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Accelerated swelling of wood for rapid dimensional stability

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ABSTRACT. Dimensional stability of wood can be determined by measuring the total swelling percentage between 0% and FSP moisture content according to the ABNT NBR 7190 (*Associação Brasileira de Normas Técnicas* [ABNT], 1997). Wood dimensional variation by the moisture content modifications must influence both structural elements and connections into timber structures. The wood swelling procedure according to the Brazilian code for saturation of wood samples can take more than a month, but the use of autoclave devices may accelerate this activity, making easier the dimensional stability determination. This paper aims to investigate the possibility of accelerating the wood swelling activity using an autoclave device, considering the Brazilian code for thirteen Brazilian commercial wood species. Contrast test for comparison between accelerated process (Stage 4 – 225 min. at 0.49 MPa pressure) and the conventional procedure for wood swelling resulted in p-value equal to 0.0730 and the average difference between groups about 1.1307% (varying between -0.0541 and 2.3156 with 95% confidence level). According to results, 225 min. at 0.49 MPa pressure provides an equivalent wood swelling compared to the conventional procedure, which can make faster the wood dimensional stability evaluation according to the ABNT NBR 7190 (ABNT, 1997).

Keywords: accelerated process; conventional procedure; dimensional stability of wood; wood swelling.

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Introduction

Wood as a hygroscopic material is under the influence of the moisture effecting its physical and mechanical properties (Almeida et al., 2017). Since the harvesting is performed the wood logs start to dry by the free water placed into the lumen that does not present strong bonds between them and the wood material (Olek, Rémond, Weres, & Perré, 2016; Majka, Rogoziński, & Olek, 2019). The wood impregnated water starts to get out of the wood microstructure when the wood samples achieve the Fiber Saturation Point (PSF - about 25% moisture content). The water into cell walls (mostly between 0 and FSP Moisture content) is slowly removed from the cell wall leading to shrinkage and increasing of mechanical properties of the wood samples (Skaar, 1988; He, Zhao, Yang, & Yi, 2014; Resende et al., 2018).

Wood dimensional stability has been studied for the best comprehension of the hygroscopic effects on the wood structural elements (Windt, Li, Van den Bulcke, & Van Acker, 2018; Mrad, Alix, Migneault, Koubaa, & Perré, 2018; Žlahtič-Zupanc, Lesar, & Humar, 2018). For structural design, homogeneous dried wood batches are considered (that is the way wood is usually found for commercialization), thus, it is common the usage of standardized wood samples for artificial swelling treatments (by water submerging) and based on those samples, to determine the dimensional variations (radial, tangential and longitudinal directions) between saturated and dried states (Lourençon, Gatto, Mattos, & Delucis, 2013; Juizo et al., 2015; Almeida et al., 2017).

According to the Brazilian code ABNT NBR 7190 (ABNT, 1997) 'Design of Timber Structures', the dimensional stability of wood batches must be investigated following the procedures of its item B.7, into the annex B 'Wood properties determinations for structure design'. For the maximum swelling percentage measurement, twelve specified specimens must remain submerged in water until their weight get a constant value, which means that cell walls have already achieved the saturation (Kollmann & Cote, 1968).

The total shrinkage or swelling percentages of wood samples based on the Brazilian code procedures must be investigated according to the general characterization of wood batches for structural classification. Dimensional stability investigations according to the Brazilian code were performed by Vidaurre et al. (2018), Almeida et al. (2017) and Cezaro, Trevisan, and Balbinot (2016) in their studies.

The dimensional quantities of wood structural elements are important for hyperstatic structures design, where considering the moisture content variations of those pieces, generating an increasing of the internal stresses (Wacker et al., 2014; Lukacs, Björnfot, Tsalkatidis, & Tomasi, 2016). Cassiano, Souza, Stangerlin, Paulino, and Melo (2013) have studied in timber structures and stated that the moisture content can vary about 6 percentage points, which may cause dimensional modifications that influences connection elements in wood.

