Physical and mechanical properties of black locust (*Robinia pseudoacacia*) wood grown in Belgium

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Abstract: The objective of this study was to characterize black locust (*Robinia pseudoacacia* L.) wood on the basis of its physical and mechanical properties. The results are compared with those reported in the literature for English oak (*Quercus robur* L.), teak (*Tectona grandis* L. f.), and afzelia (*Afzelia* sp.), since black locust is likely to be used for the same purposes as the former species. The variations between sites, trees, and radial positions in the trunk were also studied. The physical and mechanical properties of black locust wood were evaluated on clear wood specimens taken from 27 trees distributed over five sites in Wallonia (Belgium) according to Belgian and French standards. Most of the black locust's mechanical properties are higher than those of oak and teak. The black locust is classified as a "mid-heavy" (734 kg·m^{-3}) and "half-hard" (5.22) wood type with very high resilience (17.2 J·cm^{-2}), modulus of elasticity (15 700 MPa), and tensile strength in static bending (138 MPa). Its resilience is exceptional, higher than that of teak and afzelia, while its modulus of elasticity and bending strength, which surpass those of teak, are comparable with those of afzelia. Black locust shows high total volumetric shrinkage (16%), placing it in the "nervous" class, average tangential (8.8%) and radial shrinkage (5.5%) as well as average axial compressive (63 MPa) and splitting strength (17.8 N·mm^{-1}). No technological incompatibilities would prevent the use of this wood for many value-added purposes (floor, deck, exterior woodwork, and furniture); however, significant shrinkage makes it necessary to condition the wood to its service moisture.

Résumé : Cette étude vise à caractériser le bois de robinier (*Robinia pseudoacacia* L.) sur la base de ses propriétés physiques et mécaniques. Les résultats obtenus sont comparés à ceux relevés dans la littérature pour le chêne pédonculé (*Quercus robur* L.), le teck (*Tectona grandis* L. f.) et l'afzélia (*Afzelia* sp.); le robinier étant susceptible d'être utilisé dans des emplois généralement réservés à ces essences. Les variations entre sites, arbres et positions radiales dans l'arbre sont également étudiées. Les caractéristiques physiques et mécaniques ont été évaluées au moyen d'éprouvettes normalisées provenant de 27 arbres répartis dans cinq stations en Wallonie (Belgique) suivant les normes belges et françaises en vigueur. La plupart des propriétés mécaniques du robinier sont plus avantageuses que celles du chêne et du teck. Le robinier se classe comme un bois « mi-lourd » (734 kg·m^{-3}) et « mi-dur » (5,22) qui possède des valeurs très élevées de résilience (17,2 J·cm^{-2}), de module d'élasticité (15 700 MPa) et de résistance à la rupture en flexion statique (138 MPa). Sa résistance au choc est exceptionnelle, supérieure à celle du teck et de l'afzélia, tandis que son module d'élasticité et sa résistance à la rupture plus élevés que le teck, sont comparables à l'afzélia. Le robinier montre des valeurs élevées de retrait volumique (16 %) qui qualifie son bois de « nerveux » et des valeurs moyennes de retraits tangentiel (8,8 %) et radial (5,5 %), ainsi que de résistance en compression axiale (63 MPa) et au fendage (17,8 N·mm^{-1}). D'un point de vue technologique, il n'apparaît pas d'incompatibilité d'utilisation de ce bois dans plusieurs débouchés très valorisants (parquet, terrasse, menuiserie et mobilier extérieurs); son retrait important impose toutefois de conditionner le bois à l'humidité de service.

[Traduit par la Rédaction]

Introduction

Black locust (*Robinia pseudoacacia* L.), which originally comes from the eastern United States, was introduced into Europe during the 17th century. In terms of area, the black locust is the third most important fast-growing broadleaved species planted in the world after eucalyptus and hybrid poplar (Jourez 1998). It is particularly well represented in Hungary where the stands' area was around 340 000 ha in 2001. Black locust also occupies wide areas in other countries, such as Slovakia, Romania, Italy, France, Ukraine, Bulgaria, and Russia and outside Europe, China, and Korea (Anonymous 2000). Redei (2003) confirmed that the species was likely to develop greatly in the Mediterranean countries (Italy, Turkey, and Greece) as well as in China and Korea.

According to the Walloon Permanent Forest Inventory, black locust covers approximately 2000 ha, mainly in private forests, corresponding to 0.7% of the hardwood area in Wallonia (Claessens et al. 2006). This low representation explains the lack of a specific forestry tradition dedicated to this species (Fourbisseur et al. 2003). With the exception of very few pure stands, black locust is more common in sin-

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gle-tree mixed stands. Thus, well-conformed individual trees can be found, which shows that this species has the potential to yield high-quality trees in Wallonia. Given its ecological requirements and characteristics (soil aeration, high frost susceptibility in the early growing season, and sufficient heat in summer), black locust can be introduced anywhere in Wallonia, except in the Ardennes where the climatic conditions are unsuitable for this species (Weissen 1991). This tree displays strong growth in circumference, which enables approximately 50-year rotations for timber production at the best sites in Belgium (Claessens et al. 2006).

Also, this species seems to have many advantages, whether ecological, technological, or economic ones. It can provide a response to sustainable management and forest diversification objectives linked to climate change. It provides a wood type that is likely to be used very profitably and to compete with tropical woods, without requiring chemical treatment or long-distance transport (Debenne 2007; Penneroux and Mayer 2007). Obviously those advantages are not limited to Walloon forests.

