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Fiber dimensions, physical and mechanical properties of five important hardwood plants

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Abstract

The wood fiber dimensions (fiber length, fiber width, cell wall thickness and lumen diameter), physical (oven-dry density) and mechanical properties (modulus of rupture, modulus of elasticity, compression parallel to the grain) of five hardwood plants such as oak (*Quercus castaneaefolia*), beech (*Fagus orientalis*), hornbeam (*Carpinus betulus*), alder (*Alnus glutinosa*) and ash (*Fraxinus excelsior*) were investigated. These trees are important plant species for wood production in Iran. Five normal trees of each plant species were selected in north part of Iran and log samples were cut between 2-4 m of stem height to determine the mentioned properties. The relationship between physical properties (wood density) and anatomical characteristics with mechanical strength traits were determined by Pearson correlation. Results of analysis of variance (ANOVA) indicated that the types of plant species had significant effect on the different wood properties. The highest of wood density, modulus of rupture, modulus of elasticity and compression parallel to the grain values were found in hornbeam, beech, ash, and oak, respectively. The lowest of mechanical strength properties was found in alder wood.

Keywords: Fiber, hardwood, log, plant, hornbeam, beech, ash, oak, Iran

Introduction

In hardwood, the cells that make up the anatomical organization are the vessels, fibres, parenchyma cells and the wood rays. Fibres are the principal element that is responsible for the strength of the wood (Panshin & Zeeuw, 1980). Wood density is an important wood property for both solid wood and fibre products (De Guth, 1980). It is affected by the cell wall thickness, the cell diameter, the earlywood to latewood ratio and the chemical content of the wood (Cave & Walker, 1994). Panshin and de Zeeuw (1980) reported that density is a general indicator of cell size and is a good predictor of strength, stiffness, ease of drying, machining, hardness and various paper making properties (Panshin & Zeeuw, 1980). Brazier and Howell (1979) also expressed the opinion that density is one of the most important properties influencing the use of a timber. They emphasized that it affects the technical performance of wood and in particular the strength and processing behavior of sawn wood and veneer, and the yields of wood fibre in pulp production (Brazier & Howell, 1979). Philips (1941) reported that wood density is a measure of the cell wall material per unit volume and as such gives a very good indication of the strength properties and expected pulp yields of timber (Philips, 1941). Basic density is closely related to end-use quality parameters such as pulp yield and structural timber strength (Harvald & Olesen, 1987). Cown (1992) reported that the density of wood is recognized as the key factor influencing wood strength (Cown, 1992). Indeed according to Schniewind (1989) much of the variation in wood strength, both between and within species, can be attributed to differences in wood density (Schniewind, 1989).

One of the most important factors that affect the mechanical properties of timber is its moisture content. The strength of clear timber rises approximately linearly as moisture content decreases from the fiber saturation point and may increase 3-fold when the oven-dry state is reached. However, toughness decreases with drying. At moisture contents of around 15%, the strength would be approximately 40% higher than that of the saturated state, depending on the type of wood. The mechanism of the strength increase is similar to that of shrinkage in concrete; the contraction results in decreased inter-fiber spacing and, therefore, stronger bonding between fibers (Taylor, 2002; Baradan, 2003; Widehammar, 2004).

The presence of defects such as checks, cross grain, knots, pitch pockets, shakes, and warp causes a considerable reduction in the mechanical properties of the timber. Thus the presence of defects should be considered in the design of structural members. For example, beams should be positioned with the knots in the compression region if possible, since knots exert a weakening effect in tension (Keyser, 1986).

The Hyrcanian forests (north of Iran) comprise a little more than 2.1 million hectares of almost 100 percent hardwood species, primarily hornbeam (*Carpinus betulus*, 30%) and beech (*Fagus orientalis,* 23.63%). Other marketable species include iron wood (*Parrotia persica*, 10.54%), false lote-tree (*Diospyrus lotus*, 8.5%), oak (*Quercus castanefolia,* 7.65%), alder (*Alnus subcordata* and *Alnus glutinosa*, 4.9%), maple (*Acer insigne* and *Acer leatum*, 4.27%), large leaved lime (*Tiliarubra*, 1.03%) and ash (*Fraxinus excelsior*, 0.49%).These species were used for timber, pulp and paper, and wood production in Iran and hence the present investigation.

The objectives of this study were: (a) to investigate the variation of physical, anatomical and mechanical properties in five hardwood plant species such as hornbeam, beech, oak, alder and ash, and (b) to examine the relationship between wood density and anatomical properties with mechanical properties among the plants.

