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WATER ABSORPTION CHARACTERISTICS OF THREE WOOD VARIETIES

J. KHAZAEI*

University of Tehran, Iran

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ABSTRACT - *Water absorption process during wood soaking in water was studied on three varieties of wood. Two models were considered to describe the kinetics: the Peleg model and a new one based on the viscoelastic properties of materials. The soaking data were fitted to the Fick's model to determine water diffusivity. The pattern of water uptake suggested a two step-process, in which more than half of the final absorbed water occurred in the first two days of liquid water contact with wood. This was followed by a period of very slow water uptake. The mean values of water absorption at initial stages of moisture sorption for Afra, Ojamalesh and Roosi genotypes were equal to 13.44, 6.05 and 5.44 (kg/m*^{2} *s*$^{1/2}$*), respectively. The corresponding mean values of this parameter for the entire soaking process were equal to 6.8, 4.6 and 3.9 (kg/m*^{2} *s*$^{1/2}$*), respectively. The calculated diffusion coefficients for Afra, Ojamlesh, and Roosi wood varieties were 1.38x10*$^{-3}$*, 3.71x10*$^{-4}$*, and 4.88x10*$^{-4}$ *m*^{2}*/s, respectively. The newly introduced model was more accurate for describing the water absorption characteristics of wood samples. The maximum value of root-mean-square deviation was 9.36, which demonstrated the suitability of the new model for modelling the experimental absorption characteristics of wood samples.*

Key words: wood, water absorption, modelling, diffusivity, Fick's law

REZUMAT – Caracteristicile de absorbție a apei la trei specii de lemn. *Absorbția apei la trei specii de lemn a fost studiată în timpul procesului de înmuiere a lemnului în apă. Pentru aceasta, s-au folosit două modele: modelul Peleg şi un model nou, bazat pe proprietățile viscoelastice ale materialelor. Datele privind înmuierea au fost adaptate la modelul Fick, pentru determinarea caracterului de difuzie a apei. Modelul de absorbție a apei a implicat un proces în două etape, în care mai mult de jumătate din apă a fost absorbită in primele două zile de contact al lichidului cu lemnul. Apoi, a urmat o perioadă de absorbție foarte lentă a apei. Valorile medii ale absorbției apei, în stadiile inițiale, de către genotipurile Afra, Ojamalesh şi Roosi, au fost egale cu 13.44, 6.05 şi, respectiv, 5.44 (kg/m*^{2} *s*$^{1/2}$*). Valorile medii*

* E-mail: jkhazaei@ut.ac.ir

corespunzătoare ale acestui parametru, pe durata întregului proces de înmuiere, au fost de 6.8, 4.6 şi, respectiv, 3.9 (kg/m² s^1/2). Coeficienții de difuzie, calculați pentru speciile de lemn Afra, Ojamlesh şi Roosi, au fost de 1.38x10⁻³, 3.71x10⁻⁴ şi, respectiv, 4.88x10⁻⁴ m²/s. Modelul nou a fost mai precis în descrierea caracteristicilor de absorbție a apei de către speciile de lemn. Valoarea maximă a deviației rădăcinii medii pătrate a fost de 9.36, ceea ce a demonstrat precizia noului model de modelare a caracteristicilor experimentale de absorbție a apei de către lemn.

Cuvinte cheie: lemn, absorbția apei, modelare, difuzie, legea lui Fick

INTRODUCTION

Wood in storage is exposed to both periodic water absorption and desorption processes. The water absorption by wood frequently assumes great importance, especially in the structural uses of wood (Baronas et al., 2001). In residential buildings and in industrial applications, some components are often wood or wood-based (Candanedo and Derome, 2005). These components are exposed to the contact with liquid water, for example wetted by rain or by water infiltration. Thus, wood is always undergoing changes in moisture content. Understanding water absorption by wood during soaking is of practical importance, since it affects the mechanical properties of the product. The effects of moisture content on the mechanical properties of wood have been the subject of an intense investigation worldwide (Gerhards, 1998; Obataya et al., 1998; Severa et al., 2003). All strength properties decrease as wood adsorbs moisture in the hygroscopic range. Important properties such as modulus of rupture and compressive strength parallel to gram may decrease up to 4 and 6 percent, respectively, for each percent increase in moisture content (Bendtsen, 1966).

