Effect of Drying Methods on Wood Strength: A Comparison Between Microwave, Infrared, and Convectional Drying

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ABSTRACT
Wood consists not only of water but also of polymers such as cellulose, hemicelluloses, and lignin. Drying of wood is a complex operation involving transient transfer of heat and mass along with several processes, such as physical or chemical transformations, which in turn, may cause changes in product quality. The drying of wood is an important step in the processing of timber. Little detailed data is available on different heating modes during drying of wood. This paper presents experimental work using convectional air drying, microwave drying, and infrared drying of Guilan spruce woods. The experimental results show drying time of the microwave heating is significantly reduced, while the strength stays higher than that obtained in convectional and infrared drying.

Key Words: Wood Drying, Microwave, Infrared, Convectional Heat Transfer

تأثیر روش‌های مختلف خشک کردن چوب روی مقاومت مکانیکی آن و مقایسه روش‌های خشک کردن با میکروویو، اشعه مادون قرمز و روش همرفت
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چکیده
خشک کردن چوب یکی از روش‌های بسیار مهم در تهیه الیاف می‌باشد. چوب به طور خودکار در دمای بالا به‌طور خودکار خشک می‌شود و نهایتاً به پلیمر شیبیده شده و لیگنین هم تشکیل یافته است. خشک کردن چوب عمیقات می‌تواند به این داده که شامل انتقال حرارت و جرم‌ناپایا می‌باشد. انتقال فیزیکی و شیمیایی از جمله فرابنده‌های هستند که می‌توانند بر کیفیت محصول تأثیر بپذیرند. در این تحقیق با شیوه خشک کردن چوب فقط اطلاعات جزئی در دسترس می‌باشد. در این تحقیق رابطه بین شکستک چوبی از طریق انتقال گرما و شکست کردن به وسیله استفاده از میکروویو را نشان می‌دهد که شامل خشک کردن به وسیله انتقال گرما به روش همرفت، خشک کردن با میکروویو و شکست گرمایی است. خشک کردن با پرتو مادون قرمز چوب‌های کاج استان کیلیان است. تحقیقات نشان داده که در روش استفاده از میکروویو، پرتو با گرمایی و پرتو به شکل قابل توجهی کاهش می‌یابد، در صورت استفاده از میکروویو با پرتو همرفت و پرتو گرمایی است.

کلمات کلیدی: خشک کردن چوب، میکروویو، اشعه مادون قرمز، انتقال گرما به روش همرفت
Introduction
Drying is the removal of water from the material. Wood is an extremely versatile material with a wide range of physical and mechanical properties. Drying of wood is one of the most important industrial processes in wood manufacturing. Drying influences the mechanical properties of wood in three ways, namely through the direct effect of moisture loss, the internal drying stresses and strains. Almost all mechanical properties of wood can be improved.

Porous materials such as wood have microscopic capillaries and pores which cause a mixture of transfer mechanisms to occur simultaneously when subjected to heating [1]. Transfer of vapour and liquids occurs in porous bodies in the form of diffusion [2]. In essence, transfer of liquids can occur by means of diffusion arising from hydrostatic pressure gradient.

Heat and mass transfer in porous media is a complicated phenomenon and a typical case is the drying of moist porous materials. Scheidegger [3] claimed 47 years ago that the structure of porous media is too complex to be described precisely either in macro-scale or micro-scale, not to mention the combination of water with matrix to date, there is no credible work proving that Scheidegger was wrong.

Convective drying is usually encountered in wood industry. The study of this type of drying has attracted the attention of several authors. Among the works relating to this question we cite the works of Plumb et al [4] and Basilico and Martin [5]. Convective drying of timber is one of the oldest and time-consuming methods to prepare the wood for painting and chemical treatments. The drying method can obviously have significant effect on the mechanical properties of wood. Major disadvantages of hot air drying are low energy efficiency and lengthy drying time during the falling rate period. The desired to achieve fast thermal processing has resulted in the increasing use of radiation heating [6-9]. In this case, not only the removal of moisture is accelerated but also a smaller floor space is required, as compared to conventional heating and drying equipment. In the drying of many species, especially medium density and heavy hardwoods, shrinkage and accompanying distortion may increase as the temperature is raised. So with species which are prone to distort it is normal to use comparatively low kiln temperatures.

