Durability of Thermally Modified Wood of *Gmelina arborea* and *Tectona grandis* Tested under Field and Accelerated Conditions

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ABSTRACT: This study evaluated the durability in terms of decay and mechanical resistance of thermally modified (TM) wood of *Tectona grandis* and *Gmelina arborea* treated at 160, 180, 200 and 220 °C. The TM wood of both species treated above 200 °C and 180 °C respectively presents lower weight loss (WL) after 300 days exposure in field and accelerated testing. It was also found that in field testing over 180 °C, the module of elasticity (MOE) and module of rupture (MOR) of the exposed and unexposed stakes of TM wood were not affected. Accelerated tests showed that the loss in flexural resistance was reflected more in the MOR than in the MOE. Finally, the accelerated and field tests showed that *G. arborea* and *T. grandis* TM wood treated at 180, 200 and 220 °C present statistically similar values of WL and flexural mechanical resistance.

KEYWORDS: Biodeterioration, tropical species, decay, thermal modification, teakwood

1 INTRODUCTION

Wood is a biomaterial susceptible to degradation by biotic and abiotic agents. A number of treatments have been applied to wood seeking to improve decay resistance and dimension stability; for example, thermal modification of wood. In this process, the wood is exposed to temperatures between 100 and 220 °C for several hours under nitrogen conditions. Thermal modification of wood essentially involves controlled degradation of the wood, primarily resulting in the destruction of hemicelluloses [1].

Thermal modification affects multiple properties of the wood [2]: reduces its mechanical resistance, increases its resistance to decay, and affects its moisture content, among other properties [3]. Esteves and Pereira [2] made an extensive review of the decay resistance of TM wood of various species. All studies about decay resistance in this review have used accelerated tests, focusing mainly on species from temperate climates.

The environmental conditions of tropical regions, such as high temperatures and rainfall throughout the year as occur in Costa Rica, enable the development of a large variety of timber species from forest plantations [4]. Two of these forest species, *Tectona grandis* and *Gmelina arborea*, have been successfully planted in forest plantations in Costa Rica [5, 6]. Nevertheless, the high amount of sapwood and heartwood of low durability [5, 6] makes both species susceptible to degradation. These woods are already being thermo-treated to improve their resistance to biodegradation [7].

Timber susceptibility to biodegradation is a disadvantage [2]. It has long been recognized that deterioration is more rapid in warm, moist climates than in cool or dry climates; thus, 3–5 years have generally been considered sufficient data for tropical regions [2]. On the other hand, knowledge about the loss of durability of TM wood in accelerated tests is also limited. Field test studies on durability of TM wood have been conducted under conditions other than those of tropical climate [8].

Therefore, the aim of the present study is to evaluate the durability of TM wood of *Tectona grandis* and *Gmelina arborea* from forest plantations in Costa Rica at 5 different temperatures. To this end, measurements were carried out on the loss of mechanical resistance of the TM wood after 300 days exposure in a field of stakes in two different sites; in addition, accelerated tests were conducted to evaluate resistance to fungi at various times, using brown- and white-rot fungi (*Lenzites acuta* and *Trametes versicolor*, respectively).

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2 MATERIALS AND METHODS

2.1 Origin and Characteristics of the Material Used and Sampling

The wood of *Tectona grandis* and *Gmelina arborea* used was obtained from trees from the second thinning of fast-growth plantations of 11 and 8 years old, respectively. The plantations were located in the Northern Zone of Costa Rica (Latitude: 9° 50′ 59″ N and Longitude: 83° 54′ 37″ W), and belong to Ethical Forestry S.A. Thirty boards of about 7.5 cm wide × 2.5 cm thick × 2.50 m long were taken from the TM wood only. The trees were harvested in July and during the rainy season. Heartwood boards were divided into 5 parts (samples of 7.5 cm wide × 2.5 cm thick × 50 cm long). It is noteworthy that only samples of sapwood timber were available, since it was not possible to get the radial pattern.

2.2 Thermal Treatment Process

Dried lumber, with approximately 12% moisture content, was thermally treated at four different temperature levels: 160 °C, 180 °C, 200 °C and 220 °C. For each treatment, 30 boards were selected and 30 other samples were left untreated. Each thermal treatment process was made independently and performed under anoxic conditions. The boards were introduced and stacked into a Valutec® thermowood pilot plant [9]. The thermal treatment process started with drying for approximately 17 hours at a temperature ranging from 0 °C to 130 °C to obtain 0% moisture content (MC). Subsequently, the temperature was increased from 130 °C to the temperature defined for each type of thermal treatment (160 °C, 180 °C, 200 °C and 220 °C) and maintained during 6 hours. Next, a conditioning stage was applied during 7 hours; steam, water and temperature were applied to moisturize timber and achieve approximately 6% in MC. Finally, a cooling process was applied during 3 hours. The different treatments were defined as follows: control untreated wood and thermal treatments at 160 °C, 180 °C, 200 °C and 220 °C.

2.3 Evaluation of Durability of Thermally Modified Timber (TMT) Wood Stakes in Field Tests

From thermo-treated boards at 12% MC, 50 defect-free samples of 2 × 2 × 30 cm^3 from each temperature (Table 1) in each species were cut according to the ASTM D-1758-02 standard method A [10]. The samples were in contact with weed-free soil for 300 days. To this end, pots with fertile soil used in the nursery for plant reproduction were employed (Figure 1a). A total of ten stakes of 2 cm × 2 cm × 30 cm, 5 stakes of *T. grandis* and 5 stakes of *G. arborea*, corresponding to the treatments applied (4 temperatures: 160, 180, 200 and 220 °C; and untreated) were used per pot. In total, 20 different pots were filled. The stakes were buried 15 cm deep in the soil. The pots were separated into two groups of 10 pots each, each group exposed to different environmental conditions in two different sites. The first site was at 9° 50′ 59″ N and 83° 54′ 37″ W (Field tests weather condition 2) and the second site was at 10° 11′ 22″ N and 84° 31′ 23″ W (Field tests weather condition 2).

