

Bending Creep Behavior of Hornbeam Wood

Puzanje drva graba pri savijanju

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ABSTRACT • This study examined the effect of altitude on bending creep behavior of hornbeam lumber (*Carpinus betuluse*). For this purpose, 9 hornbeam trees from three different altitudes (400, 800 and 1100 m) in the northern forests of Iran were selected. Clear samples were cut from mature wood in diameter at breast height (DBH). 108 prepared samples (dimensions: 2.5 × 2.5 × 41 cm) were conditioned at room temperature of 20 °C and two relative humidities (RH) of 65 % and 95 %. First, the maximum bending load was determined by three-point static bending tests in acclimatized room and then flexural creep parameters, such as relative creep, creep modulus and creep factor; at 20 % of the maximum bending load, were calculated. Results indicated that at 65 % RH, the effect of altitude on creep parameters was significant. The maximum values of relative creep and creep factor were observed at the altitude of 800 m, and the minimum values at the altitude of 400 m. The maximum values of creep modulus were observed at the altitude of 400 m and the minimum values at the altitude of 800 m. Also, at 95 % RH, the effect of altitude on creep modulus was significant but it was not significant on relative creep and creep factor. The maximum creep modulus was observed at the altitude of 400 and the minimum at the altitude of 800 m.

Keywords: altitude, *Carpinus betuluse*, creep factor, creep modulus, relative creep, relative humidity

SAŽETAK • U radu su prikazani rezultati istraživanja utjecaja nadmorske visine staništa stabala na puzanje drva graba (*Carpinus betuluse*) pri savijanju. Za istraživanje je odabrano devet stabala graba iz šuma na sjeveru Irana, i to na tri različite lokacije – nanadmorskoj visini 400, 800 i 1100 m. Uzeti su čisti uzorci zrelog drva na visini prsnog promjera (DBH). Ukupno 108 pripremljenih uzoraka (dimenzija 2,5 × 2,5 × 41 cm) kondicionirano je pri sobnoj temperaturi od 20 °C i uz dvije relativne vlažnosti zraka (RH), 65 i 95 %. Najprije je napravljen statički test savijanja u tri točke te određeno maksimalno opterećenje (čvrstoća na savijanje) u aklimatiziranoj prostoriji. Potom su izračunani parametri puzanja pri savijanju kao što su relativno puzanje, modul puzanja i faktor puzanja u području 20 % maksimalnog opterećenja savijanja. Rezultati istraživanja na uzorcima kondicioniranim pri 65 % relativne vlažnosti zraka pokazali su da je utjecaj nadmorske visine na parametre puzanja bio značajan. Maksimalne vrijednosti relativnog puzanja i faktora puzanja zabilježene su za uzorke s nadmorske visine 800 m, a minimalne vrijednosti za uzorke s nadmorske visine 400 m. Maksimalne vrijednosti modula puzanja zabilježene su za uzorske drva s nadmorske visine 400 m, a minimalne za one s nadmorske visine 800 m. Također, na uzorcima kondicioniranim pri 95 % relativne vlažnosti zraka utjecaj nadmorske visine na modul puzanja bio je značajan, ali se taj utjecaj nije pokazao značajnim za parametre relativnog puzanja i faktora puzanja. Najveći modul puzanja zabilježen je na uzorcima s nadmorske visine 400 m, a najmanji na uzorcima s nadmorske visine 800 m.

Ključne riječi: nadmorska visina, *Carpinus betuluse*, faktor puzanja, modul puzanja, relativno puzanje, relativna vlažnost zraka

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1 INTRODUCTION

1. UVOD

In most developing countries, demand for raw materials has been increasing in recent years. Considering the limited resources, especially in natural resources sector, the supply of needed raw material of wood for industry has been one of the most important problems in recent decades. Attention should be focused on the improvement of wood specifications and modification of some properties of wood, so as to provide better consumption of wood.

One of the most important characteristics affecting wood products is their time-dependent behavior. Generally, time dependent deformation of a material under sustained load is referred to as creep. If the load is large and the duration is long, failure will occur. Creep is one of the principal characteristics of wood resulting in poor performance in certain applications. It is essential to consider creep and creep rupture (load duration behavior) if wood is to be subjected to short and long-term loads. Wood has been characterized as viscoelastic material governed by creep behavior (Fridley, 1992a; Fridley, 1992b). Creep of these materials occurs as a result of a combination of elastic deformation and viscous flow, commonly known as viscoelastic deformation (Bodig and Jayne, 1993). The creep behavior of wood depends on a variety of factors including stress level, composite formulation, temperature, and last but not least, moisture content (Liu, 1993; Chen and Lin, 1997; Christopher *et al.*, 2004; Zhang *et al.*, 2007). High temperature and changes of humidity make wood prone to creep and can lead to problems of lowered resistance and capability of use (Van der put, 1989). When wood is exposed to moisture changes, the resulting deformation is higher than when wood is exposed to environmental conditions for the same time (Bazant and Meiri, 1985; Nakano, 1999). Simultaneous effect of the load and changes of wood moisture is called mechanical absorption effect (Kaboarani *et al.*, 2013). This effect is very important in the use of wood for construction and causes failure and deformation in wooden beam (Kaboarani and Blanchet, 2014). The creep caused by mechanical absorption has been reported in different articles (Armstrong and Christensen, 1960, 1962; Armstrong and Kingston, 1962; Armstrong, 1972; Kowalski and Kowal, 1998; Hanhijarvi and Hunt, 1998).

