Maderas-Cienc Tecnol 24(2022):55, 1-20
Ahead of Print: Accepted Authors Version

DOI:10.4067/S0718-221X2022005XXXXXX

CHANGING THE CALCULATED SURFACE AREA OF WOOD SAMPLES TO DEFINE DRYING SCHEDULES FOR *EUCALYPTUS* CLONES

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Received: August 11, 2021
Accepted: August 10, 2022
Posted online: August 10, 2022

ABSTRACT

The aim of this study was to determine how varying the inputted surface area value of wood samples would affect the determination of kiln-drying schedules using the drastic drying test. For this purpose, eight individuals of two *Eucalyptus* clones were selected. Specimens were obtained for drastic drying tests at 100 °C, to measure the basic density and to determine the initial moisture content. The initial and final temperatures and the drying potential were calculated in 100 mm × 50 mm × 10 mm samples, considering the surface area to be 130 cm^2 (Updated Method), in contrast to the surface area of 100 cm^2 that is commonly used in the method known as the Standard Method. Based on these findings, kiln-drying schedules were set for the lumber from each clone. Although the significant differences aforementioned, it was observed that the drying schedules developed by Standard Method and Updated Method are similar.

Keywords: Drastic drying test, drying schedule parameters, drying quality, eucalypts, wood drying.

1. INTRODUCTION

Drying is crucial for the wood industry because the satisfactory use of wood in its final product depends on adequate drying (Simpson 1991, Awadalla *et al.* 2004, Shen *et al.* 2019). Drying can improve machinability by enhancing the dimensional stability, by reducing the mass, and by heightening the performance of varnishes, paints, and glues, in addition to reducing risks of attacks by wood-staining and decaying fungi (Batista and Klitzke 2012).

To achieve this performance, different methods for setting drying schedules for different species are reported in the literature (Carlsson and Tinnsten 2002, Taghiyari *et al.* 2014). These methods are based on the correlation of the wood behavior during drying in a conventional oven with the physical and mechanical properties of the wood and with the behavior of samples under different drying conditions (Jankowski and Luiz 2006).

Batista et al. (2016) report that some researchers have to develop equipment and solve practical problems and tools, validate and improve research on a laboratory scale. In this way, they can reproduce the behavior of conventional drying on an industrial scale. In these contexts, the choice of the method for setting drying schedules becomes essential for optimizing time and wood quality.

Drying schedules can be defined as a preset sequence, with relative air humidity content and temperature control, that should be applied to a timber load to dry the wood quickly and to ensure the quality of the material at the end of the process (Simpson 1991, Jankowsky and Luiz 2006). To shorten the time required for setting a drying schedule, Terazawa (1965) developed a method in a laboratory oven, improved over time with aid of other research, known as the “drastic drying”. According to this method, small samples dried at 100 °C tend to perform similarly to those planks subjected to conventional drying, bearing in mind the respective proportions.

Drying schedules have been developed by various authors using this method (Barbosa *et al.* 2005, Ofori and Brentuo 2010, Klitzke and Batista 2010, Batista and Klitzke 2012, Batista *et al.* 2015, Santos *et al.* 2012, Jankowsky *et al.* 2012, Effah and Cofi 2014, Eleotério *et al.* 2015, Soares *et al.* 2016, Soares *et al.* 2019). Those studies confirmed that developed drying schedules shortens times and reduces overall work. Some studies also confirmed the correlation between defects detected in wood samples during the drastic drying test and those detected in planks during kiln drying, while others did not (Batista *et al.* 2015).

In this method, the two largest opposing areas of the samples are used as a surface for water evaporation, while the lateral and top areas are not considered, even though drying also occurs on these surfaces, which may be a source of error in this method. The problem in most works that have samples dimensions of 100 x 50 x 10 mm is that they describe a surface area as 100 cm², when in fact the total surface area value is 130 cm². Employing an partial surface area value into equations for preparing drying schedules can lead to unsatisfactory results. A new approach to the equations currently used may lead to better drying schedules. Thus, the present study aimed to evaluate the effect of two options of surface areas measured in the same sample to develop drying schedules in wood of Eucalyptus clones.