Materials and methods

Materials

In this research, the anatomical, physical and mechanical properties of 5 plant species were investigated. These species are hornbeam (*Carpinus betulus*), beech (*Fagus orientalis*), oak (*Quercus castaneaefolia*), alder (*Alnus glutinosa*) and ash (*Fraxinus excelsior*). Hornbeam, beech and alder are diffuse porous hardwoods and the beech and ash wood is ring porous hardwoods. From each of species, 5 normal tress were selected in north of Iran (Nowshahr region). Logs were cut between 1-3 m height of stem trees. All of testing samples were taken from mature wood for different wood properties. The age demarcation point between juvenile and mature wood was estimated at around 25 years (Clark & Saucier, 1989). In studied region, the annual rainfall and annual average temperature was 1300 mm and 16 °C, respectively. These trees have been grown for 40-46 years at this site.

Methods

Fiber properties: A disc, 5 cm in thickness, was from each log for evaluation of anatomical properties. In order to examine the anatomical properties (fiber length, fiber width, cell wall thickness, and lumen diameter), specimens (N=50 for each species) from mature wood were prepared. Samples for fiber dimensions measurements were macerated in a mixture (1:1) of 30% of hydrogen peroxide and glacial acetic acid in a 64°C oven for 24 hours (Franklin 1964 modified method in order to lessen the reduction in fiber length). After maceration samples were washed with distilled water, and the 2 × 2 × 10 mm splinters were shaken gently in the distilled water until the individual fibers of the wood were separated. From each splinter 2 slides were prepared and 10 whole fibers on each slide were measured. All of fibers were determined by Leica Image Analyzer System.

Physical properties (oven-dry density): A disc, 5 cm in thickness, was collected from each log for evaluation of physical properties. In order to determine the physical properties, samples with dimensions of 2 ×2 × 2 cm were prepared according to ASTM-D143 (ASTM D143, Standard Methods of Testing Small Clear Specimens of Timber). The specimens (N= 50 for each species) were oven dried at 103 ± 2 °C to 0% moisture content. After cooling in desiccators, the oven-dry weights of the specimens were measured. Then the dimensions in all three principal directions were determined with a digital caliper to the nearest 0.001 mm. The oven-dry density was calculated using the following equation: $D_0 = (M_0 / V_0) \times 100$

Where D_0, M_0 and V_0 are the oven dried density, weight and volume of specimens respectively.

Mechanical properties: According to the ASTMD143-94 standard (second method), the sample dimensions were 25 × 25 × 410 mm for static bending strength tests, such as modulus of rupture (MOR) and modulus of elasticity (MOE), and 25 × 25 × 100 mm for compression parallel to the grain (maximum crushing stress, MCS). The prepared samples (N= 50 for each species) were then conditioned in a room at a temperature of 20°C and 65 ± 5% relative humidity until the specimens reached an equilibrium moisture content of about 12%. The wood density at 12% moisture content was 656, 633, 755, 535, and 688 Kg m^{-3} for oak, beech, hornbeam, alder and ash wood, respectively. The moisture content of all samples was 12-13% in this test. The load was applied in the tangential direction. The mechanical strength properties were calculated using the following equation:

$MOR = 3 \times P_{max} \times l / 2 \times b \times h^2$

$MOE = P \times l^3 / 4 \times D \times b \times h^3$

Where P = load at the limit of proportionality (kN); P_{max} = maximum load (KN), l = span of the test specimen (mm), b = breadth of the test specimen (mm), h = depth of the test specimen (mm) and D = deflection at the limit of proportionality (mm).

$\sigma_{cpl} = P_{max} / A$

Where σ_{cpl} = MCS (MPa), P_{max} = maximum crushing load at break point (KN) and A = area of cross section of the specimen on which force was applied (mm^2).

Statistical analysis

To determine the effect of hardwood species on anatomical (fiber length, fiber width, cell wall thickness and lumen diameter), physical (oven-dry density) and mechanical properties (modulus of rupture, modulus of elasticity, and compression parallel to the grain), statistical analysis was conducted using the SPSS programming method in conjunction with the analysis of variance (ANOVA) techniques. Duncan's multiple range test (DMRT) was used to test the statistical significance at the α = 0.05 level. The Pearson correlation was used to analyze the relationship among the wood's various properties.

Results and discussion

Fiber dimensions properties

Analysis of variance indicated that the species had significant difference on anatomical properties. Highest and lowest of fiber length was found in hornbeam and ash wood. The mean of fiber width is alder wood is more than other studied species. The cell wall thickness in alder wood is less and higher in beech wood, while the value of lumen diameter in Oakwood is low (Table 1).