Hornbeam, a diffuse-porous hardwood, covers about 33 % of forests in northern Iran. The wood of this

tree species is semi-hard to hard with high shrinkage and swelling, and working with it is hard (Kiaei, 2012). Considering the extent of this species and necessity of its right use, it must be given more attention. Therefore, the aim of this research is to: a) evaluate the effect of altitude on the flexural creep behavior of hornbeam wood (*Carpinus betulus* L.) harvested from Nowshahr Mashelek site, b) examine the relationship between physical and biometrical properties and displacement.

2 MATERIALS AND METHODS

2. MATERIJALI I METODE

Three hornbeam trees, of almost the same age of about 30 years, were chosen from three altitudes (400, 800 and 1100 m). Nine logs (diameter: 25 and length: 70 cm) at DBH were cut. Environmental characteristics, climate conditions habitat and specification of trees are presented in Table 1.

2.1 Preparing the samples

2.1. Priprema uzoraka

Sawn logs were stored in covered storage and environmental conditions. At first, logs were cut to 45 boards with 3.2 cm thicknesses from mature wood section (from ring 18 onwards, Makhmalbaf *et al.*, 2007), then they were kept in environmental conditions for a period of two weeks. 108 final samples (dimensions: 2.5 × 2.5 × 41 cm) were prepared (54 samples for creep test and 54 samples for bending test). Samples were placed in an acclimatized room (65 % and 95 % RH, temperature of 20±3 °C) for at least 3 weeks. All tests were done in the same conditions.

2.2 Physical and biometrical properties

2.2. Fizikalna i biometrijska svojstva

Oven-dried density and basic density were measured according to ISO 3131 (2.5 × 2 × 2 cm). The weight and size of samples were measured in the water (soaking for 48 hours) and then in the oven (24 hours).

Franklin's method (1946) was used for separating fibers. In this method, a 50/50 % ratio of acetic acid and hydrogen peroxide was used. First, the sample wood picks were placed inside a microquant, then the prepared acetic acid and hydrogen peroxide were poured on the wood samples by a calibrated pipette and the microquant was placed in an oven and heated for 48 h at 64 °C. After whitening, the samples from the microquant were washed 4 to 5 times by a calibrated pipette with distilled water until the odor of hydrogen

Table 1 Characteristics of study sites and trees

Tablica 1. Obilježja staništa i stabala uključenih u istraživanje

Site Lokacija	Elevation Nadmorska visina m	Annual temperature Prosječna godišnja temperatura °C	Annual rainfall Godišnje padaline mm	Tree height Visina stabla m	Tree diameter Promjer stabla cm
Mashelak forest-Nowshahr	400	13.5	1345	17.6	29
	800	11.5	1300	17.3	29
	1100	8.5	1300	17.2	28

peroxide and acetic acid was completely removed. Fiber dimensions were measured by optic microscope (Nikon microscopic, Eclipse 50i, for the fiber length of 10x and for fiber diameter, cell wall thickness and lumen diameter of 40x).

2.3 Bending properties

2.3. Svojstva drva pri savijanju

In order to determine the maximum bending load, three-point static bending tests were carried out in accordance with ASTM D 143-94 (2000). Three replicates of each sample were tested using a computer-controlled INSTRON (Model Universal PT 20L) machine. The speed of the crosshead was set at 1.3 mm/min. Data were collected and used to calculate the modulus of elasticity (MOE) and short-term strength (modulus of rupture or MOR).

2.4 Creep properties

2.4. Svojstva puzanja drva

Using flexural creep equipment, creep tests were performed in accordance with ASTM D 6815-09. The immediate displacement, maximum displacement and permanent displacement at the mid-span of samples were measured by an extensometer during creep and recovery time. Total time to complete every test was one overnight (14 hours creep and 10 hours recovery). The stress was at 20 % of the maximum bending load and was constant throughout the test. Based on measuring indications, creep factor, relative creep and creep modulus were calculated in accordance with equations 1, 2 and 3.

Immediate displacement is the range of displacement in one minute after loading; the maximum displacement is the range of displacement in 840 minutes after loading; immediate return is the range of returned displacement in one minute after removing the load; and permanent displacement is the range of remaining displacement in 600 minutes after removing the load (return).

$$K_t = \frac{J_t}{J_0} \quad (1)$$

$$R_c = \frac{J_t - J_0}{J_0} \cdot 100 \quad (2)$$

$$E_c = \frac{L^3 \cdot F}{4 \cdot b \cdot h^3 \cdot J_t} \quad (3)$$

Where K_t is creep factor; R_c is relative creep in percentage; E_c is creep modulus in MPa, J_t is displacement in time of t in mm; J_0 is displacement in one minute after loading; L , is length loading span in mm; F , is in Newton; b , is width of sample in mm and h , is thickness of sample in mm.