2.4 Evaluation of TMT Wood Stakes in Field Tests

After 300 days exposure, the mechanical resistance of TM wood was evaluated. Samples were extracted and placed under controlled conditions (temperature: 22 °C; relative humidity: 66%) to obtain 12% MC. Next, the stakes were weighed and their dimensions were measured. Static flexure was used to determine the mechanical resistance using the destructive method. For this, Tinius Olsen Horizon H10kT equipment was used, employing a span of 25 cm between supports and applying the load exactly on the ground line of the

Table 1 Experimental parameters determined and the number of samples for each test in TM wood of *Tectona grandis* and *Gmelina arborea*.

Test	Experimental parameters determined	Temperature of thermo-treatment (°C)					Total samples per specie
		Un-treated	160	180	200	220	
Resistance in flexural test	MOE and MOR in flexure and WL after 300 day of exposure	10	10	10	10	10	50
Accelerated test with stakes	MOE and MOR in flexure and WL each 7 days until 28 days	21	21	21	21	21	84
Accelerated soil block test	WL after 16 weeks of exposure	30	30	30	30	30	150

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(**a**) (**b**)

Figure 1 (**a**) Pots to test durability of TM wood of *Tectona grandis* and *Gmelina arborea* in field tests in two climatic conditions. (**b**) Accelerated decay test utilized in small TM wood samples of *Tectona grandis* and *Gmelina arborea* for flexural resistance determination.

stakes at 1 mm/min speed. The modulus of elasticity (MOE) and the modulus of rupture (MOR) commonly obtained in this type of test were determined.

2.5 Evaluation of Mechanical Resistance and Weight Loss for Accelerated Methods

This method was adapted from the method proposed by Silva *et al*. [11] to measure durability of wood-plastic composites by means of accelerated tests. In this test, small samples of 185 TM wood (6 mm × 6 mm × 100 mm) for each treatment (4 temperatures: 160, 180, 200, 220 °C; and untreated) and each one of the species were placed into a jar containing malt-agar culture (Figure 1b) previously inoculated with *Trametes versicolor* (white rot) and *Lenzites acuta* (brown rot). Then, 84 samples were selected for exposure to each fungus and 21 samples designated as control were separated and kept unexposed to the fungi. Three samples were placed into each jar with solidified malt-agar medium (Figure 1b). One week later, 21 wood samples per each species and fungus type were removed. Sample extraction (21 samples/species/fungus) continued in weeks 2, 3 and 4 of exposure. All of the samples extracted and the samples conditioned at 12% MC were then weighed again to determine WL due to exposure to the fungus (Equation 1). Next, the flexure test was performed using a Tinius Olsen H10kT universal testing machine with a span of 8 cm and a loading speed of 0.27 mm/min. Finally, all samples were placed at 105 °C for 24 hours and their dry weight was determined with an analytical balance.

$$Weigth\,loss(\%) = \frac{Initial\,weight - final\,weight}{Initial\,weight} * 100 \quad (1)$$

2.6 Decay Resistance in Accelerated Soil-Block Test

Decay resistance specimens measuring 2.5 × 2.5 × 2.5 cm were cut from 5 different treatments: 4 temperatures (160, 180, 200 and 220 °C) and untreated. Three hundred blocks were extracted from TMT wood boards (5 treatments × 2 fungus × 30 samples). The white-rot fungus *T. versicolor* and brown-rot *L. acuta* were again used for testing natural decay resistance following the ASTM standard D2017-81 [12]. The relative decay resistance of each soil-block test was measured as the WL percentage (Equation 1) during a 16 week exposure to the fungi.

2.7 Statistical Analysis

Firstly, a regression analysis was performed between WL and thermo-treatment temperature for the TM wood stakes that were placed in field tests for 300 days. Then, a variance analysis (ANOVA) and Dunnett's average test ($P < 0.05$) was applied to the MOE and MOR of the flexural test of the same stakes. These analyses were performed in order to determine the differences between these parameters in the case of the untreated stakes (control stakes) relative to TMT wood stakes from different temperature treatments. Lastly, an ANOVA was applied to determine the WL differences between the two types of fungi (*L. acuta* and *T. versicolor*) obtained from the accelerated test. The thermo-treatment temperatures (160 °C, 180 °C, 200 °C and 220 °C) of the wood were the independent variables of the model and the WL was defined as the dependent variable; this analysis was applied to each fungus separately. The Tukey test ($P < 0.05$) was used to confirm the presence of significant differences between treatments. All statistical analyses were computed by SAS software.

3 RESULTS

3.1 Evaluation of Stakes in Field Tests

The WL evaluation of the TM wood stakes at the end of the 300 days exposure showed that *G. arborea* TM wood (Figure 2a) presented greater WL than *T. grandis* TM wood (Figure 2b). Likewise, TM wood stakes exposed to weather condition 2 in the field tests presented greater WL than the stakes exposed to weather condition 1 in the field tests. A major aspect to observe is that WL at the end of the 300 days exposure decreases exponentially with the thermo-treatment temperature.

A small change was observed regarding WL in *G. arborea* stakes between stakes treated at 160 °C and 180 °C. However, TM wood stakes treated at 200 °C and 220 °C presented lower WL than for the previous temperatures (Figure 2a). As for *T. grandis* TM wood, a fall in the WL was observed in untreated stakes and TM wood stakes obtained at 160 °C. The differences between the other temperatures is small and relatively constant (Figure 2b).

The determination of the flexural resistance by means of the destructive method showed that the thermo-treatment reduces the values of MOR and MOE, compared to untreated wood (Table 2). In *G. arborea*, reduction of these values occurs mostly where wood was treated with temperatures of 200 and 220 °C (Table 2), whereas in *T. grandis*, MOR and MOE diminished progressively with increasing temperature.

As for mechanical resistance of stakes after exposure to the soil for 300 days, MOR and MOE diminished significantly in untreated stakes and in *G. arborea* TM wood stakes treated at 160 °C. On the other hand, no significant diminution was observed in MOR and MOE in TM wood treated with other temperatures (180, 200 and 220 °C) relative to TM wood at the same temperatures unexposed to the soil at both sites of exposure (Table 2). Meanwhile, *T. grandis* wood showed significant reduction of MOE in untreated stakes and stakes treated at 160 °C at both sites of exposure. In addition, significant diminution of MOR was observed in wood treated at 180 °C in field test 1 (Table 2).