For wood samples conventional swelling, by submerging those samples in water, it is common to take about a month until the wood sample weights get stabilized. On the other hand, autoclave devices have been used for preservative treatments (vacuum-pressure method), impregnating aqueous solution into the wood cell walls (Boschetti et al., 2016), only taking some hours for those procedures. Autoclave device can be also used for delamination tests in glulam standardized specimens (Almeida et al., 2014), simulating the dimensional variation caused by the moisture and its influence on the bond region of those structural elements in service situation.

This paper aims to investigate the possibility of accelerating the wood swelling activity using an autoclave device, comparing with the conventional procedure according to the ABNT NBT 7190 (ABNT, 1997), for thirteen Brazilian commercial wood species and to perform a general statistical approach.

Materials and methods

Wood species considered

For investigating the possibility of rapidly determinate the saturated volume of wood samples, trying to accelerate the dimension stability of wood batches evaluation according to the Brazilian code ABNT NBR 7190 (ABNT, 1997), we have considered thirteen wood species that can be found for commercialization in São Carlos – São Paulo state, being *Pinus* sp. one of them, followed by twenty Brazilian hardwoods. Table 1 presents the wood species considered for this study, their popular names and average densities at 12% moisture content (MC).

As showed the Table 1 all wood species selected are very used in the civil construction and furniture industry, being in many cases used as structural material, which makes these wood species widely commercialized in São Paulo state.

Experimental procedures

The ordinary saturation procedure takes time for being achieved, and for high density wood batches, this procedure can take more than a month for maximum swelling percentage determination. Based on this information, we tried to accelerate the saturation procedure of the Brazilian code using an autoclave dispositive and measuring the samples volume raising with the time under high pressure treatment. The Brazilian code wood specimens for dimensional stability were considered in this investigation (B.7 item). Figure 1 illustrates the wood measurement using digital caliper. Wood samples weight were determined using a 0.01 precision digital scale.

Wood batches considered were stocked at 12% MC (hygroscopic equilibrium moisture content), and the accelerated swelling procedure summarized by the Table 2 divided into six Stages.

Table 1. Wood species considered.

Popular Name	Scientific Name	Density at 12% MC (g cm^{-3})
Pinus	*Pinus* sp.	0.53
Garapeira	*Apuleia leiocarpa*	0.80
Jatobá	*Hymenaea* sp.	0.95
Eucalyptus	*Eucalyptus* sp.	0.76
Cambará	*Erima* sp.	0.62
Cupiúba	*Goupia glabra* Aubl.	0.70
Angelim	*Dinizia excelsa* Ducke	0.85
Faveiro	*Pterodon* sp.	0.80
Virola	*Virola surinamensis*	0.64
Louro	*Nectandra* sp.	0.78
Goiabão	*Planchonella pachycarpa*	0.80
Guanandi	*Calophylum* sp.	0.81
Quaruba	*Vochysia* sp.	0.80