2.5 Parabolic equations

2.5. Parabolične enačbe

To predict creep behavior, researchers depend on good judgment supported by available models. A number of empirical and theoretical methods have been developed to express time-dependent creep strains. Various researchers have investigated modeling of viscoelastic materials. Response linear and non-linear viscoelastic materials have been documented and a number of equations have been presented (Bodig and Jayne, 1993). The creep model, used in our research, is the power law proposed by Findley *et al.* (Findley *et al.*, 1989; Kobbe, 2005). This model is simple and has been proven to apply to viscoelastic materials loaded at moderate levels. The general form of model is given as:

$$\mu_t = \mu_0 + a \cdot t^m \quad (4)$$

Where μ_t is the time dependent creep strain, μ_0 is the instantaneous strain, a is the coefficient of time-dependent strain, t is the time after loading and m is the exponential material constant. The analysis of the creep behavior of wood was performed based on the Findley *et al.* power law, adjusting the experimental values to the equation:

$$\log(\mu_t - \mu_0) = \log a + m \log t \quad (5)$$

The data were plotted as $\log(\mu_t - \mu_0)$ against $\log t$, where m and a were obtained from the regression line.

3 RESULTS AND DISCUSSION

3. REZULTATI I RASPRAVA

3.1 Physical and biometrical properties

3.1. Fizikalna i biometrijska svojstva

Analysis of variance (ANOVA) results indicated that the effect of altitude on fiber length, basic density and oven dried density was significant, but it was not significant on cell wall thickness, lumen diameter and fiber diameter (Table 2). Duncan's test included the value of fiber length related to the altitudes of 400 and 1100 m in one group and the value related to the alti-

Table 2 Average results of physical and biometric properties of hornbeam wood at different altitudes

Tablica 2. Prosjezni rezultati fizikalnih i biometrijskih svojstava drva graba sa staništa na različitim nadmorskim visinama

Altitude Nadmorska visina m	Cell wall thickness Debljina stanične stijenke μm	Lumen diameter Promjer lumena μm	Fiber diameter Promjer vlakana μm	Fiber length Duljina vlakana μm	Basic Density Osnovna gustoća kg/m^3	Dry density Gustoća suhog drva kg/m^3
400	5.16	12.22	22.55	1341.41 ^b	627.85 ^b	720.89 ^c
800	4.94	13.64	23.54	1212.97 ^a	549.46 ^a	628.09 ^a
1100	5.05	12.82	22.92	1370.06 ^b	587.36 ^a	679.06 ^b
F	0.476 ^{ns}	2.667 ^{ns}	2.538 ^{ns}	10.416 ^{**}	3.424 [*]	48.972 ^{**}

** - Significant at 1 % level / *signifikantno na razini 1 %*; * - Significant at 5 % level / *signifikantno na razini 5 %*; ns - not significant / *nije signifikantno*

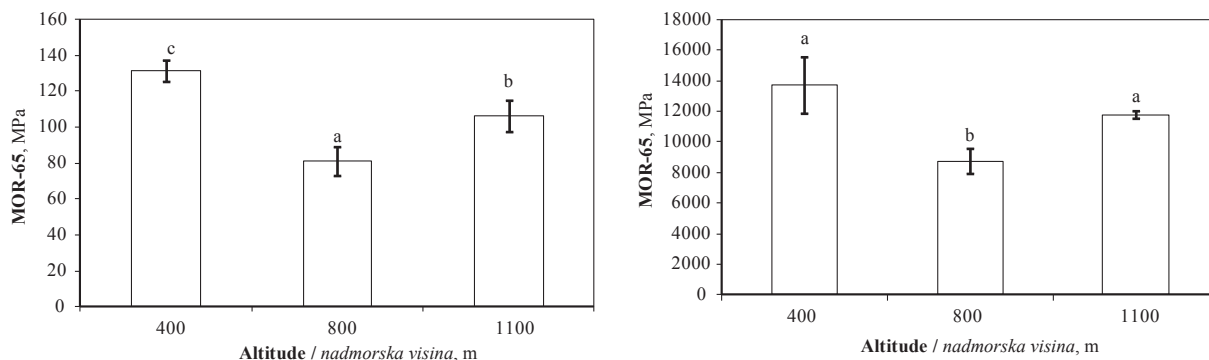


Figure 1 Hornbeam wood bending properties at three altitudes (65 % RH)
Slika 1. Svojstva drva graba pri savijanju za uzorke s tri nadmorske visine (65 % RH)

tude of 800 m in another group. For basic density, Duncan’s test also included the value of fiber length related to the altitudes of 800 and 1100 m in one group and the value related to the altitude of 400 m in another group. For oven dried density, however, these values were divided into three separate groups. The maximum average oven dried density, basic density and cell wall thickness were observed at the altitude of 400 m, maximum fiber diameter and lumen diameter were observed at the altitude of 800m and, finally, the maximum fiber length was observed at the altitude of 1100 m. Different factors such as site, cell wall thickness and early wood/late wood ratio affect density of wood (Zobel and Van Buijtenen, 1989; Zobel and Sprague, 1998; Koubaa *et al.*, 2000; Koga and Zhang, 2002; Zhu *et al.*, 2008). The increase of density at the altitude of 400 m is due to higher cell wall thickness (5.16 μm) and lower lumen diameter (12.22 μm), which are comparable with the results of Kiaei (2013).

3.2 MOE and MOR
 3.2. MOE i MOR

At 65 % RH, ANOVA results indicated that the effect of altitude on MOR and MOE was significant. The maximum and minimum average MOR and MOE were found at the altitude of 400 and 800 m, respectively. Duncan’s test considered the value of MOE at altitudes of 400 and 1100 m in one group and at the altitude of 800 m in another group. However, the results of MOR were divided into 3 separate groups (a, b, c) (Fig. 1).