After comparing the values of mechanical resistance of TM wood after exposure to soil contact for 300 days with the values of untreated wood unexposed to the soil, the highest loss of MOR and MOE evidently occurs in wood of untreated stakes of both species (Figure 3). Additionally, except for the MOR in *T. grandis* (Figure 3b), the least diminution of loss in MOE and MOR occurs in TM wood stakes treated at 160 °C. Finally, in the remaining temperatures, loss of resistance increases with increasing temperature. However, this reduction in mechanical resistance is due to thermo-treatment instead of the wood presenting higher degradation, since wood thermo-treated at over 180 °C presented no significant difference regarding resistance after 300 days exposure.

3.2 Evaluation of Mechanical Resistance and Weight Loss for Accelerated Methods

The WL increased in untreated and TM wood stakes of *T. grandis* and *G. arborea* with time of exposure to *T. versicolor* at 160, 180 and 200 °C, whereas at 220 °C, WL of TM wood remains constant with time (Figure 4a–c). As for TM wood exposed to *L. acuta* (Figure 4b–d), most WL occurs in weeks two and three for

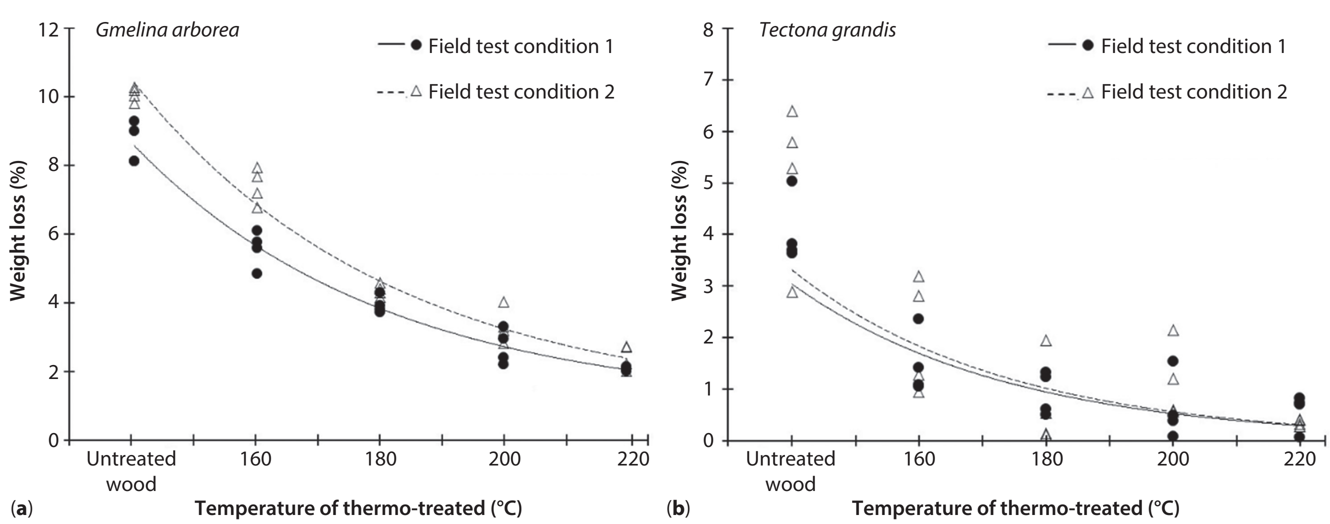

Figure 2 Weight loss percentage of TM wood stakes of *Gmelina arborea* (**a**) and *Tectona grandis* (**b**) exposed to the soil in two field tests weather conditions.

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Table 2 Comparison of module of elasticity and module of rupture of TM wood stakes of *Gmelina arborea* and *Tectona grandis* exposed 300 days to the soil in two field test weather conditions relative to untreated and unexposed stakes.

Field test weather condition	Treatment	TM wood of *Gmelina arborea*				TM wood of *Tectona grandis*			
		MOE unexposed (GPa)	MOE exposed (GPa)	MOR Unexposed (MPa)	MOR Exposed (MPa)	MOE Unexposed (GPa)	MOE Exposed (GPa)	MOR Unexposed (MPa)	MOR Exposed (MPa)
Field 1	Untreated	6.92^{A}	4.96^{B}	68.9^{A}	58.9^{B}	9.62^{A}	7.78^{B}	107.5^{A}	90.5^{B}
	160 °C	6.22^{A}	5.64^{B}	61.9^{A}	60.2^{B}	9.18^{A}	8.86^{B}	106.9^{A}	93.8^{B}
	180 °C	6.32^{A}	5.59^{A}	56.4^{A}	57.9^{A}	8.74^{A}	8.76^{A}	102.7^{A}	101.5^{A}
	200 °C	5.67^{A}	5.55^{A}	53.9^{A}	52.8^{A}	8.58^{A}	8.51^{A}	98.6^{A}	98.9^{A}
	220 °C	5.68^{A}	5.65^{A}	54.7^{A}	54.1^{A}	8.38^{A}	8.33^{A}	97.8^{A}	98.5^{A}
Field 2	Untreated	6.91^{A}	4.32^{B}	67.4^{A}	54.4^{B}	9.15^{A}	7.92^{B}	105.5^{A}	90.6^{B}
	160 °C	6.38^{A}	5.55^{B}	64.0^{A}	59.7^{B}	8.94^{A}	8.34^{B}	103.0^{A}	93.9^{B}
	180 °C	6.06^{A}	5.76^{A}	59.3^{A}	59.1^{A}	8.86^{A}	8.68^{A}	100.0^{A}	98.9^{A}
	200 °C	5.75^{A}	5.76^{A}	56.9^{A}	55.9^{A}	8.18^{A}	8.31^{A}	96.1^{A}	95.6^{A}
	220 °C	5.62^{A}	5.53^{A}	55.6^{A}	57.0^{A}	8.03^{A}	8.07^{A}	95.9^{A}	97.8^{A}

Note: Average values identified with different the letters are statistically different at $\alpha = 99\%$.

