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Physical and Mechanical Properties of Paulownia Wood (*Paulownia fortunei)* in North of Iran

Majid Kiaei

Department of Wood and Paper Science and Technology, Chaloos Branch,
Islamic Azad University, Chaloos, Iran

Abstract: Physical and mechanical characteristics of Iranian cultivated paulownia (*Paulownia fortunei* L.) wood were investigated. Physical properties including oven-dry density (0.261 g cm^{-3}), basic density (0.242 g cm^{-3}), air-dry density (0.291 g cm^{-3}), volumetric shrinkage (7.54%), percentage of cell wall (17.41%), porosity (82.59%), fiber saturation point (31.15%) and maximum moisture contents (349.72%) and the mechanical properties including modulus of rupture (41.07 MPa), modulus of elasticity (3.74 GPa) and compression strength parallel to the grain (14.61 MPa) were determined. The species is not suitable for structural applications due to low wood density and poor mechanical properties.

Key words: *Paulownia fortunei* L. · Physical properties · Mechanical properties

INTRODUCTION

Paulownia is a fast-growing shade tree native to China and South-East Asia that is grown commercially for the production of hardwood timber [1]. Paulownia wood has also been investigated as a promising raw material for the production of chemical pulp [2-6]. The most suitable species of paulownia for this purpose is *Paulownia fortunei*, with an average fiber length of 1.42mm [3]. This species is characterized by its fast development and a uniform and regular growth [4, 7]. In China and some of the other Asian countries, paulownia wood is used for a variety of applications such as furniture, construction, musical instrument, shipbuilding, aircraft, packing boxes, coffins, paper, plywood, cabinetmaking and molding.

P. fortunei was imported into Iran from China and was planted at different spacings in the forest of the north (Iran) for wood production. This exotic species has shown good adaptation to these environmental conditions. For example, the height and diameter of five years old tress paulownia at the Shastkalate-Grogan (Gloestan province) region are 10.24 m and 23.5 cm, respectively [8]. To use this material property and efficiently, it is necessary to know its different wood properties.

Wood density is an important wood property for both solid wood and fibre products in both conifers and hardwoods [9]. 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 [10]. In this direction, there is little information about the physical properties of paulownia wood, refer to Akyildiz and Kol 2010 (*P. tomentosa*) [11] and Anonymous 1986 (*P. elongata* and *P. fortunei*) [12] while there is no information available about the physical properties of *Paulownia fortunei* wood in Iran.

Modulus of rupture (MOR) and modulus of elasticity (MOE) are important properties for the use of wood as a structural material. MOR is an indication of the bending strength of a board or structural member and MOE is an indication of the stiffness. The correlation of MOR and MOE with specific gravity is typically very strong, as reported by Zhang (1997) for hardwood and softwood [13]. The objectives of this study are to examine the physical and mechanical characteristics of Iranian cultivated Paulownia fortune.

MATERIALS AND METHODS

Six trees of *Paulownia fortunei L.* were harvested from a plantation in the north of Iran (Fakhrabad Experimental Forest-Lashtnesha-Guilan province). The experimental area is located at an average altitude of 20 m. The mean annual precipitation of experimental area is 1347 about mm/year; the yearly average temperature is 17°C. The age, height and diameter of trees were 5

Corresponding Author: Majid Kiaei, Department of Wood and Paper Science and Technology, Chaloos Branch, Islamic Azad University, Chaloos, Iran. E.mail: mjd_kia59@yahoo.com

years-old, 7.2 meter and 41 cm. All climatic data were obtained from Iranian meteorology station located very near to the research area. Logs were cut between 2 and 4 m height of trees to obtain samples for different wood properties. North directions of logs were marked.

Physical Properties: A disk, 5 cm in thickness, was obtained from each log for evaluation of physical properties. Lumbers boards at 25 mm thickness were radially sawn in the four cardinal directions of radius. Then test specimens were cut from these lumbers dimensions of 20 × 20 × 20 mm according to the ASTM D143-94 and used for measuring the oven-dry density, basic density, air-dry density (12%), volumetric shrinkage and fiber saturation point, percentage of cell wall, porosity and maximum moisture humidity content. The sample size of each test was 45 samples.

The oven-dry density (D_0) was calculated as follows:

$$D_0 = M_0 / V_0$$

where M_0 and V_0 are the oven-dry weight (g) of the specimen and volume (cm^3) of specimen, respectively.

The basic density (D_b) was determined by the gravimetric method.

$$D_b = M_0 / V_g \ (g\ cm^{-3})$$

where, Vg is the green volume of the specimen (cm^3) and M_0 is the oven-dry weight of the specimen (g).

Volumetric shrinkage (βv) was determined as follows:

$$\beta_v = (V_s - V_0)/ V_s \ (\%)$$

where Vs is saturated volume and V_0 is oven-dry volume.

