Australian Journal of Basic and Applied Sciences

2020 February; 14(2): pages 22-30
DOI: 10.22587/ajbas.2020.14.2.4

Original paper AENSI Publications

Drying methods to evaluate the quality of *Eucalyptus* sawn timber

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Received date: 15 December 2019, Accepted date: 24 February 2020, Online date: 3 March 2020

Abstract

The difficulty of obtaining dry wood with quality is one of the major obstacles when it comes to drying wood of the *Eucalyptus* genus, since the species of the genus have slow drying and high propensity to the appearance of defects. Due to this, it is recommended to apply methods that combine pre-drying with conventional drying as an alternative to improve the quality of this wood. The aim of this study was to compare the final quality of *Eucalyptus* sawn timber submitted to two different drying methods. The drying methods used were: combined drying (air pre-drying + drying in a conventional kiln), and only conventional drying. In each of the drying processes, moisture loss and drying speed were monitored, and the defects before and after each drying (warping, cracking and collapse) were evaluated. Statistical analysis was performed by using descriptive statistics, analysis of variance, analyzed by means of the Analysis of Variance (ANOVA) and Tukey's test at the probability level of 95%, and regression analysis was performed by using software R. Based on the results obtained, combined drying presented a shorter time than the conventional kiln, reducing 51% of the total drying time, which is equivalent to three days less than in the dry kiln. The drying rate in the removal of hygroscopic water between conventional and combined drying methods was higher for the combined drying, i.e., higher drying speed was obtained up to the final moisture content, about twice as high as for the conventional one. Combined drying had the lowest defect rates and highest final quality of the timber, with no collapse.

Keywords: Moisture content, drying defects, drying rate, drying curve

INTRODUCTION

Currently, *Eucalyptus* spp. has been no longer an alternative raw material for the timber industry. It has become a reality for the industrial sector of solid timber products (Liebl et al., 2017). Thus, the processing of *Eucalyptus* sawn timber needs to be adapted and improved both in the mechanical processing and drying phases, since this genus is characterized by the rapid development of forest stands.

However, caution on the production of sawn timber is necessary, mainly due to the manifestation of internal growth stresses, which are responsible for the formation of checking and warping in boards during the processes of breakdown and drying (Yang and Waugh, 2001; Murphy et al., 2005). Improving the quality of boards and optimizing the wood processing industry are fundamental for the productive and financial success of these companies. These improvements generate subsidies, such as new breakdown and drying techniques, especially with regards to the drying of refractory woods, as the *Eucalyptus* genus.

Due to its low permeability, along with its anatomical constitution, which hinders the drive of moisture out of its interior, *Eucalyptus* can be considered as a species of severe drying (Oliveira and Carvalho, 2001; Rezende et al., 2018; Zen et al., 2019). The reactions of the anatomical constitution are very expressive in drying, presenting small diameters (Oliveira and Carvalho, 2001), high cell wall fraction (Zanuncio et al., 2016), which hinders the water movement by capillarity or in liquid form in the interior of this wood, in addition to high complexity, since the same anatomical structure can help in capillary water flow and interfere in the impregnated water flow (Monteiro et al., 2017). Another factor to hinder the process of hardwood drying is the presence of tyloses in the vessels. Tylose is a structure found in the heartwood of *Eucalyptus* species and may obstruct the passage of water (Siau, 1971; De Micco et al., 2016; Helmling et al., 2018).

Therefore, as for the drying of *Eucalyptus*, choosing a method influences the drying time, quality of the dry material, and moisture content desired for particular purposes. It is possible to reduce the drying time and incidence of defects and to improve the quality of the lumber when the process is properly conducted.

In order to minimize defects in *Eucalyptus* sawn timber, several studies have been conducted, such as the use of vaporization during drying (Rezende et al., 2015) and different stacking methods (Dittmann et al., 2017). Another alternative to meet these aspects is the use of pre-drying and the combination of air drying with subsequent conventional drying, providing cost reduction and process optimization due to the higher efficiency of conventional drying kilns.

In addition, this alternative attenuates the moisture gradient in lumber, which is responsible for most defects during drying (Stöhr, 1977; Campbell and Hartley, 1988; Northway, 1996; Ciniglio, 1998; Denig et al., 2000; Santos, 2003; Jankowsky, 2008). It aims at accelerating the drying process by gradually removing the maximum amount of free water with the minimum amount of defects as possible, then finishing the drying in a conventional kiln. Thus, it reduces the time in kiln and energy costs and initially eliminates defects such as collapse.

