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Research Article

An Investigation on the Moisture Adsorption of Eastern Spruce [*Picea orientalis* (L.) Link.]

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Abstract

Aim of study: The adsorption properties of the samples of full-dry Eastern Spruce (ES) [*Picea orientalis* (L). Link.] with 12.5 mm, 25 mm, 37.5 mm and 50 mm thick is to determine under the climate conditions with 42%, 65% and % 78 of relative humidity and at a constant temperature of 20 °C.

Material and method: The wood samples used in this study were the Eastern Spruce woods which were obtained from Forestry Process Management in the city of Trabzon/Turkey. With regard to mathematical modeling used to determine the wood moisture content (MC), the equation constants in case of adsorption was determined. Experiments were conducted at three different equilibrium moisture content (EMC); 8%, 12% and 16%.

Main results: Cross section had no crucial effect on the rate of accessibility to the final MC. However, EMC and thickness have been effective.

Research highlights: In practice, since dried wood is kept at outside weather conditions for a certain time before operation, an increase can be observed in the wood MC. It is practically important that under the influence of climate conditions until its utilization, the tendency of water adsorption of wood is determined as a function of time.

Keywords*:* Equation Constancy, Physical Properties, Wood Drying

Doğu Ladini Odununun [*Picea orientalis* (L.) Link.] Rutubet Adsorpsiyonu Üzerine Bir Araştırma

Öz

Çalışmanın amacı: Tam kuru Doğu ladini [*Picea orientalis* (L). Link.] örneklerinin 12.5 mm, 25 mm, 37.5 mm ve 50 mm kalınlıkta, 20 ° C sabit bir sıcaklıkta ve % 42 ,% 65 ve %78 farklı bağıl nem koşullarında adsorpsiyon özelliklerini belirlemektir.

Materyal ve yöntem: Bu çalışmada Maçka Orman İşletme Müdürlüğü'nden alınan Doğu Ladini örnekleri kullanılmıştır. Odun rutubet içeriğini belirlemek için kullanılan matematik modelleme ile adsorpsiyon durumunda denklem sabitleri belirlenmiştir. Deneyler, % 8, % 12 ve % 16 olmak üzere üç lif doygunluk noktası için gerçekleştirilmiştir.

Sonuçlar: Kesitin, denge rutubetine erişilebilirlik oranı üzerinde önemli bir etkisinin olmadığı, bununla birlikte denge rutubet miktarı ve kalınlığın etkili olduğu belirlenmiştir.

Araştırma vurguları: Kurutulmuş odunun, kullanım öncesinde belirli bir süre dış hava şartlarında tutulduğunda rutubet içeriğinde bir artış gözlemlenebilir. Kullanıma kadar iklim koşullarının etkisi altında, odunun rutubet alma eğiliminin zamanın bir fonksiyonu olarak belirlenmesi pratik olarak önemlidir.

Anahtar Kelimeler*:* Denklik Sabitlik, Fiziksel Özellikler, Ahşap Kuruma

Introduction

Wood is a material with high hygroscopicity which is closely related to many other properties, such as mechanical properties, dimensional stability, environment- humidifying ability and so on. Since relative humidity in the atmosphere is rarely constant, wood is continually subject to moisture adsorption and desorption. Therefore, study on the effect of relative humidity on moisture sorption rate of wood is helpful for understanding and controlling the dimensional stability and environment-humidifying ability of wood products in service effectively (Ma, Nakao & Zhao, 2009).

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Wood, with its hygroscopic structure, reaches equilibrium moisture content (EMC) by either adsorbing water from air or desorbing water to air under the influence of the climate conditions. Drying and reaching EMC of wood by releasing some water into air is called desorption whereas reaching EMC of wood at constant humid climate condition by collecting water from air is called adsorption.

The relationships among EMC, relative humidity (RH), temperature are the considerable and practical interest for wood materials. These relationships, known as sorption isotherms, greatly affect the strength and dimensional stability of different products during service (Wu & Suchsland, 1996). Due to the anisotropic structure of wood, its thickness chances in three different anatomical directions and in different amounts throughout moisture content (MC) change. These changes cause distortion and the value loss. Therefore, it is recommended that timber used in furniture manufacturing should be dried to the required MC for its final use, and then stored in a controlled environment to maintain it at the required MC. For instance, wrapping in PVC film would substantially reduce MC change in storage.