2. MATERIAL AND METHODS

The material was collected in Luminárias, a city located in the State of Minas Gerais, Brazil l, at a latitude of 21° 30′ 34,6″ S, longitude of 44° 54′ 15,4″ W, and altitude of 1141 m.

Woods from clone GG100 - *Eucalyptus grandis* × *E. urophylla* - and from clone 58 - *Eucalyptus urophylla* × *E. camaldulensis* - at half-rotation ages (10 and 11 years, respectively) were used in this study. The experiment had a randomized four-block design with one tree/clone/replicate. One tree from each clone was selected per block, totaling four trees from clone GG100 and four trees from clone 58.

The selected trees were cut and limbed, and three 1,30 m long logs were removed from the bottom, middle, and top (commercial height), in other words, at 25 %, 50 % and 75 % of the log, respectively (Fig. 1). The logs were identified with numerical codes (clone, replicate, and percentage of height), their ends were sealed with plastic bags to reduce drying, and they were transported to the laboratory for processing and analysis. From each log, five planks were made (Figure 1). After sawing and planing, six samples were collected from each plank, totaling 240 samples, of which only 80 were intended for conducting the experiments, with the dimensions shown in Figure 2.

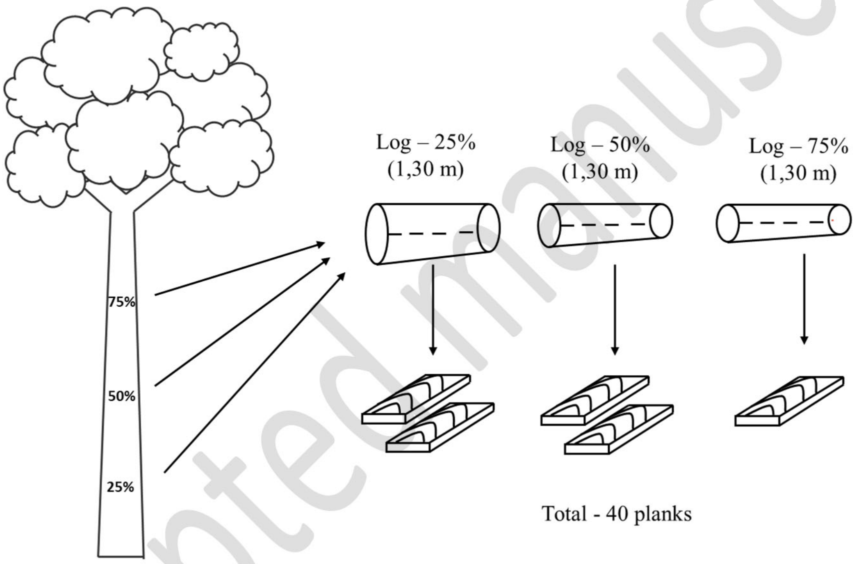

Figure 1: Scheme for the collection of samples of study material.

Of the six samples from each plank, three test specimens were dried in an electric oven at 100 °C ± 2 °C as performed by Monteiro *et al.* (2021) (Figure 2-A) and three test specimens were used to determine the moisture content and basic density (Figure 2-B), according to Brazilian National Standard NBR 7190 (ABNT 1997) and NBR 11941-02 (ABNT 2003), respectively.

