MECHANICAL PROPERTIES OF POPLAR WOOD (*POPULUS ALBA*) DRIED BY THREE KILN DRYING SCHEDULES

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The influence of three drying schedules on the selected mechanical properties of poplar wood (*Populus alba* L.) was evaluated in terms of suitability for structural applications. For this purpose, 70 mm-thick poplar lumber was conventionally dried by three different moisture content based schedules of T_5-D_2, T_5-D_4, and T_5-D_6. In these schedules, the wet bulb depression was changed as a means of increasing of the drying intensity. After drying, the mechanical properties of the lumber, including bending properties (MOE and MOR), toughness, shear strength parallel to grain, and tensile strength perpendicular to grain, were measured. Results revealed that the severe drying schedule (T_5-D_6) caused higher reductions in the mechanical properties of the dried boards, particularly the MOE and MOR. Furthermore, toughness and tensile strength perpendicular to grain were not affected by the increasing of the wet bulb depression. The influence of all the three adopted schedules on the mechanical properties was evaluated using the drying rate, final moisture content gradient, and qualitative characteristics of the dried boards.

Keywords: Drying schedule; Wet bulb depression; Mechanical properties; Poplar

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INTRODUCTION

Drying may have a negative effect on the mechanical strength of wood. According to Thiam et al. (2002), drying affects the mechanical properties of wood through three ways: 1) direct effect of moisture loss, 2) direct effect of temperature, and 3) the occurrence of internal stresses and strains. Moreover, temperature would have many knock-on effects on the drying procedure itself. For instance, the effects of increasing drying temperature on the mechanical properties of wood, particularly in high-temperature drying, may be due not only to an increased drying rate, but also to thermal degradation of wood components (Oltean et al. 2007).

Conventional kiln drying is the most commonly used drying method to systematically remove water from wood and to reach the target moisture content within a reasonable drying time (Oltean et al. 2011). Different methods are applied to accelerate the conventional wood drying processes. Nowadays, implementation of increased dry bulb temperature as a common way to raise the drying rate has aroused a lot of interest. Accordingly, many studies have been carried out on this issue, for the sake of its effects on the mechanical properties of the dried woods. Campean et al. (2007) reported that the static and impact bending strengths of beech wood increased by increasing the drying temperature from 20 to 115°C. However, the increase in drying temperature had no significant effect on the compressive strength parallel to grain, cleavage, and shear strength. Also, Oltean et al. (2011) studied the influence of four different temperatures (45, 55, 65, and 80°C) on the mechanical properties of dried boards including three-point bending test, impact bending test, and tensile test perpendicular to the grain. They stated that the mechanical properties investigated were not influenced by the drying temperatures applied. Sehstedt-Persson (1995) pointed out that there was a significant difference in shear strength among Scots pine lumber dried based on three different schedules. Thomson (1969) reported that the MOE and compression strength of Southern pine wood decreased while the drying temperature was increased from 66.7°C to 83.3°C. Schneider (1973) showed that the MOR of Scots pine and beech wood dried at the high temperatures of 130 to 180°C decreased with increasing temperature. In contrast, Teischinger (1992) observed that the MOR and MOE of spruce wood changed little with respect to drying temperature.

In the overwhelming majority of studies in which higher dry bulb temperature has been applied, mechanical properties of the dried woods have been affected, and especially MOR and MOE have declined (Schneider 1973). Moreover, increasing of dry bulb temperature would result in increased energy consumption and consequently much greater costs. On the other hand, increasing of wet bulb depression would be another way to increase the drying rate, and consequently to decrease the drying time. While considerable work has been conducted to investigate the influence of dry bulb temperature on the mechanical properties of wood, the effect of wet bulb depression on these properties has not been clarified yet. In fact, by decreasing the relative humidity of kiln, moisture evaporation flux increases from the drying wood. In contrast with the former method, increasing of the drying rate is along with decreasing of the related costs in the latter method, as less relative humidity is used in the kiln. However, increase of the drying rate in this method affects the mechanical properties again, but its detailed effects have not been clarified yet. In the initial phase of this research, the influences of the three drying schedules of T_5-D_2, T_5-D_4, and T_5-D_6 on the intensities of warps, superficial and internal cracks, residual stresses, drying rate, and final moisture gradient of poplar wood were investigated (Shahverdi et al. 2012). This research attempts to evaluate the influence of the three kiln drying schedules on the selected mechanical properties of poplar wood (*P. alba*).

EXPERIMENTAL

Sample Preparation and Drying Method

Freshly cut logs of poplar (*Populus alba*) from the Taleghan region in Iran were selected for the study. The logs were then cut into lumber, 7 cm in thickness, 220 cm in length, and 14 cm in width. Then, the lumber pieces were end-coated using an oil-based paint to prevent moisture loss from the end sections. Furthermore, the number of boards in each of the three charges was 30 boards.