The amount of water held by cellulosic materials at a given temperature and RH depends on the direction from which side equilibrium is approached (i.e., sorption hysteresis). Stamm & Loughbrough, showed that the hysteresis ratio, the quotient of the adsorption and desorption MC's, varied from about 0.75 to 0.90. The variability depends largely on the RH level and the nature of the materials (Wu, 1999). When the complete adsorption-desorption cycle is used, it ranges about 0.70 to 0.98, depending on the wood. Accoya shows the highest hysteresis ratio at 0.85 to 0.98 (Zaihan, Hill & Curling, 2009). According to Walker (2006), the hysteresis coefficient, defined as a ratio the adsorption to desorption EMC at the same relative humidity, is 0.80 - 0.85 for most timbers over the relative vapor pressure range of 0.1 to 0.9. Baronas, Ivanauskas, Juodeikiene & Kajalavičius (2001) found a 3% absolute difference between adsorption and desorption in pine wood samples. It is stated that this can correspond to 85% for the (A/D) ratio. In a study investigating the hysteresis effect, the average adsorption-desorption ratio in pine wood samples was found to be 0.79 (Wiedenbeck, Hofmann, Peralta, Skaar & Koch, 1990).

In trials conducted at three different EMC values, the average hysterias constant and the moisture speed change constant of 300 × 100 mm length and 12.5 × 25 × 50 mm thick wood samples made out of full-dry walnut were determined as (a) 0.784 and (b) 0.108 (Ucuncu, Aydın & Tasdemir, 2005). In trials conducted at three different EMC values, the average hysterias constant and the moisture speed change constant of 12.5 × 25 × 50 mm thick wood samples made out of full dry Eastern beech were determined as (a) 0.764 and (b) 0.138 (Ucuncu, 2007). In trials conducted at three different EMC values, the average hysterias constant and the moisture speed change constant of 12.5 × 25 × 50 mm thick wood samples made out of full dry eucalyptus were determined as (a) 0.808 and (b) 0.108 (Ucuncu, Aydın & Tasdemir, 2010). Ucuncu, Aydın & Tiryaki (2016) investigated that ambient EMC and cross section have no significant effect on EMC but thickness.

Dried wood is rested for a while until its utilization. The wood, dried within this period, reaches higher MC under the influence of its climate condition than that it needs for its usage area. To solve this problem, it is possible that wood is covered to isolate MC, however; this application costs higher labor expenses.

In this study, wood samples of fully dried Eastern Spruce (ES) (*Picea orientalis* (L.) Link.) at 12.5, 25.0, 37.5 and 50.0 mm thick were stored at ambient temperature at 20^{o}C and at 42%, 65% and 78% RH. Equilibrium moisture values at applied temperature and RH were 8%, 12% and 16% according to Hailwood-Horrobin equation. In these conditions, the coefficients of equations given mathematical model were determined. Thus, it was determined how long the wood can reach the balance in the amount of humidity in the climatic conditions.

Material and Methods

Material

The wood samples used in this study was the Eastern Spruce which was obtained from Forestry Process Management in the county of Maçka, in the city of Trabzon, Turkey. In this study, sample preparation, determination of MC and specific gravity (SG) were carried out in accordance with TS 2470 (1976), TS 2471 (1976), and TS 2472 (1976) standards, respectively. The full dry density of Eastern Spruce samples was determined as 0.405 g/cm^3.

Samples were obtained from sapwood. Since separation between heartwood and sapwood is impossible, Eastern Spruce samples were obtained right after 12 annual ring of the wood (Ay & Sahin, 1998). The width of annual ring was detected as 2.314 by Akyuz (2004), and the samples were taken from 30 mm radius of the heartwood.

The total numbers of samples used in this study were defined as follows.

Number of EMC (8%,12%,16%)[NOE] : 3pcs
Number of sections (tangential, radial) [NOSE]: 2 pcs
Number of thickness (12.5 mm, 25 mm, 37.5 mm, 50 mm) [NOT]: 4 pcs
Number of samples [NOSA]: 8 pcs
Total number of samples [TNOS];
TNOS = NOE × NOSE × NOT × NOSA
TNOS = 3 × 2 × 4 × 8 = 192 pcs

Samples which have 300 mm length and 100 mm width and related features are listed in Table 1. The first experiment (TN1), the second experiment (TN2), and the third experiment (TN3) were performed at 20 °C temperature and 42% RH, at 20 °C temperature and 65% RH and, at 20 °C temperature and 78% RH, respectively in Table 2.

To decelerate the water movement of short wood samples in longitudinal direction, paraffin was applied onto the cross section. The places where the samples were obtained and their crosscuts are shown in Figure 1. The diffusion directions were symbolized as R when radial samples were used, while they were symbolized as T when tangential samples were used.