Black locust wood has very thin sapwood (3–4 years) and brownish–golden heartwood. It is a ring-porous wood with large vessels in earlywood fitted with numerous tyloses and surrounded by abundant axial circumvascular parenchyma (Jacquiot et al. 1973; Schweingruber 1990). It also presents thick-walled libriform fibres. Black locust wood is generally known as hard and heavy, these characteristics tending to increase with growth rate (Jourez 1998). This wood is considered fissile, nervous to very nervous, which limits its use. Natural durability tests realised according to CEN/TS 15083-1 (2005) have shown that black locust wood is very durable, belonging to Class 1 (Pollet et al. 2008). This exceptional natural durability predisposes it more than any other European hardwood for outdoor use. Current black locust supplies mainly consist of small-diameter trees, which are valued primarily in agricultural uses (fence posts and stakes) and parquet floors. However, given its mechanical, aesthetic, and natural durability properties, this wood is susceptible to producing logs of larger section, which are valuable for exterior woodwork and urban development.

The few studies currently available on the properties of black locust wood were carried out on trees of relatively small diameter or with a limited number of sample trees. No technological study of this species has yet been conducted in Belgium, except for a recent study dealing with natural durability (Pollet et al. 2008). Therefore, to promote the use of black locust wood for noble purposes, such as interior and exterior woodwork, it is necessary to assess its physical and mechanical properties based on a representative number of sample trees of a quality that is currently available in forests. In this context, a research project was undertaken to determine the intrinsic characteristics of black locust wood produced in Wallonia, to improve the knowledge of the production potential and the specific features of black locust trees as well as wood produced in Wallonia, and to assess the scope for processing and commercialising timber.

In particular, this paper reports on the physical and mechanical properties of this wood, as affected by sites, trees, and radial positions in a trunk. The results are compared with those reported in the literature on English oak (*Quercus robur* L.), teak (*Tectona grandis* L. f.), and afzelia (*Afzelia* sp.), since black locust is likely to be used for the same purposes as the former species.

Material and methods

Material

Five sites (mixed forests) provided the required experimental material: three were located in the province of Hainaut (western Wallonia) and two in the province of Liège (eastern Wallonia). Table 1 presents the characteristics of the stands. Their altitude varies from 100 to 250 m. They are located on silty soil with favourable drainage in Liège and Lobbes. Conversely, both stations in Mons display imperfect drainage, which could be occasionaly saturated in the case of suspended groundwater. Little information was available regarding the forestry applied in the selected sites. In fact, the presence of black locust within these stands did not arise from any forestry planned by the Nature and Forest Department but it is rather some foresters' initiative.

The experimental material was selected on black locust trees that may be suitable for noble purposes, such as interior and exterior woodwork, and that could provide good samples for technological tests to describe the characteristics of black locust resources produced in Wallonia. Five or six trees were sampled in each stand. Accordingly, the choice focused on trees with a well-balanced crown, a trunk of at least 6 m without visible defects, and a girth of more than 130 cm at breast height (1.5 m). The trees' average dendrometric characteristics (age, girth, and total height) for each site are presented in Table 2.

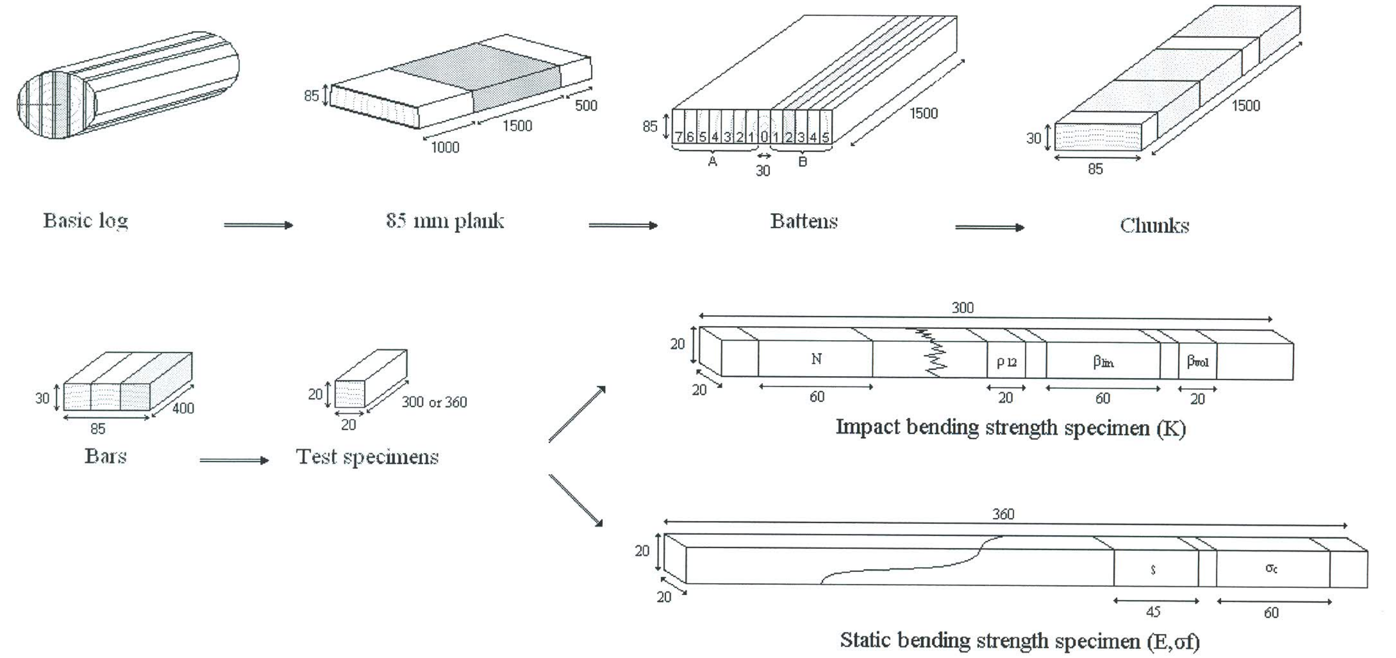
The sawing pattern of the samples is the same for the 27 trees (Fig. 1). In the 1.5 m long butt log, an 85 mm thick central plank containing the pith was cut perpendicularly to maximum radius. After natural drying under shelters, the planks were sawn from the bark and parallel to the grain into 30 mm thick battens. These were stored at standard atmosphere of 20 ± 2 °C and 65% ± 5% relative humidity to stabilize their moisture content of 12% ± 1%. The battens were then cut into chunks of a minimum length of 400 mm, optimizing the cut to discard the knots and other defects. These chunks were cut longitudinally into bars (400 mm × 30 mm × 26 mm). Four bars were selected according to criteria established by the Belgian standard NBN 225 (1956), i. e., straight grain without knots or defects. These were then planed to the final thickness and width of 20 mm × 20 mm (±0.2 mm) and the length needed for the mechanical test. For each batten (each radial position), two specimens were selected for the impact bending strength test (300 mm × 20 mm × 20 mm) and two to determine the modulus of elasticity in static bending (360 mm × 20 mm × 20 mm) according to the requirements of the standards used for these tests. The test specimens required for other qualification tests were taken from these four large samples after the impact and static bending tests were performed (Fig. 1).