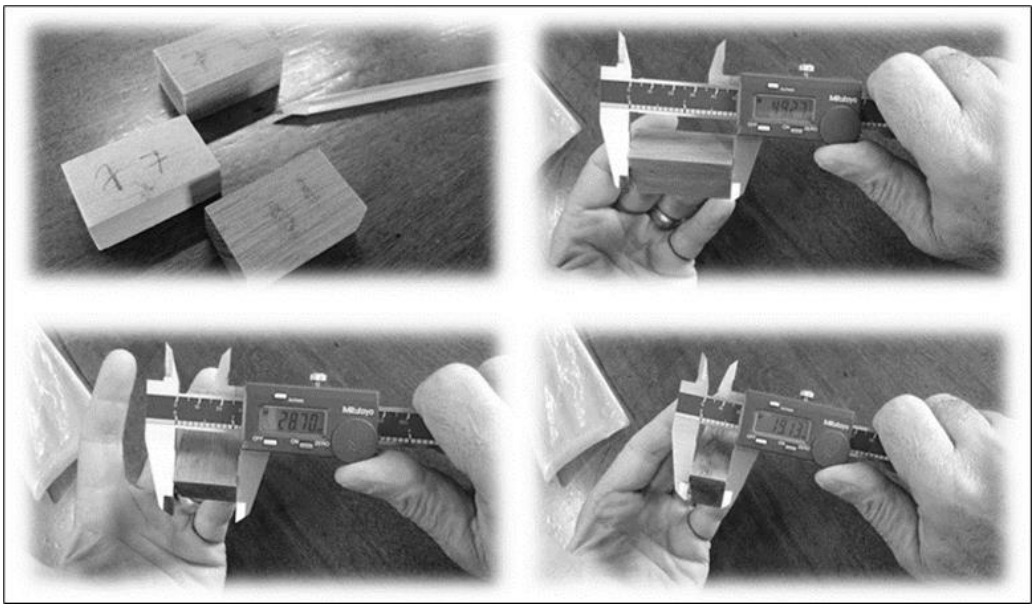

Figure 1. Wood samples measurements.

Table 2. Accelerated swelling procedure.

Treatment	Time (min.)	Pressure (MPa)
Stage 0*	0	-0,05
Stage 1	45	0,49
Stage 2	60	0,49
Stage 3	60	0,49
Stage 4	60	0,49
Stage 5	6000	0,10

Stage 0: it was the start activity, where wood samples were measured and taken to autoclave (underwater) and vacuum for 60 min. at -0.5 atm was carried out;

Stage 1: samples underwater and high pressure for 45 min.;

Stages 2-4: samples underwater and high pressure for 60 min. (the same procedure for each Stage);

Stage 5: samples underwater and atmospheric pressure for 6000 min.

Figure 2 illustrates the accelerated swelling process performed. Figure 2a shows the wood samples and the Figure 2b shows the autoclave device.

Wood standardized samples were measured at each Stage, and the wood swelling percentage was calculated based on the dried samples volume (at 0% MC). The conventional swelling procedure was conducted for determining a reference value of shrinkage percentage for the thirteen wood species of this study. The total of 936 determinations were performed.

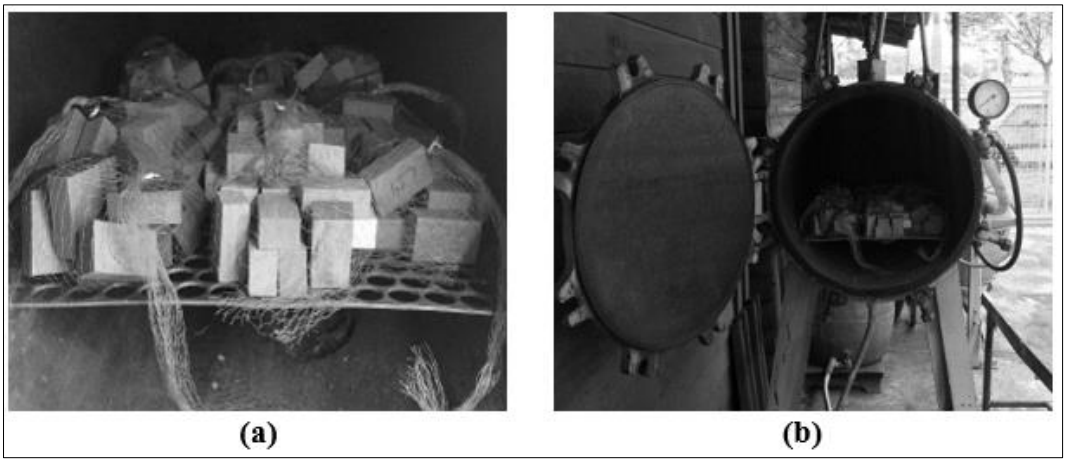

Figure 2. Accelerated swelling: (a) Wood samples for treatments. (b) Autoclave device.

