ESTABLISHING A KILN DRYING SCHEDULE FOR POPLAR (*POPULUS ALBA* L.) LUMBER OF 7CM THICKNESS

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Poplar (*Populus alba* L.) lumber with a nominal thickness of 7 cm from the Taleghan region in Iran was dried through convective kiln drying and under three different programs of T_5–D_2 (Forest Product Laboratory proposed program for poplar), T_5–D_4, and T_5–D_6 in order to obtain the optimum kiln schedule so as to protect the wood quality at an appropriate level up to final moisture content of 12±2%. Subsequently, the intensities of warps, superficial and internal cracks occurrence, residual stresses, drying rate, and final moisture gradient were measured. Results revealed that due to low warping values, more homogeneous final moisture profile, fewer internal cracks, and absence of superficial cracks in the program T_5–D_2 compared to the other two (T_5–D_4 and T_5–D_6), this program can be recommended as an optimum program for poplar lumber drying at commercial scale from the Taleghan region. On the other hand and from an energy efficiency point of view, in comparison with the mild schedule (T_5-D_2), the severe schedule (T_5-D_6) by saving 456 h of drying time, reduced electricity consumption by 6156 KWh and was therefore found to be $ 240.08 more profitable in this trial.

Keywords: Poplar; Populus alba; Drying schedule; Drying rate; Crack; Warp; Stress

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INTRODUCTION

One of the most important properties of wood is its hygroscopicity. Drying of wood takes place by utilizing this hygroscopic nature of wood. In other words, when wood is put in an environment, it takes up or repels the moisture until finally the moisture of wood and the surrounding atmosphere approaches equilibrium. Among the most important reasons for drying wood, one can mention an increase of dimensional stability, improvement of mechanical properties, prevention from rotting and fungal attacks, preparation for application of some treatments (gluing, penetration by protective, fire retardant), improvement of dye ability and trimming, reducing timber transportation costs, and reducing weight of the manufactured artifacts (Ebrahimi 1983; Ebrahimi and Faezipour 1994; Madhooshi et al. 2007).

The need for drying lumber as rapidly as practical, and simultaneously avoiding the development of defects in dried woods has prompted researchers to develop wood drying schedules in order to achieve the desirable objectives. These programs involve a set of wet and dry bulb temperatures that characterize the kiln's temperature and relative humidity (RH). Selection criterion for temperatures series and RH in a wood drying program is to achieve a suitable drying rate while taking wood quality during drying process into consideration. A wood drying program should be so organized that the stresses resulting from drying do not exceed the wood's strength; otherwise occurrence of such defects as cracks and a variety of deformations are inevitable. The wood drying schedules can be classified into two types of general and specific. By contrast, it is common practice to design and implement specific programs for particular purposes, such as programs for drying treated woods by chemical and protective materials, shortening of drying time, as well as maintaining of dried wood strength at an acceptable level. The main goals of wood drying programs may include reduced energy consumption, increased drying rate, better quality, and finally reducing drying costs (Korkut and Guller 2007). Application of optimum wood drying schedules results in savings in drying costs in the kiln in terms of time and energy consumption reduction, as well as in use of dried woods in terms of reducing losses and preserving wood quality during processing. So far, much research has been carried out with regard to composition of wood drying programs of other species (Madhooshi 1996; Tazakor Rrezaei 1997; Chavoshakbari 1998; Najafi 1998; Tamjidi and Ebrahimi 1998; Ashouri and Ebrahimi 1999; Saadat 2000; Khorsandalam 2001; Korkut et al. 2007; Korkut and Guller 2007; Rafiei and Ebrahimi 2007; Rahimi 2008; Tazakor Rrezaei and Ebrahimi 2010; Korkut et al. 2010). Some examples of wood drying programs prepared for different species are provided in Table 1.