To compare physical and mechanical properties of juvenile and mature wood, tests specimens were collected in position 1 near the pith and with an average age under 20 years (juvenile wood) and in position 4 close to the sapwood and with an average age over 50 years (mature wood). This is consistent with the study of Dünisch et al. (2010) whose results

Table 1. Characteristics of sampling sites.

Site	Province	Natural area	Altitude (m)	Topography
Lobbes/Moulin du bois	Hainaut	Mosan uplands	160	Slope
Mons/Clé du bois	Hainaut	Loess region	100	Plate
Mons/Sauwartan	Hainaut	Loess region	100	Plate
Seraing/Bois de la Vecquée	Liège	Mosan uplands	250	Plate
Liège/Fort de Lantin	Liège	Loess region	160	Plate

Fig. 1. Cutting scheme from log to test specimens (dimensions in mm). ρ_{12}, density at 12% moisture content; β_{vol}, total volumetric shrinkage; β_{lin}, total linear shrinkage; N, hardness; E, modulus of elasticity in static bending; σ_{f}, static bending strength; σ_{c}, compression strength; K, coefficient of resilience; S, splitting strength.



showed that the juvenile growth phase of black locust trees lasts for approximately 10–20 years.

Technological tests

The tests were performed on standardized specimens according to Belgian and French standards. Table 3 shows the dimensions of the test specimens and the standard used for each test.

Physical properties

Ring width (millimetres), density at 12% (kilograms per cubic metre), basic density (kilograms per cubic metre) and shrinkage (percent) are well-known wood characteristics. Shrinkage definition deserves special attention. According to NBN 225 (1956), total volumetric shrinkage (percent) corresponds to $(V_s - V_0)/V_0$, where V_s and V_0 are the volume of the water-saturated and anhydrous sample, respectively. Note that the French standard NF B51-006 (1985*b*) expresses the shrinkage as $(V_s - V_0)/V_s$. Total linear shrinkage (percent) represents $(L_s - L_0)/L_0$, where L_s is the length of the water-saturated sample in a given direction (either axial, radial, or tangential) and L_0 is the distance between the same points at anhydrous state. The ratio of the tangential and radial shrinkages, called anisotropy, expresses the deformation risks of wood pieces (mainly twist and cup) when they are dried below the fibre saturation point. Coefficients of volumetric, axial, radial, and tangential shrinkages (percent) express the wood dimensional change subsequent to a 1% moisture content variation (between the fibre saturation point and anhydrous state). The first of these coefficients determines wood nervousness (NF B51-002 1942), which thus only refers to size variation and not to the trend of the wood pieces to warp. The fibre saturation point (percent) occurs at a moisture content of between 20% and 40%, depending on the species (Gérard et al. 1998). It can be evaluated by computing $h[(L_s - L_0)/(L_h - L_0)]$, where L_s is the distance between two points measured in the tangential direction on a water-saturated sample, L_0 is the distance between the same points measured on the anhydrous sample, and L_h is the distance measured at moisture content h (h must be less than the moisture content at the fibre saturation point).

Mechanical properties

The following mechanical tests were performed with an Instron 5500 series testing machine. Hardness (no units) represents the wood resistance to the penetration of a hard body. $\text{Hardness}_{\text{NF}}$ is expressed by the inverse of the penetration depth generated by a 3 cm diameter steel cylinder with a load of 1000 $\text{N}\cdot\text{cm}^{-1}$ of the specimen's width according to NF B51-013 (1985*f*). For information purposes, the hardness

Table 2. Value (mean, minimum, and maximum) of dendrometric characteristics of sampled black locust (*Robinia pseudoacacia*) trees (*n*, number of sample trees).