Water often makes up over half the total weight of the wood in a tree. The water or moisture content (Mc) of wood is expressed, as the weight of water present in the wood divided by the weight of dry wood-substance. In general, the average moisture content may be defined as:

\[ Mc = \frac{w_a - w_d}{w_a - w_i}, \quad (1) \]

where, \( w_i \) is the initial weight, \( w_a \) absorb moisture weight, \( w_d \) dried weight, and drying rate can be defining as:

Drying rate = \( \frac{Mc}{\text{total time}} \). \quad (2)

The most common method of drying is to extract moisture in the form of water vapour [10]. To do this, heat must be supplied to the wood to provide the latent heat of vaporization. There are several ways of conveying heat to the wood and removing the evaporated moisture. Nearly all the world's timber is, in fact, dried in air. This can be carried out at ordinary atmospheric temperatures (air drying), or in a kiln at controlled temperatures raised artificially above atmospheric temperature but not usually above 100°C, the boiling point of water. Air drying and kiln drying are fundamentally the same process because, with both, air is the medium which conveys heat to the wood and carries away the evaporated moisture. When air holds the maximum possible amount of vapour, the vapour exerts what is called the saturation vapour pressure [11]. If the water vapour present is less than this maximum then the air can take up more moisture [12-14]. When a piece of wet wood is exposed to air which is not already saturated (i.e. its relative humidity is less than 100%), evaporation takes place from its surface.

Experimental methods and equipment
Fifty cylindrical green wood samples of Spruce were obtained from Guilan province. The diameter and height of the specimens were approximately 300mm and 21mm respectively. A programmable domestic microwave oven (Deawoo,KOC-1B4K), with a maximum power output of 1000 W at 2450 MHz was used. The oven has the facility to adjust power (Wattage) supply and the time of processing. The hot air drying experiments were performed in a pilot tray dryer consisted a temperature controller. Air was drawn into the duct through a mesh guard by a motor driven axial flow fan impeller whose speed can be controlled in the duct. The infrared dryer was equipped with eight red glass lamps (Philips) with power 175 W, each emitting radiation with peak wavelength 1200 nm. Radiators were arranged in three rows, with three lamps in each row. Dryer was equipped with measuring devices, which made it possible to control air parameters. The amount of water in a piece of wood is known as its moisture content. All the 50 dried samples were tested on a universal Tension Test machine model (Hounsfield HS100KS), with a loading capacity of 100 KN. During the tensile testing, the stress-strain curves as well as the peak load were recorded.

Results
Conventional hot air drying is one of the most frequently used operations. The drying curves for
conventional hot air drying of wood samples are shown in Figures 1-5. It can be observed that the drying usually take place in the falling rate period. In essence, air in the oven is saturated, by time, and forms a thick film around the wood sample. That prevents effective separation of the evaporated moisture from the wood in drying; it is obvious that the water that is loosely absorbed will be removed most easily. Thus it would be expected that the drying rates would decrease as moisture content decreases, with the remaining water being bound more and more strongly as its quantity decreases. The change from constant drying rate occurs at different moisture contents for most of time. Another point of importance is that many woods do not show a constant drying periods. They do, however, often show quite a sharp break after a slowly and steady declining drying-rate period and the concept of constant rate is still a useful approximation. The end of the constant-rate period, at the break point of drying rate curves, signifies that the water has ceased to behave as if it were at a free surface and that factors other than vapor-pressure differences are influencing the rate of drying. Thereafter the drying rate decreases and this is called the falling-rate period of drying. The rate-controlling factors in the falling-rate period are complex, depending upon diffusion through the timber, and upon the changing energy-binding pattern of the water molecules. Very little theoretical information is available for drying of woods in this region and experimental drying curves are the only adequate guide to design. This may be the reason for existence of constant rate period in this study.