The periodic water absorption has also a negative effect on wood quality. The ability of microorganisms to attack wood depends on the moisture content of the wood cell wall (Baronas et al., 2001). Hence, modelling water transfer in wood during soaking has attracted considerable attention. The amount of absorbed water in wood is dependent on the density and water diffusivity of wood. The water diffusivity coefficient describes the rate at which water moves from surface to the interior of products. These effects are caused by the porous structure of wood and the reactivity of its chemical components.

Few measurements have been done on the wetting of wood and, as a result, few models have been developed with the capacity to simulate moisture uptake by wood. The data obtained from water absorption or sorption tests can provide a good approximation of the average liquid water diffusivity of the material (Malkov et al., 2004; Kumaran, 1999).

One of the most important aspects of wood technology is modelling of the water absorption processes. The process modelling is of unquestionable importance for the design and operation of dryers and other processing systems.

The evaluation of water absorption kinetics could help us in water absorption simulation for predicting the suitable absorption conditions. From the mathematical point of view, the problem of water absorption by wood can be treated as a diffusion problem based on the Fick's second law of diffusion. However, the moisture transfer prediction is a laborious task, because of the complexity in devising accurate and repeatable measuring techniques. Firstly, wood is a very non-homogeneous three-phase system. In addition, different mechanisms may prevail when water flows into the anisotropic wood from different directions (Ekstedt, 2002; Malkov et al., 2004; Siau, 1984). Secondly, the penetration process is accompanied by numerous complicated phenomena, including non-linearity of the bulk flow, capillary condensation of vapour and surface tension in the air-liquid menisci, gas dissolution and diffusion, migration of bound water through the cell walls, swelling of wood and other chemical interactions between wood and water. These difficulties may also be attributed mainly to the slow movement of moisture through porous materials, which makes the experimental period be extensively long. The entry of water into wood may result from mass flow or diffusion of water vapour into the cell lumens and diffusion from there into the cell wall, or from a diffusion of bound water entirely within the cell wall. In most cases, both processes probably occur. The mass flow penetration, followed by the diffusion into the cell wall, is a much more rapid process than either vapour-phase or bound-water diffusion (Banks, 1973). Water absorption experiments are valuable in predicting moisture uptake regardless of the mechanisms.

The primary objective of our research was to determine the water absorption and diffusion coefficient of three varieties of wood. Knowledge of moisture uptake and transport properties are essential for predicting the moisture content. The obtained results are fitted on four kinds of models to describe the kinetics: a diffusion model for an arbitrary geometry material and three empirical equations. Meanwhile, a new model, based on the viscoelastic properties, was developed to describe the water absorption kinetics of wood. The other objective of our research was to compare experimentally the determined absorption times and moisture content gradients to those calculated by the theoretical and empirical models.

Theoretical approach. Solid materials absorb moisture when they are immersed in water or when they are placed in a humid atmosphere, until the process reaches an equilibrium state. However, in some cases, the omnipresent latent heat effects may complicate the determination of the diffusivity. Nevertheless, over the range of temperature and moisture concentration that prevails in typical applications of composites, the thermal diffusivity is about 10^6 times greater than the moisture diffusion coefficient. Thus, the thermal diffusion takes place 10^6 times faster than the moisture diffusion. As a result, the temperature will reach the equilibrium long before the moisture concentration does. This observation allows solving the mass balance separately from the energy balance (Tsai and Hang, 1980).

In order to describe the kinetics of water uptake, two kinds of models may be used, the theoretical and the empirical ones. The theoretical models allow us to relate the experimental results to physical laws. The theoretical mechanisms for the kinetics of the diffusion process have been proposed, from the simplest, the Fickian diffusion to others, more complex ones, of the non-Fickian diffusion (Marcovich et al., 1999). Water diffuses under the shape of vapour, of bound water and interstitial water. Each of these cases obeys the Fick's law (Crank, 1975):

$$J = -D.\nabla x \qquad (1)$$

The first Fick's law stipulates that the flow is proportional to the concentration gradient (Crank, 1975):

$$J = -D_e \frac{\partial M}{\partial x} \qquad (2)$$

On the other hand, the second law of Fick takes into account the temporal dependence (Crank, 1975):