Site	*n*	Age (years)			Girth (cm) at breast height (1.5 m aboveground)			Total height (m)		
		Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum
Lobbes/Moulin du bois	6	78	62	89	170	155	191	25	24	26
Mons/Clé du bois	5	65	58	82	157	138	187	26	24	31
Mons/Sauwartan	5	61	56	65	157	129	184	26	25	31
Seraing/Bois de la Vecquée	6	100	89	109	153	137	163	25	24	28
Liège/Fort de Lantin	5	75	63	85	175	142	210	25	24	26
Overall sample	27	76	56	109	162	129	210	26	24	31

number (hardness$_{NBN}$) was also calculated according to NBN 225 (1956) (measurement of the arrow increase when the load varies from 100 to 2000 N). These values are worth mentioning because the hardness$_{NBN}$ test is increasingly carried out on testing machines that give directly the value of the arrow cylinder penetration into the wood without having used the footprint width on the wood surface as shown in NF B51-013 (1985*f*). According to both French and Belgian standards, the steel cylinder has to be applied on the radial side (effort in the tangential direction) of the test specimen perpendicular to the grain. Hardness was also measured from the tangential face (effort in the radial direction) of some samples (originating from Seraing), since logs destined for flooring are usually through-sawn on a slab. Modulus of elasticity in static bending (megapascals) gives an idea of the wood rigidity and is determined in the zone of pure bending as the load applied at two points, parallel to the ring, is gradually increased. The distance between the support points is 320 mm and loading points are located 80 mm from these. Deformation is measured between a load of 200 and 600 N reached within 30 s. Static bending strength (megapascals) represents the maximum load that the wood can support momentarily before breaking when the ends of the test specimen are placed on a support and the sample is progressively loaded at two points parallel to the ring. The load is applied at a constant speed of 3000 N·min^{-1} until breaking, reached in 1.5 ± 0.5 min. Compression strength (megapascals) is determined by the maximum load producing a break or crack in the axial direction. The load is applied at a speed of 1170 daN·min^{-1}. Splitting strength (newtons per millimetre) expresses the degree of wood fissionability. The load is applied at a speed of 300 N·min^{-1}. Because NBN 225 (1956) indicates no preferential direction for the test, a preliminary test on sample pairs was performed both radially and tangentially to compare the resistance to splitting according to the direction of the tensile load. The direction of the tensile load chosen was the direction offering the lowest resistance. Impact bending strength or resilience (joules per square centimetre) measures the energy absorbed to cause the specimen's break in dynamic bending (shock). It was performed with a pendulum machine test; the hammer strikes the specimen at its center along the direction tangential to the ring.

Statistical analysis

Statistical analyses were carried out using Minitab 13.31. Descriptive statistics were calculated for each parameter. Afterwards, the equal of variance for nonindependent samples with a *t* test and normality with the Anderson–Darling test were verified after a possible transformation of variables. Analysis of variance was based on the generalized linear model because of the varying number of samples available for each factor level. The confidence level is 95% ($\alpha = 5\%$). These analyses were performed according to the mixed model where the sources of variation site and tree within site were considered as random factors and wood maturity as a fixed factor. The variability of the properties studied along the radial direction in the tree as well as the two parameters density and ring width was also analyzed using a trend curve and the coefficient of determination (R^2).

Table 3. Specimen dimensions and standards used for physical and mechanical tests.

Test type	Sample dimension (mm)	Standard reference
Density at 12% moisture content	20 × 20 × 20	NBN 225 1956 (NF B51-005 1985*a*)
Volumetric shrinkage	20 × 20 × 20	NBN 225 1956 (NF B51-006 1985*b*)
Linear shrinkages plus fibre saturation point	60 × 20 × 20	NBN 225 1956 (NF B51-006 1985*b*)
Hardness	60 × 20 × 20	NBN 225 1956 (NF B51-013 1985*f*)
Modulus of elasticity in static bending	360 × 20 × 20	NF B51-016 1987*b*
Static bending strength	360 × 20 × 20	NF B51-008 1987*a*
Impact bending strength	300 × 20 × 20	NBN 225 1956 (NF B51-009 1985*d*)
Axial compression strength	60 × 20 × 20	NBN 225 1956 (NF B51-007 1985*c*)
Splitting	45 × 20 × 20	NBN 225 1956 (NF B51-011 1985*e*)

Note: French standards corresponding to Belgian standards are in parentheses.

Results and discussion

Characteristics observed

Table 4 presents the average values for the studied wood properties. It also presents the values found in the literature for these characteristics for black locust alongside English oak and two exotic species, teak and afzelia. The following paragraphs refer to the values and references reported in Table 4.

The average ring width is 2.9 mm with extreme values ranging from 1 to 8.2 mm. The average density, determined at 12% moisture content, is 734 kg·m^{-3}, ranging between 529 and 857 kg·m^{-3}. Black locust belongs to the category of mid-heavy wood: this result is consistent with the values reported in the literature. Its density is higher than that observed for oak and teak and slightly lower than that of afzelia. The average basic density is 606 kg·m^{-3} with values ranging from 509 to 722 kg·m^{-3}. This value is higher than that observed in the literature for oak.