Table 1. Sample types and properties

Specimen type	Depth (mm)	Diffusion direction
T12.5	12.5	Tangential
R12.5	12.5	Radial
T25	25	Tangential
R25	25	Radial
T37.5	37.5	Tangential
R37.5	37.5	Radial
T50	50	Tangential
R50	50	Radial

Table 2. The experiment plan

Trial Number	Climate condition		
	T (^{0}C)	Φ (%)	EMC (%)
TN1	20	42	8
TN2	20	65	12
TN3	20	78	16

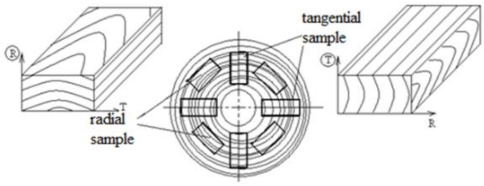

Figure 1. The cross sections of radial and tangential samples

Experimental Procedures

The test samples were initially dried in climate cabinet. After drying, the samples were rested in desiccator under constant climatic conditions. The measurements of adsorption isotherms were carried out in laboratory conditions, at average temperature of 20ºC. The samples were stored at three different relative humidity conditions; 42%, 65% and 78%. The initial state for all the measurements was dry material. All samples were measured in specified periods of time until steady value was achieved. Then, the MC was calculated. The increase in EMC as a result of moisture absorption is recorded as a function of time.

Methods

Experiments were conducted at three different EMCs; 8%, 12% and 16%. The wood MC of the samples was calculated by Eq. (1);

$$W(\%)=(M_r-M_0)/M_0\times100$$

Equation 1.Wood moisture content

where: Mr is the wet weight and Mo is the dry weight.

The wood EMC, was calculated by the Hailwood- Horrobin two hydrate (n = 2) model (Majka, Olek & Kudła-Chwiłowicz, 2014).

$$\mathrm{EMC(D)} = \frac{1800}{\mathrm{W}}\left[\frac{\mathrm{KH}}{1-\mathrm{KH}} + \frac{\mathrm{K_1KH} + 2\mathrm{K_1K_2K^2RH^2}}{1+\mathrm{K_1KH}+\mathrm{K_1K_2K^2H^2}}\right]$$

Equation 2. Equilibrium moisture content

where: H is the relative humidity of air and W, K, K_1, K_2 are the parameters of the Eq. (2).

The parameters of the Hailwood-Horrobin model were also calculated according to the proposed procedure using Eq. (3), (4), (5), and (6).

$$W = 349 + 1{,}29T + 0{,}0135T^2$$
Equation 3. Parameters

$$K = 0{,}805 + 0{,}000736T - 0{,}00000273T^2$$
Equation 4. Parameters

$$K_1 = 6{,}27 - 0{,}00938T - 0{,}000303T^2$$
Equation 5. Parameters

$$K_2 = 1{,}91 + 0{,}0407T - 0{,}000293T^2$$
Equation 6. Parameters

where: T (ºC), temperature.

The hysteresis ratio was determined, calculated as:

$$a = (EMC(A))/(EMC(D))$$
Equation 7. H*ysteresis ratio*

where: EMC(A) adsorption wood moisture balance, EMC(D) desorption wood moisture balance.

The Newton model was used for the moisture curves of the samples (Türk Toğrul & Pehlivan, 2003; Tırıs, Ozbalta, Tırıs & Dinçer, 1994; Olgun & Rzayev, 2000; Liu & Bakker-Arkema, 1997).

$$W_t = W_0 \exp(-kt)$$
Equation 8. Moisture curves

where; t is adsorption time (h), W_t is moisture content at t time (%), W_0 is initial moisture content (%),b is the adsorption speed coefficient.

The moisture content in adsorption case as a function of time was derived by using Eq. (9).

$$W_t = [W_0 - a\,EMC(D)]\exp\left(-\frac{b\,t}{\rho_0 e}\right) + a\,EMC(D)$$
Equation 9.Moisture content in adsorption

where; EMC(D) is the equilibrium moisture content in desorption case (%), ρ_0 is the full dry SG (g/cm^3), e is sample width (mm), a is adsorption (hysterias) constant.

The MC in case of adsorption W_s is equal to the possible EMC at stable climate conditions [EMC(A)].

$$W_s = EMC(A)$$
Equation 10. Moisture content

The hysterias constant in case of adsorption is the ratio of the average MC to desorption MC as shown in Eq. (11).

$$a = \frac{W_s}{EMC(D)} = \frac{EMC(A)}{EMC(D)}$$
Equation 11. Desorption moisture content

During the resting of dry wood under outside climate conditions, a and b constants were determined to assess their MC change and to use in practice. These constants were separately averaged and calculated for the radial and tangential samples.