Physical properties (wood density)

The oven-dry density value for five hardwood species

Table 1.The mean fiber properties in five studied species in Iran

Species	Fiber length	Fiber width	Cell wall thickness	Lumen diameter
Hornbeam	1.62 c	28.53 c	6.64 c	15.25 c
Beech	1.21 b	22.76 b	7.61 d	7.54 a
Oak	1.15 b	17.3 a	5.35bc	6.6 a
Alder	1.17 b	32.66 d	2.7 a	27.26 d
Ash	0.978 a	20 b	4.1 b	11.8 b

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Table 2. The relationship between wood different properties

	D_0	MOR	MOE	CPG	FL	FW	CWT	LD
D_0	1							
MOR	0.709^{**}	1						
MOE	0.792^{**}	0.979^{**}	1					
CPG	0.693^{**}	0.461^{*}	0.425^{*}	1				
FL	-0.556^{**}	-0.502^{*}	-0.418^{*}	-0.777^{**}	1			
FW	-0.344	-0.705^{**}	-0.713^{**}	-0.151	-0.155	1		
CWT	0.576^{**}	0.690^{**}	0.589^{**}	0.883^{**}	-0.859^{**}	-0.301	1	
LD	-0.529^{**}	-0.855^{**}	-0.813^{**}	-0.528^{**}	0.286	0.894^{**}	-0.696^{**}	1

D_0: oven-dry density, MOR: modulus of rupture, MOE: modulus of elasticity, CPG: compression parallel to the grain, FL: fiber length, FW: fiber width, CWT: cell wall thickness, LD: lumen diameter

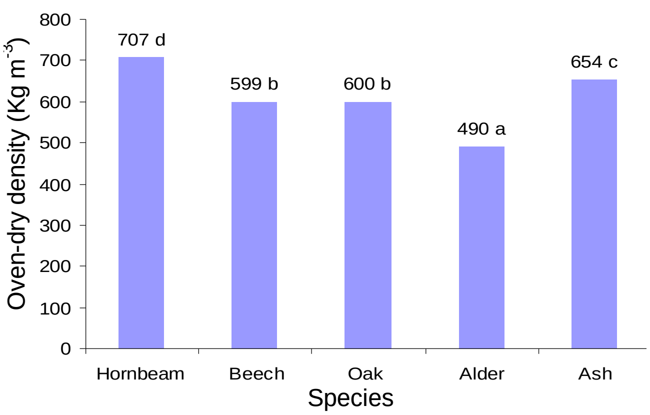
such as hornbeam (707 Kg m^{-3}), beech (599 Kg m^{-3}), oak (600 Kg m^{-3}), alder (490 Kg m^{-3}), and ash (654 Kg m^{-3}) is shown in Fig. 1. The analysis of variance (ANOVA) showed that there is significant difference between types of species and wood oven-dry density. The highest and lowest of wood density were found in hornbeam and alder wood, respectively. Within-diffuse porous hardwood, the highest of wood density were found in the hornbeam. In Turkey, the value of oven-dry density in alder and beech wood were determined 454 and 645 Kg cm^{-3} by (Guler & Ay, 2001; Bektas *et al.,* 2002).

Mechanical properties

The modulus of rupture value for five hardwood species such as hornbeam (111.01 MPa), beech (124.08 MPa), oak (109.11 MPa), alder (82.16MPa), and ash (122.63 MPa) is shown in Fig. 2. The analysis of variance (ANOVA) showed that there is significant difference between types of species and modulus of rupture. The highest and lowest of modulus of rupture were found in beech and alder wood, respectively.

The modulus of elasticity value for five hardwood species such as hornbeam (11.60 GPa), beech (12.32 GPa), oak (11.13 GPa), alder (7.48 GPa), and ash (13.32 GPa) is shown in Fig. 2. The analysis of variance (ANOVA) showed that there is significant difference between types of species and modulus of elasticity. The highest and lowest of modulus of elasticity were found in ash and alder wood, respectively.

