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EVALUATING A DRYING SCHEDULE FOR OAK LUMBER THROUGH DRYING RATE CALCULATION AND QUALITY ASSESSMENT

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Abstract:
The paper presents the results of an experimental research performed with eight 25-mm thick oak (Quercus robur L.) lumber boards, dried in a conventional kiln. The research mainly envisaged the determination of the drying rate within different moisture content intervals, covering both the removal of free water and of bound water from wood. After drying them down to a final moisture content of 10%, all boards were subjected to a quality control procedure, where the uniformity of the final moisture content, the casehardening degree, cracks, deformations and colorations were evaluated. The results showed that, for a drying schedule with drying rates varying between 0.34%/h and 0.08%/h, no cracks occurred, but moderate/severe casehardening was present. Correlating the results from the two perspectives (drying time and drying quality) is a good instrument for evaluating the performance of a drying schedule, and further, for process optimization.

Key words: *oak lumber; kiln drying; moisture content control; drying rate; casehardening; quality control.*

INTRODUCTION

Oak is one of the most difficult to dry wood species. This is mainly due to the non-homogenous structure, with compact cell walls and void cell lumina (Merela and Cufar 2013), which leads to high variability of density even within the same board. The ring-porous structure, with density variation between the earlywood and the latewood causes variable shrinkage, leading to the development of internal stresses which facilitate cracks (Campean and Lazarescu 2016). Another important feature of oak wood refers to the medullary rays of two distinct sizes (Balzano *et al.* 2020), which are fragile anatomical elements, with very thin cell walls, and thus prone to cracking. Furthermore, oak wood is very sensitive to temperature (Trübswetter 2009), and thus low temperature (max. 60-70°C, depending on species and lumber thickness) must be applied, at least until the fiber saturation state is reached.

The main defects reported by sawmills that dry oak lumber are: uneven final moisture content, and cracks.

The non-uniformity of the final moisture content within a batch, from one board to another is most often caused by an uneven flow of air in the stack, or an uneven distribution of the initial moisture content among the boards of that batch. However, more severe is the situation when high differences of the final moisture content occur within the same board. This situation is most often caused by the non-homogeneity of the structure, and therefore difficult to be controlled, especially in industrial conditions.

The main cause of the cracks is a too harsh drying schedule, unsuitable for the density variability of the wood and without taking into account the presence of both sapwood and heartwood. Cracks can also be caused when the temperature is raised too sudden or too soon, before the entire amount of free water is removed from the wood.

Also, considering that oak lumber is often stored and air-dried before being introduced into the kiln, casehardening is frequent. Unless the drying process is started with abundant spraying (relative air humidity 85-95%) at low temperature (30°C), cracks will occur, especially in thick (>50mm) lumber.

Optimizing the drying time without affecting the drying quality is the desiderate of any sawmill. Knowing the drying rate (how many percent of water are eliminated from wood per hour) during the different drying periods is an important instrument to estimate the drying time. Optimization is possible when correlating the results of a certain drying schedule in terms of time and quality.

OBJECTIVE

The main outcome of this research was to evaluate both quantitatively and qualitatively the drying behavior of oak (*Quercus robur* L.) lumber. The quantitative evaluation consisted of establishing the drying rates corresponding to different moisture content reduction intervals, for a given drying schedule. Based on these values, the drying time can be assessed, and hence, the monthly (or yearly) drying capacity of a kiln. The quantitative evaluation included the determination of the final moisture content uniformity within each board, and compared to the targeted value, a casehardening test, and visual examination of the boards in order to assess the number and gravity of cracks, deformations, and colorations. Correlating the results from the two points of view allows appreciating the efficiency of the applied drying schedule.

MATERIAL, METHOD AND EQUIPMENT

The wooden material used within this study consisted of 8 lumber boards in green state, having the following dimensions: 1.5m length, 12cm width and 25mm thickness.

All boards were placed in a conventional dryer, within the same row, at mid height of the upper stack (Fig. 1).