Adsorption speed, in the case of t →0 was calculated with Eq. (12) (Turhan, Sayar & Gunasekaran, 2002; Khazaei, 2008).

$$U_t = \left(\frac{W_{t+dt} - W_t}{dt}\right)_{t=0} [\%/day]$$
Equation 12. Adsorption speed

The effect of section, width, and EMC on MC, final MC, and reaching time to final MC were performed on SPSS software program and the dissimilarities were determined. Cross section, width, final MC, reaching time to the final MC were analyzed with variance analyses, and the factors of inequality were determined with Post Hoc (Duncan).

Results and Discussions

The final MC and reaching time for final MC of Eastern Spruce which has different width and cross sections under different climate conditions of EMC are shown in Table 3. Equation constants for tangential and radial directions (b_r, b_r, b) are given in Table 4.

Under staple EMC conditions with 8%, 12%, and 16%, the MC change of Eastern Spruce samples with different width and sections are summarized as a function of time in Figure 2. Under staple EMC conditions with 8%, 12%, and 16%, the MC change of Eastern Spruce samples with different thicknesses are summarized as a function of time in Figure 3. The adsorption speed of Eastern Spruce sample was calculated according to the sample widths and shown for different EMC as a function of time in Figure 4.

Table 3. The final moisture content and reaching times for final moisture content of Eastern Spruce (ES)

Sample	EMC (%)					
	8		12		16	
	Ws (%)	t (day)	Ws (%)	t (day)	Ws (%)	t (day)
ES-T12.5	6.77	14	10.20	14	13.60	15
ES-R12.5	6.78	13	10.20	13	13.59	14
ES-T25	6.75	25	10.22	25	13.60	27
ES-R25	6.75	23	10.22	23	13.61	25
ES-T37.5	6.76	35	10.20	37	13.60	38
ES-R37.5	6.77	33	10.20	34	13.60	36
ES-T50	6.79	45	10.21	46	13.62	48
ES-R50	6.78	42	10.22	43	13.61	45
ES-12.5	6.75	13	10.20	14	13.60	15
ES-25	6.75	24	10.22	25	13.61	27
ES-37.5	6.76	33	10.20	37	13.60	37
ES-50	6.79	45	10.22	46	13.62	48

Table 4. Mean and standard deviation values of the equation constants (b) for tangential and radial directions

Equation constant	Thicknes (mm)	EMC						Average	
		8%		12%		16%			
		x	s	x	s	x	s	x	s
bt	12.5	0.085	0.012	0.084	0.010	0.084	0.010	0.084	0.011
	25	0.087	0.012	0.087	0.012	0.090	0.009	0.088	0.011
	37.5	0.089	0.009	0.091	0.010	0.089	0.008	0.090	0.009
	50	0.091	0.012	0.092	0.012	0.103	0.011	0.095	0.012
	Average	0.088	0.011	0.089	0.011	0.092	0.010	0.089	0.011
br	12.5	0.099	0.012	0.099	0.016	0.098	0.012	0.099	0.013
	25	0.102	0.012	0.101	0.014	0.103	0.012	0.102	0.013
	37.5	0.103	0.012	0.105	0.017	0.108	0.012	0.105	0.014
	50	0.109	0.006	0.106	0.014	0.110	0.012	0.108	0.011
	Average	0.103	0.011	0.103	0.015	0.105	0.012	0.104	0.013
b	12.5	0.091	0.012	0.091	0.013	0.090	0.011	0.091	0.012
	25	0.094	0.011	0.093	0.012	0.096	0.011	0.094	0.011
	37.5	0.095	0.011	0.098	0.013	0.099	0.012	0.097	0.012
	50	0.099	0.008	0.099	0.014	0.102	0.013	0.100	0.012
	Average	0.095	0.011	0.095	0.013	0.097	0.012	0.096	0.012