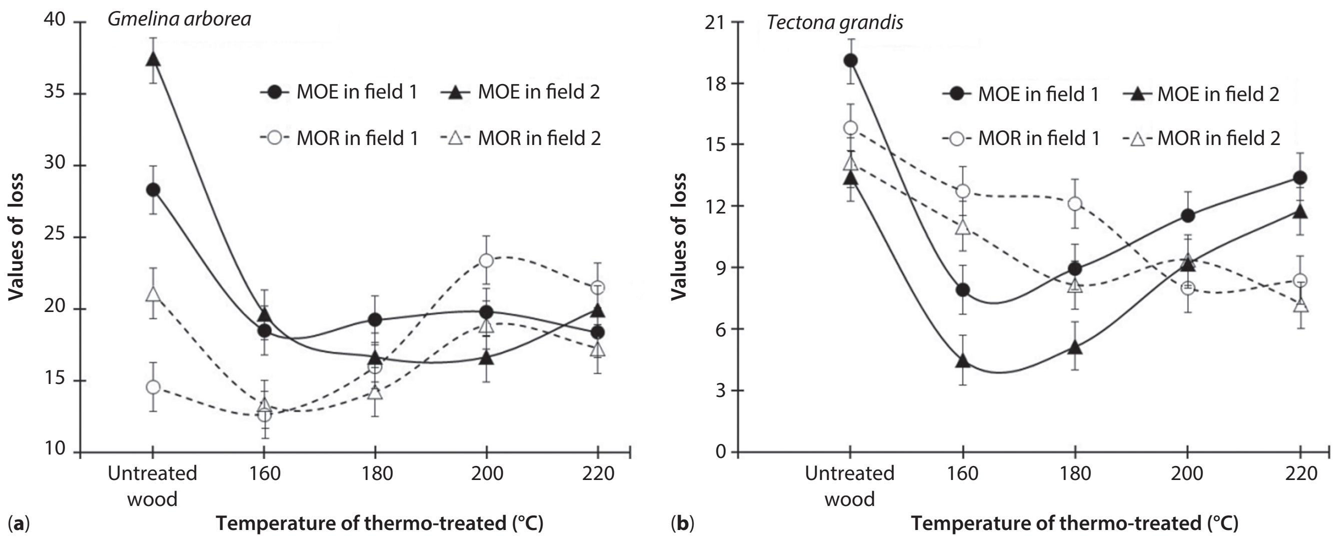

Figure 3 Loss of module of elasticity (**a**) and module of rupture (**b**) after 300 days exposed in soil for TM wood stakes of *Gmelina arborea* and *Tectona grandis* treated with different temperatures.

all treatments in two species; then, WL values remain constant for 21 and 28 days. Likewise, despite increasing their WL in the four evaluations, stakes thermo-treated at 220 °C present the lowest WL values.

The MOR variation showed the opposite effect, reducing its value with time of exposure to both *T. versicolor* and *L. acuta* in both species (Figure 5). As for the various temperatures, the TM wood samples at higher temperatures (200 and 220 °C) showed greater mechanical resistance to *T. versicolor* compared to untreated samples in both species. In addition, the lowest mechanical resistance was perceived in the thermo-untreated samples, where the decrease was high in relation to day of exposure (Figure 5a,c). Regarding *L. acuta*, the lowest values of MOR were observed at high temperatures (200 and 220 °C), while for the remaining temperatures few differences were observed between untreated and TM wood stakes (Figure 5b,d).

A different behavior was observed concerning the value of MOE, which was slightly affected by the time of exposure to the fungi, mainly in *T. grandis* (Figures 6a,b) and a higher change in *G. arborea* (Figures 6c,d). The lowest value of MOE regarding both types of fungi was observed in untreated stakes, whereas the highest values appeared for TM wood stakes at 200 and 220 °C. The samples thermo-treated at 160 and 180 °C present intermediate values between thermo-untreated stakes and TM wood stakes at 200 and 220 °C (Figure 6).

3.3 Decay Resistance in Accelerated Soil-Block Tests

According to the results obtained in the accelerated soil-block tests for *G. arborea*, the values of WL with *L. acuta* were lower than those obtained with *T. versicolor*. In addition, TM wood at 160 °C and 180 °C presented no significant differences relative to the control regarding *L. acuta* (Figure 7a). The WL values of TM wood at 200 and 220 °C were different among them, and statistically lower than in TM wood at 160 °C and 180 °C (Figure 7a). As for *G. arborea* TM wood colonized by *T. versicolor*, no differences were found in the WL between untreated wood and thermo-treated wood at 160 °C, nor were any differences observed between TM wood treated at 160 °C and 180 °C regarding WL, although differences did appear between untreated and TM wood treated at 180 °C. The lowest statistically compared WL in *T. versicolor* was for TM wood treated at 200 and 220 °C, showing no significant differences in wood at these two temperatures (Figure 7b).

The results from the accelerated soil-block test in *T. grandis* TM wood exposed to colonization by *L. acuta* and *T. versicolor* showed once again that most degradation occurred with *T. versicolor* (Figure 7c,d). The TM wood treated at 160 °C showed no significant differences in WL with both fungi compared to untreated wood (Figure 7c,d). Meanwhile, TM wood treated at 180 °C and 200 °C did not present significant differences in WL relative to *L. acuta*. The TM wood treated at 220 °C presented the lowest statistical value of WL (Figure 7c). On the other hand, TM wood treated at 180, 200 and 220 °C showed no significant differences in WL due to degradation by colonization of *T. versicolor* (Figure 7d).