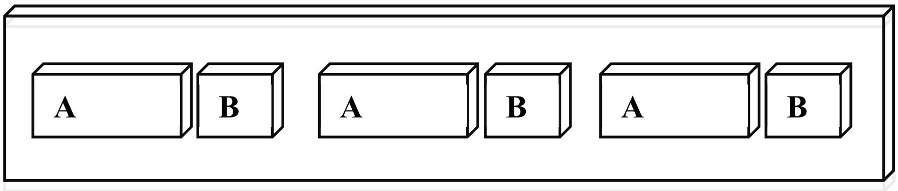

Figure 2: Scheme of the test specimen colletion from a plank: **A:** Specimens for drying (100 mm x 50 mm x 10 mm); **B:** Specimens for determining basic density and moisture content (50 mm x 50 mm x 10 mm).

The drying schedule was prepared based on the method proposed by Terazawa (1965). In the test to determine the schedule, the wood samples were dried at 100 °C in a laboratory forced-air convection oven to approximately 0 % moisture content or constant mass. During drying, the samples were periodically analyzed for their mass and their incidence of end checks.

The values of moisture loss were used to calculate the drying rates as proposed by Brandão (1989) and according to equations 1, 2, and 3 by inputting the surface area values of the samples used in the drastic drying test into these equations. The surface area value of the samples proposed by Ciniglio (1998) (herein termed "Standard Method" or SM) was compared with the value proposed in this study (herein termed "Updated Method" or UM), both used to dry samples sized 100 mm × 50 mm × 10 mm. In the SM, the drying surface area is set to 100 cm^2, which represents the length × width of the sample × 2 faces, that is, 10 cm × 5 cm × 2. In the UM, the total sample area is considered as drying surface, and the areas of the sample sides and tops are added, that is, (10 cm × 5 cm × 2) + (10 cm × 1 cm × 2) + (5 cm × 1 cm × 2), totaling 130 cm^2.

The equations proposed by Brandão (1989) and Ciniglio (1998) were adjusted by multiple regression analysis, where the initial and final temperatures, the drying potentials and cracks were related to the results observed during the drastic drying test.

Drying rate up to 5% moisture content ($R_1 - g \times cm^{-2} \times h^{-1}$):

$$R_1 = \frac{m_i - m_5}{T_1 \times A} \quad (1)$$

Drying rate up to 30% moisture content (R_2 - $g\times cm^{-2}\times h^{-1}$):

$$R_2=\frac{m_i - m_{30}}{T_2\times A} \tag{2}$$

Drying rate from 30 to 5% moisture content (R_3 - $g\times cm^{-2}\times h^{-1}$):

$$R_3=\frac{m_{30}- m_5}{T_3\times A} \tag{3}$$

Where: m_i= Mass of the sample with the initial moisture content (g); m_5 = Mass of the sample with 5 % moisture content (g); T_1 = Drying time of the sample with an initial moisture content of up to 5 % (h); m_{30} = Mass of the sample at 30 % moisture content (g); T_2 = Drying time of the initial moisture content up to 30 % (h); T_3 = Drying time from 30 % to 5 % moisture content (h); A = Surface area of the sample (cm²), being 100 cm² for the Standard Method and 130 m² for the Updated Method.

Based on the results from these methods, the variables of the drastic drying test were calculated to determine the drying-schedule parameters according to equations 4, 5, and 6, as proposed by Brandão (1989) and Ciniglio (1998). In the calculations explained by Ciniglio (1998) the surface area of the sample is represented by 100 cm². In this work, we replaced the letter "A" so that the surface area value represented the total area of the analyzed sample, in this case, 130 cm².

Initial temperature (IT):

$$IT = 27{,}9049 + 0{,}7881\times T2 + 419{,}0254\times R1 + 1{,}9483\times C2 \tag{4}$$

Final temperature (FT):

$$FT = 49{,}2292 + 1{,}1834\times T2 + 273{,}8685\times R2 + 1{,}0754\times C1 \tag{5}$$

Drying potential (DP - Ratio between the moisture content of the wood at a given drying phase and the equilibrium moisture content that the wood will reach if it remains in a given environmental condition):

$$DP = 1{,}4586 - 30{,}4418\times R2 + 42{,}9653\times R1 + 0{,}1424\times C3 \tag{6}$$

Where: R_1 = Drying rate up to 5 %; R_2 = Drying rate up to 30 %; end based on the values of the average score presented in Table 1: C_1 = check of an initial moisture content of up to 30

%; C_3 = end check from 30 % to 5 %; T_2 = Drying time of an initial moisture content of up to 30 % (h).