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}(D_e \frac{\partial C}{\partial x}) \qquad (3)$$

$$\frac{\partial C}{\partial t} = (D_e \frac{\partial^2 C}{\partial x^2}) \qquad (4)$$

Where, J is the flow of the water through wood, C is the concentration, ∇ is the gradient operator and D_e is the diffusion coefficient. The knowledge of the flux and the gradient makes possible to deduce the diffusion coefficient. The theoretical models are complex and involve numerous functions and parameters, and, therefore, are not convenient for practical computations in most situations. The empirical models are often preferred to the theoretical ones, due to their ease of computability and interpretation. The most popular empirical and semi-empirical models, which have been used to model the water absorption process of agricultural products, are the Peleg and the Exponential model. The Peleg model is as follows (Abu-Ghannam and McKenna, 1997b):

$$M_t - M_o = \frac{t}{K_1 + K_2 t} \qquad (5)$$

Where, M_o is the initial moisture content (% d.b), M_t is the moisture content (% d.b) at time *t* (day), and K_1 and K_2 are constants.

Water absorption behaviour, like viscoelastic properties of food products, is a time dependent behaviour (*Figure 1*). Therefore, it is possible to model these two different properties of agricultural materials with the same model. According to *Figure 1*, the water absorption behaviour of the agricultural products may be defined as (Mohsenin, 1986):

$$M_t - M_o = M_{ret}(1 - e^{-t/T_{ret}}) + K_{rel}t \qquad (6)$$

Where, K_{rel} is the rate of water absorption in the relaxation phase (% / min). The time of retardation, T_{ret}, is the time required by the seed moisture content to reach about 63% of the total retarded moisture content, M_{ret} (*Figure 1*). In other words, T_{ret} shows the rate of absorption in the first phase of absorption process. The highest amount of T_{ret} shows the high rate of absorbance in the first phase of absorption. In addition, K_{rel} shows the rate of absorption in the relaxation phase and is calculated by determining the slope of the tangent line on the last part of sorption curve (*Figure 1*).

The benefit of this model in respect with other empirical and semi-empirical models is its ability to determine all the constant parameters directly from the absorption curve. This model is also able to describe the second phase of moisture absorption, i.e. the relaxation phase.

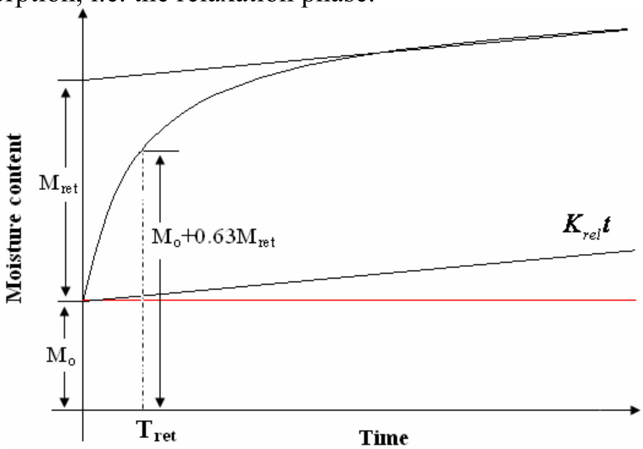

Fig. 1 - Graphical method to determine the constants of the newly introduced model (Eq. (6)).

MATERIALS AND METHODS

Three wood species were selected for the experiments: *Afra (Acer spp)*, *Roosi* (*Pinus APP)),* and *Ojamlesh.* Wood samples were cut under cubic shape of approximate dimensions L × W ×T = 70 × 50 × 35 cm³. The initial moisture content of samples was in the range of 7.4 to 10.3% (d.b). Water absorption data were obtained by placing the wood samples in 1500 ml screw-cap flasks containing distilled water. Experiments were conducted at 25°C and for immersion periods, from several minutes to about 22 days. The flasks were placed in constant-temperature water bath controlled within $\pm$ 0.5°C of the testing temperature. After soaking, the moisture content of samples was calculated based on the increase in the sample weight at corresponding times. For this purpose, at regular time intervals, ranging from 30 min at the beginning to 12 hours during the last stages of the process, the samples were rapidly removed from the test tubes and superficially dried on a large filter paper to eliminate the surface water. The samples were then weighed to determine the moisture uptake. The samples were subsequently returned into water via wire mesh baskets, and the process was repeated until the moisture content attained a range of 109-115% (d.b). At least three experiments were conducted for each wood genotype and the mean results were used for further analysis. Finally, curves showing the cumulative weight gain versus the square root of time were plotted, and linear regression curves were computed for each wood sample. The water absorption coefficient of the wood samples was determined by using the following equation (Krus et al, 1993):