The total volumetric shrinkage mean is 15.9% (minimum = 7.9%, maximum = 23.5%). In the classification given by the standard NF B51-002 (1942), this value characterizes timber with "strong shrinkage". Babiak et al. (2000) concluded a similar grading, while other references reported "average shrinkage" for this species. Black locust has a slightly lower dimensional stability than oak. It is advisable to saw black locust rapidly after felling so that shrinkage splits do not appear in the log ends with decreasing moisture content. Natural drying is slow, and the wood needs to stay away from wind and sun. Black locust shrinkage is much higher than that observed in teak or afzelia. This shrinkage has considerable implications for material processing: (*i*) during the sawing operation, a working allowance has to be provided to account for dimensional changes during the drying process, (*ii*) quarter sawing should be preferred, (*iii*) the wood needs to be conditioned to the service moisture level before machining, and (*iv*) suitable drying schedules should be used. However, this shrinkage is not a limitation in the use of black locust lumber. Moreover, as reported in Spear and Walker (2006), it should be highlighted that, beyond the shrinkage of the wood, its movement (i.e., shrinkage when air relative humidity drops from 90% to 60% at 25 °C) and responsiveness (time needed to regain equilibrium on being transferred to another environment) should also be taken into account. A high shrinkage could thus be counterbalanced by a low movement and (or) responsiveness, as observed in European oaks. The average coefficient of volumetric shrinkage is 0.52%, ranging from 0.25% to 0.77%. This value corresponds to "nervous" wood (NF B51-002 1942). Wagenführ and Scheiber (1989) reported similar results, whereas Collardet and Besset (1992) qualified black locust wood as "very nervous". The coefficient of volumetric shrinkage of black locust is higher than that of oak, which is also a "nervous" wood type, and well above those of teak and afzelia, which are "slightly nervous" wood species. The total axial linear shrinkage is on average 0.29% with values ranging from 0.01% to 0.9%. This result exceeds the value indicated in the literature for black locust but is lower than values of axial shrinkage data for oak and teak. The value of axial shrinkage is negligible compared with the values of both radial and tangential shrinkages: it is not a factor limiting the use of this wood. The total tangential linear shrinkage average is 8.76% with values ranging from 4.0% to 14.7%. This result is lower than that reported by Babiak et al. (2000) but higher than the value given by the three other authors for this species, which is close to the values reported for oak and is above those for teak and Afzelia. The average coefficient of tangential shrinkage is 0.28% (minimum = 0.16%, maximum = 0.38%). This result is lower than that observed by Sell and Kropf (1990); the former is close to the values reported for oak and teak and higher than the values reported for afzelia. The total radial linear shrinkage is on average 5.5% with values ranging from 2.4% to 8.1%. This result is similar to values reported in the literature. Depending on the authors, the total radial shrinkage of black locust is slightly higher (Wagenführ and Scheiber 1989) or lower (Benoit 1997) than that of oak but it is higher than the values reported for teak and afzelia. The average coefficient of radial shrinkage is 0.18% (extreme values 0.08% and 0.25%). This result is lower than that reported by Sell and Kropf (1990) for the same species, close to oak values, and higher than teak and afzelia values. The anisotropy of shrinkage is 1.6. According to Bary-Lenger et al. (1999), this value can be considered as low when it is less than 1.4. Black locust anisotropy is the same as that of oak; it approximates that of afzelia and is lower than that of teak (based on the tangential and radial shrinkages given by Benoit 1997). The fibre saturation point is on average 31%, which is normal according to the classification of Sallenave (1955), with values ranging from 21% to 48% (less than 5% of the sample has a fibre saturation point above 40%). In comparison, the fibre saturation point is slightly higher than that found for oak (Bary-Lenger et al. 1999).

Table 4. Physical and mechanical properties evaluated on standardized samples of black locust wood grown in Wallonia.

	Present study, black locust			Literature			
Characteristic	*n*	Mean	SD	Black locust (*Robinia pseudoacacia*)	English oak (*Quercus robur*)	Teak (*Tectona grandis*)	Afzelia (*Afzelia* sp.)
RW (mm)	446	2.99	1.2				
ρ_{12} (kg·m^{-3})	446	734	46	580–900[k], 650–900[e]	710[d]	700[d]	750[d]
ρ_0 (kg·m^{-3})	446	606	35		535[g]		
β_{vol} (%)	444	15.99	2.8	11.4–12.2[k], 14–15[e], 17.4[b], 11.4[h]	12.2–15.0[k]	6.9–9.4[k]	6.4–7.2[k]
Coefficient β_{vol} (%)	437	0.52	0.09	0.4[k], 0.55–0.75[e]	0.45[k]	0.24–0.32[k]	0.23[k]
β_{ax} (%)	441	0.29	0.179	0.1[h,k], 0.16[a]	0.4[k]	0.4–0.6[k]	
β_{rad} (%)	439	5.50	0.97	4.4[h,k], 6.08[2], 5.3[a]	3.5–4.7[k], 6.0[d]	2.1–3.0[k], 3.9[d]	2.2–2.7[k], 3.1[d]
Coefficient β_{rad} (%)	437	0.18	0.03	0.20–0.26[j]	0.18–0.22[j]	0.13–0.15[j]	0.11–0.13[j]
β_{tang} (%)	441	8.76	1.7	6.9[h,k], 10.6[b], 6.67[a]	7.7–10.0[k], 9.3[d]	4.2–5.8[k], 7.3[d]	3.6–4.3[k], 4.6[d]
Coefficient β_{tang} (%)	439	0.28	0.04	0.32–0.38[j]	0.28–0.35[j]	0.24–0.29[j]	0.17–0.22[j]
T/R	438	1.6	0.23	1.26[a]	1.6[d]	1.9[d]	1.5[d]
FSP (%)	441	31	4.6		28[c]		
N_{NBN}	442	2.38	0.28				
N_{NF}	442	5.22	1.0	9.5[j]	3.3–3.7[j]	4[j]	7.4[j]
E (MPa)	448	15700	2100	9000–13600[k], 13600[i], 11000–15700[j], 12631–13384[i], 14413[h]	11700–13200[k]	9500–13200[k]	12000–22000[k]
σ_f (MPa)	443	138	20	103–169[k], 140[e], 118–145[j], 152[i], 136.4[f]	88–105[k], 97[d]	58–109[k]	110–120[k], 173[d]
σ_c (MPa)	448	63.3	6.9	62–81[k], 70[e], 58–72[j], 72.5[f]	61–67[k], 58[d]	42–59[k], 70[d]	70–79[k], 74[d]
K (J·cm^{-2})	447	17.21	5.5	11.2–13.5[j], 17.5[i]	6.2[d]	4[d]	6.8[d]
S (N·mm^{-1})	446	17.80	2.9				

