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The influence of heat on shrinkage and water absorption of *Dendrocalamus giganteus* bamboo as a functionally graded material

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HIGHLIGHTS

- Heat treatment of bamboo slows down the rate of water absorption. The short term water absorption of bamboo reduces from 7.5% per hour and for not heated specimens to about 3% per hour when subjected to 200 °C for 24 h. The weight increment due to natural water observation for bamboos heated in different temperatures is around 100%. The untreated specimens can absorb more water up to 20% in comparison with treated bamboo at 225 °C for 3 h. Heating bamboo up to 225 °C for 3 h or 200 °C for 24 h reduces the water absorption capacity up to 15% compared with the non-heated specimens. The effect of heating at 175 °C for 24 h is the same as heating at 200 °C for 3 h and both can reduce significantly the swelling in radial and tangential directions due to water absorption. The long term water absorption of treated and unheated bamboo for four weeks follows a three phase model; rapid, transition and slows for all heated cases for 3 and 24 h. There is no significant difference between shrinkage at external and internal parts of a bamboo section. The swelling of external side of bamboo due to water absorption in average is about 40% more than the internal part. The fibers expand five times more than the matrix due to water absorption up to saturation point. The fiber swelling coefficient does not change up to 200 °C and a drop of 2% after this temperature. The matrix swelling coefficient is 4% at 100 °C and gradually decreases to 2% at 225 °C.

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ABSTRACT

The main objective is to present the results of an investigation on the effect of heat and time exposure on hygroscopic property of *Dendrocalamus giganteus* bamboo. The shrinkage and water absorption of bamboo segments in longitudinal, radial and tangential directions, due to heat effect of seven different temperatures from ambient to 225 °C during 3 h and 24 h has been investigated. An equation based on the principal of curve fitting has been established for rapid, transition and slow phases of water absorption. The non-uniform shrinkage and water absorption tests in tangential direction at different temperatures during 3 h carried out to obtain the fiber and matrix shrinkage and water absorption separately. The water absorption test result shows that by increasing the temperature and time exposure the hygroscopic property of bamboo is reduced. Subjecting to heat at higher temperatures can slow down the rate of water absorption in short term.

1. Introduction

Due to the actual energy crisis in the world, which has been started in the seventies of the twentieth century, some researchers started to investigate the physical, chemical and mechanical properties of nonconventional materials such as bamboo and vegetal fibers at macro, meso, micro and nano levels [1]. Bamboo as a biomaterial is an all-purpose, non-timber forest product. Some of the advantages of bamboo as a construction and building material are: rapid growth, being renewable, affordability, workability and high mechanical resistance, with a mean tensile strength that is comparable to that of steel. Bamboo as an optimized and ready tubular element can be used as scaffolding, bridge construction, trusses, beams, columns and many other types of building components. Bamboo also can be used as reinforcement in concrete and cement mortar. The interactions between bamboo strips and mortars or concrete become an important factor due to water absorption of the bamboo. During the curing period of the concrete, bamboo starts to swell due to water absorption which may cause cracks in the concrete [2,3]. After the concrete has been cured the bamboo starts to lose its absorbed water, leaving a gap between bamboo and concrete. To control the cracks and create more cohesion between materials,

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the large dimensional changes should be reduced to a minimum. In general, the immutability and consistency and fewer dimension changes due to water and humidity absorption or temperature variation is more acceptable for woody materials which are used in construction as structural or non-structural elements. One of the low-cost and feasible ways to improve some properties such as stabilizing the dimension of the woody materials is exposing them to a specific temperature during a specific time.

Bamboo, as other organic, arboreal, woody and herbaceous materials, by being exposed to moisture, humidity or water, reacts by absorbing water and swelling. Hygroscopicity of the bamboo can be changed by exposing it to the heat. There are various investigations about heat effect (heat treatment) on water absorption and physical behavior of different types of hard and soft woods. The result of those studies shows exposing wood to a specific temperature-time can improve the dimensional stability and resistance to biological deterioration for different types of wood and makes it more hydrophobic [4]. In most cases, for hard and soft wood, there is a nearly direct relation between elevating the temperature and reducing the water absorption capacity. The tests carried out by O. Unsal et al. [5] on heat treated Eucalyptus specimens at 180 °C during 10 h shows a swelling reduction of about 14% and 21.5% in radial and tangential directions respectively, in relation to non-heated specimens. The test by D. S. Korkut and S. Hiziroglu [6] on oak and pine specimens show 39.8% and 28.7% lower tangential swelling values, as a result of exposure to a temperature-time of 200 °C-8 h with regards to control specimens. But the test results of S. Metsä-Kortelainen et al. [7] on pine sapwood show that the water absorption increases with heat treatment from 170 °C up to 230 °C, contrary to results presented by other types of wood and wood segments. W. Scheiding et al. [8] also mentions the water uptake difference between heat treated heartwood and sapwood of *Pinus sylvestris*. These results, of which some are contradictory, proves the necessity of carrying out water absorption tests on heat treated specimens of *D.G.* bamboo (*Dendrocalamus giganteus* bamboo). The same as wood, heat treatment changes the bamboo appearance, mechanical and physical property such as swelling and water absorption capacity [9–11].