When individually applied, these two drying processes (air and conventional drying) have characteristics that do not favor the drying of *Eucalyptus* lumber and are often not recommended. On the one hand, air-drying depends on local atmospheric conditions, and the environmental variables cannot be controlled. On the other, conventional drying allows for total process control, which reduces the incidence of defects in the initial phases. However, it requires a skilled workforce, increasing operating costs (Rosso, 2006). Thus, this study aims at evaluating the quality and drying parameters of *Eucalyptus* sawn timber submitted to two different drying methods: combined drying (air pre-drying + drying in a conventional kiln), and only conventional drying.

MATERIAL AND METHODS

Material Preparation

For this study, *Eucalyptus* sawn timber from forest stands with an average age of 15 years, belonging to the company *MADEMAPE Madeiras* (municipality of Campina Grande do Sul, state of Paraná, Brazil), was used. The logs were selected in the yard of the sawmill and were sawn in simple vertical band saw, in the nominal dimensions of 25 mm x 110 mm x 2500 mm (thickness, width, and length, respectively), at green state. Later, they were separated and transported for the drying processes.

The following drying methods were used: combined drying (air pre-drying + drying in a conventional kiln), and only conventional drying. For pre-drying, the nominal dimensions of 25 mm x 110 mm x 2500 mm (thickness, width, and length, respectively) were used. The timber was naturally exposed in the city of Curitiba (state of Paraná, Brazil), at the facilities of the Forest and Wood Science Center (*Centro de Ciências Florestais e da Madeira* – CIFLOMA) of the Federal University of Paraná. A well-drained, flat, unobstructed ventilation site was selected for good air circulation. The air-drying stacking was built on concrete load supports with lumber blocking at the height of 30 cm from the ground. It was formed by 20 layers of boards. Seven timber battens per layer were placed at 35 cm from each other to minimize the incidence of defects. The timber was exposed until it reached the moisture content desired.

For drying in a conventional kiln (both combined and only conventional drying), the boards were resized at 25 mm x 110 mm x 650 mm (thickness, width, and length, respectively). Samples of 25 mm were taken at each end of the piece to determine the initial moisture content for both methods. Each load consisted of 60 pieces, and the wood was stacked in dry kiln trucks. The boards were arranged in the transverse direction to the airflow of the dry kiln and were allocated and separated by stickers of square section of 25 mm and length of 1100 mm. Airflow in the dry kiln was measured with an anemometer and had a value of approximately 2.0 m/s.

Moisture Monitoring and Evaluations

Moisture monitoring of the lumber boards in conventional drying was performed by four pairs of pin electrodes (two long and two short), totalling sixteen pins, which had resistance operation. Drying curves and rates were achieved based on the data obtained by the kiln. In the air drying, moisture was monitored through control samples allocated in the stack at the entrance and exit of air. The moisture loss in this test was monitored according to Equation 1 (Brandão, 1989):

$$\mathrm{UA} = \frac{\{[\mathrm{MA} * (\mathrm{UI} + 100)]}{\mathrm{MI}} - 100 \quad (1)$$

Where: UA = moisture content of the specimen at any given time (%); MA = mass of the specimen at the same given time (g); UI = initial moisture of the specimen (%); and MI = initial mass of the specimen (g).

Before starting the drying process, the initial moisture content of each sample was determined through the gravimetric method, according to the recommendation NBR 7190 (Brazilian National Standards Organization – ABNT, 1997).

Based on the data obtained by the dry kiln through the pin electrodes and control samples, the drying rates for each method were established according to Equation 2:

$$TS = TUi - TUf/T \quad (2)$$

Where: TS = drying rate (U%.h^{-1}); TUi = initial moisture content (%); TUf = final moisture content (%); and T = time (days).

Drying Program

Drying programs were developed under two conditions, using the same initial parameters: one was based on the greenwood, and the other, on the pre-dry wood (air drying at 23% of moisture content). To elaborate the program, the methodology presented by Ciniglio (1998) and Jankowsky (2009), so-called drastic drying, was used. Table 1 presents the drying program elaborated for *Eucalyptus* spp, under both conditions.

Table 1: Conventional drying program for *Eucalyptus* spp lumber in a dry kiln.