Note: Results are compared with values found in the literature for black locust, oak, teak, and afzelia. RW, ring width; ρ_{12}, density at 12% moisture content; ρ_0, basic density; β_{vol}, total volumetric shrinkage; coefficient β_{vol}, coefficient of total volumetric shrinkage; β_{ax}, total axial linear shrinkage; β_{rad}, total radial linear shrinkage; coefficient β_{rad}, coefficient of total radial linear shrinkage; β_{tang}, total tangential linear shrinkage; coefficient β_{tang}, coefficient of total tangential linear shrinkage; T/R, anisotropy of shrinkage; FSP, fibre saturation point; N_{NBN} and N_{NF}, hardness according to NBN 225 (1956) and NF B51-013 (1985*f*), respectively; *E*, modulus of elasticity in static bending; σ_f, static bending strength; σ_c, compression strength; *K*, coefficient of resilience; *S*, splitting strength.

[a] Adamopoulos and Voulgaridis (2003).

[b] Babiak et al. (2000).

[c] Bary-Lenger et al. (1999).

[d] Benoit (1997).

[e] Collardet and Besset (1992).

[f] Forest Products Laboratory (1987).

[g] Jourez et al. (2003).

[h] MSZ 6786 (1966), in Stringer (1992).

[i] Nemeth et al. (2000).

[j] Sell and Kropf (1990).

[k] Wagenführ and Scheiber (1989).

The hardness$_{NF}$ value displays an average value of 5.22 with values ranging from 2.72 to 8.58. This result puts black locust wood in the "half-hard" category (NF B51-002 1942). The literature does not provide much information to compare the hardness of different species but generally considers black locust as a "very hard" wood. Although black locust remains in the same class of "half-hard" woods, its hardness is higher than that of oak and teak, but it remains below that of afzelia. Surface hardness is an important characteristic in woodwork, especially in flooring (floors and decks). The variance analysis with one factor of classification (face) on the preliminary test shows that the hardness$_{NF}$ measured on the tangential face is significantly higher than the hardness$_{NF}$ measured on the radial side (Table 5). The hardness$_{NBN}$ value is 2.38 with extreme values ranging from 1.64 to 3.17. No reference was found in the literature on black locust hardness$_{NBN}$ obtained according to this standard. The average modulus of elasticity in static bending is 15 700 MPa, ranging from 10 500 to 22 600 MPa. Black locust has a high modulus of elasticity. The values measured in this study are higher than those mentioned in the literature for this species as well as those of oak and teak. The rigidity of black locust is similar to that of afzelia. This high value of modulus of elasticity is interesting for structural purposes. The static bending strength displays an average value of 138 MPa (minimum = 44 MPa, maximum = 186 MPa). This result is consistent with the literature. Only Nemeth et al. (2000) obtained a higher value measured on 35- to 40-year-old trees, younger than the trees in our study. The static bending strength of black locust is higher than those of oak and teak and, depending on the authors, higher (Wagenführ and Scheiber 1989) or lower (Benoit 1997) than that of afzelia. The average axial compression strength is 63.3 MPa with extreme values between 47.3 and 84.3 MPa. According to this value, the black locust is in the "higher" category (NF B51-002 1942). The compression strength is close to those of oak and teak and slightly lower than that of afzelia. The resilience average value coefficient is 17.21 J·cm^{-2} with values ranging from 4.82 to 39.49 J·cm^{-2}. The resilience coefficient obtained in this study, higher than that reported by Sell and Kropf (1990), is consistent with the result obtained by Nemeth et al. (2000) in Hungary. This result ranks black locust wood as "extremely resilient" (Steiger 1974), slightly more than hickory, also known for its resilience and often used for tool handles (Sell and Kropf 1990), and much more than oak and afzelia ("resilient" woods) or than teak ("fragile" wood). Black locust wood was commonly used to make cartwheels. The splitting average value strength to a load applied in the tangential direction is 17.80 N·mm^{-1}, ranging from 10 to 27 N·mm^{-1}. The variance analysis with one factor of classification (direction of the load) shows that splitting strength corresponding to a radially oriented effort is significantly higher than that obtained with a tangentially oriented effort (Table 5). No value was found in the literature regarding black locust fissionability. However, Collardet and Besset (1992) reported a relative fissionability of locust wood so that drilling holes is required before nailing and screwing, as is the case for oak.