At 95 % RH, ANOVA results indicated that the effect of altitude on MOR and MOE was significant. The maximum and minimum MOR and MOE were ob-

served at the altitude of 400 and 800 m, respectively. Duncan’s test included the value of MOR and MOE in two classes of altitude - 400 and 1100 m in one group (b) and 800 m in another group (a) (Fig. 2).

At 65 % and 95 % RH, the increase of MOE and MOR at the altitude of 400 m is due to the increase of wood density. As well known, there is a direct correlation between density and mechanical properties of wood (Zhang and Zhong, 1990; Zhang, 1997; Treacy *et al.*, 2000; Charifo Ali, 2011). Also, average MOE and MOR is higher at 65 % RH than at 95 % RH, which is compatible with the results of Kaboorani *et al.*, (2013) and Ishmaru *et al.* (2001).

3.3 Creep / Recovery behavior
 3.3. Puzanje / povratak u početno stanje

At 65 % RH, creep/recovery curve related to the altitude of 800 m was formed in a higher level and curves related to the altitudes of 400 m and 1100 m were formed in a lower level, so that curves of these two classes of altitude almost overlap (Fig. 3a). At 95 % RH, the highest and lowest curves of creep/recovery were observed at altitudes of 800 m and 400 m, respectively (Fig. 3b). Considering the effects of MOE and MOR on creep behavior of materials (Kaboorani *et al.*, 2013), placing the creep/recovery curves of hornbeam wood samples resulting from the altitude of 800 m in an upper level can be due to the deficiency of bending properties at this altitude. Also, placing the curve of the altitude of 400 m in a lower level can be due to the increase of the MOE and MOR at this altitude.

At 65 % RH, equilibrium moisture content (EMC) of samples at altitudes of 400, 800 and 1100 m

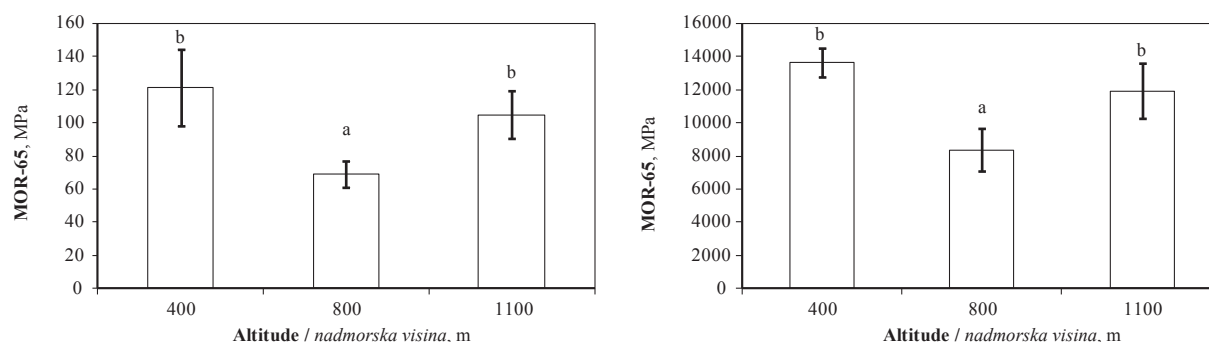


Figure 2 Hornbeam wood bending properties at three altitudes (95 % RH)
Slika 2. Svojstva drva graba pri savijanju za uzorke s tri nadmorske visine (95 % RH)

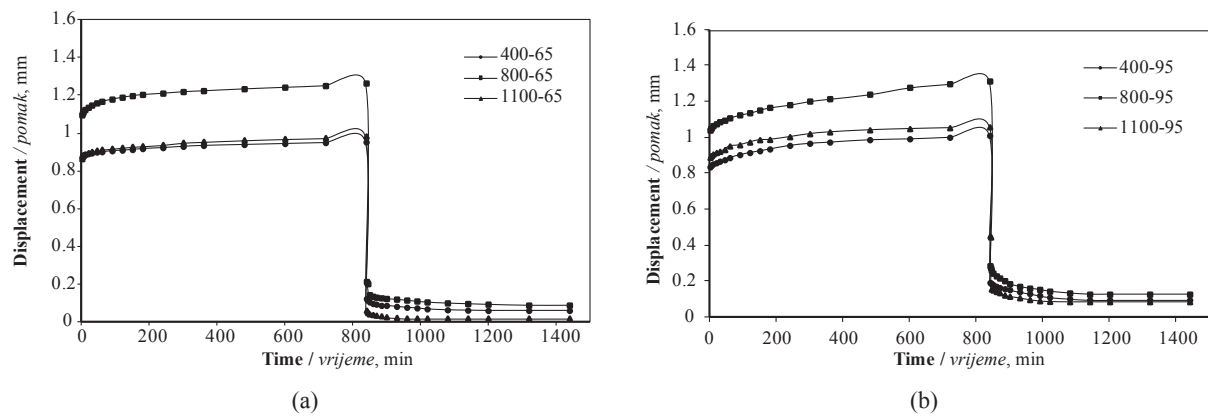


Figure 3 Creep/Recovery curves of hornbeam wood samples at different altitudes at (a) 65 % and (b) 95 % RH

Slika 3. Krivulje puzanja/oporavka uzoraka drva graba sa staništa na različitim nadmorskim visinama kondicioniranih pri: a) 65 % RH i b) 95 % RH

was 30 %, 30 % and 29 %, respectively. ANOVA results indicated that altitude had a significant effect only on creep coefficient, while this factor had no significant effect on immediate displacement, maximum displacement, immediate return, permanent displacement and percentage of return (Table 3). According to Duncan's test, the average creep coefficient obtained from the altitude of 800 m and 1100 m was classified in one group, and the results obtained from the altitude of 400 m were classified in another group. The maximum average immediate displacement, maximum displacement, immediate return and permanent displacement and creep coefficient were observed at the altitude of 800 m and the maximum average return percentage was observed at the altitude of 1100 m.