Statistical analysis

Summary of results were made for the best presentation of results (mean and coefficient of variation for each wood species at each Stage of the treatment). A general approach was conducted and a boxplot of the swelling percentage values for each Stage was made for visually compare the treatments evolution. For comparing groups, Analysis of variance (ANOVA) was performed at 5% significance level, and after that, the Tukey's contrast test was performed for multiple comparison of each Stage with the conventional swelling treatment results at the same significance level. For ANOVA validation the Shapiro-Wilk normality test and the Bartlett`s test of homogeneity of variance were performed at 95% confidence level ('SW' and 'Bt' tests, respectively). Statistical analysis was performed using the software R version 3.5.2.

Results and discussion

After autoclave treatment, for all stages (0 to 5), no surface problems due the applied pressure were detected on the specimens. The specimens remained their physical integrity.

Performing the accelerated and conventional swelling treatments and measuring the wood samples volume at each Stage considered, it was possible to calculate the swelling percentage for each wood species. Table 3, 4 and 5 show the summary of results.

Table 3 shows the results for Stages 0 and 1. At the Stage 0 the samples at the hygroscopic equilibrium moisture content were measured and conducted to the underwater vacuum step. The maximum swelling percentage at this condition was 8.27% for Jatobá wood, and the Garapeira wood presented 2.34% of swelling related to the dried sample volume. For the Stage 0 the coefficients of variation were between 9.50 and 29.06% for Eucalyptus and Goiabão woods, respectively.

Table 3. Summary of Stages 0 and 1 swelling percentage results.

Statistics	Stage 0		Stage 1	
	Mean	CV (%)	Mean	CV (%)
Pinus	5.83	20.66	15.10	13.09
Garapeira	2.34	28.17	5.27	26.43
Jatobá	8.27	12.00	11.35	13.22
Eucalyptus	6.22	9.50	9.57	23.96
Cambará	4.29	21.67	10.63	27.28
Cupiúba	5.79	18.21	11.68	16.73
Angelim	4.53	22.21	5.52	21.84
Faveiro	2.73	27.56	6.20	23.59
Virola	5.21	21.00	10.51	25.72
Louro	6.40	21.21	7.82	25.07
Goiabão	2.84	29.06	2.31	28.89
Guanandi	4.97	20.87	8.59	17.70
Quaruba	3.42	26.81	5.79	20.13

Table 4. Summary of Stages 2 and 3 swelling percentage results.

Statistics	Stage 2		Stage 3	
	Mean	CV (%)	Mean	CV (%)
Pinus	13.19	13.25	11.21	16.65
Garapeira	6.57	35.40	6.50	23.87
Jatobá	15.90	13.07	16.88	14.68
Eucalyptus	13.52	11.00	13.91	10.86
Cambará	13.03	35.28	13.78	29.32
Cupiúba	9.92	9.56	8.88	19.09
Angelim	6.88	18.89	8.69	15.33
Faveiro	6.51	28.36	7.34	23.65
Virola	11.51	22.62	13.48	24.18
Louro	9.47	24.32	11.90	17.84
Goiabão	3.75	24.87	6.57	28.17
Guanandi	8.81	14.94	8.33	13.85
Quaruba	5.50	26.77	7.51	20.58

Table 5. Summary of Stages 4, 5 and conventional swelling percentage results.

Statistics	Stage 4		Stage 5		Conventional	
	Mean	CV (%)	Mean	CV (%)	Mean	CV (%)
Pinus	13.03	16.41	12.33	12.79	11.21	8.77
Garapeira	8.31	25.04	8.23	26.39	12.01	7.13
Jatobá	16.92	9.47	16.71	8.78	14.40	8.73
Eucalyptus	15.51	8.35	16.63	5.83	17.18	2.58
Cambará	14.46	23.21	12.77	23.90	14.84	22.11
Cupiúba	11.01	14.06	10.66	12.53	15.87	7.68
Angelim	10.32	27.05	11.42	12.65	11.71	6.35
Faveiro	8.89	28.63	9.41	22.52	10.86	5.61
Virola	13.67	20.38	12.10	23.76	9.78	25.44
Louro	11.51	13.54	13.08	13.95	11.39	6.53
Goiabão	6.75	23.41	8.30	19.91	12.88	8.94
Guanandi	11.28	22.27	10.26	11.04	10.86	5.88
Quaruba	8.41	24.16	10.06	16.21	12.25	8.59