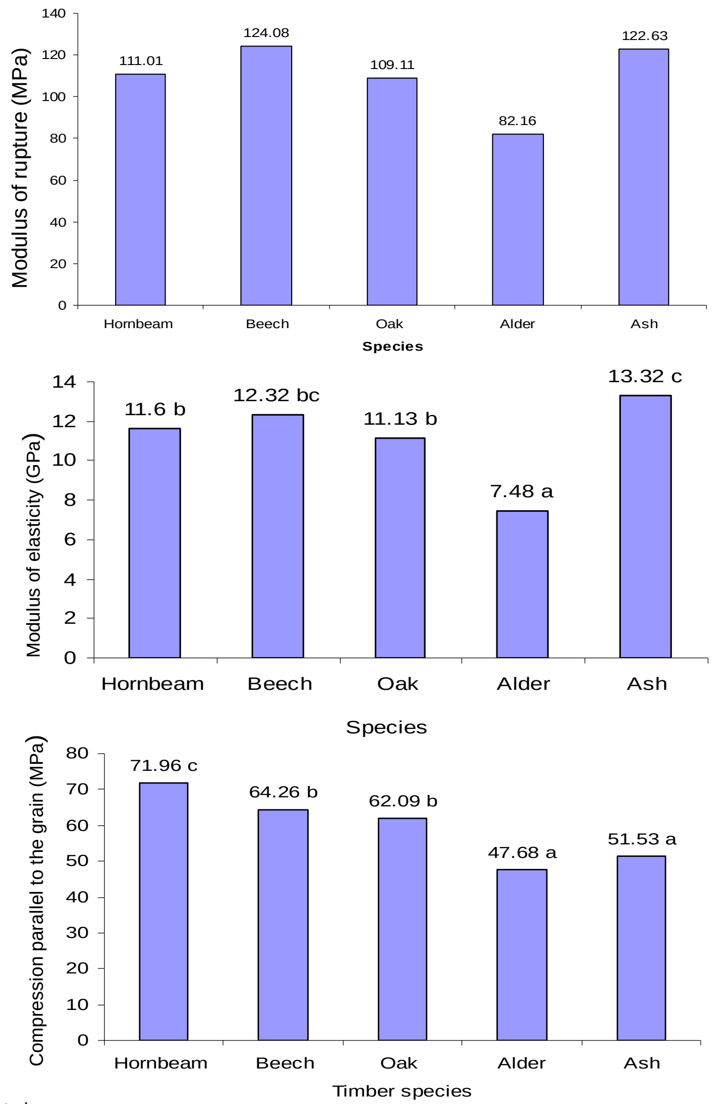
Fig. 1. Oven-dry wood density in five plant species



The compression parallel to the grain value for five hardwood species such as hornbeam (71.96 MPa), beech (64.26 MPa), oak (62.09 MPa), alder (47.68 MPa), and ash (51.53 MPa) is shown in Fig. 2. The analysis of variance (ANOVA) showed that there is significant difference between types of species and compression parallel to the grain. The highest and lowest compression parallel to the grain were found in ash and alder wood, respectively.

Overall, wood species had significantly effect on anatomical, physical, mechanical properties. The reason of these variations at different species can be related to types of hardwood timbers. Hornbeam, beech and alder are diffuse porous hardwoods and the beech and ash wood are ring porous hardwoods (Parsapajouh, 1998). These species have different structure and chemical properties.

Fig. 2. The mechanical strength properties of five hardwood species



Relationship between wood density-fiber properties and mechanical features

The relationships between oven-dry density and mechanical properties are shown in Table 2. Results showed that there are positive correlation between wood density and MOR (R^2=0.709), MOE (R^2=0.792), and compression parallel to the grain (R^2=0.693) at species levels. The relationship between wood density and mechanical properties within a species has been studied by many researchers. A significant linear relationship between wood density and mechanical properties of timber was reported by (Shepard & Shottafer, 1992; Zhang, 1995). Zhang (1997) showed that modulus of rupture and the maximum crushing strength in compression parallel to the grain are most closely and almost linearly related to wood density, whereas modulus of elasticity is poorly and least linearly related to wood density (Zhang, 1997). The density of timber is a function of both cell wall thickness and lumen diameter and there exists correlation between strength and density of timber. Thus density is the best predictor of timber strength (Dinwoodie, 2000).

There are positive relationship between wood density and mechanical strength properties with biometry features (fiber length, fiber width, cell wall thickness), and negative relationship between wood density and mechanical strength with fiber lumen diameter at the five species levels. These results correlate with previously reported by Bisset *et al.* (1951). Others relationships between wood properties are shown Table 2.

Conclusions

Analysis of variance (ANOVA) indicated that the hardwood plant species had significant difference on wood density, fiber properties and mechanical strength properties. The oven-dry density, compression parallel to the grain in hornbeam wood is higher than other hardwood species, while the values of mentioned properties in alder wood are low. The modulus of rupture in beech wood is higher than other timber species while the value of MOR in alder wood is low. The highest and lowest of modulus of elasticity was recorded in ash wood and alder wood, respectively. There are positive relationships between wood density and fiber properties with mechanical strength properties at five species levels. The fiber length, fiber width, cell wall thickness and lumen diameter is higher in hornbeam, alder, beech and alder wood than other species, respectively.

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