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The effect of growth conditions in specific areas of Croatia and the Czech Republic on the physical and mechanical properties of black alder wood (*Alnus glutinosa* Gaertn.)

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Abstract: In this paper, static bending (modulus of rupture, MOR, and modulus of elasticity, MOE) and compression strength parallel to grain (σ_{cll}) of black alder wood (*Alnus glutinosa* Gaertn.) were investigated. For experimental testing, we used black alder wood from two different areas: Crni Jarci, Croatia, and Malá Bystřice, Czech Republic. Experimental tests were carried out according to the Czech national standards: ČSN 49 0115 and ČSN 49 0116 for static bending and ČSN 49 0110 for compression strength. The samples from Malá Bystřice showed lower values of MOR (~14%), MOE (~30%), and σ_{cll} (~4%), when compared to the samples from Crni Jarci. The relationship between density and strength was investigated. The difference between the studied groups at the 0.05 significance level was confirmed. The average linear correlation was found between density and the observed mechanical properties (for σ_{cll}). The average density was 549 kg m^{-3} for samples from Crni Jarci and 469 kg m^{-3} for samples from Malá Bystřice. The results were compared with values indicated in similar studies.

Key words: Black alder wood, compressive strength, modulus of elasticity, modulus of rupture, static bending, wood density

1. Introduction

Wood has relatively low weight and good strength, which is a prerequisite for every good construction material (Desch and Dinwoodie, 1996). Wood properties are influenced by many factors such as climatic conditions, tree growth, rainfall, groundwater level, temperature, hours of sunshine per year, and other factors (Bodig and Jayne, 1993; Hon and Nobuo, 2001). Wood is a natural material, and the tree is subject to many constantly changing influences. These changes may have influence on the individual properties of wood such as MOR, MOE, and other properties (Tsoumis, 1991; Forest Products Laboratory, 2010).

Changes in properties are common to all materials. With increasing age, the width of the annual rings of the tree decreases, and there is a loss of earlywood and an increase in latewood. Latewood has higher density and therefore higher mechanical properties (Panshin and de Zeeuw, 1980; Raiskila et al., 2006). Wood density is a commonly used wood quality indicator that is related to other wood properties, such as wood strength (Panshin and de Zeeuw, 1980; Kiaei, 2011). Mechanical properties are affected by anatomical characteristics such as wood density, grain angle, tracheid length, and microfibril angle of the S2 layer in the cell wall (Tokumoto et al., 1997). Wood density influences most physical and mechanical properties. Wood density is one of the most effective criteria for assessing wood properties (Kollmann and Coté, 1968).

The purpose of this study was to investigate whether differences in growing conditions within the Croatia and Czech Republic locations (cadastre Crni Jarci and Malá Bystřice, respectively) can significantly influence the physical and mechanical properties of black alder wood, because different properties of wood affect its processing in industrial manufacturing and usage. The lack of comparative studies of black alder wood grown in the given geographic areas can be supplemented by this study. Therefore, the objective of this study was the description of the physical and mechanical properties of black alder wood (*Alnus glutinosa* Gaernt.) depending on the different growing conditions in both areas.

2. Materials and methods

2.1. Climatic conditions in the areas of tree growth

Two areas were chosen for sampling. The first is the cadastre area of Crni Jarci, between the Kalinovac and Podravske Sesvete villages in Croatia. This area is suitable for the growth of alder (*Alnus glutinosa* Gaertn.) trees. Alder stands grow in the sandy soil of the Drava River basin. The second area chosen for sampling is the cadastre

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area of the Malá Bystřice village. It is contained within the protected landscape area of the Vsetín highlands. The geological bedrock is composed of sandstone and clay layers. The Bystřice River and many hillside streams are also in this area. Table 1 shows the growth conditions in the presented areas.

2.2. Experimental test samples

The test samples (for static bending and compressive strength) without defects (cracks, knots, etc.) were cut from the black alder wood. The average tree-ring width of samples was similar for both areas. The samples were conditioned at 65% of relative humidity (RH) and at 20 °C until equilibrium of moisture content (EMC) was reached (~12%).