Table 1. Examples of Some Wood Drying Programs Prepared for Different Species

Researcher	Date	Suggested Schedule	Nominal Thickness (cm)	Species
Madhooshi	1996	T_5-D_1	5	Beech
Tazakor Rrezaei	1997	T_4-B_2	7.5	Beech
Najafi	1998	T_5-D_3	3.2	Oak
Chavoshakbari	1998	T_4-D_3	5	Oak
Tamjidi & Ebrahimi	1998	T_8-E_4	5	Alder
Ashouri & Ebrahimi	1999	T_4-D_3	2.5	Oak
Saadat	2000	T_3-B_1	5	Hornbeam
Khorsandalam	2001	T_5-E_3	5	Acer
Korkut et al.	2007	Mild schedule	5	Red-bud Maple
Korkut and Guller	2007	Mild schedule	5	European Hophornbeam
Rafiei & Ebrahimi	2007	T_4-B_2	7.5	Hornbeam
Rahimi	2008	T_9-F_4	5	Poplar
Tazakor Rrezaei & Ebrahimi	2010	T_6-C_4	7.5	Beech
Korkut et al.	2010	Mild schedule	5	Rowan

Nowadays, the extent to which the wood is used in each form is noticeably increasing. Besides, a deficiency in potential preliminary and required resources for use in the wood-related industries has drawn attention to the plantation of fast-growing species all over the world. Moreover, there are plenty of gaps which still need to be filled, and problems to be solved. One of the most striking gaps in our knowledge of fast-growing plantations is in their drying process. The need to extend our knowledge of the drying characteristics of such species to improve the utilization of them is rapidly becoming more acute. Above all these factors, it can be said that use of proper wood drying program for control of wood drying process should be considered as an inevitable issue. Aspen (*P. alba*) is one of these important fast growing species in Iran that no program for properly drying of it has ever been prepared. With these factors in mind, the establishment of a drying schedule for *P. alba* with 7 cm thickness for use at commercial scale is stated as purpose of this research.

EXPERIMENTAL

Materials

Freshly-cut logs of poplar (*Populus alba* L.) with approximately 17-20 years of growth and 30-35 cm diameter, belonging to a forest close to the Taleghan region in Iran were selected for the study. Sample lumber pieces were cut in the tangential direction of the log to produce uniform blocks with a nominal thickness of 7 cm, a length of 220 cm, and a width of 14 cm at a private sawmill. Next, their cross sections immediately were completely covered with oil paint in order to prevent occurrence of local cracks. A 3 m^3 capacity semi-automatic kiln with convective drying method was used. Estimation of kiln stacks' current moisture is done by means of samples that were provided from the kiln stack and identified as control samples. Six planks were selected as control samples, which in fact represent average physical quality of kiln stacks. From each side of the control samples, test specimens of humidity indication with 2.5 cm length were cut. The remaining planks of 60 cm were the control samples. The control samples after cross section covering were weighed and put in the designated place in the kiln stack.

Drying Procedure

Three different programs were used for drying (Tables 2 to 4). The course of changes in the programs was as follows: Program 1 - The proposed code of Forest Products Laboratory (F.P.L) (T_5–$D_{2)}$; Program 2 - A higher wet bulb depression was selected (T_5–D_4); and Program 3 - wet bulb depression was again increased (T_5–D_6). The course of changes in kiln's dry and wet bulb temperatures is shown in Fig. 1. According to F.P.L proposed method, the program's beginning was set based on the kiln stack's initial Moisture Content (MC), and the program continued until MC reached 12 ± 2 %. In order to determine the program's new condition at different stages of the work, the control samples, depending on kiln stack moisture draining rate, were weighed at least once a day. The stack moisture was calculated and the program's steps were changed based on the average MC of the wettest half of the control samples (Simpson 1991). In each schedule, the drying process was terminated without any conditioning treatment.