$$m_w = A\sqrt{t} \qquad (7)$$

Where, m_w is the amount of water absorbed in kg/m^2, and A is the water absorption coefficient (kg/m^2 s$^{1/2}$). Following the definition, the water absorption coefficient A is given by the slope of the fitted curve divided by the contact area.

In this study, the Fick's second law of diffusion was used to determine the diffusion coefficients of water in wood samples, as it follows; it has been demonstrated that for a short period of soaking time, the following mathematical model may be used to correlate the normalized water uptake ratio $((M_t\text{-}M_o)/(M_s\text{-}M_o))$ with diffusion of water in solids of arbitrary shape during soaking in water (Marcovich et al., 1999):

$$\frac{M_t - M_o}{M_s - M_o} = \frac{2}{\sqrt{\pi}}(S/V)\sqrt{D_e t} = \alpha_b\sqrt{t} \qquad (8)$$

Where, M_s and M_o are constants for wood samples, depending on the physical properties, and the ratio of volume-to-surface area (V/S) may be taken as constant, irrespective of moisture content. To determine the diffusion coefficient, data were plotted as normalized water uptake data against the square root of time, $\sqrt{t}$. If the initial part of the curve was linear, it would be possible to determine its slope, α_b , and the coefficient of diffusion, D_e, by the following relation:

$$D_e = \frac{\pi}{4}\left(\frac{V}{S}\right)^2(\alpha_b)^2 \qquad (9)$$

For the mathematical modelling of the variation of either moisture content or moisture ratio of the wood samples during soaking, the newly developed model and the Peleg model were tested. The parameters of the models were estimated by nonlinear least squares. To evaluate the goodness of each model fit, two criteria were used. The coefficient of determination (R^2) and the root mean square error, as it follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(M_{r,i} - M_{p,i})^2}{N}} \qquad (10)$$

RESULTS AND DISCUSSION

The water-absorption patterns of the three wood genotypes are presented in *Figure 2*. The samples presented the characteristic moisture absorption behaviour. The wood samples exhibited an initial high rate of moisture sorption followed by slower absorption in the later stages, the relaxation phase (Kumar and Flynn, 2006). The pattern of water uptake suggests a possible two- step process, in which more than half of the final absorbed water occurred in the first two days of liquid water contact with the wood. This was followed by a period of very slow but ongoing slight water uptake. It is evident that *Afra* and *Roosi* samples quickly reached a moisture level in excess, of 60%. For the hard wood samples of *Ojamlesh,* uptake is slower over the immersion period, and there is no evidence of an initial rapid uptake mechanism as in case of the soft samples. For this variety, over typical immersion times, the moisture content reaches more than 56.78%. Similar results have been reported by Kumar and Flynn (2006). This is generally attributed to the natural capillaries present in the wood, which quickly attain equilibrium with the hydration medium by capillary inhibition. At the beginning of the water absorption process, capillaries and cavities near the surface are filled up very fast. Hence, it can be assumed that the water concentration at the surface is raised to saturation almost instantaneously. The moisture movement is restricted to inside the material only. Water moves freely in the large cavities, but in the small ones, the presence of trapped air bubbles influences the water movement inside the material.