Microwave drying is an alternative drying method, which is recently used in different industries. The effect of changing power output in the microwave oven on the moisture content is shown in the Figures 6-8. Also Figures 9-10, show drying rate curve for the three different power of microwave. At all power levels, drying rates were tended to end at about the same time. The observed initial acceleration of drying may be caused by allowing rapid evaporation and transport of water. In Fig. 9, 10 it can be seen the drying rates for three different power units are nearly the same, this is because (M.W 100% power unit) compare with (M.W 80% power unit), make no much differences because of short time interval (TI=20 sec).
Fig. 4: Drying rate curve (Conventional hot air at T=100°C).

Fig. 5: Drying rate curve (Conventional hot air at T=100°C).

Fig. 6: Drying curve for microwave-dried wood at 80% power unit.

Fig. 7: Drying curve for microwave-dried Wood at 100% power unit.

Fig. 8: Drying rate curve for microwave-dried wood at 100% power unit.

Fig. 9: Drying rate curves for microwave-dried wood at three different power unit.
Infrared radiation is transmitted through water at short wavelength; it is absorbed on the surface. Infrared radiation has some advantages over convective heating. Heat transfer coefficients are high, the process time is short and the cost of energy is low. In this study, the drying time was reduced by nearly 34% compared to hot air drying. The infrared drying’s curves were plotted in Figures 11 and 12. In contrast to the hot air drying curves which had a short constant rate period followed by a falling rate period, Figures 11 and 12 indicates that the infrared had only a falling rate period, Fig. 13, shows the natural convection curve which took 30 Hr to dry it up. The results of tensile loading of dried samples are presented in Figures 14-15. It is clear that the microwave dried spruce specimen with failure strength of 49.6 Mpa has made a significant property improvement (Figure 14). The normal stiffness of infrared dried sample is reported as 35.0 Mpa (Figure 15) whereas the oven dried sample showed strength of about 44.5 Mpa (Figure 16). At the start of drying, when the initial water content is sufficient, the porous medium approaches the temperature of the wet bulb. During this transition phase, the higher the initial temperature is, the greater the drying rate. When the drying becomes stable, the temperature is uniform within porous medium. When the liquid phase becomes discontinuous, the liquid migration stops. Thus the moisture content decreases notably at the surface of the medium which becomes hygroscopic. The pressure of the vapour at the interface, and thus the drying rate decreases. The gradient of vapour pressure generates gaseous diffusion towards the surface and evaporation inside the porous medium.

From Figure 17 it is revealed that the natural convection dried specimens are the strongest (51.3 Mpa). In practice the drying time for this can take up onths and years. In Figure 18 the strength of dried wood samples are compared for a better judgment.
Fig. 14: Stress-strain for microwave dried wood.

Fig. 15: Stress-strain for infrared dried wood.

Fig. 16: Stress-strain for convective dried wood.

Fig. 17: Stress-strain for natural convection dried wood.

Fig. 18: Strength of dried wood samples in three different drying modes.

Microscopically, the dimensional change with (Mc) is anisotropic (referring to the fact that wood has very different properties parallel to the fact grain versus the transverse direction). As the (Mc) decreases, wood shrinks; conversely, as the (Mc) increases, wood swells or grows larger. The process of drying focuses on producing wood with a Mc about the same as the equilibrium value for the intended service environment. For the design of dryers it is necessary to carry out drying experiments at various drying conditions. Experimentally determined drying times, transition points, and constant-rate regime temperature can then be used as a base case for the analytical results. Based on the information from the experimental trials, runs with lower amounts of moisture to evaporate, higher dryer temperatures, should be expected to dry faster and reach transition point more rapidly. Contrary to the
results presented in [9] microwave heating improved the strength in comparison to the strength obtained in conventional hot-air drying. It should be noted that by applying natural convection the highest strength can be obtained with the highest drying duration. This can take weeks, months or even years [9]. After an initial increase or decrease of the rate of drying, the drying process enters the constant rate period. This initial change of the rate of drying is caused by a variation of the surface temperature which in turn results in a change of vapour density. It can be noted that time interval of drying process is solely determined by external conditions. Once the drying process has entered the falling rate period, the external conditions become relatively unimportant compared to the internal parameters.