Table 2. T$_5$-D$_2$ Kiln Drying Schedule for *P. alba* Lumber with 7 cm Thickness

Moisture content (%)	Wet bulb temperature (^oC)	Dry bulb temperature (^oC)	Wet bulb depression (^oC)	Relative Humidity (%)	Equilibrium moisture content (%)
MC > 50	47	49	2	90	20.9
50	46	49	3	85	18.4
40	45	49	4	79	16
35	41	49	8	61	11.4
30	37	54	1	31	6.5
25	32	60	28	10	2.5
20	37	65	28	6	1.6
12	43	71	28	24	5.2
Equalization	43	71	28	24	5.2

Table 3. T$_5$-D$_4$ Kiln Drying Schedule for *P. alba* Lumber with 7 cm Thickness

Moisture content (%)	Wet bulb temperature (^oC)	Dry bulb temperature (^oC)	Wet bulb depression (^oC)	Relative Humidity (%)	Equilibrium moisture content (%)
MC > 50	45	49	4	79	16
50	44	49	5	74	14.5
40	41	49	8	61	11.4
35	35	49	14	38	7.6
30	32	54	22	17	4
25	32	60	28	10	2.5
20	37	65	28	6	1.6
15	43	71	28	24	5.2
12	43	71	28	24	5.2
Equalization	43	71	28	24	5.2

Table 4. T$_5$-D$_6$ Kiln Drying Schedule for *P. alba* Lumber with 7cm Thickness

Moisture content (%)	Wet bulb temperature (^oC)	Dry bulb temperature (^oC)	Wet bulb depression (^oC)	Relative Humidity (%)	Equilibrium moisture content (%)
MC > 50	41	49	8	61	11.4
50	38	49	11	48	9.1
40	32	49	17	29	6.1
35	21	49	28	2	0.6
30	26	54	28	5	1.4
25	32	60	28	10	2.5
20	37	65	28	6	1.6
15	43	71	28	24	5.2
12	43	71	28	24	5.2
Equalization	43	71	28	24	5.2

The kiln stack was 1 m wide. Furthermore, 2.5 × 2.5 cm^2 stickers from the same species were used in this study. Air movement speed was also about 2 m.s^{-1}, provided by internal fans, and air was horizontally circulated in the kiln.

Moreover, density values were calculated by dividing oven-dry weight by oven-dry volume. Comparison of three schedules in terms of electricity consumption and cost were made possible by use of the following equations:

$$\text{ECon} = \text{KEC} \times \text{DT} \tag{1}$$

$$\text{ECost} = \text{ECon} \times \text{EUP} \tag{2}$$

where ECon = electricity consumption, ECost = electricity cost, KEC = kiln electrical energy consumption (13.5 kWh), DT = drying time, and EUP = electricity unit price (0.039 $ / kWh).

Drying Defects

Residual stresses intensity in dried lumber was determined using the prong response method. Prong response test samples with dimensions equal to lumber's full thickness and width, and a length of 20 mm were cut from each of the dried control samples using a band saw. Then, remaining stresses were calculated from the equation below (Fuller 1995):

$$PR = \frac{x - x'}{l^2} \tag{3}$$

In this equation PR is prong response of test sample (mm^{-1}), x is the distance between outer prong edges before cutting (mm), x' is the distance between outer prong edges after cutting (mm), and l is the length of each test sample's prong.

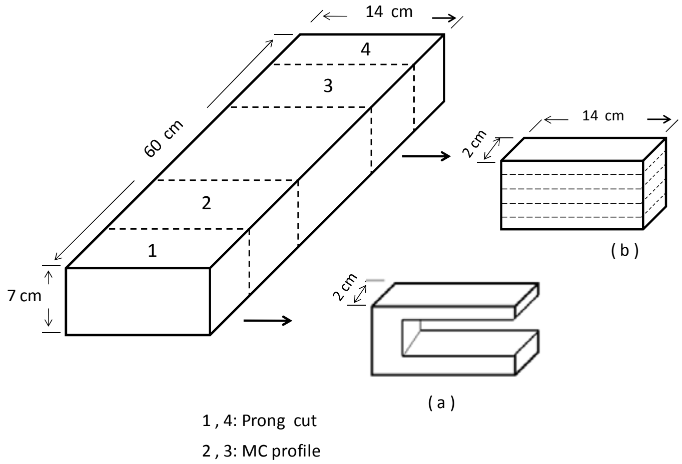

Fig. 2. Cutting method of specimens for measurement of Casehardening (a) and MC gradient (b)

To determine dried woods' MC gradient, a layer cutting test was used. First, pieces with dimensions equal to boards' thickness and width, and a length of 20 mm were cut from each of the dried control samples. Next, from these pieces, 9 layers each with thickness of 0.6 mm were prepared and the layers were put in oven at 100^{o}C until a constant weight was reached. Samples cutting pattern for measuring of residual stresses and also MC gradient are shown in Fig. 2.