Fig. 1.
Placement of the experimental oak boards within the stack.

In order to measure the moisture content inside wood, a resistive V2A moisture sensor (Fig. 2) was introduced in each experimental board, at half length, half width, and at 15mm depth of the board. The eight sensors were connected to the sensor box placed on the kiln wall (Fig. 3), and then further to the control panel of the kiln, which displayed throughout the drying process the values measured by the eight sensors. Thus, the moisture content decrease could be monitored at all times.

The drying schedule applied to this experimental batch, as displayed by the control panel of the kiln, is presented in Table 1.

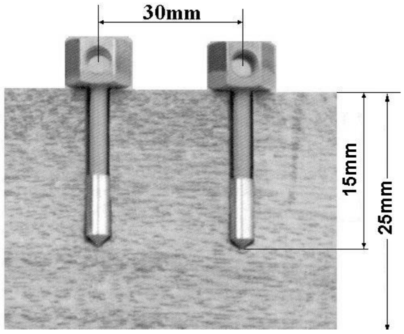

Fig. 2. V2A sensors for measuring the moisture content inside wood during the drying process.

Fig. 3. Connecting the moisture sensors to the sensor box placed on the lateral kiln wall.

Table 1

Drying schedule for experimental oak batch

Phase	Wood moisture content, %	Temperature, °C	Equilibrium moisture content, %	Drying gradient
Initial heating	60	33	18	-
Actual drying	60...50	33	14	-
	50...30	35	10.8	2.6
	30...20	40	9.4	2.6
	20...10	52	3.8	2.6
Cooling	10	30	-	-

The drying parameters (wood moisture content – *U*, air temperature – *t*, and equilibrium moisture content – *EMC*) were entered at intervals of 24h in a kiln sheet.

The process was considered completed when the average final moisture content of 10% was reached.

At each reading of the moisture content during the actual drying phase, the drying rate (*w*) was calculated, according to Eq.(1):

$$w = \frac{\Delta U}{\Delta t} \quad [\%/h] \qquad (1)$$

where:
ΔU is the moisture content reduction within a given time interval, in %;
Δt – considered time interval, in h.

After drying, the stack was left for one week to cool down, and then the test boards were subjected to a quality control (Cividini 2000; Campean 2005), envisaging the determination of:
- the moisture content uniformity within each piece of lumber;
- the casehardening degree;
- the number of surface cracks and their depth;
- the number of end cracks and their length;
- the number of internal cracks,

and also:
- if any deformations and / or colorations occurred.

An observation sheet was filled in for each piece of lumber, by respecting the following protocol:
- the measurements concerning the distribution of the final moisture content within one piece of lumber were made in three positions, two of them being located at 0.25m from the board ends and one measurement in the middle of the board (at half length). Then, the difference (ΔU) between the highest and the lowest value was calculated for each board, and also the average of the three values (U_f), in order to be compared to the

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targeted value (U_{target} = 10%). The measurements were performed by means of a capacitive moisture-meter type FMW-T by BROOKHUIS (The Netherlands);

• the evaluation of the casehardening degree (as indicator of the presence of internal stresses) was carried out by means of a sample taken from mid length of each board, having a width of 2cm and a length equal to the lumber width. Each test sample was split in half at half thickness, and then the two halves of each specimen were introduced into a climate chamber at temperature t = 20ºC and relative air humidity RH=55% for 48 hours, for conditioning (Trübswetter 2009). The gap (opening) between the two halves was then determined. A value higher than 3mm means severe casehardening.

The presence of cracks, deformations, and colorations was examined with the naked eye and the results of the examination were also recorded for each board in the observation sheet.

RESULTS AND DISCUSSION

The kiln sheet recorded during the drying process of the experimental batch is given in Table 2.