Three moisture-based schedules were used to dry the lumber inside a convective laboratory kiln. The first one was T_5-D_2, which is the suggested code of the Forest

Products Laboratory (F.P.L) for drying of poplar lumber with nominal thickness of 70 mm. In the second and third schedules, a higher wet bulb depression was selected (T_5-D_2 → T_5-D_4 and T_5-D_2 → T_5-D_6). Three kiln batches were applied for each schedule. Six pieces of lumber, free of knots, diagonal grain, splits, and stains were selected as the control samples. To determine the initial moisture content of each kiln batch, moisture measurement pieces were cut from both ends of control samples. Changes in dry and wet bulb temperatures during drying were controlled and recorded. The lumber of each schedule was dried to the average final moisture content of 11±2 percent. In order to determine new conditions for each schedule, daily control samples were weighed at least once per day, depending on the rate of lumber moisture reduction. The next step of each schedule was performed based on the average moisture content of the samples. In each schedule, the drying process was terminated without any conditioning treatment.

Mechanical Tests

To carry out the mechanical tests, the test samples were cut according to D143–94R ASTM standard. Before mechanical tests, the prepared samples were stored at a temperature of 20 ± 1°C and relative humidity of 65 ± 5% inside a climatic chamber for two weeks. The mechanical properties of the samples, including modulus of rupture (MOR), modulus of elasticity (MOE), shear strength parallel to grain, and tensile strength perpendicular to grain were measured using an INSTRON testing machine of IX series (Model 4486). Toughness was measured by an AMSLER testing machine.

Statistical Analysis

Statistical analysis was conducted using SPSS software program, version 13. One way ANOVA was performed to conclude significant difference at 95% confidence level. Grouping was then made between treatments using the Duncan's multiple range test.

RESULTS AND DISCUSSION

Characteristics of Applied Drying Schedules

Decreasing of the relative humidity at the stages above the fiber saturation point (FSP) is done for accelerating of water evaporation among the free water domain. As mentioned above, in this research the three moisture based schedules were adopted, in which dry bulb temperature was constant and it was the wet bulb depression that changed. In fact, the wet bulb depression is a measure of the evaporation potential of the air. The larger the wet bulb depression, the greater the evaporation potential of the air, and the lower the humidity is. On the other hand and from the energy efficiency point of view, increasing of the dry bulb temperature is not an efficient way to increasing the drying rate and it is the time that increasing the wet bulb depression comes in. Though, this measure would have own consequences that should be considered.

This research was carried out following the initial phase of this study by the authors (Shahverdi et al. 2012). Overall results revealed that applying of T_5-D_6 schedule has resulted in a much higher drying rate as against T_5-D_2 one. As regards, the drying rates for the T_5-D_2, T_5-D_4, and T_5-D_6 schedules were about 0.0945, 0.0814, and 0.2141

%/h, respectively. Increasing of wet bulb depression for the sake of decreasing of relative humidity in the kiln will result in increasing of moisture evaporation flux from drying wood in the sever schedule (T_5-D_6) compared to the two other implemented schedules. Furthermore, the severe schedule caused a more irregular final moisture content gradient through the thickness of dried boards. On the other hand, increased drying rate in this schedule (T_5-D_6) resulted in increasing of drying induced stresses (casehardening) in the boards. Consequently, drying defects (warps) and internal cracks were inevitably emerged in the dried boards under this schedule.

Crack formation in wood during drying might differ due to different parameters, such as the kiln drying schedule and the moisture gradient within the wood, but also due to the micro-structure of different wood species and dimension of specimens (Oltean et al. 2007). Results of statistical analysis showed that in terms of internal cracks, there was a significant difference between the programs. In addition, results of Duncan test showed that the two schedules of T_5-D_6 and T_6-D_4 were placed into one group and the milder schedule (T_5-D_2) in a separate one (Table 1).