Check length was measured using a digital caliper accurate to 0,01 mm and check width was measured with the aid of a feeler gauge, always considering the longest defect. The magnitude of the end checks was converted into a score, according to the classification outlined in Table 1.

Table 1: Score of end checks from Ciniglio (1998).

SCORE	END CHECK
1	Absent
2	CL < 5,0 and CW < 0,5
3	CL > 5,0 and CW < 0,5
4	CL < 5,0 and 0,5 < CW < 1,0
5	CL > 5,0 and 0,5 < CW < 1,0
6	CL > 5,0 and CW > 1,0

CL = check length (mm); CW: = check width (mm).

The moisture content data of the samples from the beginning to the end of each test were interpolated to determine the exact times at which each sample reached 30 % and 5 % moisture content. To calculate the mass of the samples with 30 % and 5 % moisture content, the moisture content equation was solved for wet mass.

The experiment had a completely randomized design. Statistical analysis was performed using descriptive statistics and analysis of variance, and graphs were used to plot the drying curve. Variables expressing changes in sample area or drying quality at different temperatures were compared using the *Mann-Whitney* nonparametric test. Nonparametric tests were run for discrete, nonnormal data, such as scores and counts (Klitzke and Batista 2010).

RESULTS AND DISCUSSION

3.1 Initial moisture content and basic density

Table 2 presents the results of moisture content and basic density of the wood from the two clones.

Table 2: Mean moisture content and basic density of woods from clone 58 (*Eucalyptus urophylla* × *E. camaldulensis*) and clone GG100 (*E. urophylla* × *E. grandis*).

Clone	**N**	**MCi (%)**	**Max (%)**	**Min (%)**	**CV (%)**	**BD (g×cm^{-3})**	**Max (%)**	**Min (%)**	**CV (%)**
58	30	128,7	195,4	95,99	20,45	0,52	0,61	0,37	12,13
GG100	30	150,4	211,81	100,33	16,26	0,47	0,60	0,36	11,32

N = number of samples; MCi (%) = initial moisture content; Max. = maximum; Min. = minimum; BD = basic density; CV (%) = coefficient of variation in percentage.

Clone GG100 had the higher mean initial moisture content, which can be explained by the low basic density of this clone in comparison to clone 58. According to Soares *et al. (*2016), the maximum water retention capacity of the wood is related to the proportion of inter and intracellular spaces of the wood structure. The higher the percentage of volume occupied by the woody substance (cell wall), the lower the voids, which are recipients for free water in the wood. In the same way, the higher the percentage of volume occupied by the woody substance, the higher the basic density.

Meneses *et al.* (2015) and Mauri *et al.* (2015) in research with the clone GG100, observed basic density variation of 0,40 g×cm^{-3} to 0,47 g×cm^{-3} and 0,46 g×cm^{-3} to 0,51 g×cm^{-3}, respectively. These values are similar with that seen in Table 2 for the same clone. However, the mean basic density of clone GG100 found in this study was lower than the value investigated by Castro *et al.* (2016) also for clone GG 100, which was 0,52 g×cm^{-3}. Basic density observed in Table 2 for clone 58 was higher than the reported by Protásio *et al.* (2021), who found mean basic density of 0,39 g×cm^{-3}, in analysis of the same hybrid with age of 7 years. Differences among these materials may have been due to differences in ages, plant spacing or influence of the sites where the trees were planted.