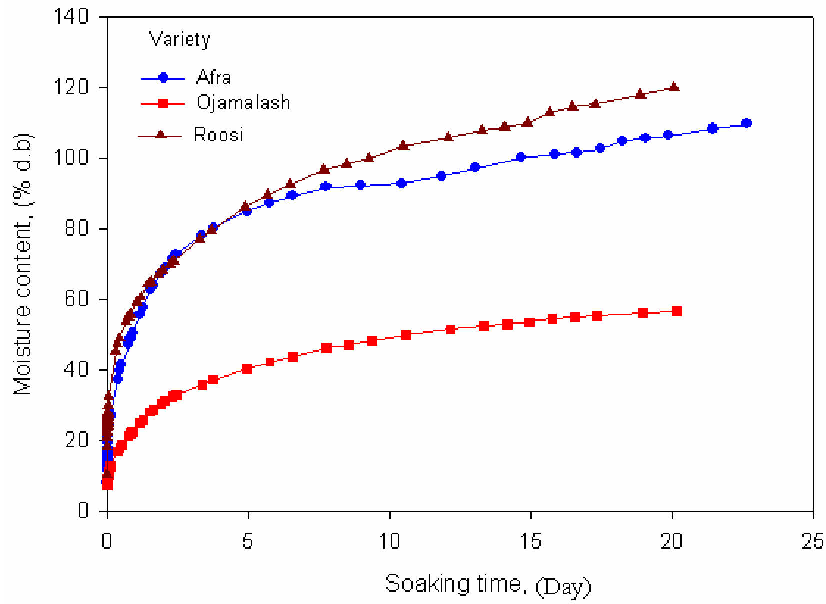

Fig. 2 - Water absorption curves during soaking of wood samples in plain water

The reason for higher initial water absorption rate can also be explained by the diffusion phenomenon. Diffusion is the process by which a fluid migrates and spreads itself through capillaries, vessels and cellular walls of wood. Water is present in wood in two forms: interstitial water and bound water. The interstitial water is contained in the cellular cavities, and dependent water is retained in the cellular walls. The rate of water absorption depends on the difference between the saturation water content and the water content at a given time, which is called the driving force. In other words, the moisture diffusion into the wood takes place because of the moisture gradient between the surface and the centre. As sorption proceeds, the water content increases, diminishing the driving force and, consequently, the absorption rate. The process ceases when the grains attaine the saturation in moisture content. Generally, the force, which retains the interstitial water molecules, is relatively weaker than that exerted on the bound water molecules. During the diffusion process, a difference in concentration between the various cellular layers is established. Water migrates then from the more concentrated medium towards the less concentrated one.

According to Eq. (7), the water absorption coefficient of the three wood varieties at initial high rate of moisture sorption (i.e., at t < 2 days) was determined (*Figure 3*). The mean values of the water absorption coefficient *A* at initial stages of moisture sorption for *Afra, Ojamalesh,* and *Roosi* genotypes were determined equal to 13.44, 6.05 and 5.44 ($kg/m^2\ s^{1/2}$), respectively. Corresponding mean values of this parameter for the entire soaking process were determined equal to 6.8, 4.6, and 3.9 ($kg/m^2\ s^{1/2}$), respectively.