This study presents the results of an investigation concerning the effect of heat on shrinkage and swelling of *D.G.* bamboo specimens in longitudinal, radial and tangential directions from ambient temperature up to 225 °C for 3 and 24 h. Based on the water absorption diagrams, a two component curve fitting equation is proposed to cover the rapid and slow phases of water absorption. Finally, to establish the difference between fiber and matrix hygroscopicity, the non-uniform shrinkage and water absorption test in tangential direction for internal and external parts was carried out and the hygroscopic property of each component was measured separately. A piece of a five year old *D.G.* bamboo culm has been used for this investigation. The culm had been air dried in a sheltered place under climatic conditions for one year.

1.1 Bamboo macro and meso structure

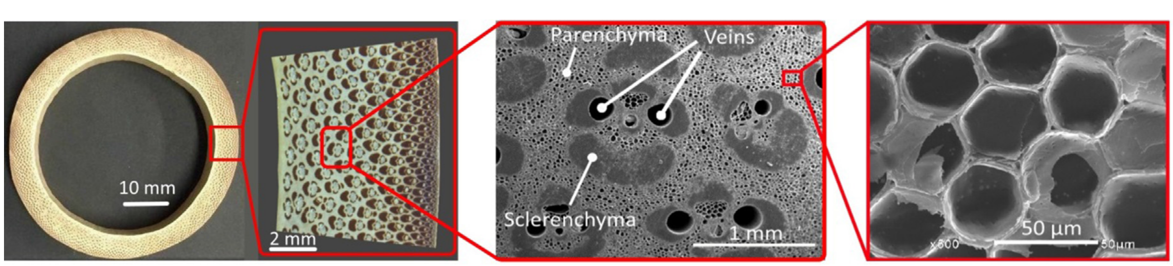
The cross section of a bamboo culm is shown in Fig. 1a and b. Bamboo is a natural composite with two principal components, sclerenchyma which is considered as fibers and parenchyma assumed as matrix presented in Fig. 1c. Sclerenchyma with high resistance parallel fibers along the entire length of the bamboo surrounded by parenchyma which is the matrix of this composite. Fig. 1c shows the parenchyma as spongiform and porous structure, sclerenchyma as solid areas and veins as hollow tubes. The shape of the wall cells and porosity of parenchyma is magnified and presented in Fig. 1d.

2. Experimental procedure and analysis

To determine the heating range and the temperature intervals, TGA (Thermal Gravimetric Analysis) was carried out. Cubic specimens as can be seen in Fig. 2a were prepared to establish the shrinkage of the bamboo specimens subjected to heat. Then the specimens were immersed in water to measure the short and long term water absorption capacity. By using different cubic specimens, the non-uniform shrinkage and water absorption at external and internal parts of the bamboo were measured. The image processing was used to show the fiber, matrix and vein volume fraction at internal and external parts which used to establish the water absorption properties of the fiber and matrix components. The principal directions and faces for a cubic specimen of bamboo are shown in Fig. 2b.

2.1. The heating range

The chemical composition of bamboo consists of hemicellulose, cellulose, lignin and extractives [12]. The temperature range of decomposition of hemicellulose and cellulose is 200–380 °C and 250–380 °C respectively, while lignin decomposition has a wide range from 180 °C up to 900 °C [13,14]. The TGA result for a *D.G.* bamboo with 10 °C/min heating rate [15], shows that the weight change and degradation of bamboo starts at about 150 °C as can be seen in Fig. 3. The continuous curve is the weight loss percentage regarding temperature and the dotted curve shows the derivative weight loss (percentage per min). Up to 150 °C, the humidity and some of the volatile extractives of bamboo are exited and it reaches to the most stable situation at about 150 °C based on the derivative weight loss curve. Increasing the derivative weight loss after this temperature shows the starting of the material degradation. The selected heating range starts from the ambient temperature up to the torrefaction temperature. Torrefaction is a thermal treatment at temperatures of 200–300 °C for the purpose of upgrading solid biomass fuel [16]. At the thermal torrefaction range, the bamboo transfers into charcoal. Based on wood species



(a) bamboo culm cross section (b) bamboo segment (c) bamboo cross section components (d) porosity of parenchyma

Fig. 1. Bamboo macro and meso structure.