In addition, the intensity of warping in dried woods of each kiln stack, including twist, bow, crook, and cupping, was measured according to DIN-EN 1310 standard.

Further, after drying, the probability of occurrence of superficial cracks on woods' edge and surface as well as internal cracks intensity were examined according to DIN-EN 1310 standard. After cutting of the test samples related to moisture gradient and residual stresses, the remaining parts from the control samples were cut into parts with 2 cm thickness in order to determine the extent of the internal cracks.

RESULTS AND DISCUSSION

Drying Rate and Moisture Gradient

The poplar lumber drying rates in all the three schedules are shown in Fig. 2. In T_5–D_2, the initial MC was within the range of 54 to 79%, in T_5–D_4 within 41 to 77%, and in T_5–D_6 between 42 to 65%. In T_5–D_6, due to use of higher wet bulb depression, the drying rate was higher under this program. In fact, woods using this program reached the final MC faster (Figs. 1 and 3), and this is consistent with results achieved by Tarmian et al. (2010) and Shahverdi et al. (2010).

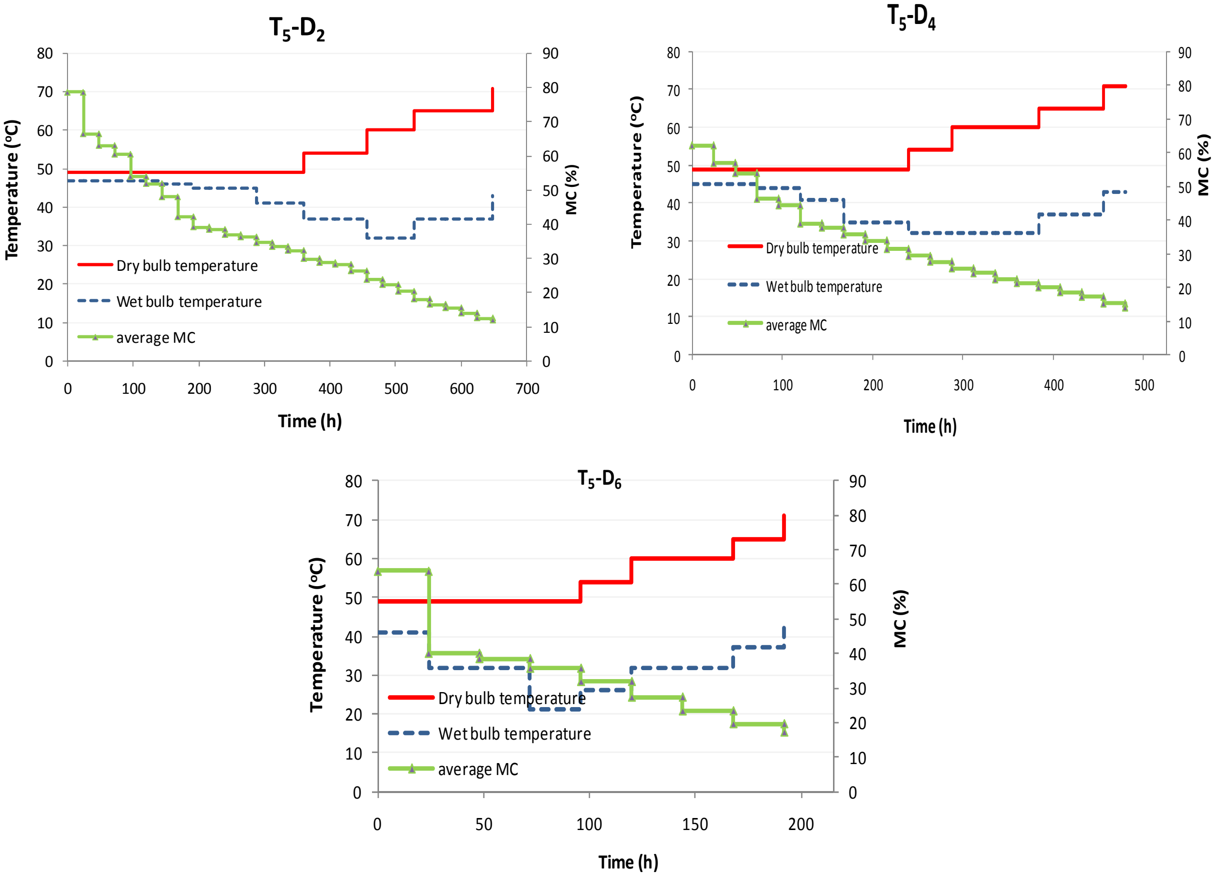

Fig. 1. Changes in dry- and wet bulb temperatures and the average MC of poplar lumber vs. time during the whole drying process in the three schedules

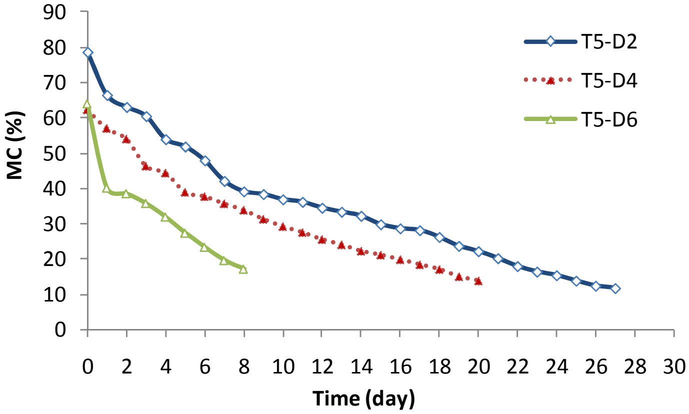

Fig. 3. Reduction of MC according to time under the three schedules