For the Stage 1 the highest swelling percentage was 15.10% for Pinus and the lowest value of this variable was 2.31% for Goiabão. At this Stage the coefficients of variation were between 13.09 and 28.89% for Pinus and Goiabão woods, respectively.

In Table 4 are presented the Stage 2 results. The biggest swelling percentage of the Stage 2 was 15.90% for Jatobá wood and the smallest value of this variable was 3.75% for Goiabão wood samples. The coefficients of variation of Stage 2 results were between 9.56 and 35.40% for Cupiúba and Garapeira woods, respectively.

The smallest swelling percentage for the Stage 3 was 6.5% for Garapeira wood and the greatest value of this dimensional stability parameter at this Stage was 16.88% for Jatobá wood. Coefficients of variation at the Stage 3 were between 10.86 and 29.32% for Eucalyptus and Cambará woods.

Table 5 presents the summarized results for Stages 4 and 5 accelerated swelling and the maximum swelling percentage determined by the conventional procedure (reference values). For the Stage 4, the greatest shrinkage percentage was 16.92% for Jatobá wood and the smallest value of this parameter was 6.75% for Goiabão wood. At the Stage 4 coefficients of variation were between 8.35 and 28.63% for Eucalyptus and Faveiro woods, respectively.

For the final Stage of accelerated swelling treatments, the lowest value of swelling percentage was 8.23% for Garapeira wood, and the highest value of this variable was 16.71% for Jatobá wood. At the Stage 5 the coefficients of variation were between 5.83 and 26.39% for Eucalyptus and Garapeira woods, respectively.

For the reference of maximum swelling percentage values, the conventional swelling procedure was conducted. For the conventional treatment, the greatest swelling percentage was 17.18% for Eucalyptus wood and the smallest value of this variable was 9.78% for Virola wood. Coefficients of variation were between 2.58 and 25.44% for Eucalyptus and Virola woods. These results are similar to the ones found in the Almeida et al. (2017) and Cezaro et al. (2016) studies.

A general approach was conducted in order to determine the treatment Stage that the accelerated swelling data turns up equivalent to the conventional procedure. Figure 3 presents the boxplots of general results for visual comparison of results for each Stage of accelerated swelling (*st0 – st5*) and the conventional procedure (*conv.*). The horizontal red line is the average value of the conventional procedure results, and the average value for each accelerated swelling Stage is represented by red points.

As can be seen in Figure 3, the accelerated swelling Stages raised the swelling percentages to values close to the ones found to the conventional swelling performed.

ANOVA was performed for comparing the seven groups showed by the Figure 3. ANOVA results are presented in the Table 6, and its p-value (p) was lower than the significance level, leading to reject the equivalence among groups hypothesis. 'DF', 'SS', 'MS' and 'F' are degrees of freedom, sum-of-squares, Mean squares and F ratio, respectively, being them the parameters of the ANOVA test. Figure 4 presents the quantile chart and the p-values of the ANOVA validation tests (SW and Bt tests).

According to the results presented by the Table 6 and the Figure 4, the results of swelling percentages presented by the Figure 3 are not equivalent, and for multiple comparison of groups, the Tukey`s contrast test was performed at 5% significance level.

Table 7 presents the confidence intervals and the p-values of the contrast tests for each Stage of accelerated swelling, compared to the conventional procedure results, composing the general approach of the thirteen wood species of this investigation.