Fiber saturation point (FSP) was calculated by the following equation [11, 14]

$$FSP = \beta_v / D_b \ (\%)$$

where β_v is the volumetric shrinkage (%) and D_b is the basic density (g cm^{-3}).

Percentage of the cell wall and porosity were calculated by the following equations [14].

$$V_c = D_0 / D_C \times 100 \ (\%)$$

$$V_H = 100 - V_c \ (\%)$$

where V_c is percentage of the cell wall (%), D_0 is oven dry density (g cm^3), D_c is oven-dry density of the cell wall (1.5 g cm^{-3}) and V_H is percentage of the porosity (%).

Maximum moisture content (M_{max}) was calculated by the following equation:

$$M_{max} = (1.5 - D_b) / (1.5 \times D_b) \ (\%)$$

Mechanical Properties: Lumbers with 8 cm in width were cut from logs according to ISO 3129. Sawdust was removed from the surface and lumbers were stored in an uncontrolled condition in an unheated room for air drying. Following the air-drying process, small and clear specimens were cut from the boards according to ISO standards to determine compression strength parallel to grain (ISO 3787), bending strength (MOR) (ISO 3133) and modulus of elasticity in bending (MOE) (ISO 3349). Then the specimens were conditioned at 20±2°C temperatures and with 65±5% relative humidity to reach equilibrium moisture content throughout 8 weeks according to ISO 554. Afterwards acclimatization, mechanical properties of the paulownia wood were determined. At the end of experiments, moisture contents of specimens were measured according to ISO 3130 and the moisture content of specimen in which moisture content deviated from 12% determined. The sample size of each test was 30 samples. Then strength values were corrected (transformed to 12% moisture content) by using the following strength conversion equation:

$$\delta_{12} = \delta_m \times [1 + \alpha (M_2 - 12)]$$

where δ_{12} = strength at 12% moisture content, δ_m = strength at moisture content deviated from 12%, α = constant value showing relationship between strength and moisture content (α = 0.05, 0.04, 0.02 for compression strength parallel to the grain, modulus of rupture and modulus of elasticity respectively), M_2 = moisture content during test. In addition, p value (ratio of static bending strength and compression strength parallel to grain) and static quality (ratio of compression strength parallel to grain and 100× density at 12% moisture content) were calculated for evaluating the properties and use of paulownia wood.

RESULTS AND DISCUSSION

Physical Properties: All descriptive statistics were given in Table 1 for air-density (12%), oven-dry density, basic density, volumetric shrinkage, fiber saturation point and

Table 1: Basic statistics for physical properties of paulownia wood

Properties	N	Mean	Max and Min	SD
Oven-dry density (g cm^{-3})	45	0.261	0.228 - 0.297	0.027
Basic density (g cm^{-3})	45	0.242	0.215 - 0.283	0.025
Air-dry density (12%, g cm^{-3})	45	0.291	0.249 - 0.335	0.030
Volumetric shrinkage (%)	45	7.45	6.59 - 8.65	0.75
Percentage of cell wall (%)	45	17.41	15.2 - 19.8	1.78
Porosity (%)	45	82.59	80.20 - 84.8	1.78
Fiber saturation point (FSP)	45	31.15	29.82 - 32.97	0.91
Maximum moisture content (%)	45	349.72	286.69 - 398.45	41.71

SD: Standard deviation

Table 2: Comparison of physical properties of Iranian paulownia with other tree species

Species	a	b	c	d	e	Reference
P. fortunei	0.261	0.242	0.291	7.45	31.15	This study
P. tomentosa	0.294	0.272	0.317	7.78	28.79	Akyildiz and Kol (2010)
P. elongata	0.209	-	0.264	8.12	-	Anonymous (1986)
P. fortunei	0.258	-	0.309	8.96	-	Anonymous (1986)

a: Oven-dry density (g cm^{-3}); b: basic density (g cm^{-3}); c: air-density (12%, g cm^{-3}); d: volumetric shrinkage (%); e: fiber saturation point (%)

maximum moisture content of paulownia wood. Percentage of the cell wall and percentage of porosity were calculated 17.41% and 82.59%, respectively.

The results of physical properties of Iranian paulownia (studied species) were compared to values of *P. tomentosa* [11], *P. elongata* [12] and *P. fortunei* [12]. According to the Table 2, the volumetric shrinkage value of Iranian paulownia is lower than *P. tomentosa*, *P. elongata* and *P. fortunei.* But the oven-dry density for the studied species is lower than *P. tomentosa* (in Turkey) and is higher than *P. elongata* (in China) and *P. fortunnei* (in china).

