



Flexural properties of four fast-growing eucalypts woods deteriorated by three different field tests

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ABSTRACT. Durability is a wood characteristic determined by several factors, making it difficult to investigate the service life of pieces designated for outdoor use. In this study, the decaying of juvenile and adult woods of four fast-growing eucalypts from southern Brazil subjected to three different exposure environments was monitored through mechanical properties (flexural test). The study material was obtained from adult trees of *Eucalyptus botryoides*, *Corymbia citriodora*, *Eucalyptus paniculata* and *Eucalyptus tereticornis*. Field tests were conducted in the city of Piratini, southern Brazil, and samplings were carried out during 540 days of experiment. Comparing the four eucalypts, the decreasing order of biological resistance was: *Eucalyptus tereticornis*, *Corymbia citriodora*, *Eucalyptus paniculata* and *Eucalyptus botryoides*. The mature wood showed greater and more stable physical-mechanical properties than juvenile wood.

Keywords: Biodegradation, biodeterioration, soil contact, outdoor exposition, brittleness.

Propriedades em flexão da madeira de quatro eucaliptos de rápido crescimento deterioradas por meio de testes de campo

RESUMO. A durabilidade é uma característica da madeira atribuída à diversos fatores, o que dificulta a determinação da vida útil de peças destinadas ao uso externo. Nesse estudo, os lenhos juvenil e adulto de quatro eucaliptos de rápido crescimento oriundos do sul do Brasil degradados por meio de três diferentes campos de apodrecimento foram monitorados por meio de propriedades mecânicas (teste de flexão). O material de estudo foi proveniente de árvores adultas de *Eucalyptus botryoides*, *Corymbia citriodora*, *Eucalyptus paniculata* e *Eucalyptus tereticornis*. Os testes de campo foram instalados na cidade de Piratini, estado do Rio Grande do Sul e as amostras foram coletadas ao longo de 540 dias de experimento. Na comparação entre as quatro espécies, em ordem decrescente de resistência biológica, definiu-se: *Eucalyptus tereticornis*, *Corymbia citriodora*, *Eucalyptus paniculata* e *Eucalyptus botryoides*. O lenho adulto apresentou propriedades físico-mecânicas maiores e mais estáveis do que o lenho juvenil.

Palavras-chave: Biodegradação, biodeterioração, contato com o solo, exposição externa, fragilidade.

Introduction

The current scenario of the global forestry market has a dwindling number of mature forests, due to the growing demand for wood from fast-growing species. Overall, assessing the culture of the latter species, Brazilian and foreign forestry producers have obtained greater financial benefits from the use of species that allow shorter crop cycles. As such, the attractiveness of plantations of species of the genera *Eucalyptus* and *Corymbia* has grown.

In addition to the above factors, eucalypts wood has numerous other advantages, such as those related to its planting: high adaptability and productivity, high resistance to pests and diseases, easy hybridization, consolidated management culture, and tolerance to stress conditions. There are

also positive aspects related to the wood, exemplified by: high homogeneity properties, good mechanical properties and the possibility of using their oils in alternative industries.

However, its rapid physiological activity gives rise to a chemical composition and anatomical structure that makes it highly resistant to natural wood degrading agents. In this context, it is known that the wood degradation process is a very complex mechanism, given that until today it has not been possible to adjust mathematical models to predict this behavior effectively (Carvalho, Canilha, Ferraz, & Milagres, 2009). For this reason, several laboratory studies have been directed to evaluating and monitoring the technological properties of wood when subject to deterioration attributed to biological (Negrão et al., 2014; Thybring, 2013) and

non-biological agents (Barreto & Pastore, 2009; Huang, Kocaefe, Kocaefe, Boluk, & Pichette, 2012a and 2012b).

Although the collection of data via this route is more costly, field tests are preferable because they subject samples to conditions closer to the reality of their practical use, for instance degradation resulting from biotic and abiotic agents together (Brischke, Meyer, & Olberding, 2014; Edwin & Ashraf, 2006). Within this framework, several gaps in knowledge about this issue have been explored in current studies, such as the variation of the degradation attributed to different exposure environments (Delucis, Cademartori, Missio, & Gatto, 2016) and the comparison of the degradation occurring in juvenile and mature woods (Latorraca, Dünisch, & Koch, 2011).