3.2 Drying curves

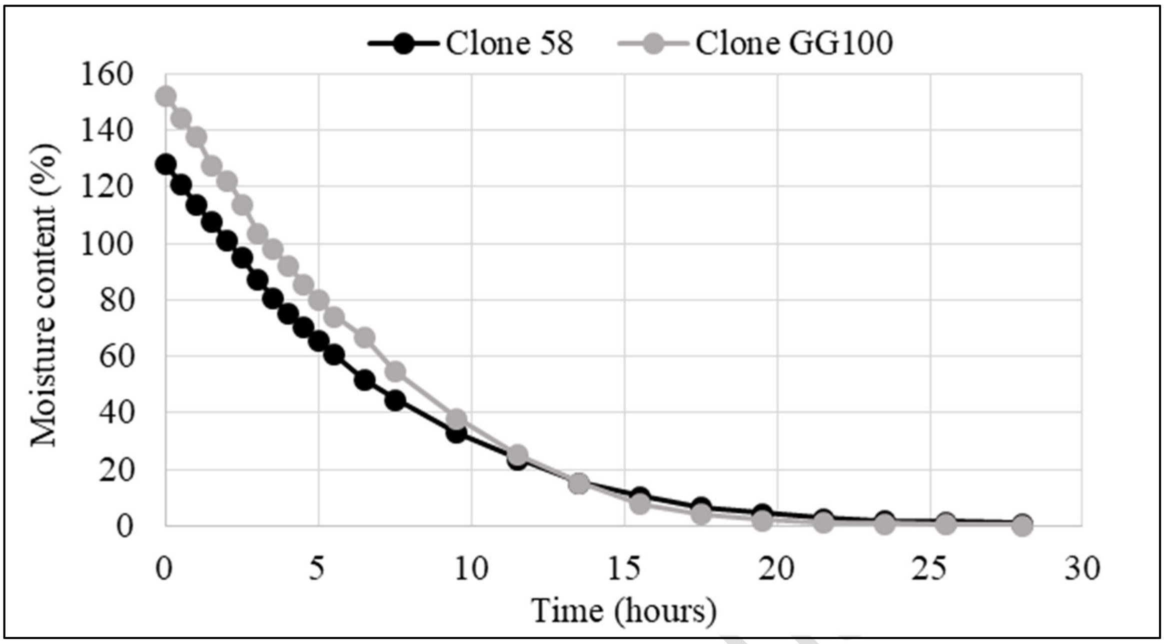

Figure 3: Drying curve at 100 °C of the wood of clone 58 (*Eucalyptus urophylla* × *E. camaldulensis* hybrid) and clone GG100 (*E. urophylla* × *E. grandis*), at 11 and 10 years of age.

Figure 3 shows that, until reaching approximately the saturation point of the wood fibers, free water exited more easily from clone GG100 than from clone 58. From the saturation point of the wood fibers until close to 0 % moisture, the output of the adsorbed water was practically the same in the wood of the two clones. The drying curves of both clones showed an exponential trend, as found in studies performed with drastic drying (Barbosa *et al.* 2005; Soares *et al.* 2016; Soares *et al.* 2019).

3.3 Drying rates

Table 3 shows the results from the mean drying rates up to 5 %, up to 30 %, and from 30 % to 5 % moisture content, comparing the values of the Standard Method (SM) with those of the Updated Method (UM) in drastic drying tests at 100 °C for clones 58 and GG100. Table 3 also shows the calculated U values, which is a statistical analysis to see if the values are considered significant. The U test is the non-parametric version of the Student's T test, for independent.

Table 3: Mean drying rates comparing the standard method with the updated method for woods of clones 58 (*Eucalyptus urophylla* × *E. camaldulensis*) and GG100 (*E. urophylla* × *E. grandis*) subjected to the drastic drying test.