By comparing runs with the same initial moisture, we see that as oven temperature increases, the transition points are reached more quickly and total drying times are shorter. Sample temperatures are higher because they are exposed to higher heat transfer rates, giving rise to higher mass transfer rates during the constant-rate regime.

The experimental study suggests that the humidity of the free stream should be as low as possible. Partial recirculation, 100% fresh air intake, or dehumidifications are some of the possible ways to accomplish this task, but a cost analysis is imperative before deciding on any option.

Reduction of the drying time in microwave heater seems to be a motivating cost saving factor for industries. In this case a moderate mechanical property is obtained (Table 1). To minimize directional variations in use, wood needs to be dry enough to match the service environment.

**Conclusion**

Although many methods of drying timber have been tried over the years only a few of these enable drying to be carried out at a reasonable cost and with minimal damage to the timber. The most common method of drying is to extract moisture in the form of water vapor. To do this, heat must be supplied to the wood to provide the latent heat of vaporization. The temperature of a piece of wood and of the air surrounding it will also affect the rate of water evaporation from the wood surface. With kiln drying, warm or hot air is passed over the timber and at the start of the drying process the temperature differential between the air and the wet wood will usually be large. As a result, heat energy will be transferred from the air to the wood surface where it will raise the temperature of both the wood and the water it contains. Water, in the form of vapor, will then be lost from the wood surfaces, provided the surrounding air is not already saturated with moisture. This results in the development of a moisture content gradient from the inside to the outside of the wood. As the temperature is raised this increases not only the steepness of this moisture gradient, but also the rate of moisture movement along the gradient and the rate of loss of water vapor from the surface of the wood. At a given temperature the rate of evaporation is dependent on the vapor pressure difference between the air close to the wood and that of the more mobile air above this zone.

Unfortunately the considerable benefits obtainable by raising the drying temperature cannot always be fully exploited because there are limits to the drying rates which various wood species will tolerate without degrade. In the drying of many species, especially medium density and heavy hardwoods, shrinkage and accompanying distortion may increase as the temperature is raised. So with species which are prone to distort it is normal to use comparatively low kiln temperatures. In contrast to air drying a modern radiation drying provides temperature control and a steady and adequate flow of air over the timber surface. The air flow rate and direction is controlled by fans and the temperature and relative humidity of the air can be adjusted to suit the species and sizes of timber being dried. It is thus possible to make full use of the increase in drying rate which can be achieved by raising the temperature to the maximum value which a particular timber species can tolerate without excessive degrade.

The experiments shows that in microwave heating, the drying time is significantly reduced while the strength were relatively improved in comparison to the strength obtained in conventional drying. It is also noted that the infrared drying can reduce the strength of the spruce woods significantly. The above discussion suggests further investigation for future work on different specimens.
Table 1: Average strength properties of samples (σ values in brackets refer to standard deviations).

<table>
<thead>
<tr>
<th>Drying Method</th>
<th>Failure Strength (Mpa)</th>
<th>Failure Strain %</th>
<th>Yield Strength (Mpa)</th>
<th>Modulus of elasticity (Gpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural convection Dried wood</td>
<td>51.3 (2.44 σ)</td>
<td>9.43</td>
<td>12.8 (0.615 σ)</td>
<td>0.544 (0.058 σ)</td>
</tr>
<tr>
<td>Hot air dried wood</td>
<td>44.53 (1.72 σ)</td>
<td>10.5</td>
<td>13.3 (0.51 σ)</td>
<td>0.424 (0.05 σ)</td>
</tr>
<tr>
<td>Infrared dried wood</td>
<td>35.04 (1.16 σ)</td>
<td>10.86</td>
<td>10.5 (σ 0.35)</td>
<td>0.322 (0.035 σ)</td>
</tr>
<tr>
<td>Microwave dried wood</td>
<td>49.6 (4.51 σ)</td>
<td>14.02</td>
<td>17.0 (1.28 σ)</td>
<td>0.354 (0.054 σ)</td>
</tr>
</tbody>
</table>

REFERENCES