Table 1. The Severity of Internal Cracks in Dried Boards by the Three Schedules

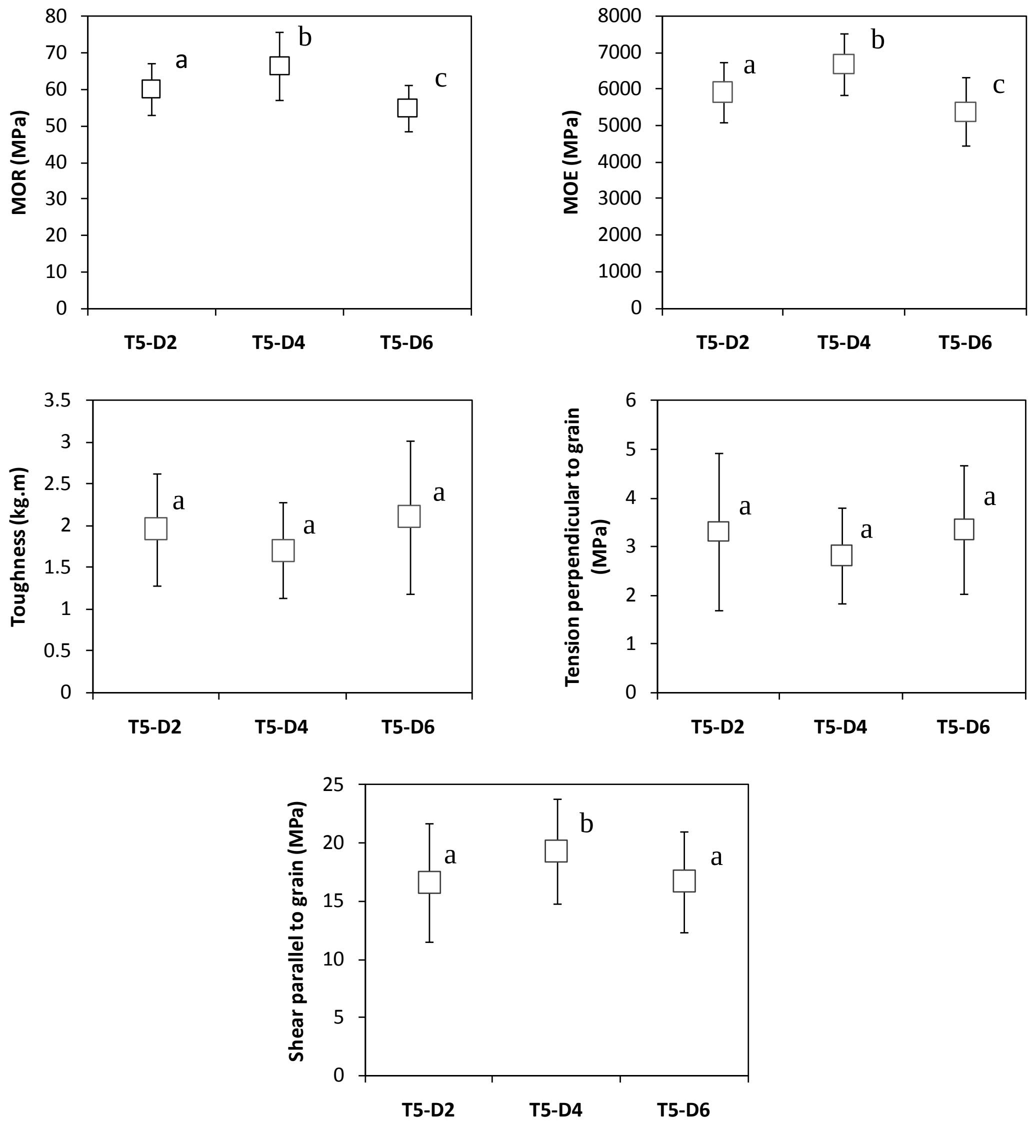
	Schedule		
	T_5-D_2	*T_5-D_4*	*T_5-D_6*
Internal crack (mm)	10.56^a	18.31^b	19.55^b
	$(7.21)^*$	(10.20)	(15.18)

*: Standard deviation; a, b, and c denote grouping results made between schedules using the Duncan's multiple range test.

Mechanical Properties

The average values of mechanical properties of the boards dried by these schedules are summarized in Figs. 1 through 5. Results of the statistical analysis, one way ANOVA (at 5% significance level), showed that there were significant differences in the MOR and MOE among the boards dried by the studied schedules. As regards the MOR and MOE, the results of Duncan test showed that all the three schedules are put into the separate groups. The MOR and MOE of boards dried by schedule T_5-D_6 were found to be less than those of boards dried by schedules T_5-D_2 and T_5-D_4. In fact, the least MOR and MOE were associated with the greatest drying rate or residual drying stresses. Our results are in agreement with those found for Southern pine (Thompson 1969), Western hemlock (Thiam et al. 2002), Norway spruce (Bengtsson and Betzold 2000), Scot pine, and beech (Schneider 1973).

Our results also indicated that there was no significant difference in toughness and tensile strength perpendicular to grain among the three schedules. In other words, the toughness and tensile strength of poplar wood was not affected by drying schedule (i.e. drying rate or the severity of residual drying stresses). In contrast to our results, Campean et al. (2007) and Gerhards (1979) reported the dependence of tensile strength of beech and Douglas fir upon drying schedule.