Statistical analysis showed that in terms of drying rate at α = 0.01, there was significant difference between the programs. In addition, results of Duncan test showed that the two programs of T_5–D_2 and T_5–D_4 are put into one group and the other (T_5–D_6) in a separate one. This means that, as was expected wood's drying rate under the program T_5–D_6 was higher compared to the other two schedules (0.2141 %/h), and this was due to higher wet bulb depression of this program. In Table 5 the drying rate averages of control specimens are given with respect to the three schedules, and the correspondence standard deviations are shown. Anderson et al. (2005) and Boonstra et al. (2006) considered that crack occurrence and also increasing cracks in cell walls and consequently increase of permeability, are further reasons for this result.

Table 5. Average Boards Drying Rates under the Three Implemented Schedules

Schedule	Drying Rate (%/h)	Standard Deviation
T_5-D_2	0.0945	0.0158
T_5-D_4	0.0814	0.0300
T_5-D_6	0.2141	0.0336

The MC gradient through the board thickness may cause internal stress and strain, and such stresses can be sufficient to cause different types of warp in lumber. Results showed that the MC gradient between boards surface and core in the T_5–D_2 and T_5–D_4 programs had more homogeneity in comparison with the other program and this may be due to more drastic drying condition in this schedule (T_5–D_6) that can result in lower MC in boards surface than at the center of them (Fig. 4).