A total of 392 samples were produced for static bending for both areas. The static bending test was carried out by the three-point loading method using universal testing machine Zwick Z050 with 50 kN load cell (Zwick Roell, Germany). The load was applied in the tangential direction. The experimental test production and the evaluation of the results were derived from ČSN 49 0115 and ČSN 49 0116 standards. Samples with dimensions of 300 × 20 × 20 mm^3 were used. The span of the supports was 240 mm and the radius of the supports and the forcing head was 15 mm. The value of MOR was calculated from the maximum loading force as given in the following equation:

$$MOR = 3F_{max}l/2bh^2,$$

where F_{max} = the maximum loading force (N), l = the span of the supports (mm), b = the width of cross-section of sample (mm), and h = the thickness of the sample (mm).

Calculation of MOE was based on forces measured at 10% and 40% of the maximum loading force and the corresponding deflections of a bent beam measured by extensometer. The value of MOE was calculated with the following equation:

$$MOE = l^3(F_{40\%}-F_{10\%})/4bh^3(u_{40\%}-u_{10\%}),$$

where l = the span of the supports (mm), $F_{40\%}$ and $F_{10\%}$ are forces at 40% and 10% level of the maximum force F_{max} (N), b = the width of cross-section of sample (mm), h = the thickness of the sample (mm), and $u_{40\%}$ and $u_{10\%}$ are deflections at forces $F_{40\%}$ and $F_{10\%}$ (mm).

The experimental test of compressive strength parallel to grain ($\sigma_{c||}$) was derived from the ČSN 49 0110 standard (samples of 30 × 20 × 20 mm^3). A total of 1623 samples were produced and tested for both areas. The following equation was used for the calculation of the compression strength parallel to grain:

$$\sigma_{c||} = F_{max}/ab,$$

where F_{max} = the maximum loading force (N), a = the width of sample (mm), and b = the thickness of sample (mm).

Wood density was examined in compliance with the ČSN 49 0108 standard. The density was determined at EMC of ~12%.

2.3. Statistical evaluation

The statistical significance was explored by analysis of variance (ANOVA). The significance level was fixed at α = 0.05 for all statistical analyses. All statistical analyses were conducted using Statistica (StatSoft 10.0, USA.). The linear regression model was used to analyze the relationship between density and selected mechanical properties.

3. Results and discussion

Descriptive statistics of selected mechanical properties (MOR, MOE, and $\sigma_{c||}$) and density of black alder wood are given in Table 2 for both areas.

The results of the statistical analyses indicated that the conditions of growth significantly affected the investigated physical and mechanical properties of black alder wood. Bektaş et al. (2002) and Forest Products Laboratory (2010) reported that variations in the mechanical properties in the same species are due to different factors such as growth conditions and ecological factors. In particular, altitude, soil,

Table 1. Growth conditions in the observed areas of tree growth.

	Crni Jarci (Croatia)	Malá Bystřice (Czech Republic)
Age (years)	95	85
Altitude (meters above sea level)	110	600
Groundwater level (mm)	1300	-
Air temperature of the period (°C)	10.3 (1990–2010)	4.9–8.7 (2000–2010)
Annual precipitation (mm)	832	646–1101
Hours of sunshine (hours per year in 2011)	1978	1431
Source	(Pernar et al., 2012); Meteorological and Hydrological Service in the Đurđevac station (DHMZ)	Czech Hydro-meteorological Institute (ČHMÚ)

Table 2. Descriptive statistic of the examined properties of black alder wood.

Mechanical properties MOR (MPa)		Static bending		Compression strength parallel to grain	Density at 12% EMC
		MOE			
		(GPa)	(MPa)	(kg m^{-3})	
Crni Jarci (Croatia)	Number of samples	282		979	979
	Mean value	79.9 (18.9)*	10.6 (2.8)	42.3 (7.7)	549.0 (44.0)
	Variation coefficient	23.7	26.1	18.3	8.0
Malá Bystřice (Czech Republic)	Number of samples	110		644	644
	Mean value	68.1 (7.7)	7.4 (1.0)	40.7 (4.1)	469.0 (31.3)
	Variation coefficient	11.3	13.5	10.1	6.7

* st. dev. in parentheses.

and climatic conditions affect the mechanical properties of wood. Figure 1 shows the variability of the investigated properties (MOR, MOE, $\sigma_{c||}$, and wood density) of black alder wood. The comparison of these results (MOR, MOE, and $\sigma_{c||}$) with other studies is also presented in Table 3.

