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Impact of cyclic compressive loading and moisture content on the mechanical behavior of *Aucoumea Klaineana Pierre*

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Abstract: The mechanical behavior of *Aucoumea Klaineana Pierre* (*AKP*) under progressive static and cyclic compressive loading at various moisture content (MC) stages is investigated herein. This tropical species, also called Okume, originates from the Congo Basin, particularly Gabon. The experimental device used is composed of: an electronic testing machine, a system yielding the corresponding MC, and *AKP* wood samples. In all, 15 *AKP* samples were loaded in statics, at different MC levels, until the first cracks led to characterizing the mechanical behavior of the species in static compression along the longitudinal direction. Next, 7 samples of *AKP* were gradually loaded at distinct MC values, with 5 under cyclic longitudinal compression. Results show that under a static longitudinal compressive loading, the modulus of elasticity (MOE) of *AKP* decreases as sample MC increases. For the cyclic compressive loading after the first cycle, sample MOE increases with both the intensity and number of loading cycles as well as with the permanent deformation of each cycle. Moreover, it can be observed that within the plasticity domain, the impact of MC variation on the mechanical behavior of *AKP* is negligible.

Keywords: Tropical species, Congo Basin forest, Okume, experiment.

Nomenclature

<i>AKP</i>	<i>Aucoumea Klaineana Pierre</i>
δ	Specimen density
t	Specimen thickness
L	Specimen height
MC	Moisture Content
w	Specimen width
PD	Amplitude of permanent deformation
FSP	Fiber Saturation Point
MOE	Modulus of elasticity
l_i	Amplitude of cycle i
M	Specimen mass
M_H	Specimen mass at a specific MC
M_0	Specimen mass in the dry state

Introduction

In central Africa and particularly in the equatorial region, the forest plays a key role in regulating our environment by sequestering greenhouse gases (Odounga *et al.* 2016). In the year 2000, Gabon produced over 4 million m³ of timber (Medzegue *et al.* 2007), of which 72% was *Aucoumea Klaineana Pierre* (*AKP*). This species is mainly used for plywood construction, in veneer, and finished or semi-finished products such as pulp and paper (Manfoumbi Boussoungou *et al.* 2010, 2012, 2014). In addition, *AKP* is essential to the construction of timber structures including bridges, especially in this country's most remote places (Ikogou *et al.* 2016). However, with over 1,900 mm of annual precipitation, around 85% relative humidity and a mean temperature near 27°C, the environmental conditions in Gabon are very arduous. Consequently, the mechanical behavior of *AKP* largely depends on temperature and moisture changes (Ndong Meye *et al.* 2015; Pambou Nziengui *et al.* 2016). Studying this tropical wood under cyclic loading is thus crucial to learning about the durability of timber structures designed using this species.

The background literature suggests that the mechanical behavior of *Aucoumea Klaineana Pierre* has not been sufficiently studied (Pambou Nziengui *et al.* 2015, Odounga *et al.* 2016). Some authors however have investigated its behavior in various fields of the wood sciences. For instance, Safou Tchiana *et al.* (2007) explained the physicochemical characteristics of *AKP* in the goal of initiating a wood industrial waste recovery process in Gabon, by means of formulating wood based-composites. In the same manner, Medzegue *et al.* (2007) revealed the influence of humidity and soil type in the physical and mechanical properties of *AKP*. These examples show that over a specific period, the focus was aimed at a simple characterization of this species (Brancheriau *et al.* 2002). Recent investigations of *AKP* mechanical behavior under different loadings (Brancheriau *et al.* 2010) and natural drying processes (Ikogou *et al.* 2016) have been pursued without considering the combined impact of environmental conditions and loading effects. Moreover, Odounga *et al.* (2016) examined the fracture toughness of *AKP* at room temperature only under a tensile loading, with results being compared to other tropical species. Such a detailed evaluation can be justified by the fact that this species is the most widely harvested and used in Gabon (Safou Tchiana *et al.* 2007, Medzegue *et al.* 2007) as well as around the world. It appears essential to determine the impact of humidity variation on the *AKP* mechanical behavior in order to predict the behavior of *AKP* wood-based structures, yet the mechanical behavior of *AKP* under cyclic compressive loading has not been sufficiently studied (Pambou Nziengui *et al.* 2015).

The objective of this work is to identify the correlation, or experimental impact, of both moisture content (MC) coupled with cyclic loading and loading intensity on the mechanical behavior of *AKP* subjected to longitudinal compression.

Materials and methods

Materials

The material used in this work is *Aucoumea Klaineana* Pierre (*AKP*), which is a tropical wood species that grows extensively in central Africa (Fig. 1a); it is considered an endemic species of the Gabon forest yet can also be found in Cameroon, Congo and Equatorial Guinea. *AKP* is harvested when its diameter at breast height exceeds 0.7 m, as observed in Figure 1b (Medzegue *et al.* 2007). *AKP* specimens from the Congo Basin rain forest (Gabon) were used for our experiments; these woods were delivered to the laboratory by our partners after first being sized to sawn timber (Fig. 1c). The choice of specimens studied herein was made randomly.