From an energy efficiency point of view, in comparison with the mild schedule (T_5-D_2), the moderate schedule (T_5-D_4) by saving 168 h of drying time, reduced electricity by 2268 KWh and was found to be $ 88.45 more profitable. The severe drying schedule (T_5-D_6) (from about 60% initial MC to 12% final MC) took 192 h in total, and the drying time was 456 h shorter with this schedule. As far as the energy cost is concerned, this translates into a 6156 kWh reduction in electricity consumption and $240.08 savings per drying load for this trial as against the mild drying schedule (T_5-D_2). In addition, an average of 0.422 gr/cm^3 (±0.063) was measured for dry density.

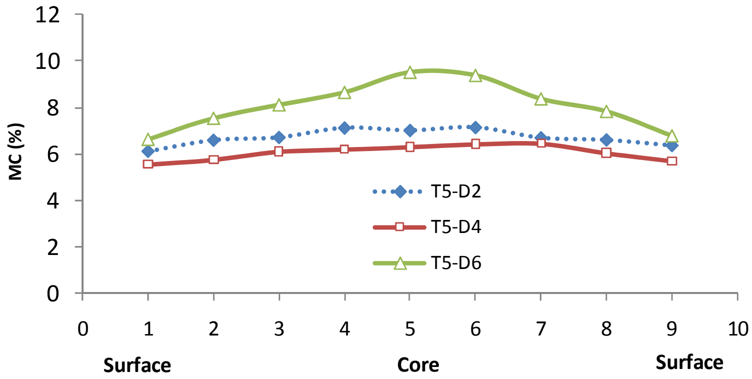

Fig. 4. MC gradient through boards thickness under the three schedules

Intensity of Residual Stresses

Drying stresses are caused by moisture difference between a board's surface and its interior. The intensity of this difference depends on kiln temperature, relative humidity, air flow, and species characteristics. Increase of moisture gradient through board's thickness will result in greater wood drying stresses. In case these stresses exceed wood strength, they cause superficial and internal cracks.

The intensities of remaining stresses in dried boards with each one of these programs are shown in Fig. 5. Statistical analysis showed that in terms of remaining stresses in dried woods, there was a significant difference (α = 0.01) between programs. In addition, comparison results of data analysis with Duncan test showed that the two programs of T_5-D_2 and T_5-D_4 could be placed into one group and T_5-D_6 in a distinct group.

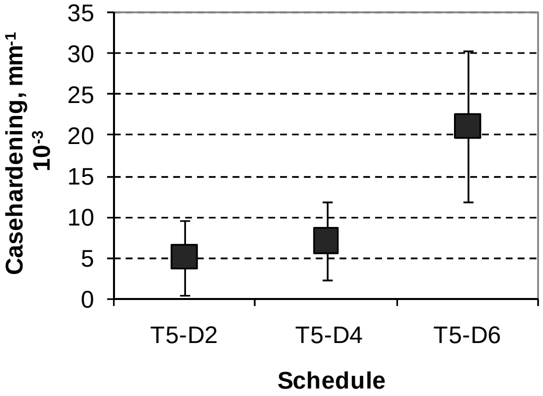

Fig. 5. Intensity of residual stresses in dried boards under the three schedules

Superficial and Internal Cracks

Several studies have been performed concerning the occurrence and development of cracks during drying (Schniewind 1963; Mackay 1972; Kozlik and Ward 1981; Kozlik and Boone 1987; Hanhijärvi et al. 2003). Crack formation in wood during drying might differ due to different parameters, such as the kiln drying schedule, the moisture gradient within the wood, but also due to the micro-structure of different wood species and dimensions of specimens (Oltean et al. 2007).

With regard to superficial cracks only in the T_5-D_6 program, one crack within range of 61 to 70 mm as well as one crack within range of 131 to 140 mm was seen. A high level of kiln relative humidity in early stages of wood drying operation (61-90%) helps to decrease occurrence of superficial cracks. It should be noted that even if superficial cracks occur in early steps, during stress reversal and in intermediate and final steps, these cracks can become closed (Tarmian et al. 2010).