At 95 % RH, EMC of samples at altitudes of 400 m, 800 m and 1100 m were 34 %, 35 % and 33 %, respectively. ANOVA results indicated that the effect of altitude on immediate displacement, maximum displacement, immediate return permanent displacement

and percentage of return and creep coefficient was not significant. The maximum average immediate displacement, maximum displacement, permanent displacement and creep coefficient were observed at the altitude of 800 m and the maximum average immediate return and percentage of return were observed at the altitude of 1100 m (Table 4).

3.4 Relationship between wood properties and immediate creep and maximum creep

3.4. Odnos između svojstava drva s neposrednim puzanjem i s maksimalnim puzanjem

Pearson's correlation results indicated that there was no relationship between fibers dimensions, density and bending properties and immediate and maximum displacement at 95 % RH. At 65 % RH, MOE had a significantly reverse relationship with immediate and maximum creep. A negative and significant relationship was also observed between densities and maximum displacement (Table 5).

Table 3 Values of hornbeam creep displacement at three altitudes (65 % RH)

Tablica 3. Veličine pomaka pri puzanju uzoraka drva graba sa staništa na različitim nadmorskim visinama (65 % RH)

Altitude Nadmorska visina m	RH %	EMC %	ID ^a mm	MD ^b mm	IR ^c mm	PD ^d mm	RP ^e	CC ^f
400	65	30	0.86	0.95	0.12	0.05	84.61	1.097 ^a
800		30	1.09	1.26	0.21	0.08	93.02	1.15 ^b
1100		29	0.86	0.98	0.06	0.01	98.18	1.13 ^b
F			3.532 ^{ns}	4.420 ^{ns}	4.848 ^{ns}	0.985 ^{ns}	1.591 ^{ns}	20.069 [*]

a - Immediate displacement / neposredni pomak; b - Maximum displacement / najveći pomak; c - Immediate return / neposredni povratak, d - Permanent displacement / trajni pomak; e - Return percentage / postotak povratka, f - Creep coefficient / koeficijent puzanja; * - Significant at 5 % level / signifikantno na razini 5 %; ** - Significant at 1 % level / signifikantno na razini 1 %; ns - not significant / nije signifikantno

Table 4 Values of hornbeam creep displacement at three altitudes (95 % RH)

Tablica 4. Veličine pomaka pri puzanja uzoraka od drva graba sa staništa na različitim nadmorskim visinama (95 % RH)

Altitude Nadmorska visina m	RH %	EMC %	ID ^a mm	MD ^b mm	IR ^c mm	PD ^d mm	RP ^e	CC ^f
400	95	34	0.38	1	0.18	0.09	91.53	1.20
800		35	1.02	1.31	0.28	0.12	91.08	1.25
1100		33	0.88	1.055	0.24	0.08	92.58	1.19
F			1.831 ^{ns}	1.727 ^{ns}	0.572 ^{ns}	0.184 ^{ns}	0.035 ^{ns}	0.953 ^{ns}

a - Immediate displacement / neposredni pomak; b - Maximum displacement / najveći pomak; c - Immediate return / neposredni povratak, d - Permanent displacement / trajni pomak; e - Return percentage / postotak povratka, f - Creep coefficient / koeficijent puzanja; ns - not significant / nije signifikantno

Table 5 Relationship between wood properties and immediate and maximum creep of hornbeam wood at two levels of RH – 65 % and 90 %

Tablica 5. Odnos između svojstava drva s neposrednim i s maksimalnim puzanjem za uzorke od drva graba kondicionirane pri 65 i 95 % relativne vlažnosti zraka

RH Relativna vlažnost zraka %	Creep Puzanje mm	MOE	MOR	Dry density Gustoća suhog drva kg/m ³	Lumen diameter Promjer lumena µm	Cell wall thickness Debljina stanične stijenke µm	Fiber length Duljina vlakana µm	Fiber diameter Promjer vlakana µm
65	I ^a	-0.679*	-0.589	-0.643	0.490	-0.473	0.405	-0.215
	M ^b	-0.718*	-0.662	-0.700*	0.461	-0.439	0.385	-0.269
95	I	-0.481	-0.614	-0.635	0.249	0.017	0.354	-0.235
	M	-0.414	-0.529	-0.618	0.203	0.073	0.322	-0.295

a - Immediate / neposredno; b - Maximum / maksimalno; * - Significant at 5 % level / signifikantno na razini 5 %