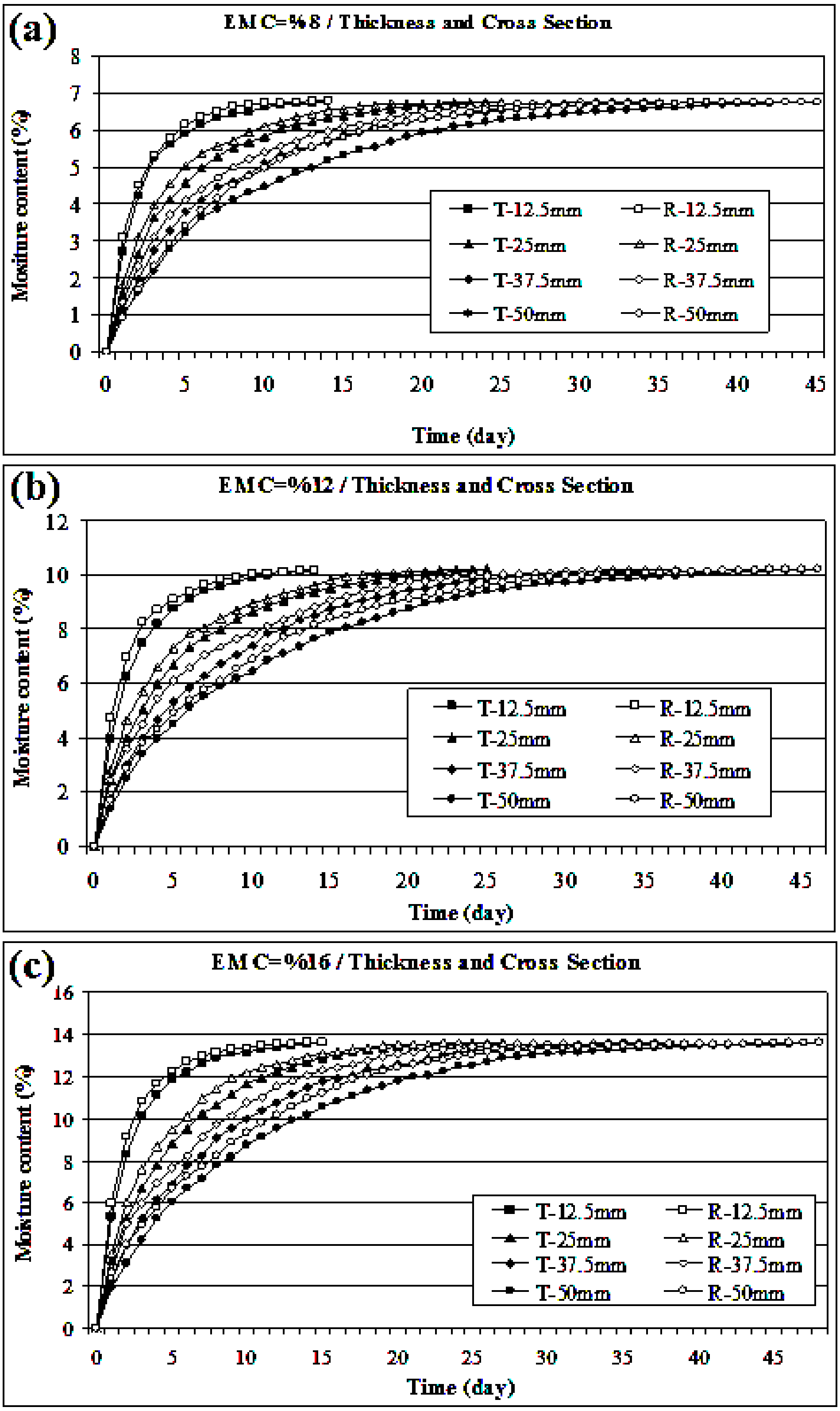

Figure 2. Moisture content change of the samples according to their section and width in adsorption case for EMC = 8% (a), 12% (b) and 16% (c)