4 DISCUSSION

The WL found for *G. arborea* and *T. grandis* subsequent to 300 days exposure to the field test varied within

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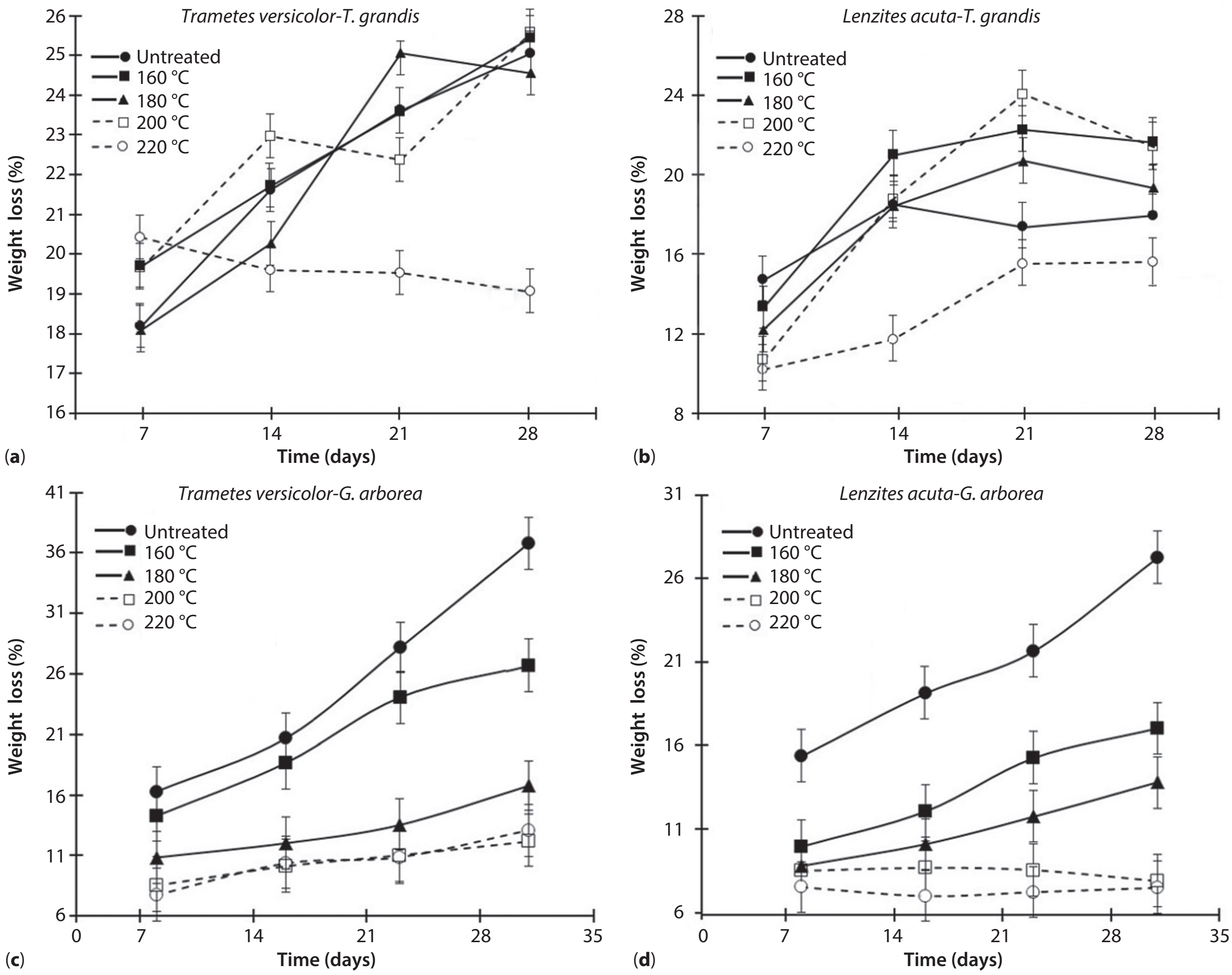

Figure 4 Variation of weight loss percentage of TM wood stakes of *T. grandis* (**a,b**) and *G. arborea* (**c,d**) exposed to accelerated test with *T. versicolor* and *L. acuta* during several days.

the range of 1.0 to 11.0% (Figure 2). For both species, WL of TM wood stakes at low temperature (160 °C) or stakes without thermo-treatment was higher compared to WL of TM wood stakes treated at higher temperatures. Differences were also observed between these two species concerning WL; thermo-treatment of *T. grandis* at higher temperatures increased its decay resistance against the deterioration agents in the field test compared to *G. arborea* treated under the same conditions (Figure 2).

The thermal modification of temperate species has been proven to enhance wood durability [7, 13]. The improvement of resistance to fungal attack is due to modifications of the chemical components (cellulose, lignin and hemicellulose) of the wood that reduce the vulnerability of the material to biological degradation [14]. In addition, degradation of these polymers by thermal modification also decreases water absorption, which limits shrinking and swelling, as well as absorption of water, which may also be conducive to diminished fungal growth [13].

There are some aspects that can explain the variations of decay resistance due to temperature. Firstly, water absorption creates conditions for the development of fungi, which in the end will affect the decay resistance. According to Boonstra *et al*. [15], with thermal treatment at low temperature, the low thermal and moisture conductivity of wood leads to high moisture variation close to the surface. As a result, conditions that favor fungi development appear [16], therefore the diminished durability of wood at low temperatures.

Another aspect that may explain the difference in durability of TM wood under multiple temperatures is the formation of several chemical components in the wood. High temperatures improve decay resistance,