Temperature °C							
Phase	Moisture	DBT	WBT	RH %	EM %	Time (hours)	DP
Heating	-	40	40	100		3	-
1	35	40	38	87	18	-	2
2	31	44	42	82	16	-	1.9
3	28	46	42	76	14	-	1.9
4	24	48	43	73	12	-	1.9
5	20	52	43	63	10	-	1.9
6	18	56	45	58	9	-	1.9
7	15	60	46	54	8	-	1.9
8	12	63	46	40	6	-	1.9
9	9	65	47	35	5	-	1.9
Standardization	10	63	43	63	9	8	
Acclimation	10	61	53	72	11	8	
Cooling	10	44	37	54	9	4	

Where: DBT = Dry-bulb temperature (°C); WBT = Wet-bulb temperature (°C); RH = Relative Humidity (%); EM = Equilibrium Moisture (%); DP = Drying Potential.

Incidence of Defects and Final Quality of the Timber

Evaluations on defects were performed according to the recommendation NBR 14806 (ABNT, 2002). The defects evaluated were crooking, bowing, cupping, and surface and top checking. Collapse checking was performed according to the recommendation of Galvão and Jankowsky (1985) and was classified according to the recommendation of Welling (1994) (Table 2).

Table 2: Collapse degree.

Collapse Degree	**Reduction in thickness (d_c), representing the current level of collapse**
Severe	$d_c \leq 6$ mm (or removed with planing)
Moderate	$d_c \leq 4$ mm (or removed with planing)
Light	$d_c \leq 2$ mm (or removed with planing)

Source: Adapted from Welling (1994).

Statistical Analysis

Statistical analysis was performed by using descriptive statistics, analysis of variance, and regression analysis. The variables relative to the quality of the lumber were statistically analyzed by means of the Analysis of Variance (ANOVA) and Tukey's test at the probability level of 95%. Bartlett's test was applied to verify the homogeneity of the variances. Regression analysis was performed by using software R.

RESULTS

Fig. 1 presents the results for the combined drying curve of *Eucalyptus* lumber according to the moisture loss over the days. For the combined drying method, the initial moisture content in the pre-drying phase was 88%, reaching the final moisture content of 23.1% after 65 days. Drying was finished in a conventional kiln, and the timber reached 9% of moisture in three days (72 hours).

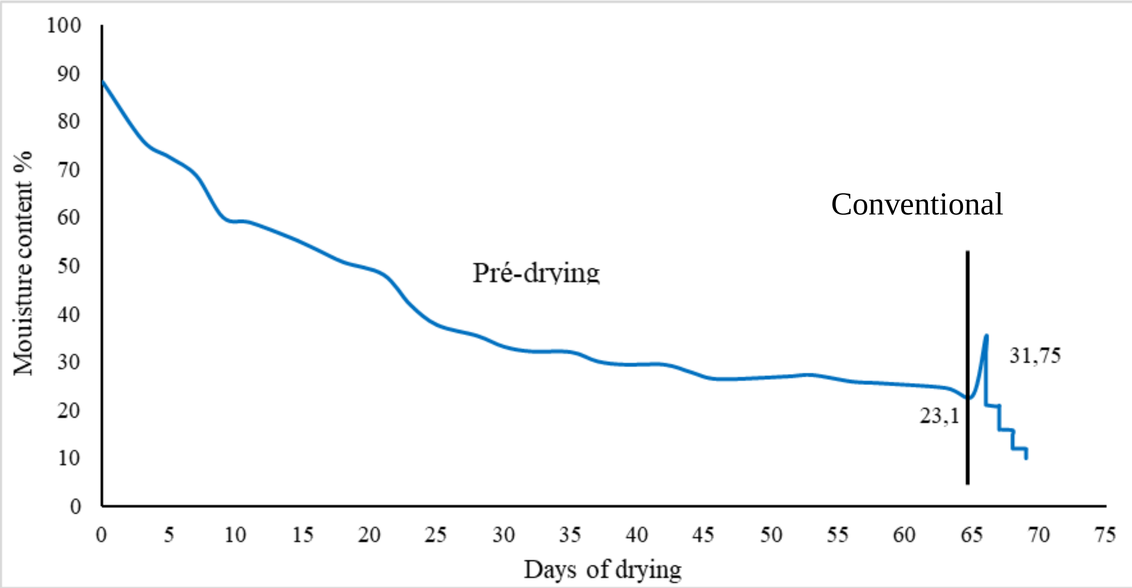

Fig. 1: Combined drying curve for *Eucalyptus* sawn timber.