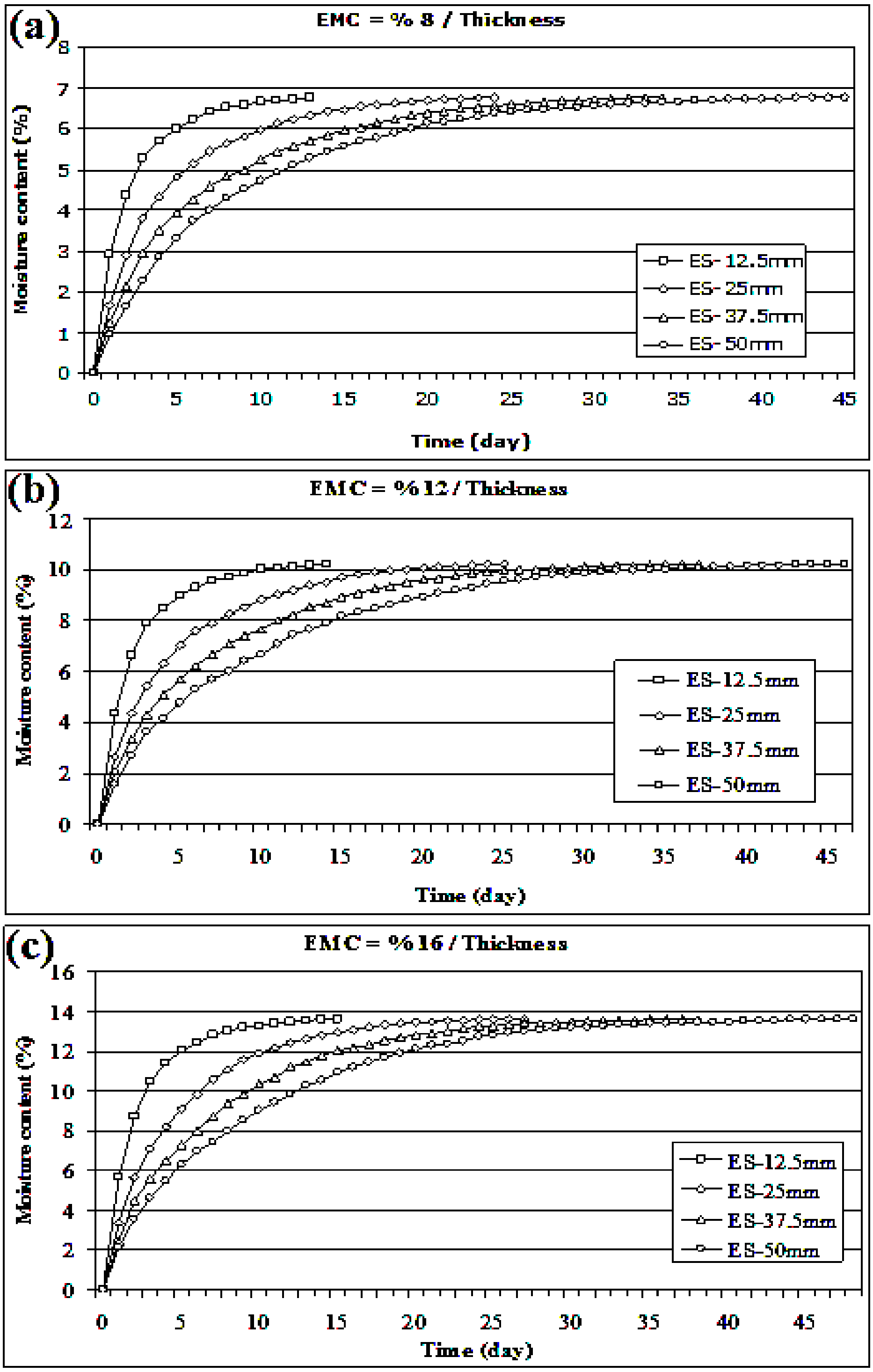

Figure 3. Moisture content change of the samples according to different thicknesses in adsorption case for EMC = 8% (a), 12% (b) and 16% (c)