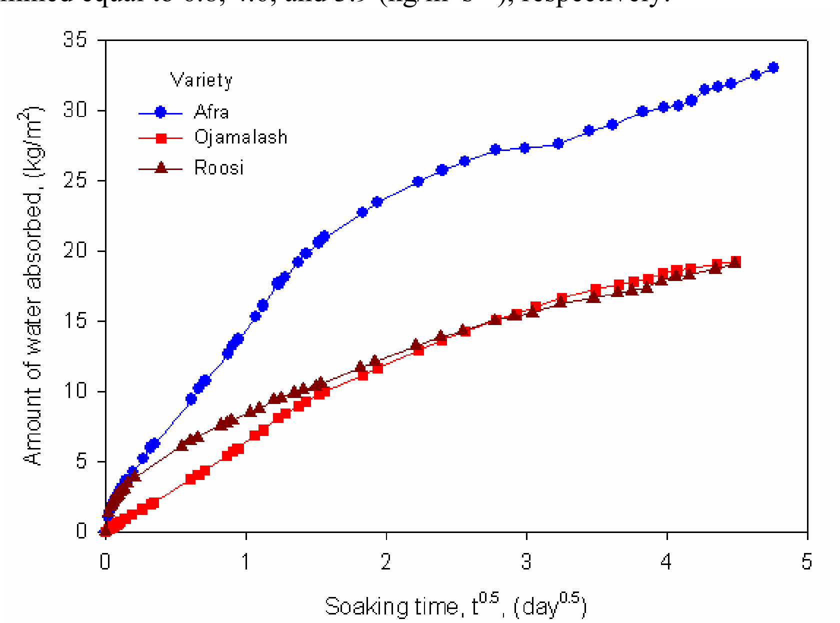

Fig. 3 - Variation in amount of water absorbed versus square root of time

Diffusion coefficients of wood samples. The diffusion coefficients for wood samples were calculated after fitting the absorption data to Eq. (8). Figure 4 shows the normalized water uptake data against square root of time. Generally, by using the initial slope of the absorption curves and neglecting the non-Fickian behaviour, the diffusion coefficients were estimated. The calculated diffusion coefficients for *Afra, Ojamlesh,* and *Roosi* wood varieties were 1.38×10^{-3}, 3.71×10^{-4}, and 4.88×10^{-4} m^2/s, respectively. The diffusion coefficient measured for the *Ojamlesh* variety was smaller than those obtained for the other two varieties. Probably, the chemical composition and the cell wall organisation in the *Ojamlesh* variety differ so much from the two others, that they can affect the flow of bound water. The density of the samples may also affect the diffusion coefficient of the wood samples. Moisture diffusivity is an important transport property, necessary for the design and optimization of all the processes that involve internal moisture movement, including drying (Simpson, 1993). The diffusion coefficient is the factor of proportionality, representing the amount of substance diffusing across a unit area through a unit concentration gradient in unit time.

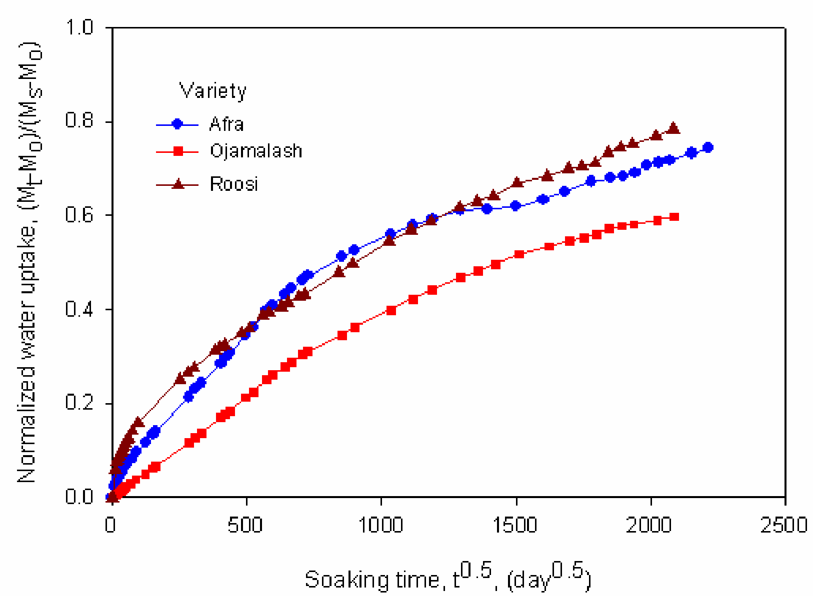

Fig.4 - Variation of $(M_t-M_o)/(M_s-M_o)$ against the square root of time

Mathematical modelling. *Table 1* presents the results of non-linear regression analysis of fitting the Peleg and the newly introduced model in Eq. (6) to the experimental water absorption data and comparison criteria used to evaluate goodness of fit, namely R^2 and RMSE. It is clear from *Table 1* that the newly introduced model was more accurate for describing the water absorption characteristics of wood samples. The maximum value of root mean square deviation was 9.36, which demonstrates the suitability of the new model for modelling the experimental absorption characteristics of wood samples. *Figure 5* shows the experimental data with the predicted curves by the Peleg and the newly developed model.