After this phase, the moisture content loss is reduced. At the beginning, the desorption rate is high, and as it approaches the FSP, it is drastically reduced. When analyzing only conventional drying (Fig. 2), the average moisture content was 69%, given 172 hours (7.16 days in the dryer), up to the final moisture content of 9%.

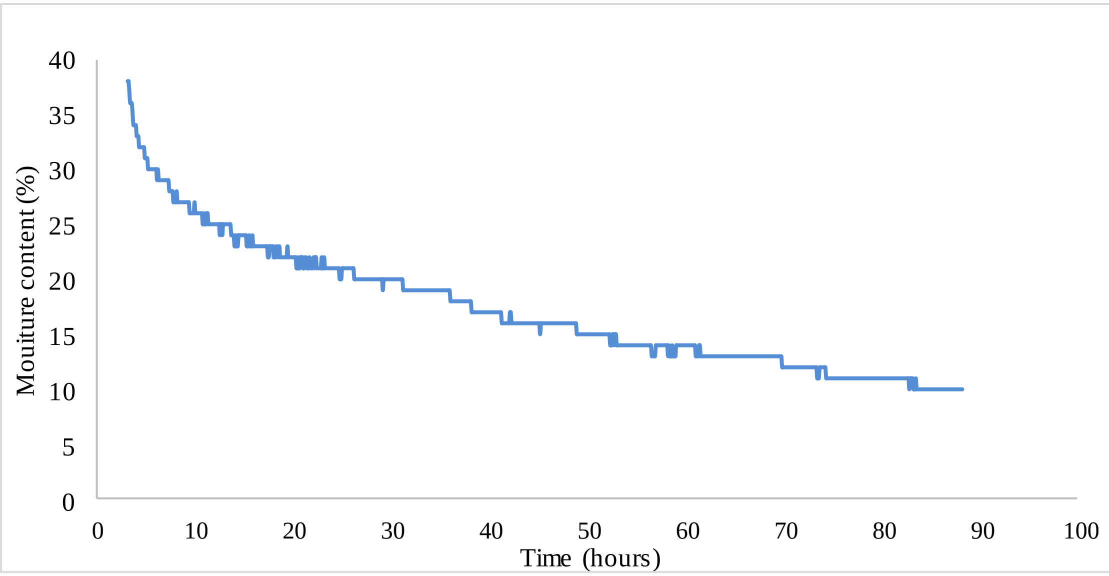

Fig. 2: Conventional drying curve for *Eucalyptus* sawn timber.

Drying Rate

Table 3 shows the mean drying rates in the following moisture content conditions: green up to 30% (capillary water); green up to 9% (capillary and impregnated water); and conventional drying from 30% up to 9% and combined drying only from 23% to 9% (impregnated water). The results were presented in U%.h^{-1}, for the pairs of pin electrodes of the dry kiln.

Table 3: Mean drying rate for *Eucalyptus* spp. Lumber for conventional drying and combined drying in the conventional kiln.

	Drying Rate %U.h^{-1}			
Drying	Green up to 30% (Capillary Water)	From 30 to 9% (Impregnated Water)	Green up to 9% (Impregnated and Capillary Water)	F
Conventional	0.7468	0.17153 b*	0.2845	36.1187**
Combined	-	0.32548 a*	-	

Where: * removal of impregnated water from 23% of moisture; ** significant for Tukey's test at $p < 0.01$.

For the purpose of comparing the mean drying rates in the conventional and in the combined drying methods, F-test was performed only for hygroscopic water range, since the combined drying results from a pre-drying in which the removal of free water has already occurred. Thus, it only shows this moisture range.