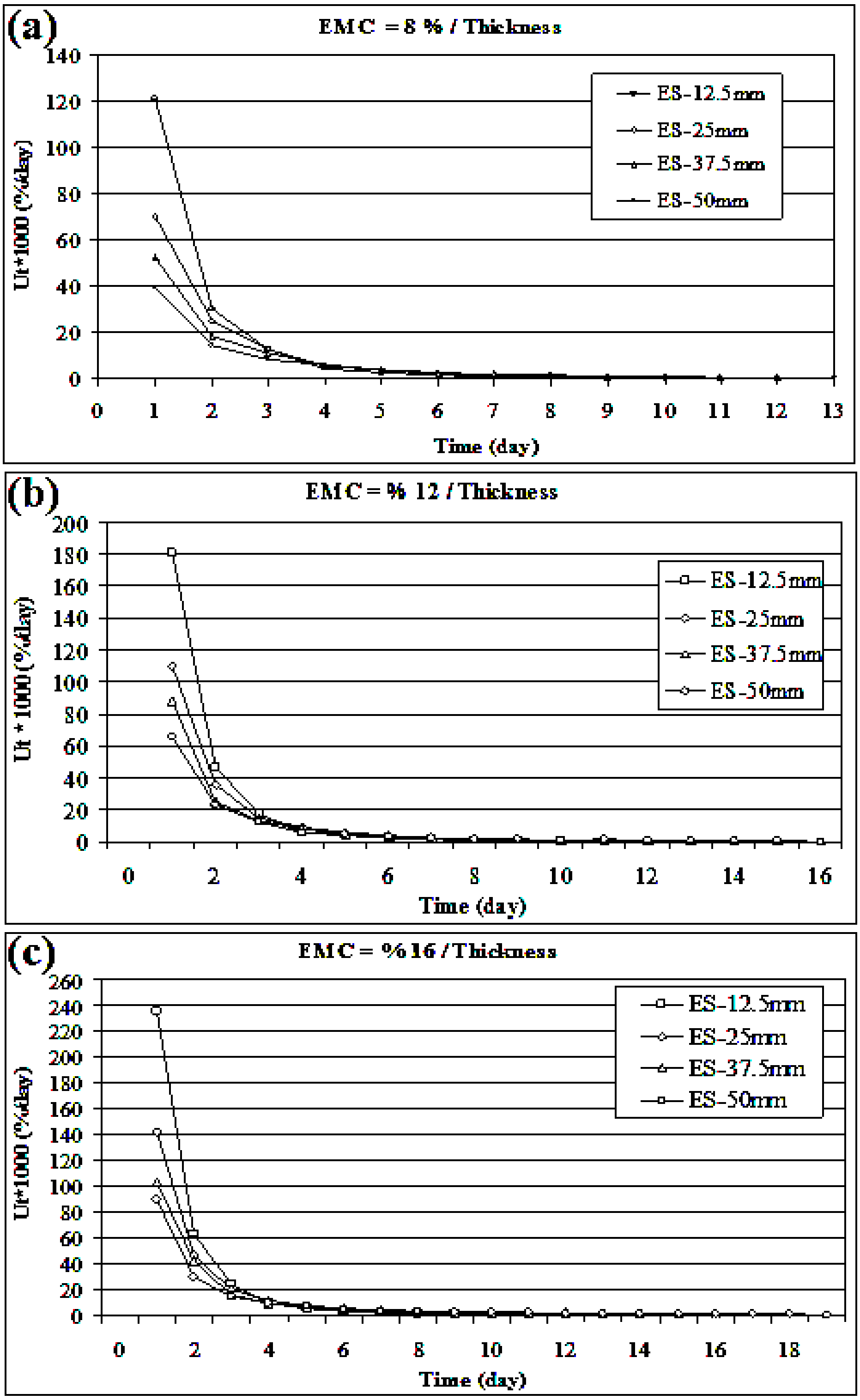

Figure 4. Wood adsorption speed for EMC = 8% (a), 12% (b) and 16% (c)

The thickness and EMC are effective on the adsorption speed, and thus the adsorption speed increases with increasing EMC and decreasing width. It is obvious that Eastern Spruce sample did not reach EMC in case of desorption compared to the one in case of adsorption under hysteric influence. The rate of the average MC in case of adsorption with hysteria constant to the one in case of desorption was calculated as 0.849. Likewise, the average moisture speed change rate was calculated as 0.096. Full dried Eastern Spruce reached EMC in accordance with its environment EMC:

$$W_s = EMC(A) = 0.849\, EMC(D)$$

Equation 12a. Eastern Spruce reached EMC

$$a = \frac{EMC(A)}{EMC(D)} = 0.849$$

Equation 12b. Eastern Spruce reached EMC

Likewise, by taking certain constants into account, the equation for in case adsorption was shown as follow;

$$W_t = [W_0 - 0.849\, EMC(D)] \exp\left(-\frac{0.096\, t}{\rho_0 e}\right) + 0.849\, EMC(D)$$

Equation 13. Adsorption

Variance analyses showed that section and thickness do not have an effect with 95% significance level on the MC that Eastern Spruce samples reached under stable climate conditions. It has been also found that EMC had an important effect on the final MC of Eastern Spruce samples, and that final MC which corresponds each EMC created a separate group.

The effect of thickness, section, and EMC on the MC in case of adsorption, the final EMC and the reaching time to EMC are listed as following:

Moisture Content;

- Section has a significant effect on wood MC with 95% significance level.
- Thickness has a significant effect on wood MC with 95% significance level.
- EMC has a significant effect on wood MC with 95% significance level, and there is a significant difference among wood MCs under each different EMC.

Table 5. Relationship between experimental and calculated amounts of wood moisture (Correlation coefficients)

Thickness (mm)	Cross-section	EMC(%)	r	*p*
12.5	Tangential	8	0.998	0.001
	Radial	8	0.996	0.001
25	Tangential	8	0.998	0.001
	Radial	8	0.995	0.001
37.5	Tangential	8	0.997	0.001
	Radial	8	0.997	0.001
50	Tangential	8	0.997	0.001
	Radial	8	0.998	0.001
ES12.5	General	8	0.997	0.001
ES25	General	8	0.998	0.001
ES37.5	General	8	0.998	0.001
ES50	General	8	0.999	0.001
12.5	Tangential	12	0.998	0.001
	Radial	12	0.993	0.001
25	Tangential	12	0.997	0.001
	Radial	12	0.995	0.001
37.5	Tangential	12	0.996	0.001
	Radial	12	0.996	0.001
50	Tangential	12	0.996	0.001
	Radial	12	0.998	0.001
ES12.5	General	12	0.997	0.001
ES25	General	12	0.997	0.001
ES37.5	General	12	0.997	0.001
DL50	General	12	0.997	0.001

Table 5. (continued)