Generally, wood resistance to biodegradation is attributed to its extractable compounds content, particularly terpenes and phenolic groups (Antwi-Boasiako & Allotey, 2010). Regarding the exposure environment, factors influencing the biodegradation of wood that stand out are: soil conditions such as pH, salinity and content of organic matter and nutrients (Brischke et al., 2014), as well as atmospheric conditions, such as temperature and relative humidity (Råberg, Edlund, Terziev, & Land, 2005).

Mechanical properties stand out as parameters for assessing the deterioration of wood subjected to field tests, due to the proximity of their results to the reality of the stresses imposed on wood pieces used in real service conditions. The mechanical properties of wood are conditioned to their anatomical characteristics, mainly the diameter and the length of their fibers (Abruzzi, Dedavid, Pires, & Ferrarini, 2013), which vary according to soil and climate conditions, as well silvicultural treatments (Gatto et al., 2013; Nugroho et al., 2012).

Therefore, due to the great importance of eucalypts wood and the dependence on mechanical properties for its correct use, this study aims to monitor the deterioration occurred over 540 days to juvenile and mature woods of four species of eucalypts submitted to three different field decay tests through mechanical properties obtained by flexural tests.

Material e methods

Raw material selection

For the present study, we selected twenty trees of the species *E. botryoides*, *C. citriodora*, *E. paniculata* and *E. tereticornis* from plantations that were about 60 years old, located in the city of Charqueadas, Rio

Grande do Sul State. The selection criteria were crowded trees located on sloping grounds and that presented irregular forest form. However, in order to guide the material selection for reliable technical parameters, we used the regulatory procedure D5535-94 of American Society for Testing and Materials (ASTM, 2010).

A baseline log 1.5 m in length, taken at a height of 0.1 m from the ground was selected from each felled tree. The logs were transformed into central planks with a thickness of 8 cm. The planks were then subjected to an outdoor drying procedure for a period of about three months. Subsequently, samples were fabricated oriented relative to the longitudinal axis of the planks, with dimensions of 1 x 1 x 20 cm, with the largest dimension oriented in the longitudinal direction. These samples were taken from the regions near the pith and the bark of the planks in order to characterize the juvenile and mature woods, respectively.

Conditioning of the samples and installation of the decaying fields

After their manufacture, the samples were stored in a climatic chamber, where they were conditioned to equilibrium moisture content of 12%, under the conditions of 65% RH and 20°C temperature. The decaying fields were installed in the 4th sub-district of Piratini city, Rio Grande do Sul State. In the decaying fields, the samples were buried until half of their length and organized in blocks of four samples each. Within each block, the samples were placed so their positioning layout formed a square of sides equal to 10 cm. A distance of 30 cm was kept between blocks, as shown in Figure 1.

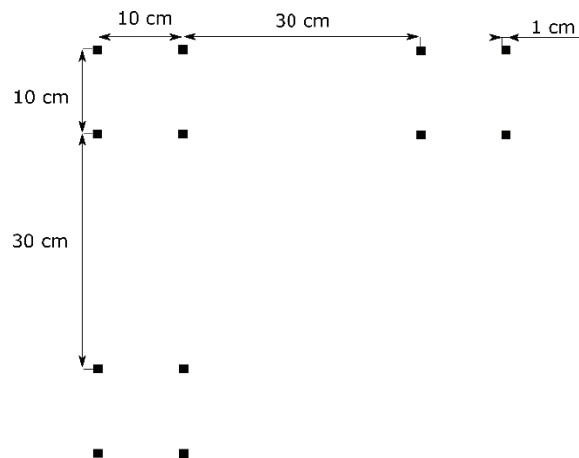


Figure 1. Layout of the samples distributed in decaying fields.

Additionally, we proposed three types of exposure environments. The first was an outdoor field, where the samples remained fully exposed to weathering agents as the ground had almost non-existent vegetation. The second field was installed in a partially flooded area, where the specimens were partially immersed in a water slide with a height of approximately 2 cm. The last field test was conducted within a homogeneous plantation of *Pinus elliottii*, wherein during the test the trees were between 5 and 6 years old, with an average height of about 8 m.

A total of 864 samples were subjected to field tests, and the other 72 were kept during the experiment as control samples. To monitor the decay mechanism, three samples of each reference (combination of the factors species and wood) were taken from each field every 45 days for a total of 540 days, totaling 12 withdrawals.