Table 1 - Estimation of the parameters and goodness of fit of the models applied to the data on moisture uptake by wood samples, during immersion in plain water

Variety	Peleg's model					
	K1 (day / %)	K2 (1/ %)	R^2	RMSE (%)		
Afra	0.0120	0.0101	0.978	9.93		
Ojamlesh	0.0465	0.0188	0.992	7.14		
Roosi	0.0120	0.0095	0.919	17.16		
Variety	**The newly introduced model (Eq. (6))**					
	M_o (% d.b)	**M_{ret} (% d.b)**	**T_{ret} (day)**	**K_{ret} (% / min)**	**R^2**	**RMSE**
Afra	8.2461	66.9	1.1435	1.631	0.978	8.18
Ojamlesh	7.3058	29.1661	1.3748	1.120	0.993	4.70
Roosi	10.327	54.8132	0.3588	3.098	0.939	9.36

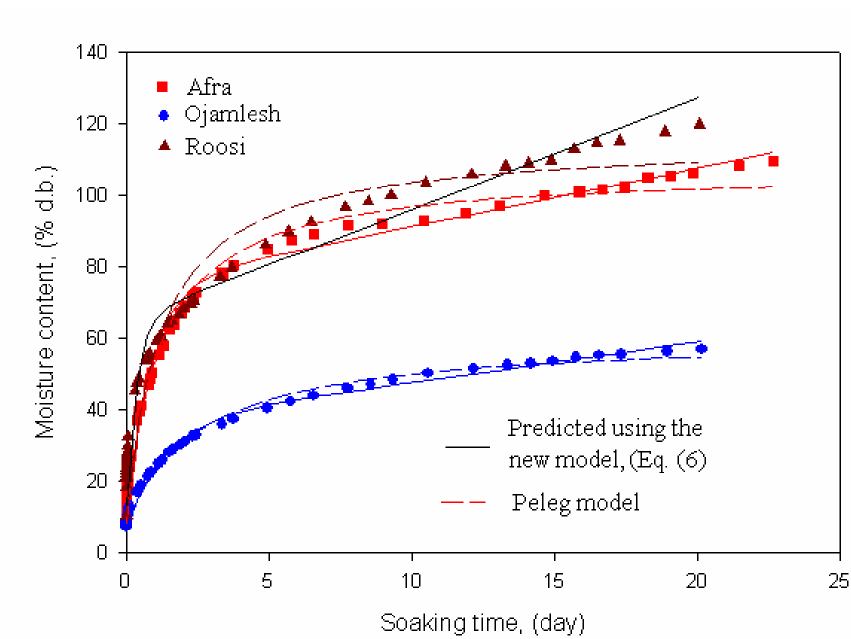

Fig. 5 - Experimental and predicted data of moisture content (Peleg and the new model (Eq. (6)) for water absorption behaviour in wood

In the Peleg model, the term $1/K_1$ is called the initial rate of absorption, thus, at a given temperature, as K_1 decreases, the amount of water absorbed becomes greater. According to Peleg model in Eq. (5), the water absorption velocity, at the very beginning times of soaking, i.e., when $t \rightarrow 0$, may be obtained by the following equation (Turhan et al., 2002):

$$R_o = \left(\frac{M_{t+dt} - M_t}{dt}\right)_{t=0} = \frac{1}{K_1} \qquad (17)$$

Knowing the constant of K_1 for each wood samples, the mean values of R_o were calculated and reported in Figure 6. At higher times of soaking, the sorption velocities were obtained using the experimental data, dM/dt. From this figure we may conclude that the initial slope of the sorption curve increases with temperature, although the water intake slow down quickly, thus reflecting a lower water diffusion coefficient. The reason for higher initial water absorption rate can be explained by the diffusion phenomenon. The rate of water absorption depends on the difference between the saturation moisture content and the water content at a given time, which is called the driving force. As hydration proceeds, the water content increases, decreasing the driving force and consequently the sorption velocity. The water absorption process ceases when the sample attains the equilibrium in water content.