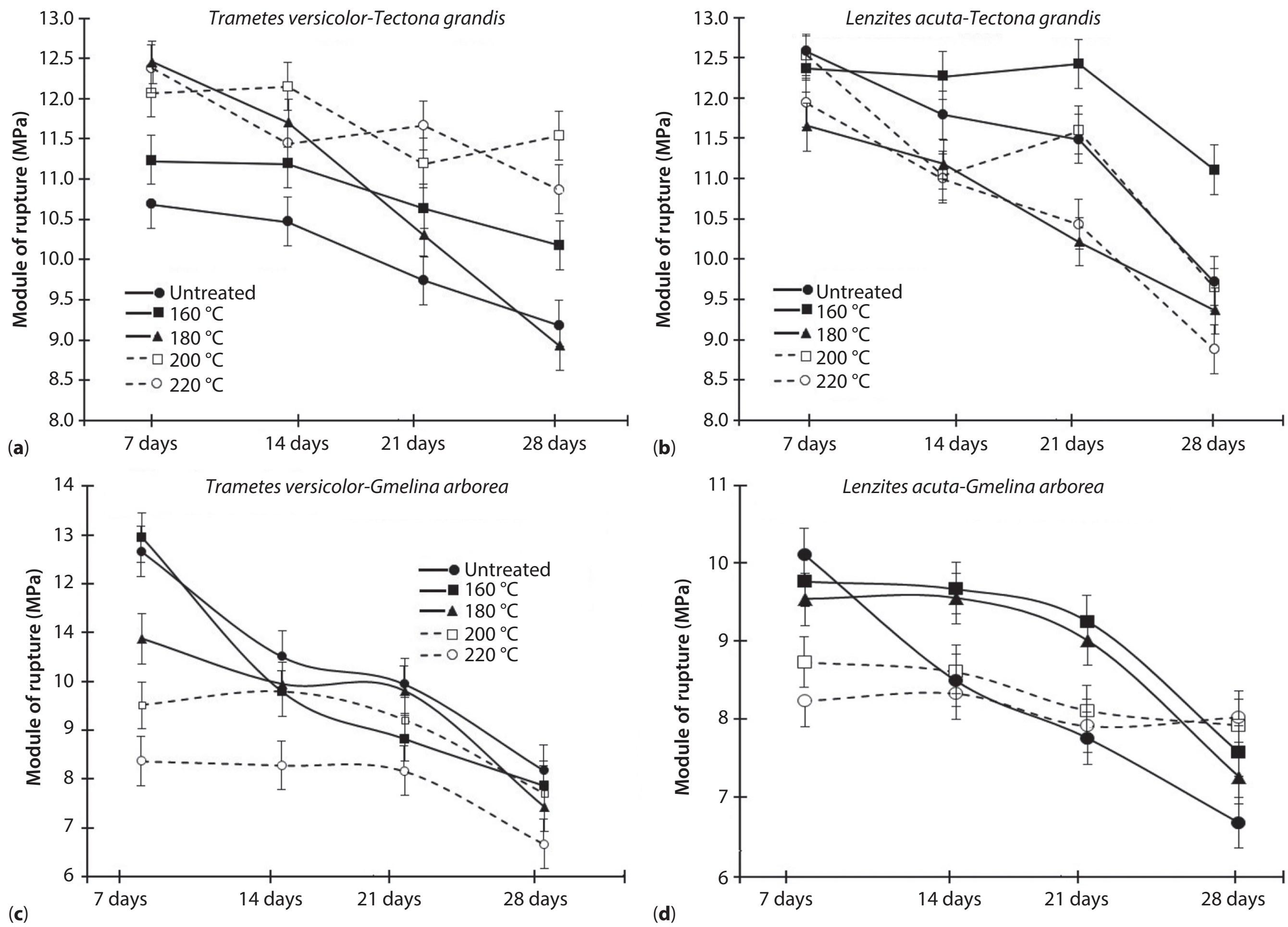

Figure 5 Variation of module of rupture of TM wood stakes of *Tectona grandis* (**a,b**) and *Gmelina arborea* (**c,d**) exposed to accelerated test with *T. versicolor* and *L. acuta* during several days.

as observed in this study (Figure 2) and in other studies on species from temperate climates [14]. Hakkou *et al*. [14], Trevisan *et al*. [17], and Del Menezzi *et al.* [18] stated that polymer degradation and chemical modification, well known to happen above 200 °C, are more plausible reasons to explain the durability improvement. Therefore, the adequate decay resistance obtained in both species in this study agrees with the findings of the above authors.

It was also observed that loss of decay resistance occurred in both thermo-untreated and TM wood. Both MOE and MOR of stakes thermo-treated at 160 °C and untreated exposed 300 days in the soil in two field test weather conditions (Table 2), and MOE and MOR of stakes of both species exposed to accelerated test with *T. versicolor* and *L. acuta* for several days (Figures 5 and 6), decreased with time. Loss of mechanical resistance in stakes is caused by the degradation of polymers, mainly cellulose and hemicellulose [19]. During wood decay, hemicellulose side chains such as arabinose and galactose are degraded first; afterwards, the main-chain hemicelluloses of mannose and xylose are mineralized [2]. Microscopic consequences of degradation of hemicellulose are produced by the development of cavities in the secondary walls of wood fibers, or the erosion of the wood cell wall outward from the cell lumen [19]. Consequently, decomposition of cellulose chains, the presence of cavities and the erosion in the cell wall produce structural weakening of the wood [20].

The WL with time (Figure 4), especially when the wood is exposed to accelerated testing with specific fungus, such as *T. versicolor* and *L. acuta* (Figure 4a and 4b), can be explained by the process of degradation of the wood. At the initial stages of exposure to the fungus, cavities appear on the cell wall [19] that produce early losses of resistance of low magnitude. These cavities enlarge as the process of degradation continues, allowing fungus hyphae to penetrate the cell wall until reaching the lumen and further extend the cavities [20]. The progressive increase of cell wall degradation caused by the hyphae produces this gradual