Mass loss measurements

For this, we utilized the data obtained by the weighing carried out before and after the 540 days of field tests, considering the aforementioned conditioning in terms of stabilization of the moisture content (12%). Given this data, we used the equation 1 to calculate the percentage mass loss (MI) of the tested samples.

$$MI = \frac{(im - fm)}{im} \cdot 100 \quad (1)$$

where:

MI= mass loss (%); im= initial mass (g); fm= final mass (g).

Flexural tests

Through the three point flexural test, the modulus of elasticity (E_f) and flexural strength (σ_f) were evaluated. For the tests, we used a electromechanical and informative universal testing machine, EMIC brand with nominal capacity of 300 kN. As a guideline for testing, the product software was configured in accordance with the regulatory requirements of D143-94 procedure of American Society for Testing and Materials (ASTM, 2014).

After the tests, the moisture content was determined by the gravimetric method, and the mechanical parameters of stiffness (E_f) and strength (σ_f) were corrected to standard moisture content (12%), using the equations provided in the NBR 7190 of Associação Brasileira De Normas Técnicas (ABNT, 1997).

Brittleness

After the mechanical tests, the graphs of stress vs. strain were exported from the software and analyzed according to the methodology described by Phuong, Shida, and Saito (2007). Thus, weighing up the respective areas of the elastic and plastic regions of the analyzed charts, Brittleness was calculated for each sample by the ratio between their resilience and toughness (Equation (2)).

$$\text{Brittleness} = \frac{\text{Elastic area}}{(\text{Elastic area} + \text{Plastic area})} = \frac{\text{Resilience}}{\text{Toughness}} \quad (2)$$

Results and discussion

The results for the mechanical parameters obtained by multifactorial ANOVA indicate a similarity in the changes occurring due to the effects of the factors proposed for this study (Specie, Type of wood, Exposure environment and Exposure time). Thus, it appears that the three mechanical parameters (E_f , σ_f and Brittleness) were sensitive to the factors Specie, Type of wood and Exposure time. However, the effect of Type of field was not statistically significant. Finally, the mass loss was significantly affected for all the factors shown in Table 1.

Table 1. F and p values of multifactorial ANOVA performed for the physicomechanical parameters of wood subjected to field tests.

	Specie	Type of wood	Exposure environment	Exposure time
MI	706.98**	55.12**	374.43 *	-
E_f	28.55**	138.38**	0.71 ^{NS}	8.58**
σ_f	10.00**	23.53**	2.19 ^{NS}	7.25**
Brittleness	11.81**	20.25**	0.93 ^{NS}	7.15**

Where: MI= mass loss; MOE= modulus of elasticity; MOR= flexural strength; *= significant at 5% of probability of error; **= significant at 1% of probability of error; ^{NS}= not significant.

Confronting the statistical parameters obtained by the multifactorial ANOVA, we note that the mass loss was the most sensitive and effective parameter to express the deterioration occurred in the field tests because it was the only property able to differentiate the depreciation mechanism occurring in samples of the three different exposure environments. This statement is an endorsement of the findings of similar previous studies (Curling, Clausen, & Winandy, 2002; Delucis et al., 2016; Råberg et al., 2005). Although it does not necessarily mean that the evaluation of other technological properties of the wood would not contribute interesting additional information.

According to previous studies, from 10% mass loss onwards the wood samples exposed in the field

present a structural impairment (Curling et al., 2002; Venäläinen, Partanen, & Harju, 2014). This indicates that the time proposed for this experiment was satisfactory, as all species and types of wood eventually exceeded this mass loss range after 540 days of exposure (Figure 2).

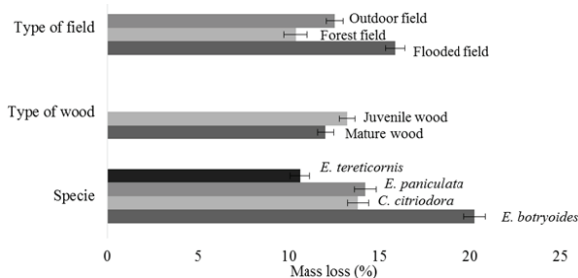


Figure 2. Average values of mass loss.