As for internal cracks (honeycombing), the boards were affected with internal cracks, particularly near the cross sections (Table 6). These cracks occurred along wood rays, which have parenchyma structure (Schniewind 1963; Mackay 1972). Results of statistical analysis showed that in terms of internal cracks and at $\alpha = 0.01$, there was 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 other (T_5-D_2) in a separate one. In program T_5-D_2, due to application of mild drying circumstances compared to the other two schedules (use of lower wet bulb depression), less internal cracks were observed (Ebrahimi and Faezipour 1994). Kozlik and Boone (1987) also observed that excessive cracking of red alder board ends and cracks in rays decreased as the wet-bulb temperature decreased. Tarmian et al. (2010) have stated that use of high dry bulb temperature in intermediate steps of a wood drying program (FSP range) is one of the main reasons for internal cracks, particularly radial cracks.

Table 6. Intensity of Internal Cracks in Dried Boards under the Three Schedules

Crack Length (mm)	Abundance in T_5-D_2	Percentage in T_5-D_2	Abundance in T_5-D_4	Percentage in T_5-D_4	Abundance in T_5-D_6	Percentage in T_5-D_6
1-10	76	57.58	7	28	40	37.04
11-20	47	35.61	8	32	24	22.22
21-30	6	4.55	4	16	18	16.67
31-40	3	2.27	6	24	14	12.96
41-50	0	0	0	0	8	7.41
51-60	0	0	0	0	2	1.85
61-70	0	0	0	0	2	1.85

Warps

Warping refers to any kind of deviation of the board’s surface or its edges from linearity or any kind of angle change from the edges’ upright state relative to surfaces. Different types of warping often are a result of difference in tangential, radial, or longitudinal shrinkage, spiral grain, fiber deviation, presence of juvenile wood, density changes in boards’ different parts, or stresses and strains due to tree growth (Rahimi 2008).

Results of statistical analysis showed that in terms of cupping defect at $\alpha = 0.01$, there was significant difference between programs. In terms of other warps (twist, bow, and crook), there were no significant difference between the schedules (Table 7).

Table 7. Average Intensity of Warps in Dried Boards under the Three Schedules

Defect type	Schedule		
	T_5-D_2	T_5-D_4	T_5-D_6
Twist (mm)	4.07 (6.65)*	12.00 (9.32)	8.88 (9.16)
Crook (mm)	11.36 (14.54)	2.13 (6.01)	8.25 (11.65)
Bow (mm)	5.29 (7.98)	3.00 (5.66)	8.38 (8.53)
Cup (mm)	0.14 (0.53)	0.75 (1.39)	2.00 (0.93)

*: Standard Deviation

The results show that when a better quality is necessary, the mild drying schedule (T_5-D_2) should be applied. On the other hand, as the contribution of energy to the total drying cost is increasing and as the changing production and market strategies put more pressure to reduce drying times while asking for acceptable drying quality (Korkut and Guller 2007), the more severe drying schedules (T_5-D_4, T_5-D_6) can become an alternative solution for kiln owners for improving the profitability of their operation.

In addition, in order to optimize crucial factors in drying process, research continuation with regard to comparison with other thicknesses and also with the same thickness for other growing fields is recommended. Given the importance of conditioning treatment and its role in removing wood stresses, its implementation in future researches is recommended in order to obtain the desirable time for this stage.

CONCLUSIONS

1. Among the most important reasons for occurrence of superficial cracks in dried lumber is a low relative humidity in the kiln in the early steps of a wood drying process. Hence, it seems that a high value of kiln relative humidity in the wood drying programs designed in this research at early stages has helped to decrease occurrence of superficial cracks.
2. Occurrence of internal cracks in the two programs of T_5-D_4 and T_5-D_6 was with higher frequency compared to T_5-D_2. The occurrence of these cracks is caused by extreme internal stresses as a result of using the intensive wood drying schedules and consequently high drying rate.
3. Although shorter drying times by 168 and 456-h were obtained with a moderate (T_5-D_4) and intense schedule (T_5-D_6), respectively; the mild drying schedule (T_5-D_2) gave better results for the drying of poplar (*P. alba*) lumber when comparing final MC gradient, and drying defects (i.e. crack occurrence, warps, and residual stresses).

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