Figs. 1-5. Mechanical properties of poplar lumber dried using the three adopted schedules (a, b, and c denote grouping results made between schedules using the Duncan's multiple range test and also the used error bars are standard deviation)

The greatest shear strength parallel to grain was found in the schedule of T_5-D_4, while there was no significant difference between the schedules of T_5-D_2 and T_5-D_6. Thiam et al. (2002) and Sehlstedt-Persson (1995) also found that the shear strength of Western hemlock and Scot pine wood species was affected by drying temperature and schedule. In contrast, Campean et al. (2007) found that the beech shear strength was not affected by drying temperature in the range of 20 to 115°C.

As can be detected from the Figs. 1 through 5, MOR, MOE, and shear strength parallel to grain of the dried boards under the T_5-D_4 schedule increased compared to the milder schedule (T_5-D_2); and in the severe schedule (T_5-D_6), MOR and MOE have reversely decreased as against the other two schedules. In the analyses of mechanical data, at first, we should evaluate the reasons why the drying rate in the T_5-D_4 would have been lower in comparison to the milder schedule. It can be understood that the wet bulb depression only experienced a slight increase relative to schedule T_5-D_2. In fact, as wet bulb depression increases, the temperature at the surface of the wood decreases, compared with the dry bulb temperature and the time to heat the center increase. The increased heating time is presumed to be caused by cooling as water evaporates from the surface. The effect of cooling would be to reduce the temperature gradient from the surface inward, and since heating rate is proportional to temperature gradient, the heating time increases (Simpson 2003).

In other words, by a slight increase of the wet bulb depression, it could not be expected that the drying boards experience a significant increase in the drying rate. In the T_5-D_4 schedule, for the sake of a slight increase of wet bulb depression as against the T_5-D_2 one, the surface temperature of drying boards decreased and cooling of superficial layers occurred. This is because of the increased vapor in these zones, that consequently more heating time is needed to compensate for the decreased temperature in the core layers at the constant temperature (Simpson 2003). Hence, it would be a reason why the drying rate decreased from the milder schedule (T_5-D_2) to the T_5-D_4 one, which is in agreement with Simpson (2003) results.

As regards the most severe schedule (T_5-D_6), as it would be expected, the drying rate increased noticeably, and statistical analysis also showed that this program is put in a separate group. As it is completely conspicuous, this schedule noticeably influenced the MOR and MOE of the dried boards. Increased drying rate, moisture content gradient, and residual drying stresses as result of implementing of the T_5-D_6 schedule, would be among the most influential factors affect these mechanical properties compared to the other two schedules. Accordingly, Oloyede and Groombridge (2000) mentioned that oven temperature, convective air flow rate, and rate of evaporation are of the other items that have influence on the mechanical properties of wood. Furthermore, they also are of the opinion that the increasing of the drying rate will affect the strengths of the dried lumber.

Internal cracks occurrence is another issue that definitely has a negative effect on the mechanical properties of the dried boards. Increase of the drying rate and moisture content gradient, and consequently drying induced stresses play a pivotal role in crack formation. This kind of cracks occurs when the moisture content of the core layer of the drying board is noticeably higher than the FSP and the surface layers are being dried at the same time (Simpson 1991). The study by Poncsak et al. (2006) indicated that an increasing difference in the relative humidity of the kiln and drying wood will result in increase of the moisture evaporation flux, which will consequently result in crack formation in the boards. Oltean et al. (2007) also pointed out that crack formation is an important factor affecting the mechanical properties of the dried lumber. Hence, it can be concluded that the increased drying rate and also moisture content gradient under the sever schedule (T_5-D_6) (Shahverdi et al. 2012), and internal cracks occurrence affect the mechanical properties, particularly MOR and MOE, of the dried boards.

It can be recommended that, for some applications where the allowable MOE, MOR, or shear strength parallel to grain of poplar wood are important, a mild schedule

(T_5-D_2), resulting in moderate residual drying stresses (casehardening) should be applied to dry the poplar lumber. In contrast, a severe drying schedule (T_5-D_6) can be employed to dry the poplar lumber when only toughness or tensile strength perpendicular to grain is important.

CONCLUSIONS

Based on the results of this study, the following main conclusions can be drawn:

1. The severity of residual drying stresses and consequently drying defects (particularly internal cracks) in the poplar lumber dried by the conventional drying schedules depends on the drying rate and final moisture content profile, i.e., the higher drying rate and more irregular moisture profile, the greater residual drying stresses and internal cracks.
2. In contrast to toughness and tensile strength perpendicular to grain, the shear strength parallel to grain, MOE, and MOR of poplar lumber were affected by the drying schedule. The MOE and MOR decreased significantly by increasing the intensity of the drying schedule.

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