Clone	Method	R_1	Calculated U	R_2	Calculated U	R_3	Calculated U
58	Standard	0,0157	0,00*	0,0244	14,00*	0,0057	86,00*
58	Updated	0,0110		0,0207		0,0039	
GG100	Standard	0,0170	0,00*	0,0245	5,00*	0,0044	119,00*
GG100	Updated	0,0131		0,0210		0,0046	

R1 = Drying rate up to 5% moisture content ($g \times cm^{-2} \times h^{-1}$); R2 = Drying rate up to 30% moisture content ($g \cdot cm^{-2} \cdot h^{-1}$); R3 = Drying rate from 30 to 5% moisture content ($g \times cm^{-2} \times h^{-1}$); Calculated U = Nonparametric analysis where the lower the value of U, the greater the evidence that the populations are different;* = significant at 5%, Mann-Whitney test.

In the drastic drying test at 100 °C, significant differences were found between the UM and the SM for all drying rates (Table 3). The drying rates were, on average, 27 % slower when using the UM than when using the SM. Believing that wood has a faster drying rate than reality can lead to misunderstandings during the drying process. Not reaching a moisture content within a certain time can be detrimental to its final use. Clone 58 showed lower drying rates and a higher density than clone GG100. These results are coherent because they comport with the theory that the density is inversely proportional to the wood drying rate (Simpson 1991).

3.4 Checks

The end check scores of each clone after the drastic drying test are included in Table 4.

Table 4: Mean number of end checks in the samples of clone 58 (*Eucalyptus urophylla* × *E. camaldulensis*) and clone GG100 (*E. urophylla* × *E. grandis)* subjected to drastic drying test.

Clone	**C1**	**C2**	**C3**
58	1	1	1
GG100	1	1	1

C_1 = number of end checks from the initial moisture content up to 5%; C_2= number of end checks from the initial moisture content up to 30%; C_3 = number of end checks from 30 to 5% moisture.

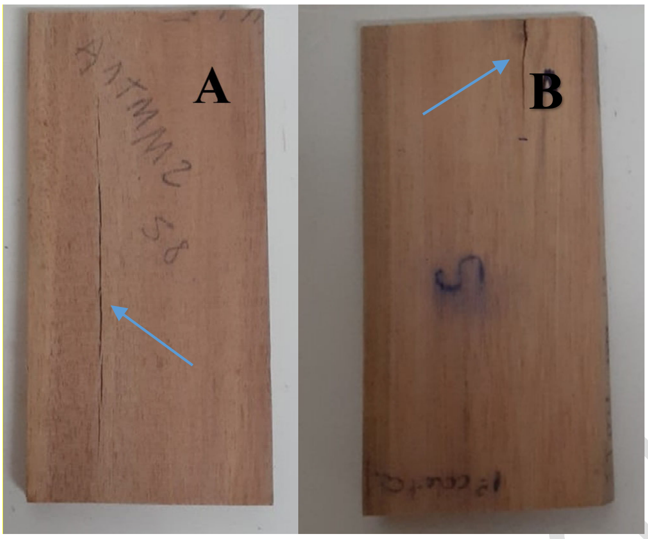

Figure 4: Checks derived from drastic drying in test samples of clone 58 (A) is more evident than in clone GG100 (B).

The checks derived from drastic drying were more evident in test specimens of clone 58 than clone GG100 (Figure 4). This incidence of defects may be more related to the initial moisture content and density of the samples (Simpson 1991) than to drastic drying at 100 °C, as noted in a study published by Effah and Kofi (2014) on different species. Woods less susceptible to this type of defect can, in general, endure more severe drying at higher initial and final temperatures and higher drying potentials.

The drastic drying method for defining drying schedules in which it has been increasingly studied in search of its improvement. Juvenile and adult wood samples of *Eucalyptus saligna* were investigated by Soares *et al.* (2016), and the authors proved that it is possible to carry out the development of different drying schedules for juvenile and adult wood, with the mildest one being used for juvenile wood (Soares *et al.* 2016). Drying schedules for wood of different species, also developed from the drastic drying methodology, were indicated by Andrade *et al.* (2001). The authors demonstrated that, among the wood species analyzed, it was possible to group those with a tendency to similar defects in the same drying schedules, as well as those with the same initial moisture content and the same drying speed. According to the drastic drying methodology, there is no need to correlate the dimensions of samples with the dimensions of the plates for which the drying schedule is created.