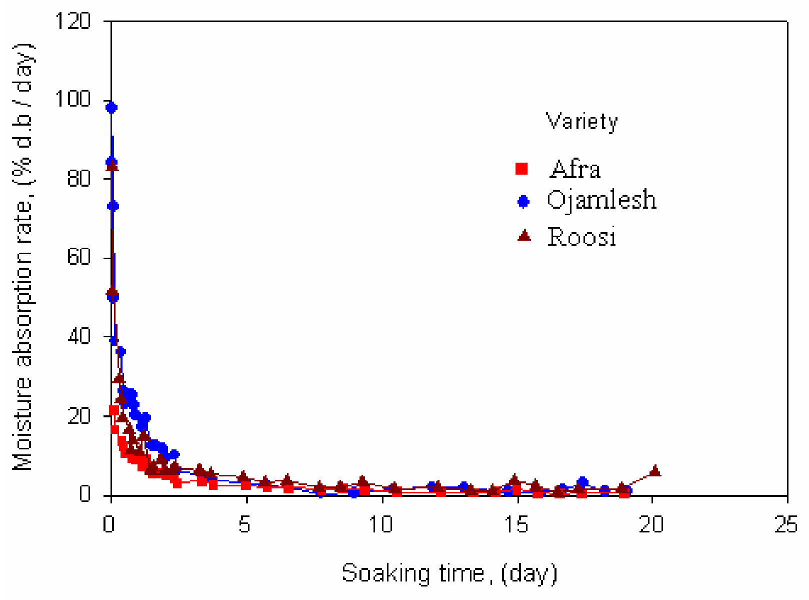

Fig. 6 - Water absorption rates for wood samples in plain water

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REFERENCES

Abu-Ghannam N., & McKenna B., 1997 - *The application of Peleg's equation to model water absorption during the soaking of red kidney beans (Phaseolus vulgaris L.).* Journal of Food Engineering, 32, 391–401

Baronas R., Ivanauskas F., Juodeikienė I., Kajalavicius A., 2001 - *Modelling of Moisture Movement in Wood during Outdoor Storage.* Nonlinear Analysis: Modelling and Control, 6 (2), 3-14

Banks W.B., 1973 - *Water uptake by Scots pie and its restriction by the use of water repellents.* Wood Sci. and Tech. 7:271–284

Bendtsen B.A., 1966 - *Sorption and swelling characteristics of salt-treated wood.* U. S. Forest Service Research Paper FPL 60

Candanedo L., Derome D., 2005 - *Numerical simulation of water absorption in softwood.* Ninth International IBPSA Conference Montréal, Canada

Crank J., 1975 - *The mathematics of diffusion.* Oxford University press, 412 pp

Ekstedt J., 2002 - *Studies on the barrier properties of exterior wood coatings.* Doctoral Thesis. KTH- Royal Institute of Technology Department of Civil and Architectural Engineering Division of Building Materials Stockholm

Gerhards C.C., 1998 - *Effect of moisture content and temperature on the mechanical properties of Wood: an analysis of immediate effects.* Wood and Fiber Science, 14, 154-163

Krus M., 1996 - *Moisture Transport and Storage Coefficients of Porous Mineral Building Materials. Theoretical Principles and New Test Methods.* Fraunhofer IRB Verlag. Germany, 106 p. plus appendix

Kumar A., Flynn P.C., 2006 - *Uptake of fluids by boreal wood chips: Implications for bioenergy.* Fuel Processing Technology 87, 605–608

Kumaran M.K., 1999 - *Moisture diffusivity of building materials from water absorption measurements.* Journal of Thermal Envelope and Building Science, 22, 349-355

Malkov S.Y., Kuzmin V.A., Baltakhinov V.P., Tikka P., 2004 - *Modelling the process of water penetration into softwood chips.* Journal of Pulp and Paper Science, 25, 123-129.

Marcovich N.E., Reboredo M.M., Aranguren M.I., 1999 - *Moisture diffusion in polyester–woodflour composites.* Polymer 40, 7313–7320

Mohsenin N.N., 1986 - *Physical properties of plant and animal materials.* 2nd ed. Gordon Breach Science, Publ; New York

Obataya E., Norimoto M., Gril J., 1998 - *The effects of adsorbed water on dynamic mechanical properties of wood.* Polymer, 39(14), 3059-3064

Severa L., Buchar J., Krivanek I., 2003 - *The influence of the moisture content on the fracture of the notched wood beam.* 8th International IUFRO Wood Drying Conference

Siau J.F., 1984 - *Transport Processes in Wood,* Springer-Verlag, New York, 245 p

Simpson W.T., 1993 - *Determination and use of moisture diffusion coefficient to characterize drying of northern red oak* (*Quercus rubra)* Wood Sci. Technol. 27:409-420

Tsai W., Hang H.T., 1980 - *Hygrothermal behaviour. In: Introduction to composite materials.* USA: Technomic, Chap. 8.

Turhan M., Sayar S., Gunasekaran S., 2002 - *Application of Peleg model to study water absorption in chickpea during soaking.* Journal of Food Engineering, 53, 153–159