Analysis of variation sources

Regarding most physical and mechanical properties, statistical analyses show a significant difference between trees. Only a few properties are influenced by the site factor (ring width, axial and tangential shrinkages, and coefficients of volumetric and radial shrinkage). Nepveu (1994) suggested that the variability between trees is the consequence of several causes, i.e., individual, genetic, and site conditions. Because of the lack of information concerning the history of the stands, and because of the large variation in tree age and size, even within a given site, the impact of the site and the tree revealed by statistical analysis is difficult to interpret.

The correlation between ring width and density was significant ($r = 0.164$). As has been reported by many authors, the relationship between ring width and density known for ring-porous hardwood, such as oak and black locust, was also underlined in our study: a decrease in ring width induces a decrease in density (Nepveu 1994). In their study concerning European oaks, Zhang et al. (1993) explained that the percentage of latewood, and therefore the density, increases significantly with ring width, whereas earlywood width varies relatively less. Nevertheless, Adamopoulos et al. (2010) reported that "latewood percentage and ring width exert an inconsistent influence on density of black locust wood". Several radial patterns in wood density variations have been reported (Panshin and De Zeeuw 1980). According to Zobel and Van Buijtenen (1989), most ring-porous hardwoods tend to have a high density near the pith, which first decreases and then increases, to a certain extent, towards the bark. In our study, the variation in density and ring width decreases from pith to bark. A recent study on black locust wood also showed that the ring width of old-growth trees (up to 85 years) and young trees (11 years) decreased significantly from pith to cambium (Dünisch et al. 2010). However, Adamopoulos and Voulgaridis (2002) reported that ring width in ten 18- to 37-year-old black locust trees increased in the first five to nine growth rings from the pith and then gradually decreased. Stringer and Olson (1987) and Stringer (1992) showed that density increases radially from the pith to the cambium in ten 10- to 12-year-old black locust trees.

The physical and mechanical properties increased significantly and linearly along with density, despite the relatively large variability in the data set (R^2 ranging from 0.08 to 0.35). The relationship between the values of various physical and mechanical properties and the ring width is less significant (R^2 ranging from 0.05 to 0.27). These relationships are no longer significant when only the juvenile wood (samples taken in position 1) or the mature wood (samples taken in position 4) is considered. Table 6 presents the results of statistical analyses conducted on this subsample of juvenile and mature wood. The values observed in the juvenile wood are significantly higher than those in mature wood, except axial shrinkage (β_{ax}) for which the value in juvenile wood is significantly lower than that in mature wood and basic density (ρ_0), surface hardness (N), axial compression (σ_c), and resilience (K) for which no significant difference was evidenced between juvenile and mature wood. The paradoxal results showing a significant effect of wood maturity on density and no effect on basic density can be understood as a consequence of the higher volumetric shrinkage observed in juvenile wood.

Figure 2 shows the parameters' relative variation expressed as a percentage of the value observed in position 1 (near the

Table 5. Hardness (NF B51-013 1985*f*) and splitting (NBN 225 1956) values of preliminary tests in radial and tangential directions in black locust (*Robinia pseudoacacia*) (*P* values were estimated with a general linear model with a significance level of $P < 0.05$).

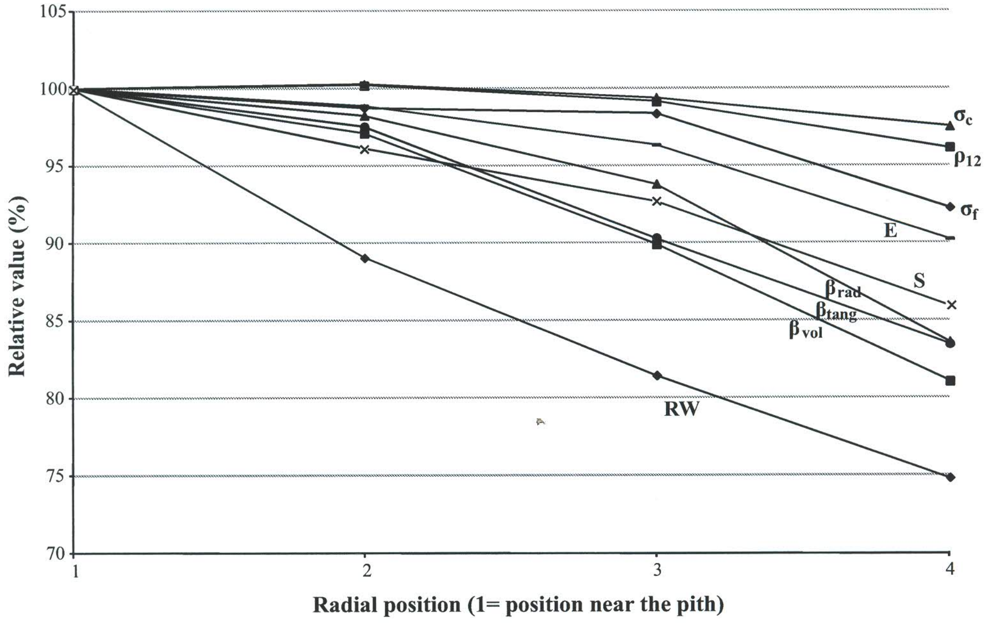
	Radial			Tangential			
	n	Mean	SD	*n*	Mean	SD	*P*
Hardness	94	**6.66**	1.4	97	**6.13**	0.95	**0.003**
Splitting ($N \cdot mm^{-1}$)	39	**20.65**	3.85	39	**16.56**	2.57	**0.000**

Table 6. Comparison of mean and standard deviation values of various properties observed in mature and juvenile black locust (*Robinia pseudoacacia*) wood.