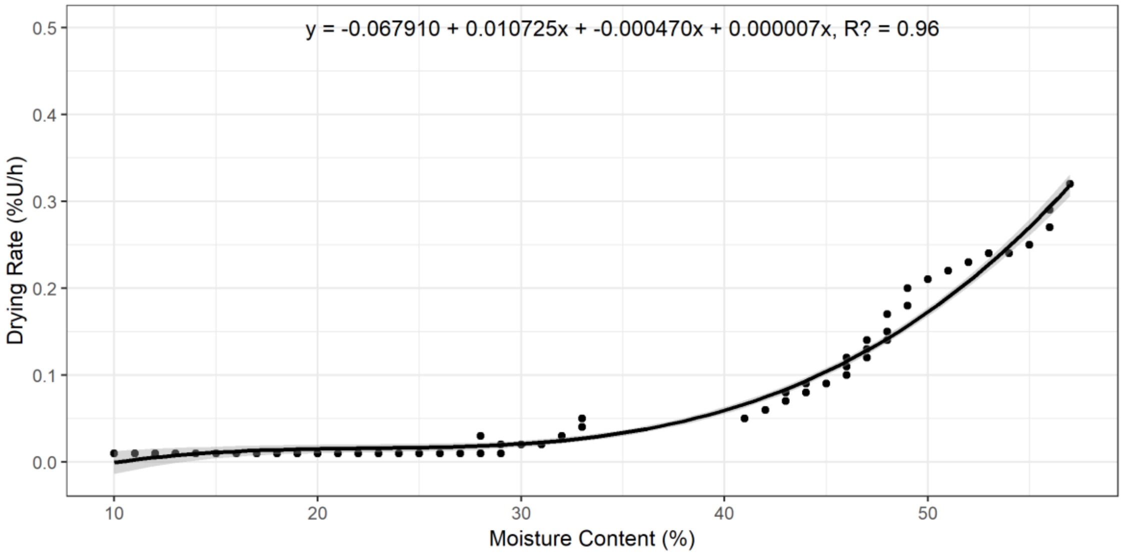

Fig. 3: Characteristic drying curve of *Eucalyptus* spp. Sawn timber for conventional drying rate.

Quality of *Eucalyptus* Lumber for Conventional and Combined Drying Methods

Surface and Top Checking

Eucalyptus lumber showed no surface checking during conventional drying. However, during combined drying, it presented the minimum number of checking of 1.67% (nearly insignificant). The top checking rate has reduced in both methods. On the one hand, for conventional drying, top checking was absent at all stages of evaluation. On the other, for combined drying, top checking rate was 3.33% after a breakdown and absented after drying.

Warping (Crooking, Bowing, and Cupping)

Table 4 presents the warping rate for *Eucalyptus* lumber in both methods. The average crook increased after drying for the boards in the conventional drying. Even though crooking was low after a breakdown, the boards continued to crook during the moisture loss. In the combined drying, the average crook decreased after drying, which can be considered as very low. After analyzing the average crooks, according to NBR 14806 (ABNT, 2002), all pieces presented crooking inferior to 5 mm/m and were not defective in both methods.

Table 4: Warping of *Eucalyptus* lumber.

Defect	**Methods**	
Crooking (mm/m)	Conventional Drying	Combined Drying
After Breakdown	0.29	0.10
After Drying	0.87	0.05
Bowing (mm/m)	Conventional Drying	Combined Drying
After Breakdown	1.03	1.51
After Drying	1.34	1.33
Cupping (mm)	Conventional Drying	Combined Drying
After Breakdown	0.28	0.48
After Drying	1.11	0.48

Collapse

Table 5 presents the percentage of collapse, level of collapse, and mean deformation (d_c) of the boards for the conventional and combined drying methods.

Table 5: Percentage of defective parts and level of collapse of *Eucalyptus* lumber for conventional and combined drying methods.

	Level of Collapse (%)				
Drying	Pieces with Collapse (%)	Light	Moderate	Severe	Mean d_c (mm)
Conventional	11.66	0.00	5	6.66	2.27
Combined	0.00	0.00	0.00	0.00	0.00

Where: d_c = mean deformation of the collapsed boards (mm).

According to Table 5, the collapse occurred in the conventional drying, presenting a high percentage of pieces (11.6%, where 5% had moderate level and 6.66%, severe level). No collapse was observed in combined drying.

DISCUSSION

Initial Moisture Content, Time, and Drying Curves

According to Hill et al. (2010), lumber sorption behaviour can be described by a model called parallel exponential kinetics (PEK). This model is composed of two exponential terms representing the fast and slow processes with characteristic time and moisture content associated with them (Hill et al., 2010; Hill et al., 2012).

Thus, air drying of the sawn timber was conducted up to the moisture content of 23%, since it was the moment when the control samples presented greater moisture homogeneity for transfer to the dryer. After moving from the drying stack to the dryer, it was possible to observe moisture gain by the heating phase and then high moisture content loss due to the conditions of the artificial drying (Figure 1).

In addition, the moisture content increased from 23.1% to 31.7% in the heating phase for the combined drying curve, when the lumber was in the conventional kiln. This result is normal for the dryer, as there is thermal equilibrium between air and lumber in the heating phase. As it is undesirable for the lumber to start the drying process at this phase, high relative humidity and low temperature are used, promoting this thermal equilibrium (Andrade, 2000).