In conjunction with a defect score characterization method, the drastic drying methodology was used by Klitzke and Batista (2010) to determine the drying quality of *Eucalyptus grandis*, *Eucalyptus saligna* and *Eucalyptus dunnii* wood for drying in a conventional oven. Batista *et al.* (2016), with the same wood species and age analyzed by Klitzke and Batista (2010), applied the drying schedule that they proposed. The hypothesis of using the drastic drying test defect score as a way to predict the conventional drying behavior of the studied species was rejected, showing that there was a need for better investigations into the drastic drying efficiency. There were gaps regarding the relationship of drastic drying with basic density and the total volumetric contraction of the wood.

With regard to the density, as in clone 58, the denser wood tends to present higher shrinkages associated to the adsorption water removal and, thus, greater dimensional instability tends to be promoted. These conditions promote stresses that causes deformations and checks in the wood. Apparently, the basic density factor was more prevalent in the occurrence of end checks in the studied clones than the initial moisture content factor.

Besides that, some intrinsic characteristics, such as lower percentage area occupied by vessels in the transversal surface of a given wood, can increase its mechanical strength to the tensions that causes end checks (Soares *et al.* 2021). Thus, the material can be less susceptible to this type of defect and endure more severe drying at higher initial and final temperatures, besides higher drying potentials, without checking in larger proportions.

3.5 Estimates of parameters of drying schedules

Table 5 shows the initial and final temperatures and the drying potential, which were estimated using equations 4, 5, and 6, and compares the UM and the SM in tests at 100 °C for clones 58 and GG100, respectively.

Table 5: Mean initial temperature, final temperature and drying potential calculated by the Standard Method and Updated Method for clone 58 (*Eucalyptus urophylla* × *E. camaldulensis*) and clone GG100 (*E. urophylla* × *E. grandis*).

Method	**Clone 58**			**Clone GG100**		
	Mean IT (°C)	Mean FT (°C)	Mean DP	Mean IT (°C)	Mean FT (°C)	Mean DP
Standard	46	71	1,5	48	73	1,6
Updated	42	68	1,5	46	72	1,6
Calculated U	16,00*	32*	152,00^{ns}	0,00*	5,00*	186,00^{ns}

IT = initial temperature; FT = final temperature; DP = drying potential; ns = no significant at 5 %; * = significant at 5 %, Mann-Whitney test.

IT and FT mean values in Table 5 are similar to those reported in the literature by Brandão *et al.* (1989), Barbosa *et al*. (2005), Eleotério *et al*. (2015), Batista *et al.* (2015), Kang *et al.* (2015), Tari *et al.* (2015), Phonetip *et al.* (2018a) and Phonetip *et al.* (2018b), in which IT ranged from 39 °C to 49 °C and FT ranged from 62 °C to 76 °C. However, the mean DP presented in Table 5 was lower to the related by these authors (ranged from 2,0 to 2,7), which may be a disadvantage regarding the drying time. Nevertheless, low DP is an advantage regarding the drying quality because the lower the DP is, the lower the drying stresses intensity on the wood load will be, thus reducing the incidence of defects. The drying potential of a drying schedule helps to determine how the drying will evolve, and the lower the value is, the slower the drying will be.

In the drastic drying tests, significant differences in estimates of the initial and final temperatures were found when comparing the SM with the UM, but no significant differences were found in the drying potential.

3.6 Drying schedules

With the parameters calculated from the Standard and Updated Methods, drying schedules were specifically developed for each clone and method (Table 6).

Table 6: Drying schedules elaborated for Clone 58 (*Eucalyptus urophylla* × *E. camaldulensis*) and clone GG100 (*E. urophylla* × *E. grandis*) from the parameters determined using the Standard Method and the Updated Method of calculation.