Wood density is a basic physical quantity that also affects other physical and mechanical properties (Gryc et al., 2008). The differences between density values may be attributed to the different conditions in the growth areas of the examined trees, especially different altitudes

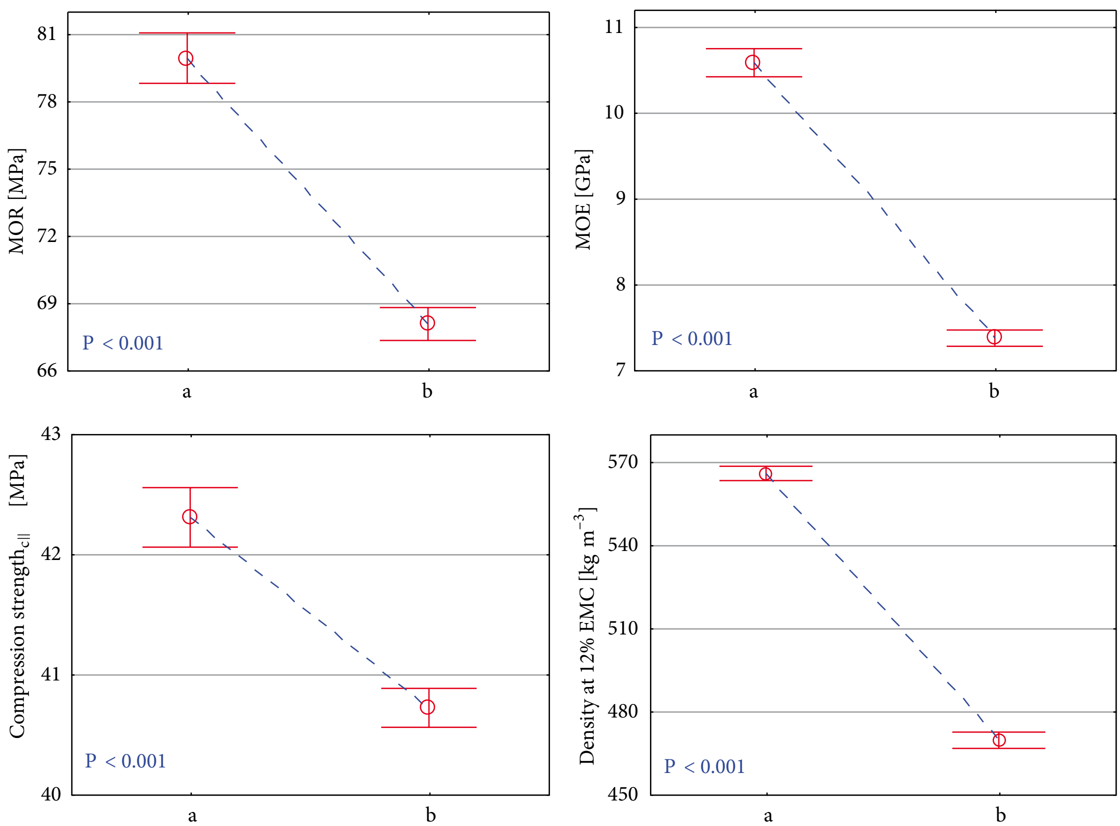

Figure 1. The variability of the examined properties (MOR, MOE, compression strength parallel to grain, and wood density) of black alder wood for observed areas: **a)** Crni Jarci, **b)** Malá Bystřice. Circles and bars are the mean value and standard deviation, respectively.

Table 3. Comparison of selected mechanical properties of samples from observed areas of black alder wood with other alder species.