Similarly to the results disclosed previously about the Figure 2, as well as reported in previous studies about the mass loss (Delucis et al., 2016), Figures 3, 4 and 5 show that there was a gradual decrease of mechanical properties related to the flexural test as the exposure period of the field material increased. This proves the close relationship between the physical and mechanical properties of wood during its decay process (Ali Uetimane Júnior, Råberg, & Terziev, 2011; Mattos, Cademartori, Lourençon, Gatto, & Magalhaes, 2014).

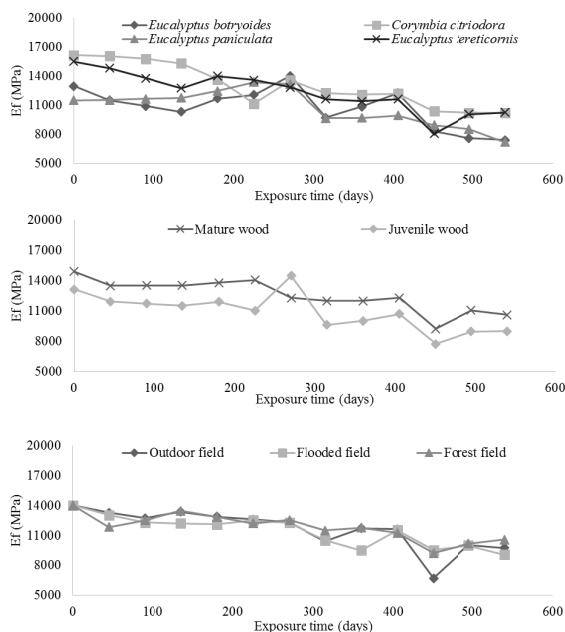


Figure 3. Average values of modulus of elasticity (E_t) according to the exposure time.

Comparing the fresh samples and the samples collected at the end of the tests (540 days of exposure),

the analysis of the decreases recorded in the mass and in the mechanical properties of the wood indicates that for the *E. botryoides* and *E. paniculata* woods, the mechanical properties levels decreased twice as much when compared to the mass. As for the *C. citriodora* and *E. tereticornis* woods, in the same comparison, the levels of mechanical properties (E_f , σ_f and Brittleness) declined around three times compared to the mass.

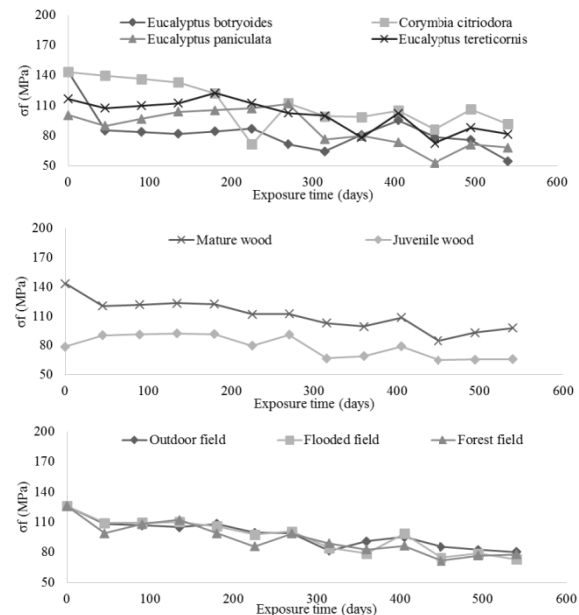


Figure 4. Average values of flexural strength (σ_f) according to the exposure time.

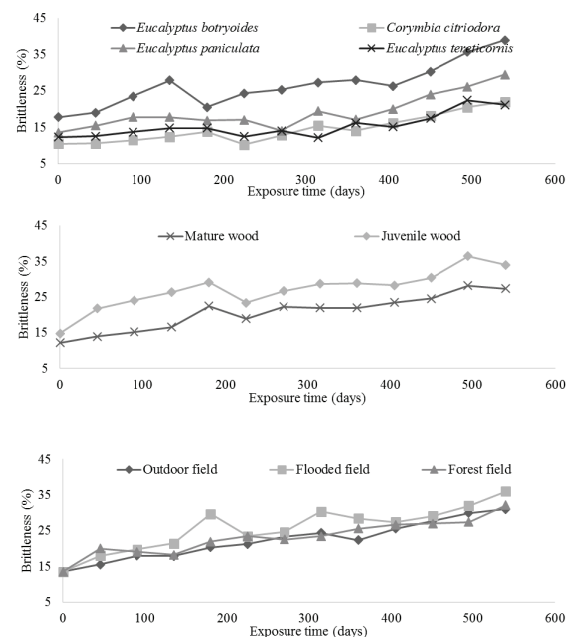


Figure 5. Average values of Brittleness according to the exposure time.