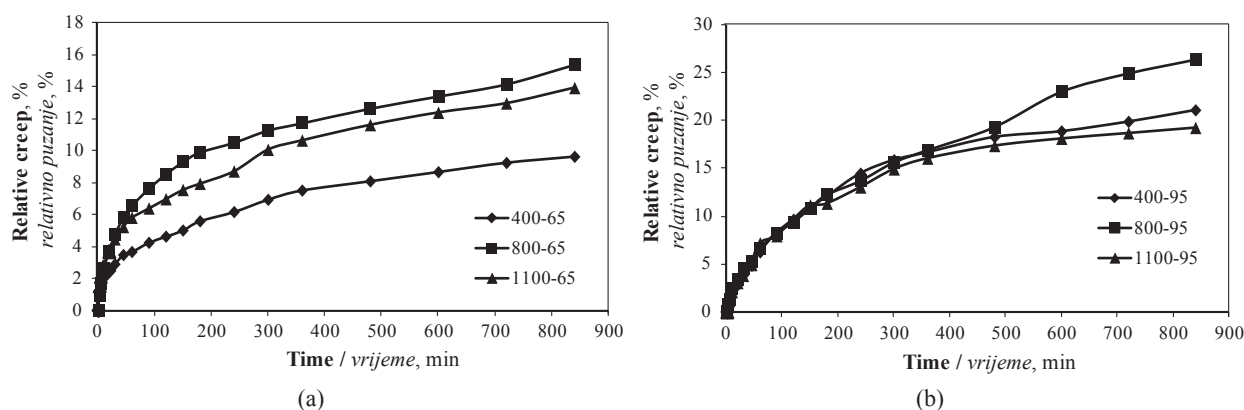


Figure 4 The effect of altitude on relative creep at 65% (a) and 95% RH (b)

Slika 4. Utjecaj nadmorske visine staništa na relativno puzanje uzoraka drva graba kondicioniranih pri: a) 65 % RH i b) 95 % RH

3.5 Relative creep
3.5. Relativno puzanje

At 65 % RH during loading, the highest and lowest curves of relative creep at altitudes of 800 m and 400 m were observed (Fig. 4a). At 95 % RH until 480 minutes, the percentage of relative creep at each of the three altitudes showed small differences. From this time onwards, the maximum value of relative creep was observed at the altitude of 800 m, and the minimum value of relative creep was observed at the altitude of 1100 m (Fig. 4b).

Figure 5 shows the interaction effect of the three altitude classes at two levels of RH (65 % and 95

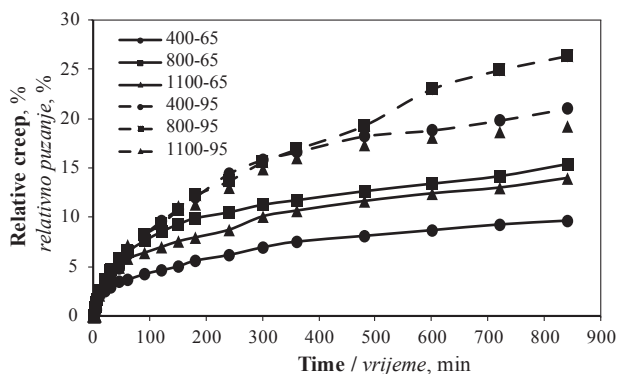


Figure 5 Interaction effects of altitudes and RH on relative creep in hornbeam wood

Slika 5. Interakcija utjecaja nadmorske visine staništa i relativne vlažnosti zraka pri kondicioniranju uzoraka na relativno puzanje drva graba

%) on relative creep. Results indicated that curves of relative creep at 95 % RH, related to each of the three altitudes, were higher than relative creep curves at 65 % RH.

3.6 Creep modulus
3.6. Modul puzanja

At two levels of RH (65 % and 95 %) all the time, the highest and the lowest curves of creep modulus were observed at the altitude of 400 m and 800 m, respectively (Fig. 6a and b). Figure 7 shows the interaction effect of three altitude classes at RH of 65 % and 95% on relative creep. The curves of creep modulus obtained at 65 % RH were above the curves of this parameter at 95 % RH.

3.7 Creep factor
3.7. Faktor puzanja

At 65 % RH during loading, the highest and the lowest curves of creep factor were observed at the altitude of 800 m and 400 m, respectively (Fig. 8a). At 95 % RH, until 480 minutes, creep factor curves in each of the three altitude classes showed small differences between each other and from this time onwards, the highest and the lowest curves were observed at the altitude of 800 m and 1100 m, respectively (Fig. 8b).

Figure 9 shows the interaction effect of the three altitude classes and two levels of RH (65 % and 95 %) on creep factor. At 95 % RH, curves of creep factor were placed the same as relative creep for each of the three altitude levels, upper than at 65 % RH. At

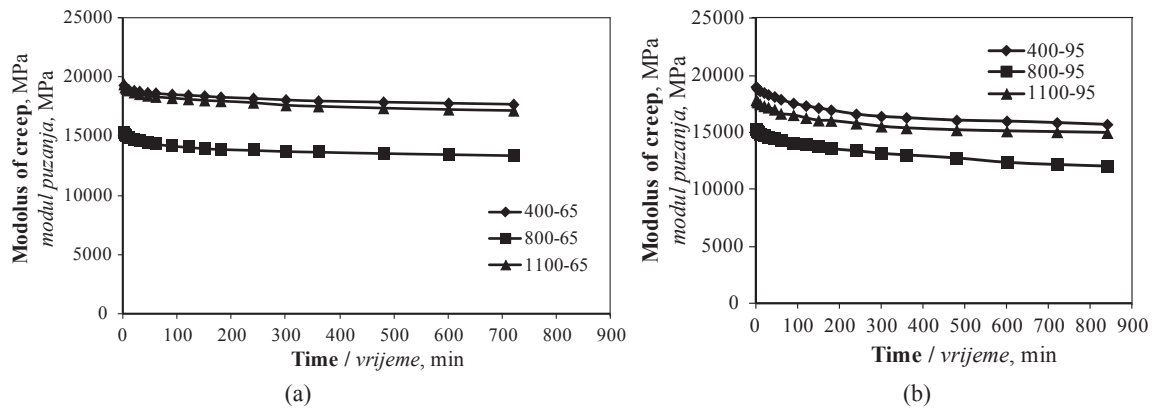


Figure 6 The effect of altitude on creep modulus at 65 % (a) and 95 % RH (b)
Slika 6. Utjecaj nadmorske visine staništa na modul puzanja uzoraka drva kondicioniranih pri: a) 65 % RH i b) 95 % RH