Thickness (mm)	Cross-section	EMC(%)	r	*p*
12.5	Tangential	16	0.999	0.001
	Radial	16	0.876	0.001
25	Tangential	16	0.997	0.001
	Radial	16	0.998	0.001
37.5	Tangential	16	0.997	0.001
	Radial	16	0.998	0.001
50	Tangential	16	0.997	0.001
	Radial	16	0.998	0.001
ES12.5	General	16	0.998	0.001
ES25	General	16	0.998	0.001
ES37.5	General	16	0.998	0.001
ES50	General	16	0.998	0.001

Table 6. Effect of cross-section, thickness and wood MC on wood moisture (Duncan test results)

Effect of cross-section				
EMC (%)	Thickness (mm)	Factor	F	*p*
8	12.5	Cross-section	0.043	0.837
8	25	Cross-section	0.167	0.684
8	37.5	Cross-section	0.247	0.621
8	50	Cross-section	0.472	0.494
12	12.5	Cross-section	0.073	0.789
12	25	Cross-section	0.161	0.690
12	37.5	Cross-section	0.244	0.623
12	50	Cross-section	0.402	0.670
16	12.5	Cross-section	0.055	0.816
16	25	Cross-section	0.133	0.717
16	37.5	Cross-section	0.277	0.600
16	50	Cross-section	1.537	0.670
Effect of thickness				
EMC (%)	Cross-section	Factor	F	*p*
8	Tangential	Thickness	0.310	0.993
8	Radial	Thickness	0.100	0.999
12	Tangential	Thickness	0.014	0.998
12	Radial	Thickness	0.024	0.995
16	Tangential	Thickness	0.028	0.994
16	Radial	Thickness	0.012	0.998
Effect of thickness				
EMC (%)	Wood	Factor	F	*p*
8	ES	Thickness	1.272	0.287
12	ES	Thickness	0.019	0.997
16	ES	Thickness	0.019	0.996

Table 6. (continued)

Effect of EMC				
Thickness	Cros-section	Factor	F	*p*
12.5	Tangential	EMC	14.115	0.001
12.5	Radial	EMC	15.435	0.001
25	Tangential	EMC	21.803	0.001
25	Radial	EMC	30.987	0.001
37.5	Tangential	EMC	39.378	0.001
37.5	Radial	EMC	46.222	0.001
50	Tangential	EMC	50.016	0.001
50	Radial	EMC	55.659	0.001

Wood Final MC;

- Section has a significant effect on wood MC with 95% significance level. The final MC of the samples with the same MC and thickness were involved in the same group.
- Thickness has a significant effect on wood MC with 95% significance level. The wood final MC belonged each thickness group with the same EMC are involved in a group.
- EMC has a significant effect on wood MC with 95% significance level. The final MC values in each EMC case with the same thickness are involved in each separate group.

Time to reach to the final MC;

- Section has not a significant effect with 95% significance level on time to reach of wood MC, and the final MC values with the same MC and thickness but different section were involved in the same group.
- Thickness has a significant effect on wood MC with 95% significance level. The samples with the same MC but different thickness were involved in the separate group.
- EMC has not a significant effect on wood MC with 95% significance level. The final MC values with the same thickness and under different EMC conditions are involved in the same group.

The final EMC that the wood reached, time to reach this EMC, and the effect of the thickness on these factors were quite appropriate with previous studies. The constants, final EMCs, and the reaching time for final EMC obtained from the study are pretty close to the previous studies in literature (Wiedenbeck et al., 1990; Ucuncu, 2007).

There is small difference between the final MCs of radial and tangential samples, and this difference showed increase when thickness and environment EMC increase. Nevertheless, the effects of the MC, the final EMC of the cross section of samples, and time to reach for sample EMC were found significant at 95% significance level. Accordingly, the wood MC at adsorption case could be evaluated regardless of the MC of the cross section.

Conclusions

This paper investigated the adsorption properties of the samples of full-dry Eastern Spruce under different climate conditions. It is observed that the thickness has an effect on time to reaching to the final MC of wood samples. Therefore, the MC of dried wood samples could be determined as a function of time by using the obtained results (a and b constants).

If covering process cannot be performed for the wood that is dried until reaching the proper EMC under the climate conditions in its operation area by determining the climate conditions of resting area, the MC that wood samples reach should be determined and checked as a function of time. Thus, the wood could be stopped from reaching the moisture at a higher rate which is not appropriate for the climate conditions in the area of usage.

Thanks to mathematical modeling used to determine the wood MC, the equation constancy in case of adsorption was determined. In addition, it was shown that crosscut had no crucial effect on the rate of accessibility to the final MC, while thickness of wood and EMC did.

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