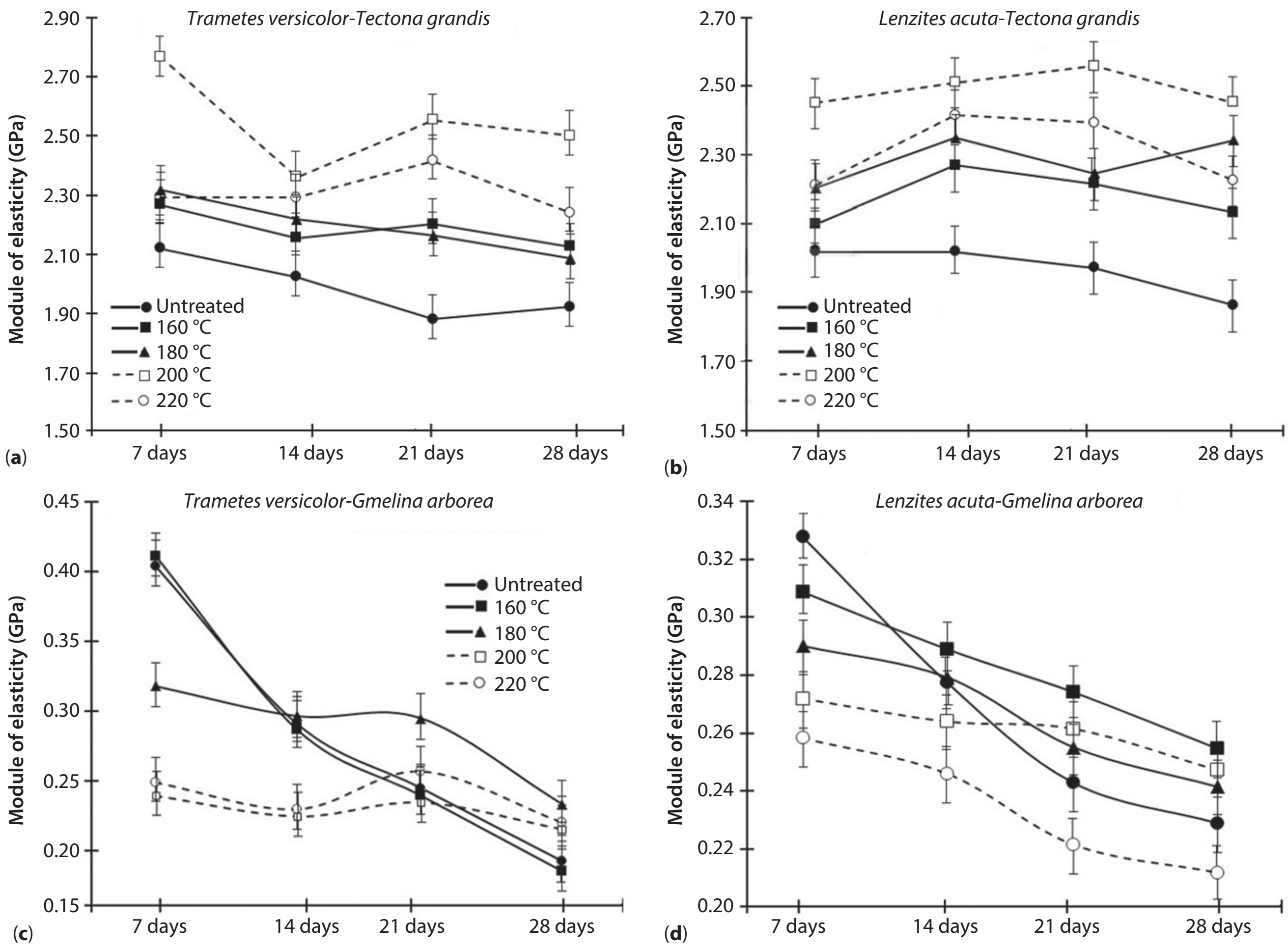

Figure 6 Variation of module of elasticity of TM wood stakes of *Tectona grandis* (**a,b**) and *Gmelina arborea* (**c,d**) exposed to accelerated test with *T. versicolor* and *L. acuta* during several days.

diminution of the mechanical resistance of the wood (Figures 5 and 6) due to weakened cell wall.

The TM wood showed loss of mechanical resistance after 300 days exposure to field test, compared to wood that is untreated and unexposed to field test. This should be taken with caution. First of all, it should be pointed out that thermo-treatment decreases the mechanical resistance of the wood, which was confirmed by the loss of mechanical resistance of the two species studied (Table 2); additionally, this loss is positively correlated to increasing thermo-treatment temperature [21]. This weakening is produced by the degradation of the polymers that compose the wood [3, 7, 22, 23]. Changes in the structure of the cell wall, such as the development of microcracks, also help weaken the mechanical resistance of the wood with thermo-treatment [24].

However, no statistical differences were observed in MOR and MOE of TM wood in the field test and stakes unexposed after 300 days of exposure (Table 2), mainly with respect to TM wood treated at temperatures above 180 °C in the two species evaluated (Figure 3). This indicates that loss of MOR and MOE in TM wood in relation to untreated wood and unexposed wood was due, not to biological degradation during soil exposure, but to natural loss of mechanical resistance caused by thermo-treatment. In both species evaluated, durability was achieved with TM wood at lower temperature (180 °C) and thermo-untreated wood. It was found that MOE and MOR of TM wood decreased after 300 days of exposure (Table 2; Figure 3). Low thermo-treatment temperatures, such as 160 °C, cannot completely modify the conditions of the cell wall nor the chemical components of the wood as to inhibit fungal attack [7, 21]; therefore, protection against biological degradation is not achieved as in wood treated at higher thermo-treatment temperatures.

One more important difference relative to loss of decay resistance of the two species evaluated in the test of TM wood exposed to accelerated test with specific fungi, such as *T. versicolor* and *L. acuta*, was that MOR presented greater loss (Figure 6a,b)