The initial moisture content of the sawn timber is influenced by many variables, such as: age, species, site, season of the year when it was cut, besides transport-related operational factors, log storage time, and sawdust up to drying. Despite the low initial moisture content, the drying curve behaved as typical as the characteristic *Eucalyptus* curve for dryers (Jankowsky et al., 2003), with no constant moisture loss rate, and proving its impermeability. Low permeability implies the need for slow drying, with low drying power and temperature, especially at the beginning of the process. It is in accordance with the drying program elaborated previously in Table 2.

According to Figures 1 and 2, a comparison between the drying times according to the moisture content for both methods shows the reduction of 51% of the total drying time, which is equivalent to four days less in the conventional kiln, when using only conventional drying. Therefore, it is possible to affirm that these results are satisfactory since the productive capacity of the kiln has increased.

By reducing the days of drying, a higher rotation of loads in the kiln and significant reduction in both thermal and electrical energy consumption, as well as low reduction of the defect rate (mainly for collapse), are possible. Several authors, such as Northway (1996) and Ciniglio (1998), have indicated that applicable methods, such as pre-drying for *Eucalyptus* lumber and the combination of air and conventional drying, are satisfactory to reduce the time in drying kilns. This combination provides cost reduction and process optimization by higher kiln operation.

Drying Rate

According to Table 3, the drying rate for the removal of hygroscopic water between conventional and combined drying methods differed statistically at the probability level of 1%. For the combined drying, the drying rate was higher, i.e., higher drying speed was obtained up to the final moisture content, about twice as high as for the conventional one. The higher temperatures used in the combined drying may explain this result, in accordance with Langrish and Walker (2006), who have reported on the influence of temperature on the increase of the drying rate. Similar behaviour was described by Batista et al. (2015) for the drying rate of three species of *Eucalyptus*. The author verified the lowest drying rate in the impregnated water range.

In addition, according to Table 3 and Fig. 3, the drying rate for conventional drying was normal, and the removal of free water (green up to 30%) has occurred as expected. It presented a high mean drying rate, thus providing higher drying speed, i.e., greater removal of free water when compared to impregnated water. This result is justified by the high moisture content of the lumber and the short elapsed time, regardless of the drying program. In the phase of removal of hygroscopic water, the drying rate decreased as the lumber moisture approached the final moisture content. Finally, a slight reduction in the total removal range of both free and hygroscopic water is observed.

Quality of *Eucalyptus* Lumber for Conventional and Combined Drying Methods

Surface and Top Checking

The probable reasons for the low rate of surface checking found in this study may be related to the low initial temperatures used in the drying programs, especially for conventional drying, for which this defect was absent. Besides, the surface moisture content may have decreased, or even the drying stresses in the pieces that presented surface checking in the evaluation after breakdown may have reversed, sealing the cracking initially verified, after drying.

Vermaas (1995) states that, above the PSF, *Eucalyptus* lumber presents a great tendency to check and collapse, especially at high temperatures. To dry *Eucalyptus* lumber with a thickness of 25 mm or more, the temperature should not exceed 45°C during the initial stages of the process (Campbell and Hartley, 1988; Hartley and Gough, 1990; Severo, 2000). Otherwise, this timber becomes prone to the development of surface checking. Similar results were found by Batista et al. (2015), who has also obtained low percentage values of surface checking when evaluating the drying of *E. saligna* and *E. grandis*.

The low top checking rates found are justified by the fact that the drying programs elaborated, both for combined and conventional drying methods, were ideal. Low temperatures, high relative humidity, and low drying rate, along with low moisture gradient, favored the absence of top checking after drying. According to Susin (2012), one of the biggest difficulties during *Eucalyptus* lumber drying is reducing, avoiding, and controlling the incidence of top checking.

Warping (Crooking, Bowing, and Cupping)

The higher average crooks for the conventional drying, when compared to the combined one, may have resulted from the different initial moisture contents (due to pre-drying) since the contractions in conventional drying were higher, and mainly, the lumber still presented stresses in the boards. Rocha (2000) states that the manifestation of this defect is more associated with stresses than with the drying process.