As shows the Table 7 the Stages 4 and 5 presented average equivalence of swelling percentage compared to the maximum swelling percentage determined by the conventional procedure (p-values greater than 0.05). For the comparison between Stage 4 (225 min. at 0.49 MPa pressure) and conventional procedure results, the p-value was 0.0730 and the average difference between groups was 1.1307% (varying between -0.0541 and 2.3156 with 95% confidence level). Comparing the Stage 5 (225 min. at 0,49 MPa pressure and 6000 min. at 1 atm) with the conventional procedure results, the p-value was 0.1741 and average difference between them was 0.9897% (varying between -0.1970 and 2.1727 with 95% confidence level).

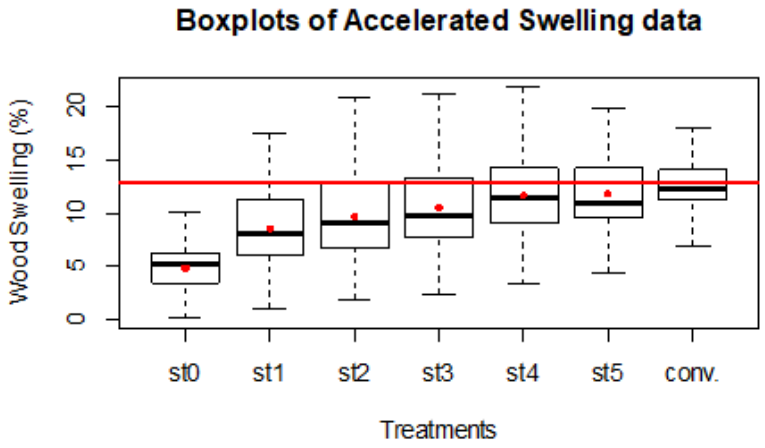

Figure 3. Boxplots of general results for all Stages and the conventional procedure.

Table 6. ANOVA test table.

Stat.	DF	SS	MS	F	p
Source	6	6219	1037	86.49	0.0000
Residuals	1085	12416	12		
Total	1091	18635			

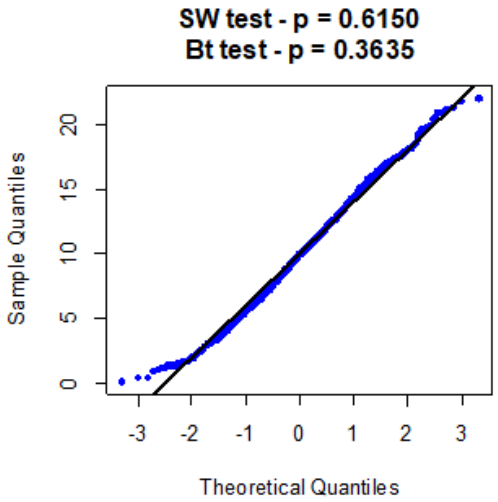

Figure 4. Quantile chart of results and p-values of ANOVA validation tests.

Table 7. Confidence intervals and p-values of the contrast tests between Stages and Conventional results.

Stage	Difference	Lower limit	Upper limit	p
Stage 0	7.8517	6.6668	9.0365	0.0000
Stage 1	4.2005	3.0157	5.3854	0.0000
Stage 2	3.0901	1.9052	4.2749	0.0000
Stage 3	2.2838	1.0989	3.4686	0.0000
Stage 4	1.1307	-0.0541	2.3156	0.0730
Stage 5	0.9879	-0.1970	2.1727	0.1741

Conclusion

Performing the described accelerated swelling procedures as well as the conventional procedures of total wood swelling procedures and comparing results, it was possible to conclude that performing 60 min. of vacuum (at -0,05 MPa) and 225 min. of pressure (at 0,49 MPa) on submerged in water wood samples (same dimensions of the Brazilian code), it is possible to reach the saturated volume of those samples with 95% confidence level. This information can make faster the wood dimensional stability evaluation according to the ABNT NBR 7190 (ABNT, 1997).

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