Table 2

Kiln sheet

Date	Time	Wood moisture content, %									*t*, °C	*EMC*, %	Observations
		S1	S2	S3	S4	S5	S6	S7	S8	Mean			
15.11	12:00	64.9	58.1	64.9	63.5	66.2	57.8	63.6	58.2	62.1	20.1	7.9	Heating
15.11	18:00	61.4	60.6	58.4	58.5	56.9	58.5	60.2	59.0	50.19	34.3	12.6	Actual drying begins
17.11	08:30	53.3	50.3	51.6	48.8	48.3	52.0	51.0	52.2	50.94	34.3	12.6	
18.11	08:30	48.8	42.7	43.8	43	38.5	43.2	42.8	43	43.23	36.1	12.5	
19.11	08:30	44.8	38.0	37.4	38.0	32.3	39.2	39.6	38.8	38.51	36.1	12.5	
20.11	08:00	37.5	33.0	31.9	32.4	27.7	32.0	31.5	32.2	32.28	36.2	12.6	MC≅30% Temp↑ 40°C
21.11	08:00	30.2	27.6	28.2	28.2	25.0	25.6	26.2	27.8	27.35	36.9	12.9	
22.11	08:00	25.6	24.5	23.8	22.3	23.6	24.5	25.0	25.8	24.39	37.7	9.0	
23.11	08:00	24.1	22.7	22.4	21.3	21.6	21.7	23.2	22.8	22.48	39.8	9.0	MC≅20% Temp↑ 50°C
24.11	08:00	21.1	19.0	20.0	19.5	18.7	18.8	18.3	19.6	19.38	42.5	9.0	
25.11	08:00	20.1	18.9	19.2	20.3	17.8	18.5	18.0	19.0	18.98	48.6	9.0	
26.11	08:00	17.9	17.3	16.8	16.9	15.4	16.3	17.3	18.0	16.99	49.9	9.0	
27.11	08:00	15.4	14.3	15.0	15.2	13.3	14.2	14.3	14.7	14.55	50.4	7.4	
28.11	08:00	12.4	12.7	13.4	12.6	11.1	12.2	12.7	12.4	12.44	50.4	6.9	
29.11	08.00	11.2	11.3	11.9	11.0	10.8	10.5	11.0	11.0	11.09	50.3	6.8	Cooling begins
30.11	08:00	10.4	10.2	10.1	9.9	8.9	8.9	9.6	10.2	9.78	30	-	Process completed

It can be observed that, due to some technical limitations (especially, too low spray water pressure, and low boiler power), the foreseen drying schedule could not be entirely respected. Thus, the equilibrium moisture content (*EMC*) at the beginning of the process was too low, and the maximum foreseen temperature (52°C) was not actually reached.

The values calculated for the drying rate under these conditions, by means of Eq. 1, and based on the moisture content values recorded for each board at the given time intervals are presented in Table 3.

Table 3

Drying rate of 25-mm thick oak lumber over different moisture decrease intervals

Moisture content decrease interval, %	Drying rate, in %/h, for board:								
	N° 1	N° 2	N° 3	N° 4	N° 5	N° 6	N° 7	N° 8	Average
60...50	0.34	0.43	0.28	0.40	0.36	0.27	0.38	0.28	**0.34**
50…40	0.19	0.32	0.33	0.24	0.40	0.37	0.34	0.38	**0.31**
40...30	0.30	0.21	0.23	0.23	0.19	0.30	0.34	0.28	**0.26**
30…20	0.13	0.15	0.10	0.08	0.12	0.12	0.20	0.13	**0.11**
20…15	0.09	0.07	0.10	0.14	0.10	0.09	0.08	0.09	**0.10**
15…10	0.09	0.07	0.10	0.14	0.10	0.09	0.03	0.04	**0.08**

The values presented in Table 3 show that the drying rate during the free water removal is three times higher than that of the bound water removal. The drying rate decreases as the moisture content of wood becomes lower.

The values characteristic to the free water elimination period ranged between 0.19%/h and 0.43%/h, while the values characteristic to the bound water elimination period got as low as 0.07%/h.