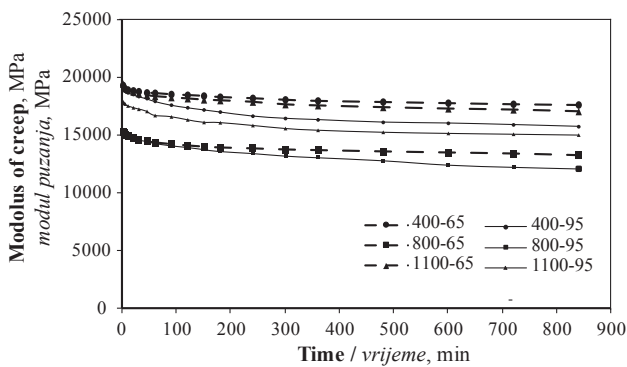
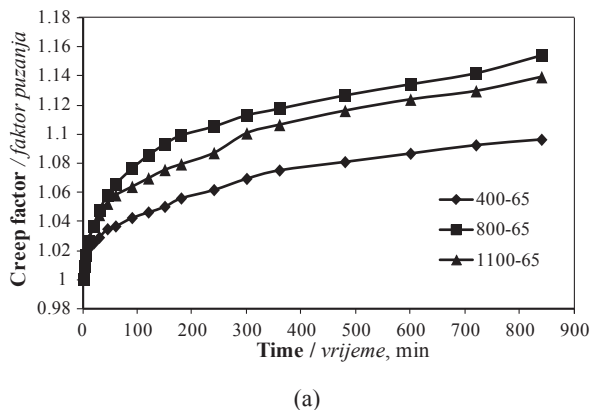


Figure 7 Interaction effects of altitudes and RH on creep modulus in hornbeam wood

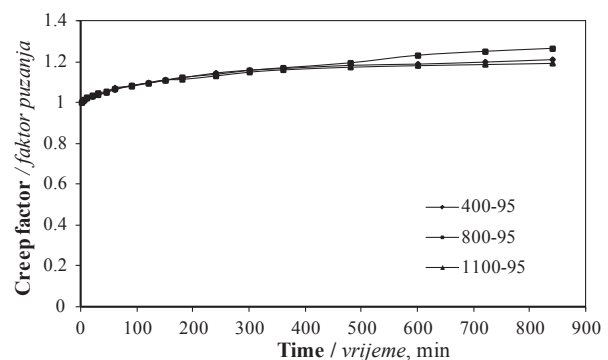
Slika 7. Interakcija utjecaja nadmorske visine staništa i relativne vlažnosti zraka pri kondicioniranju uzoraka na modul puzanja drva graba

95 % RH, the highest curve was observed at the altitude of 800 m and at 65 % RH, the lowest curve was observed at the altitude of 400 m.

At two levels of RH (65 % and 95 %), the relative creep and creep factor increase at the altitude of 800 m, due to a lower value of MOE at this altitude, because there is an inverse relationship between immediate creep and maximum creep and MOE (Taniuchi and Ando 2010; Table 5). At the two levels of RH (65 % and 95 %), the lack of significance related to MOE at two altitudes, 400 m and 1100 m, (Fig. 1 and 2) caused a little change in the procedure of measuring



(a)



(b)

Figure 8 Effect of altitude on creep factor at 65 % (a) and 95 % RH (b)

Slika 8. Utjecaj nadmorske visine staništa na modul puzanja uzoraka drva graba kondicioniranih pri: a) 65 % RH i b) 95 % RH

the relative creep and creep factor, as the least relative creep was observed at the altitude of 400 m and creep factor at the altitude of 1100 m. There is, also, an inverse relationship between creep modulus and relative creep and creep factor, and for this reason maximum creep modulus was observed at the in altitude of 400 m for both levels of RH (65 % and 95 %). Relative creep and creep factor were higher at 95 % RH than at 65 % RH, which is compatible with the results of Van de kuilen research (1999).

Besides moisture, numerous factors affect the creep behavior of wood in the same way as load, microfibril angle (MFA) and temperature. Kojima and Yamamoto (2004) and Dong *et al.*, (2010) reported that the increasing of MFA causes the decreasing of mechanical resistances and increasing of creep in wood.

3.8 Fitting parabolic equations and curves to creep behavior of samples under study

3.8. Prilagođivanje parabolične jednađbe i krivulje ponašanja analiziranih uzoraka pri puzanju

At the two levels of RH (65 % and 95 %), two samples of empirical behavior compatible with treatments at the altitude of 400 m have been shown (Fig. 10). Having the value of *a* and *m* by plotting the related graphs and based on equation 4, parabolic equations can be obtained for each sample.