According with Ali et al. (2011), decreased levels of physical and mechanical properties are due to the weakening of the cell wall of the wood caused by the action of xylophagous fungus. In a study examining three fast-growing eucalypts woods subjected to field tests, Mattos et al. (2014) attributed the decrease of physical and mechanical properties of wood to the decrease in cellulose and hemicellulose levels.

As previously mentioned, according to other studies, wood decayed in a field test becomes mechanically compromised, with a mass loss of approximately 10% (Curling et al., 2002; Venäläinen et al., 2014). This statement is divergent with the results obtained in this study, since the levels of mechanical properties for the woods with higher mass loss ($> 10\%$) were within the same range as the other samples in the study (samples with $MI < 10\%$). Thus, regardless of the exposure environment and the species, at the end of the 540 days of exposure the average E_f and σ_f levels for all the combinations of factors studied were above 7,000 and 60 MPa, respectively.

In the comparison between the four species of eucalypts, it appears that wood of *C. citriodora* showed the highest levels of mechanical properties when unexposed. Nevertheless, when comparing the samples *in natura* and those collected after 540 days of experiment, it appears that such wood depreciated more than *E. tereticornis* wood, and the percentage of decrease for the E_f and σ_f was 33.88 and 30.16% for *E. tereticornis* and 37.06 and 36.17% for *C. citriodora*, respectively.

This behavior confirms the results obtained from the analysis of mass loss, confirming the superiority of the *E. tereticornis* wood with respect to biological resistance, followed in decreasing order by *C. citriodora*, *E. paniculata* and *E. botryoides*.

In analyzing the results obtained by Santos, Cademartori, Prado, Gatto, and Labidi (2014), about the chemical properties of the same four eucalypts woods used in this study, selected according to the same methods as this study, it appears that the extractives content does not explain the durability of the *E. tereticornis* wood when compared to the others eucalypts. This is because the authors reported a mean of $1.1 \pm 0.3\%$ for *E. tereticornis* and higher levels for *E. paniculata* and *C. citriodora* ($2.9 \pm 0.6\%$ and $4.4 \pm 0.4\%$, respectively) (Santos et al., 2014). Thus, possibly the greater durability of *E. tereticornis* wood compared to others eucalypts is due to the chemical constitution of their extractive compounds and not the quantity thereof.

Regarding the comparison between the mechanical properties of juvenile and mature woods

of the four eucalypts studied, similar to the results seen in the mass loss of the samples, when compared to the juvenile wood, the mature wood showed higher levels and chronologically more stable structural stiffness (E_f) and strength (σ_f). The variability of the Brittleness of the two mentioned woods indicates that, compared to the juvenile wood, the mature wood showed greater absorption capacity without permanent deformation.

This result, taken to a practical situation of the use of eucalypts wood, indicates that depending on the durability required for a particular piece of solid wood designated to an outdoor environment, it is necessary to use longer harvesting cycles in order to achieve adult trees, i.e., individual trees that have a significant growth of mature wood in their trunks. Another possibility is the use of grinding techniques according to the formation periods for each of the two woods, in order to suppress or enhance the growth at a particular time of planting. In this context, according to the literature, in general, fast-growing species from *Eucalyptus* and *Corymbia* genres planted on Brazilian soil begin to form mature wood in its constitution at around 20 years of age (Lara Palma, Leonello, & Ballarin, 2010; Ramos et al., 2011).

Conclusion

E. tereticornis was the most resistant wood to decay, followed by (in decreasing order of decay resistance): *C. citriodora*, *E. paniculata* and *E. botryoides*.

Mature wood showed greater durability than juvenile wood.

Besides the mass loss results, the flexural properties provide highly relevant information, because they differentiate wood samples by species and types.

In general, the loss of flexural properties were double the mass loss for the *E. botryoides* and *E. paniculata* woods, and three times for the *C. citriodora* and *E. tereticornis* woods.

Based on mass loss, the flooded field enabled the most suitable environmental for wood-decaying agents.

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