Mechanical properties	Static bending		Compression strength parallel to grain	Moisture content	Source
	MOR	MOE			
	(MPa)	(GPa)	(MPa)	(%)	
Alnus rubra	67.6	9.5	40.1	12	(Alden, 1995)
Alnus glutinosa B.	95.0	-	55.3	-	(Örs and Ay, 1999)
Alnus rubra	68.0	9.5	40.1	12	(Forest Products Laboratory, 2010)
Alnus rubra	56.1	8.8	-	-	(Evans et al., 2000)
Alnus glutinosa L.	77.5	8.6	41.5	12	(Güller and Ay, 2001)
Alnus	82.1	-	44.9	-	(Gürsu, 1967)
Alnus glutinosa G.	97.0	-	55.0	-	(Wagenführ, 2000)
Alnus glutinosa Gaertn.	79.9	10.6	42.3	12	Crni Jarci (Croatia)
Alnus glutinosa Gaertn.	68.1	7.4	40.7	12	Malá Bystřice (Czech Republic)

and water systems. The difference in altitude between the two investigated areas (Crni Jarci and Malá Bystřice) is approximately 490 m. Different altitude is a very important factor for the growth and resulting properties of wood. The determined wood density is very similar to that of other studies (Table 4). Wood density for samples from Malá Bystřice is lower than that of samples from Crni Jarci.

The effect of density on mechanical properties, static bending, and compression strength parallel to grain was tested statistically by linear regression analyses, which are presented in Figure 2. Figures 2a–2d shows the relationship between density, MOR, and MOE in static bending for both areas. The coefficient of correlation (r) is 0.64 for MOR and 0.68 for MOE in Crni Jarci, and the coefficient of correlation is 0.65 for MOR and 0.66 for MOE in Malá Bystřice. Figures 2e and 2f show a lower dependence of compression strength on density in the Malá Bystřice area (r = 0.39) compared to the Crni Jarci area (r = 0.82). The differences may be attributed to the more differentiated annual rings of samples from the Malá Bystřice area compared to samples from the Crni Jarci area. Due to changes in anatomical structure among neighboring early and latewood, more crack lines arise, and cause failure of samples that is less dependent on wood density.

Table 4. Comparison of wood density of samples from the observed areas with other alder species.

Wood species	Density	Moisture content	Source
	(kg m^{-3})	(%)	
Alnus rubra	449	12	(Alden, 1995)
Alnus rubra	410	12	(Forest Products Laboratory, 2010)
Alnus rubra Bong.	390	0	(Harrington and DeBell, 1980)
Alnus glutinosa L.	490	-	(Morin, 1974)
Alnus glutinosa L.	430	-	(Vurdu and Bensend, 1979)
Alnus glutinosa G.	450-600	-	(Wagenführ, 2000)
Alnus formosana (Burk.)	502	9	(Zwolinski et al., 1992)
Alnus glutinosa Gaertn.	549	12	Crni Jarci (Croatia)
Alnus glutinosa Gaertn.	469	12	Malá Bystřice (Czech Republic)