Najafi and Kazemi Najafi (2009) reported that strain creep can be predicted for different times of loading and by parabolic equation. Calculated values

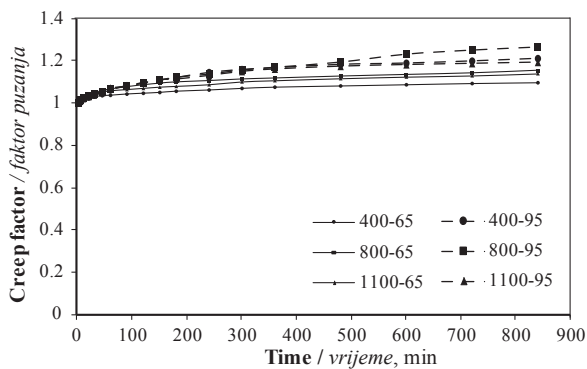


Figure 9 Interaction effects between altitudes and RH on creep factor in hornbeam wood

Slika 9. Interakcija utjecaja nadmorske visine staništa i relativne vlažnosti zraka pri kondicioniranju uzoraka na faktor puzanja drva graba

of m , a and parabolic equations of all treatments are shown in Table 6. Based on the results it can be concluded that creep behavior of studied samples follows the power law proposed by Findley *et al.* (1989).

4 CONCLUSION 4. ZAKLJUČAK

1. The maximum density and cell wall thickness were present in samples from the altitude of 400 m, the highest fiber length was detected at the altitude of 1100 m and the largest fiber diameter and lumen diameter were observed at the altitude of 800 m.

2. At 65 % and 95 % RH, the maximum and the minimum amounts of MOE and MOR were observed at the altitude of 400 m and 800 m, respectively.

3. At 65 % and 95 % RH, the maximum average immediate displacement, maximum displacement, permanent displacement and creep coefficient were observed at the altitude of 800 m. Also the range of return creep was higher at 95 % RH than at 65 % RH.

4. At 95 % RH, there was no relationship of fiber size, density and bending properties with immediate displacement and maximum displacement, while at 65 % RH, MOE showed a reverse and significant relationship with immediate creep and maximum creep. Also, a negative and significant relationship was observed between oven-dry density and maximum displacement.

5. At 65 % and 95 % RH, the maximum values of relative creep and creep factor were observed at the altitude of 800 m and the maximum and minimum creep modulus at the altitude of 400 m and 800 m, respectively.

6. The results of this research indicate that the use of hornbeam wood harvested at the altitude of 800 m is not recommended in applications under high bending forces, while wood harvested at altitudes of 400 and 1100 m is suitable.

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Table 6 Calculated values of m and a in parabolic equation
Tablica 6. Izračunane vrijednosti m i a u paraboličnoj jednadžbi

Altitude Nadmorska visina m	RH %	m	a	μ_0	$\mu_0 + a t^m$	R^2
400	65	0.35	0.007	0.86	$0.86 + 0.007 \cdot t^{0.35}$	0.99
800		0.45	0.009	1.09	$1.09 + 0.009 \cdot t^{0.45}$	0.95
1100		0.38	0.009	0.86	$0.86 + 0.009 \cdot t^{0.38}$	0.98
400	95	0.58	0.004	0.83	$0.83 + 0.004 \cdot t^{0.58}$	0.98
800		0.59	0.005	1.03	$1.03 + 0.005 \cdot t^{0.59}$	0.99
1100		0.57	0.004	0.88	$0.88 + 0.004 \cdot t^{0.57}$	0.97

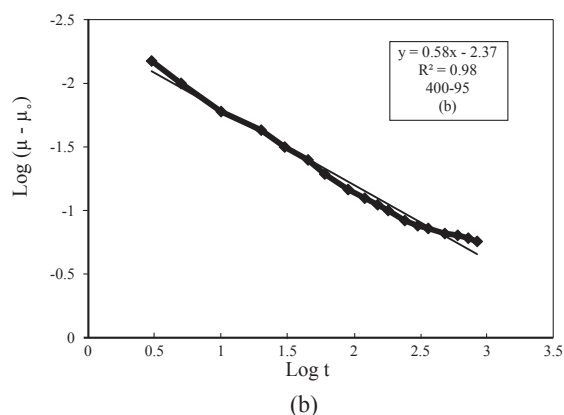
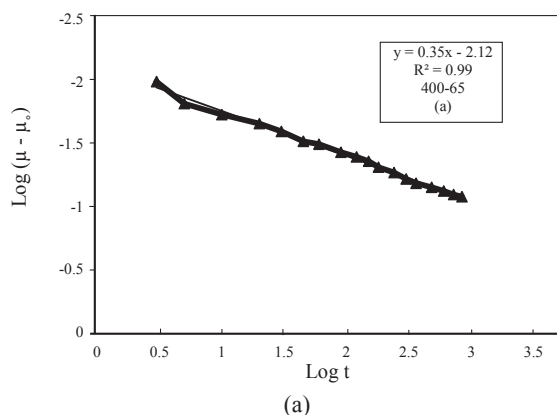


Figure 10 Creep behavior fitting plots for two samples at altitude of 400 m at 65 % (a) and 95 % RH (b)

Slika 10. Prikaz prilagođenih krivulja koje pokazuju puzanje drva za uzorke s nadmorske visine 400 m kondicionirane pri: a) 65 % RH, b) 95 % RH

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