Paulownia fortunei grown in Iran has a quite low density because of fast growth and low percentage of the cell wall. So, it has a quite high percentage of porosity. Decreasing the ratio of cell wall increases the porosity, decreasing the wood density. Consequently, maximum moisture content was 349.72% which can be considered as a high value (due to low density). Density closely correlates with physical, mechanical, hardness, transportation, heat value of wood, abrasion resistance, machining, electrical, acoustical and drying properties. Simpson (1991) reported that the maximum moisture content in lumber is important because of its influence in controlling kiln-drying schedules. In addition, porosity is linearly and inversely related to wood maximum moisture content and wood density, respectively [15].

Water exists in wood either as bound water (in the cell wall) or free water (in the cell cavity). As bound water, it is bonded (via secondary or hydrogen bonds) within the wood cell walls. As free water, it is simply present in the cell cavities. When wood dries, most free water separates faster rate than bound water because of accessibility and the absence of secondary bonding. The moisture content at which the cell walls are still saturated but virtually no water exists in the cell cavities is called the fiber saturation point [16, 17]. In the present study, fiber saturation point (FSP) value for paulownia wood was determined to be 31.15%, which is higher than *Paulownia tomentosa* (28.79%, [11]).

Mechanical Properties: All descriptive statistics are given in Table 3 for modulus of rupture (MOR), modulus of elasticity (MOE) and compression strength parallel to the grain of paulownia wood. The modulus of rupture (MOR), modulus of elasticity (MOE) and compression strength parallel to the grain of paulownia wood were determined 41.07 MPa, 3.74 GPa and 14.61 MPa, respectively.

The results of mechanical properties of Iranian-grown paulownia wood were compared to values of *P. tomentosa* [10], *P. elongata* [12] and *P. fortunei* [12]. According to the Table 4, the modulus of elasticity (MOE) and compression strength parallel to the grain of Iranian paulownia wood is lower than the other species. The modulus of rupture (MOR) of studied species is higher than *P. elongata* and *P. fortunei*, while it is lower than *P. tomentosa.*

The static quality and p values of studied species and other trees species are shown in Table 5. Hardwoods can be classified as low ($I_S < 6$), fair ($6 < I_S < 7$) and good ($7 < I_S$) static quality value (I_S). Limit values for the classification change depend on density and hardness of species [16]. According to this classification, *Paulownia*

Table 3: Mechanical properties of paulownia wood

Properties	MOR (MPa)	MOE (GPa)	Compression parallel to the grain (MPa)
N	30	30	30
Mean	41.07	3.74	14.61
Max	50.68	4.76	16.87
Min	34.06	2.63	11.45
Stdev	6.19	0.78	1.77

Table 4: Comparison of mechanical properties of Iranian paulownia with other tree species

Species	a	b	C	d	e	Reference
P. fortunei	41.07	3.74	14.61	5.01	2.85	This study
P. tomentosa	43.56	4.28	25.55	8.10	1.70*	Akyildiz and Kol (2010)
P. elongata	28.34	4.11	15.59	5.98*	1.81*	Anonymous (1986)
P. fortunei	39.72	6.17	18.44	6.04*	2.15*	Anonymous (1986)

a: modulus of rupture (MPa); b: modulus of elasticity (GPa); c: compression strength parallel to the grain (MPa); d: static quality (I_s); e: p value; *: These indexes were calculated according to the information in the text.

fortunei (I_S = 5.01) has a low static quality wood, with a value lower than the other species. For an ordinary wood species, the p value, the ratio between static bending strength and compression strength, is considered to be 1.75 [18]. In the present study, the p value was determined 2.85, with an index is higher than Paulownia grown in Turkey and China.

Wood density is one of the most important wood properties [19] and it is a commonly or generally used indicator of wood quality and cell size, since it is a good predicator of timber strength, stiffness, ease of drying, hardness and it is related to fiber properties, pulp yield and various paper making properties [20, 21]. Blair *et al.* (1975) reported that high-density wood is preferred for construction and furniture uses and it has generally been assumed to be preferred for pulping [22]. However, if the main purpose is the conversion to sawn lumber, then high density will confer the best strength properties should be the criteria of choice. Research has shown that higher density species tend to have stronger timber than lower density species [23]. In the present study Paulownia wood has a low density.

CONCLUSION

In this study, the physical and mechanical properties of paulownia wood (*Paulownia fortunei*) at the Guilan region were determined and these results were compared with of other sites or other species in different regions in world. The following conclusions were obtained from this research:

The paulownia wood planted at this site (studied region), due to its low density, mechanical properties and static quality, is not suitable for structural applications than wood from the other sites and other paulownia species.

The variations in the wood properties in the same species are due to different factors, such as growth conditions and ecological factors. In particular, exposure, altitude, soil and climate conditions can affect the wood properties of wood. Sample size and properties (e.g. ring orientation) and the test procedure can also affect the test results. In addition, the wood properties value of this species is different than that of other species such as *P. tomentosa* and *P. elongata*.

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