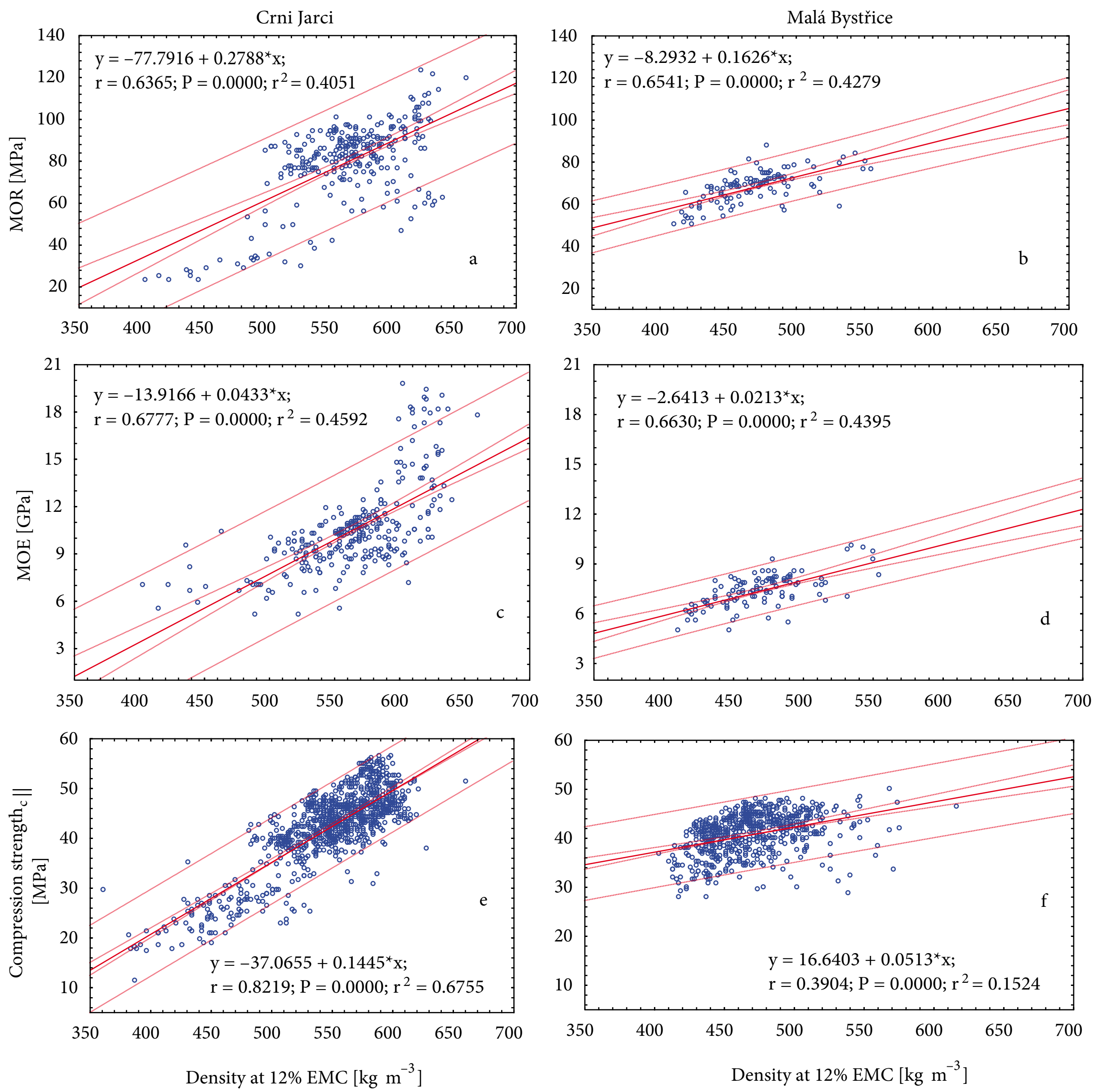

Figure 2. Relationship between density and examined mechanical properties of black alder wood.

It was found that the specific climatic and growth conditions in the cadastre of Crni Jarci, Croatia, are more suitable for xylem formation of black alder wood, exhibiting higher physical and mechanical properties when compared with the conditions in the cadastre area of Malá Bystřice, Czech Republic. In fact, the Crni Jarci area has more water sources (especially groundwater) and 30% more hours of sunshine per year; furthermore, average temperature is higher. These parameters are the most important for xylem formation in a tree.

The principal mechanical properties (static bending and compression strength parallel to grain) were determined. Results were compared to samples from two areas with different climatic and growth conditions (in Crni Jarci and Malá Bystřice) and to the results of other similar studies. The experimental results proved that the black alder samples from Crni Jarci have higher strength, stiffness, and wood quality than the black alder samples from Malá Bystřice. These differences may be explained by different regional conditions, which affect the growth characteristics and properties of the wood. The lower black alder wood density of the samples from Malá Bystřice has led to lower mechanical properties.

This research investigated a linear relationship between selected mechanical properties and the density of black alder wood for both areas. The linear regression model was significant for compression strength parallel to grain ($\sigma_{c||}$) of the Crni Jarci samples only.

The influence of different climatic and growth conditions in the observed areas (in Crni Jarci and Malá Bystřice) was found to be a significant factor for the investigated properties of black alder wood from Crni Jarci and Malá Bystřice.

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