Clone 58										
Phase	**DBT (°C)**		**WBT (°C)**		**ARM (%)**		**EMC (%)**		**DP**	
Method	SM	UM	SM	UM	SM	UM	SM	UM	SM	UM
Heating	46	42	46	42	100	100	*	*	*	*
IMC to 30 %	46	42	45	40	91	91	20	20	1,5	1,5
30 % to 25 %	52	49	50	46	87	87	17	17	1,5	1,5
25 % to 20 %	59	55	54	50	78	78	13	13	1,5	1,5
20 % to 15 %	65	61	57	53	67	66	10	10	1,5	1,5
15 % to 10 %	71	68	58	53	53	50	7	7	1,5	1,5
Equalizing	71	68	63	60	68	68	10	10	*	*
Conditioning	71	68	66	63	79	79	12	12	*	*
Clone GG100										
Heating	48	46	48	46	100	100	*	*	*	*
IMC to 30 %	48	46	47	44	92	91	19	20	1,6	1,5
30 % to 25 %	54	53	51	50	85	87	16	17	1,6	1,5
25 % to 20 %	61	59	56	54	78	79	13	13	1,6	1,5
20 % to 15 %	67	66	65	58	67	67	10	10	1,6	1,5
15 % to 10 %	73	72	57	58	47	50	6	7	1,6	1,5
Equalizing	73	72	66	64	73	68	10	10	*	*
Conditioning	73	72	68	67	80	79	12	12	*	*

IMC = initial moisture content; DBT = dry bulb temperature; WBT = wet bulb temperature; ARM = air relative moisture; EMC = equilibrium moisture content; DP = drying potential; SM = Standard Method; UM = Updated Method.

Based on the method for determining the drying schedule recommended by Simpson (1991), in all schedules, the initial temperatures remained unchanged until the samples reached 30 % moisture content. The drying schedules met the expectations for each species, with a milder drying in wood samples of clone 58 than in those of clone GG100. However, a conclusive analysis of the effectiveness of all drying schedules developed in this study requires conducting tests in industrial kilns.

Drying schedules met the expectations for each species, considering the wood properties discussed previously, suggesting a slightly milder drying schedule for the clone 58 than the drying schedule for the clone GG100. In addition, a analysis of the effectiveness of the drying schedules presented in Table 6 will be conducted with tests in industrial kilns and the results will be published in future papers.

The proximity between the parameters of drying schedules (Table 5) calculated by SM and UM is reflected on the Table 6. The drying schedules for each clone, elaborated using SM and UM, are similar. This indicates that the application of the drying schedule obtained from the SM or UM for a given clone probably will result in a similar response to the dry wood of both species.

As reported in several studies (Barbosa *et al.* 2005, Klitzke and Batista 2010, Effah and Cofi 2014, Eleotério *et al.* 2015, Lima *et al.* 2019) the application of the drying schedules shown in Table 6 for wood from clones GG100 and 58, when placed under drying conditions in a conventional oven, it will allow a conclusive analysis of the efficiency of these schedules. Of course, as for all schedules published in the technical literature, it will be necessary to make adjustments, considering the variable conditions of the raw material, the operating conditions of the equipment and the environmental conditions (Simpson 1991).

4 CONCLUSIONS

The samples of clone 58 (*E. urophylla* × *E. camaldulensis*) had a higher mean basic density, longer drying time, and more cracks than the samples of clone GG100 (*E. urophylla* × *E. grandis*). The analysis of the results demonstrated that changing the surface area value of the samples from 100 cm² to 130 cm² led to significant differences in the initial and final temperatures of either study clone. The parameter drying potential showed no significant difference between groups. A drying schedule was developed for each clone from the drastic drying tests at 100 °C. The surface area value was the crucial point for the difference statistic.

Although the significant differences aforementioned, it was observed that the drying schedules developed by Standard Method and Updated Method are similar.

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