	Mature wood		Juvenile wood		*P*		
Property	Mean	SD	Mean	SD	Site	Tree	Wood maturity
RW (mm)	2.6	0.875	3.4	1.58	**0.005**	**0.000**	**0.000**
ρ_{12} ($kg \cdot m^{-3}$)	718.4	48.22	746.4	40.7	0.691	**0.000**	**0.000**
ρ_0 ($kg \cdot m^{-3}$)	598.2	33.69	605.9	33.05	0.768	**0.000**	0.13
β_{vol} (%)	14.1	2.5	17.4	2.59	0.751	**0.000**	**0.000**
Coefficient β_{vol} (%)	0.47	0.087	0.55	0.087	**0.000**	**0.002**	**0.000**
β_{ax} (%)	0.31	0.18	0.27	0.19	**0.019**	**0.000**	**0.036**
β_{rad} (%)	4.9	0.8	5.9	0.91	0.069	**0.000**	**0.000**
Coefficient β_{rad} (%)	0.17	0.03	0.19	0.024	0.063	**0.031**	**0.000**
β_{tang} (%)	7.8	1.56	9.4	1.63	**0.049**	**0.000**	**0.000**
Coefficient β_{tang} (%)	0.27	0.043	0.3	0.037	0.151	**0.000**	**0.000**
N_{NF}	5.21	1.12	5.17	0.92	**0.026**	**0.000**	0.159
E (MPa)	14762	1981	16354	2031	0.379	**0.000**	**0.000**
σ_f (MPa)	130	22.52	141	18.81	0.482	**0.000**	**0.013**
σ_c (MPa)	62.1	7.4	63.8	6.5	0.151	**0.000**	0.853
K ($J \cdot cm^{-2}$)	16	4.4	17.1	5,535	0.507	**0.000**	0.067
S ($N \cdot mm^{-1}$)	16.4	2.46	19.15	3.25	0.098	**0.000**	**0.000**

Note: The number of observations varies from 75 to 78 in mature wood and from 79 to 83 in juvenile wood. Since of weak interest, the mean and SD values are obviously not provided for sites and trees. *P* values associated with site, tree (site), and wood maturity were estimated with a general linear model (significance level of $P < 0.05$). Refer to the legend of Table 4 for properties.

Fig. 2. Mean values of various characteristics, expressed as a percentage of the value obtained in position 1 (near the pith), depending on the radial direction in the tree. RW, ring width; ρ_{12}, density at 12% moisture content; β_{vol}, total volumetric shrinkage; β_{rad}, total radial linear shrinkage; β_{tang}, total tangential linear shrinkage; *E*, modulus of elasticity in static bending; σ_f, static bending strength; σ_c, compression strength; *S*, splitting strength.



pith) according to the radial position. All of the parameters decrease from position 1 to position 4, except axial shrinkage (β_{ax}), which increases significantly, and surface hardness (N) and resilience (K), which do not vary significantly with radial position (not presented on Fig. 2). The ring width (RW), shrinkages (β_{vol}, β_{tang}, and β_{rad}), and splitting (S) show a considerable decrease, from 15% up to 25%. The modulus of elasticity (E) and the static bending strength (σ_f) decrease less, approximately 10%. Finally, the axial compression strength (σ_c) and density (ρ_{12}) decrease only slightly (<5%) towards outer locations. Intratree variations according to the radial position are difficult to interpret, probably due to the fact that age and size are very different from tree to tree.

Apart from these few details on the radial variation in density and ring width within tree, little information currently exists on intratree variations in mechanical properties in black locust. Adamopoulos et al. (2007) studied the variation in mechanical properties in the juvenile and mature wood of five 21- to 37-year-old black locust trees. Contrary to our results, they showed that the values of modulus of elasticity, the static bending strength, and the resilience observed in juvenile wood are significantly lower than those in mature wood. This trend has not been shown for the values of the axial compression strength. The authors explained that the lower values obtained in the juvenile wood could be attributable to differences in anatomical and chemical properties rather than to differences in density of test specimens. Taking into account the anatomical characteristics would certainly refine the understanding of observed radial variations within tree, as suggested by Polge and Keller (1973) in their study on oak.

Conclusion

In Belgium, black locust wood shows moderate to high mechanical properties but poor dimensional stability. Compared with oak and teak, black locust demonstrates higher or similar physical and mechanical properties. Only shrinkages are less favourable. Possible uses for black locust seem so multiple: among noble purposes, those requiring both mechanical strength and high natural durability such as framing doors and windows, decks, and outdoor furniture, for instance. Its own weight apart, black locust could be suitable for structural uses (traditional carpentry and structural apparent woodwork). Black locust nervousness can be controlled by drying wood to its mean equilibrium moisture content under use conditions. Then, a finishing treatment can be applied to slow down further exchanges of moisture and to reduce wood movement.

The statistical analyses evidenced significant differences between sites for a few properties and between trees for all of them. Moreover, these analyses showed that several properties are significantly lower in mature wood. In particular, lower shrinkages are a plus point for exterior woodwork. Relationship between density, ring width, and most studied characteristics suggests that it should be possible to increase significantly circumferential tree growth, which would be an extra advantage for this species.

No substantial offer of black locust wood is expected on the Belgian market; its offer will stay too low for timber of such quality. Nevertheless, it was important to demonstrate that this species deserves the interest that has recently arisen. Forest managers should be encouraged to grow more black locust trees in suitable sites.

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