The average crook may have reduced in the combined drying since the dimensions of the boards were smaller. Another explanation may be the fact that the pieces already result from pre-drying, when crooking decreases, positively contributing to defect reduction when dried in the conventional kiln. According to Souza et al., (2012), the manifestation of crooking in pieces at the end of the drying process is one of the most laborious defects to control, as the boards are arranged with no edge restriction that prevents them from deforming.

After drying, the average bow reduced for the combined drying, whereas it increased for the conventional one (Table 4). This decrease may be justified by the fact that the crooked parts were carefully positioned at the bottom of the stack (first layers) and with the concave face down during the stacking of the boards, causing this rate to be reduced. Using additional loads on the stacks as well as placing the bowed boards in the first layers of the stack favour the minimization of this defect at the end of the drying process (Ciniglio, 1998; Klitzke, 2007; Susin, 2014).

Bowing increase in the conventional drying may be justified by the fact that the lumber presents higher initial moisture content at green state in this method, unlike in the combined drying, in which it has undergone pre-drying, and the lumber water has been gradually removed. Another factor may be the greater proportion of tangent pieces. The presence of abnormal logs and tangentially oriented boards favour lumber bowing. Moreover, Simpson (1991) and Denig et al. (2000) report that bowing is not one of the most problematic lumber defects, as it can be eliminated by performing proper lumber stacking for drying. According to Klitzke, (2007), bowing is influenced more by stacking than by the drying process.

Table 4 shows that the boards already had a low cupping rate after a breakdown in both methods. The cupping rate increased for the conventional drying, whereas it remained constant for the combined one after drying (0.48 mm). The values found for the combined drying in this study are justified by the fact that the boards already had low moisture content due to pre-drying, when the rates were low, and that the contractions of the boards were not expressive, causing this defect to not be very present. Besides, the good stacking performed in the dry kiln also favored these low rates.

It is noteworthy that the maximum value allowed for this defect is 4 mm, according to NBR 14806 (2002). In both methods, all boards presented values below the maximum one. Therefore, 100% of the boards were classified as suitable, with no defective parts. Rosso (2006) and Stangerlin et al. (2009) did not verify pieces with cupping superior to 4 mm either, for *C. citriodora* and *E. saligna*. The cupping rate may have increased in conventional drying due to the presence of boards close to the pith and of tangential and radial faces in the same board.

Collapse

We attempted to standardize the quality of the dry sawn timber in the different treatments in order to avoid the concentration of boards of a single region of the log in a single stack since the origin region of the board affects the presence of collapse in *Eucalyptus*. Ananías et al. (2014) have found the greater presence of this defect in boards of *Eucalyptus nitens* from the transition region between the heartwood and the sapwood. Thus, the results found in this study may be explained by the fact that collapse occurs during the removal of capillary water (Table 5). Besides, it is directly related to the permeability of the lumber, which is influenced by density and capillary diameter and obstructions, such as tyloses (Galvão and Jankowsky, 1985).

Despite the low temperature used until the complete removal of capillary water along with the high relative humidity for conventional drying, the boards presented susceptibility to the manifestation of collapse, which is normal for lumbers such as the *Eucalyptus*. Considering the drying potential of 1.90 and the initial temperature of 40°C, the use of lower temperature and drying potential for this situation followed the recommendations of (Pratt, 1974; Northway, 1996; Ciniglio, 1998; Andrade, 2000; Keey et al., 2000). Reducing the temperature and drying potential further would considerably increase the time of this stage and might make it unfeasible. As a result, the low percentage of the collapse was satisfactory in both methods. It is worthy of highlighting the final drying quality of the sawn timber.

The absence of collapse in the combined drying occurred due to the loss of capillary water in the lumber during air drying, remaining only part of the impregnated water to be removed. Such a process is slower and does not require low temperatures in the final stages. A collapse is a form of shrinkage that occurs in the drying process in most wood species, greatly reducing the size of lumens (Kuo and Arganbright, 1978; Blakemore and Northway, 2009). It occurs in the initial drying stages in the presence of liquid water above the SPF, whereas normal shrinkage occurs in the hygroscopic domain (Panshin and Zeeuw, 1980; Hart, 1984).

CONCLUSION

Overall, the results show that combined drying has reduced drying time in the dryer by 51% when compared to the conventional drying method. It also had a higher rate of removal of impregnated water. The programs developed and applied for *Eucalyptus* lumber in conventional and combined drying methods are considered to be soft. Combined drying presented better results for the quality of the timber in relation to conventional drying. Besides, it has obtained a lower defect rate, with no collapse.

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