and mature wood from 170.50 KJ/m^2 to 133.44 KJ/m^2 and from 195.63 KJ/m^2 to 164.60 KJ/m^2, respectively.

Mean strength values for juvenile and mature black locust wood calculated in this study were quite similar to those reported in the literature (Table 5). Almost all references provide average strength values without giving information separately for juvenile and mature wood. Only one study (Ahn 1985) was carried out on juvenile wood from young black locust trees aged 9–11 years. However, review of the mechanical properties of black locust wood was beyond the scope of this paper. Such a review can be found in Stringer (1992) where mechanical properties of black locust are compared with other commercial North American hardwoods.

According to ASTM D 143-83 standards (ASTM 1988), static bending and toughness failures were classified to the "splintering tension" type of failure for both juvenile and mature wood specimens. In static bending specimens of both juvenile and mature wood, the fractured

TABLE 5. *Comparison of strength values of juvenile and mature wood with respective values from literature.*

Property	Present study		Literature	
	JW	MW	JW	JW+MW
Static bending, N/mm^2				
– MOR	128.30–153.54	142.84–156.75	129.95–159.05[1]	102.41–161.00[2]
– MOE	13,507–15,416	14,437–15,256		11,074–20,997[2]
Axial compression, N/mm^2	61.57–65.56	64.48–71.02	64.68–77.03[1]	55.54–72.80[2]
Toughness, KJ/m^2	133.44–170.50	164.60–195.63		154.84–179.52[3]

JW: juvenile wood, MW: mature wood.

[1] Ahn (1985).

[2] So et al. 1980, Shukla et al. 1986, Forest Products Laboratory 1987, Keresztesi 1988, Kopitovič et al. 1989, Stringer 1992, Molnar 1995.

[3] So et al. 1980, Kopitovič et al. 1989, Molnar 1995.

surfaces showed many and small splinters. In toughness, juvenile wood specimens gave typical fibrous surfaces showing thin splinters, relatively small while the fractured surface in mature wood specimens was more extended and splinters were larger. This "splintering tension" type of failure is characteristic for sound specimens with typical structure and true tangential and radial surfaces. In compression test, both juvenile and mature wood specimens exhibited a "shearing" type of failure. In this type of failure, the plane rupture makes an angle of more than 45 degrees with the top of the specimens (ASTM D 143-83).

The strength values and the differences between juvenile and mature wood obtained in this study are expected to provide practical information for processors and silviculturists of black locust, leading to a more appropriate usage of the species. The presence of juvenile wood has to be taken into consideration with respect to the use of black locust for construction purposes particularly when bending and dynamic strength properties are critically important factors. Lower strength properties of juvenile wood imply that strength properties of black locust trees depend on their juvenile wood contents. Thus, timber with large percentages of juvenile wood, especially from fast-growing trees, will be less desirable for solid wood products. Considering efficiency in utilizing black locust timber, reducing the volume of juvenile wood is advantageous. This can be achieved through genetic improvement or management systems with a longer rotation age that lead to production of larger sawlogs with a lower juvenile wood content.

CONCLUSIONS

The conclusions of this study may be summarized as follows:

- Comparisons between juvenile and mature wood specimens of similar densities showed that juvenile wood of black locust had on average significantly lower static bending strength (MOR, MOE, and PMOE), dynamic strength (SWMOE), and toughness strength than the mature wood.
- Mean compressive strength did not vary significantly among juvenile and mature wood.
- Mean strength values for juvenile and mature wood were approximate to the values obtained by other authors for black locust.
- Both juvenile and mature wood specimens showed a "splintering tension" type of failure in static bending and toughness and a "shearing" type of failure in compression.
- Strength differences between juvenile wood and mature wood suggest that black locust forests can be manipulated effectively through appropriate management practices (e.g. longer rotation age) to reduce juvenile wood content.

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