Based on the average values listed in Table 3 for each interval, the drying time was estimated depending on the initial and final moisture content of the lumber batch (Table 4). The values given in Table 4 apply for 25-mm thick oak wood. Based on these values, which rely on experimentally obtained values of the drying rate, a sawmill can estimate the monthly (or yearly) drying capacity of its kilns.

Table 4

Estimated drying time of 25-mm thick oak lumber, in hours

Initial moisture content, % Final moisture content, %	60	50	40	30
15	241	212	179	141
10	304	274	242	203

The observation sheets obtained after the final quality control of each piece of lumber are presented in Table 5. An example of a casehardening sample (S2) is given in Fig. 4.

Table 5

Results of the final quality control performed after 1-week conditioning of the dried oak boards

Criterion	Board:							
	N° 1	N° 2	N° 3	N° 4	N° 5	N° 6	N° 7	N° 8
Final MC: end	8.7	9.5	9.0	10.0	8.3	8.9	9.2	9.1
mid length	8.8	10.3	9.2	10.2	8.5	9.1	10.0	10.4
end	8.7	9.2	8.9	9.8	8.4	9.0	9.1	10.1
ΔU	0.1	1.1	0.3	0.4	0.2	0.2	0.9	1.3
Average U_f	8.73	9.67	9.03	10.00	8.40	9.00	9.43	9.87
U_f - U_{target}	-1.27	-0.33	-0.97	0.00	-1.60	-1.00	-0.57	-0.13
Casehardening	3mm	3.5mm	3mm	2mm	2.5mm	2mm	3mm	2.5mm
Surface cracks	no	no	no	no	no	no	no	no
End cracks	no	no	no	no	no	no	no	no
Inner cracks	no	no	no	no	no	no	no	no
Deformations	no	no	no	no	no	no	no	no
Colorations	no	no	no	no	no	no	no	no

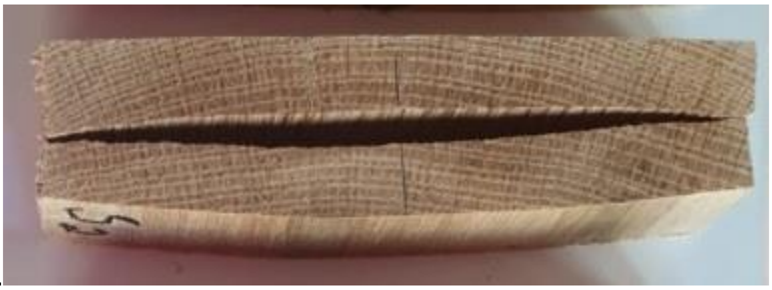

Fig. 4.
Casehardening sample (S2), with highest casehardening degree (3.5mm).

The values given in Table 5 show a good drying quality in terms of the uniformity of the final moisture content. With values of ΔU ranging between 0.1% and 1.3%, the final moisture content within the board can be considered even. Also, the deviation of the final content reached by each individual board is in the range of 10 ± 2%. The difference between the highest and the lowest final moisture content is 1.6%, much less than the allowed limit of 5%, which indicates a very uniform drying within the batch.

The casehardening degree, with gap values of 2.0-3.5mm, can be described as moderate/severe. It could have been avoided if the foreseen drying schedule (Table 1) had been respected entirely, and the *EMC* at process beginning had been 17-18% instead of 12-13%. However, no cracks occurred.

Deformations were absent, which was expected considering that all analyzed boards were dried under the weight of the boards stacked on top of them.

CONCLUSIONS

According to the values assessed, the drying of 25-mm thick oak lumber by applying the drying schedule presented in Table 2, leads to a drying time of 12.6 days (304h) and a very good drying quality. Considering the development of a moderate to severe casehardening degree in all boards due to too low *EMC* in the heating phase and the initial actual drying phase, an optimization measure would be to apply the schedule given in Table 1. This would block the development of internal stresses, and reduce the risk of cracking, but it would also lengthen the drying time. Therefore, considering the absence of cracks and the very good uniformity of the final moisture content within the batch and within each board, the applied drying schedule can be validated as an efficient one.

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