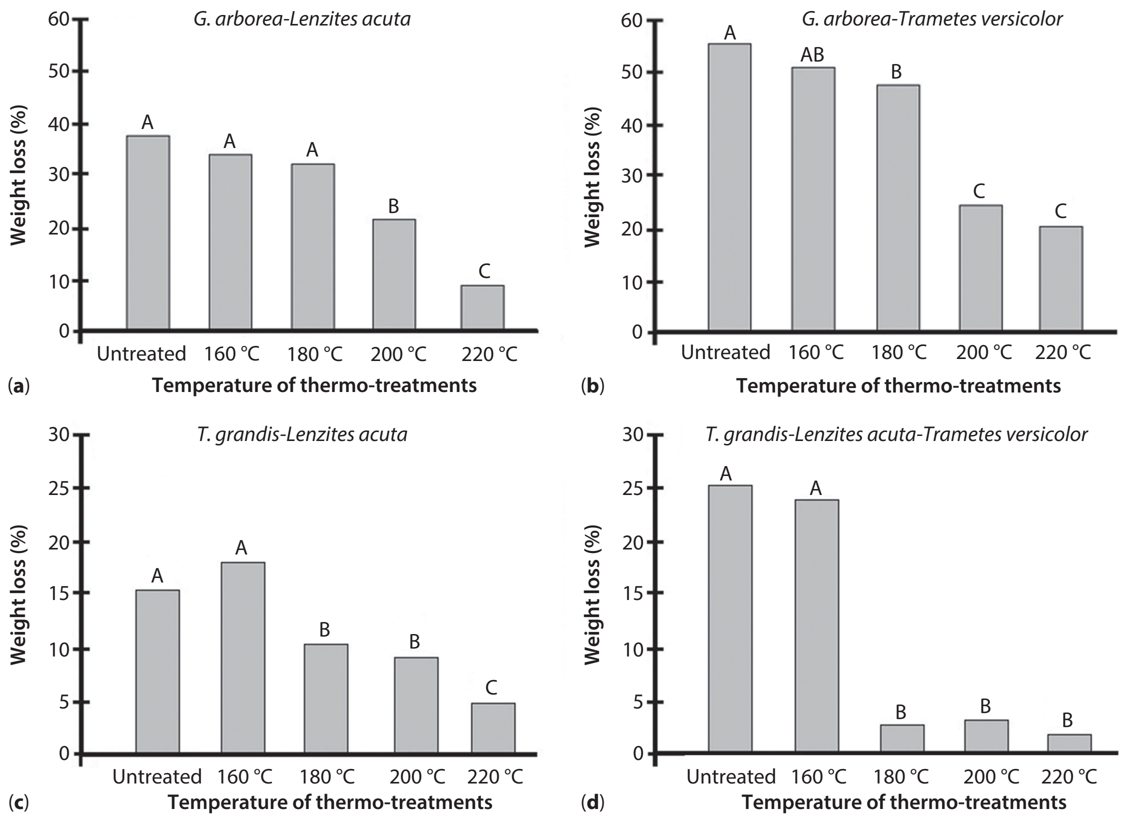

Figure 7 Weight loss percentage of TM wood of *Gmelina arborea* (**a,b**) and *Tectona grandis* (**c,d**) exposed to accelerated soil-block test with *T. versicolor* and *L. acuta*. Note: Average values identified with different letters are statistically different at $\alpha = 99\%$.

than MOE (Figure 6c,d; Figure 7c,d). According to Sandberg and Kutnar [1], the bending strength, which is a combination of tensile stress, compressive stress, and shear stress, is commonly used to compare mechanical properties of different processes. However, they mentioned that in general there is only a small change in MOE while a major decrease in MOR, independent of the process or the species. This same behavior was observed in the wood of *G. arborea* and *T. grandis*, also agreeing with tests carried out with Scots pine [25] and Norway spruce [26], which found that the MOR was more affected than the MOE.

Typical durability tests are accelerated tests under soil contact condition (Figure 7). According to the ASTM D2017 standard [12], the results of these tests can be classified into 4 different categories according to WL obtained after 16 weeks: highly resistant for WL under 10%; resistant for WL varying between 11% and 24%; moderately resistant if WL ranges from 25% and 44%; and slightly resistant to nonresistant if WL stands above 45% [12]. Consistent with the results obtained for WL, *G. arborea* TM wood presented higher values than TM wood of *T. grandis* (Figure 7a,b) and therefore *G. arborea* was generally classified as low durability. The TM wood of *G. arborea* treated at 160 °C and 180 °C and tested with two types of fungi was classified as moderately resistant, while *T. grandis* TM wood at the same temperatures and evaluated with the same types of fungi was classified as resistant. *G. arborea* TM wood treated at 200 and 220 °C was classified as resistant (WL between 11–24%), whereas TM wood of *T. grandis* at those same temperatures was classified as highly resistant (WL lower than 10%) with the two types of fungi.

An explanation of the improvement of resistance to fungi attack that results from the process of thermal modification of wood is that the formation of furfural might form toxic compounds and thermal treatment quickly degrades hemicelluloses [14, 17, 18].

The TM wood with the highest temperatures (200 and 220 °C) was classified as having the best durability compared to wood thermo-treated at lower temperature (Figure 7). Hermoso *et al*. [23] and Kocaefe *et al*. [21] explain that when higher temperature is applied during thermal treatment there is a reduction of hemicellulose content, humidity and other constituents, such as starch, fatty acids and lipids,

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which are essential for fungal growth. This chemical modification is explained by the fact that thermal treatments at above 200 °C modify the wood's structure, increasing its resistance to deterioration.

Lastly, TM wood showed greater WL with the white-rot *T. versicolor* than with the brown-rot *L. acuta* fungus (Figure 7), implying there was greater degradation of the structural polymers (lignin) of wood with the first fungus species. According to Kirk and Highley [27], this occurs because white-rot fungus has the capability to degrade wood cellulose and hemicellulose in greater proportion, after reducing lignin availability, while brown-rot fungus is more selective, degrading the cellulose of the cell wall only. The white- and brown-rot fungi removed the mannan, and usually xylan, faster than glucan, but the difference was not as pronounced for the white-rot as for the brown-rot organisms [27].

5 CONCLUSIONS

Thermal treatment in *G. arborea* and *T. grandis* wood from fast-growth plantations improves wood durability, noticeably increasing the decay resistance to accelerated tests with *T. versicolor* and *L. acuta* and in the field condition. However, the higher degradation occurred in *G. arborea* TM wood. The evaluation of the static flexural test showed that TM wood treated above 180 °C produced the lowest losses of MOE and MOR. But the accelerated tests showed more evidence of losses of flexural resistance than the field tests, the loss of resistance in the MOR being higher than in the MOE. According to results, the wood of *G. arborea* and *T. grandis* from fast-growth plantation thermo-treated at temperatures of 180, 200 and 220 °C, can be recommended. However, thermo-treatment at 160 °C in both species is not recommended.

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