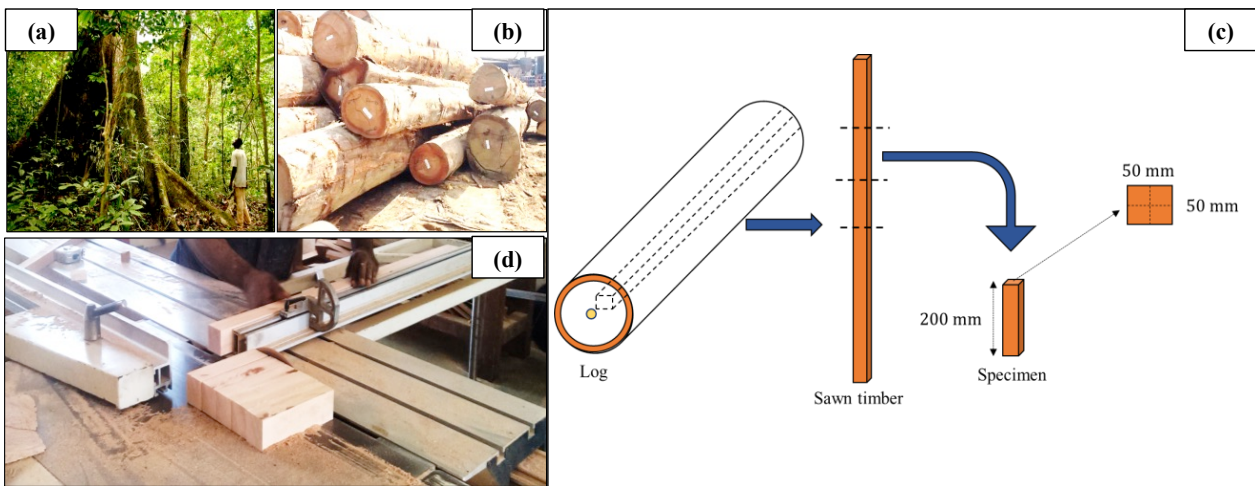


Figure 1: a) hillsides of *AKP* in a Gabon forest; b) view of stored *AKP* woods on the premises of Gabon's Société Equatoriale de Déroulage (S.E.D.); c) specimen preparation procedure; d) sizing of sawn timber into specimens

Methods

Six clear specimens of these *AKP* timbers sawn along the fiber axis were dimensioned according to Standard ASTM-D-143 (ASTM-D-143, 2014) (Fig. 1d). Figure 1c also shows the technique employed to cut the various samples. The geometric shape and dimensions of the specimens can be visualized. Twenty-two specimens, dimensioned according to the American Standard ASTM-D-143 and conditioned at different MC levels, were tested; Table 1 lists the set of sample characteristics. The choice of samples tested herein was made so as to avoid those specimens with initial flaws like cracks and knots.

As observed in Table 1, 22 samples dimensioned at $50 \times 50 \times 200 \text{ mm}^3$ for the compression tests, as shown in Figure 1c, were selected. As a next step, the samples were moistened with liquid water in order to obtain the corresponding MC, according to Equation 1.

Table 1. Characterization of the *AKP* specimens studied

Sample No	l(mm)	t (mm)	L (mm)	MC (%)	M (g)	δ (g/cm ³)	Type of load
1	49.0	51.0	210.0	52.6	186.0	0.354	Static load
2	51.0	50.0	210.0	31.4	179.0	0.334	Static load
3	50.0	51.0	200.0	25.2	201.0	0.394	Static load
4	49.0	51.0	205.0	30.7	197.0	0.384	Cyclic load
5	50.5	51.0	210.0	20.5	240.0	0.443	Static load
7	50.5	51.0	210.0	39.0	188.0	0.347	Static load
9	50.5	51.5	205.0	26.2	211.0	0.395	Cyclic load
10	50.5	51.0	210.0	20.1	211.0	0.390	Cyclic load
11	50.0	50.5	205.0	40.9	179.0	0.345	Cyclic load
12	50.5	50.5	200.0	27.7	184.0	0.360	Static load
13	51.5	51.5	205.0	36.0	192.0	0.353	Cyclic load
14	51.0	50.5	210.0	37.3	182.0	0.336	Static load
15	51.0	50.0	205.0	52.2	194.0	0.371	Static load
16	51.0	50.0	201.0	82.3	246.0	0.479	Static load
18	51.0	51.5	205.0	27.0	183.0	0.339	Static load
21	50.5	51.5	205.0	24.0	184.0	0.345	Static load
22	50.0	50.0	210.0	40.5	203.0	0.386	Static load
24	51.0	52.0	210.0	18.0	291.0	0.522	Static load
25	50.0	51.0	205.0	23.5	202.0	0.386	Static load
26	52.0	50.5	200.0	28.1	185.0	0.352	Static load
27	51.0	50.5	200.0	17.2	244.0	0.473	Cyclic load
28	50.0	50.0	201.0	24.0	207.0	0.412	Cyclic load

$$MC (\%) = \frac{M_H - M_0}{M_0} \quad (1)$$

Two loading methods were introduced. The first entails the static compressive loading, with 15 samples being loaded (Fig. 2) onto a 100 kN-capacity electromechanical press until rupture. For this experimental campaign, the objective is to ascertain the mechanical characteristics of *AKP* samples under a static compressive loading (Table 3). Results obtained for the static loading were statically analyzed using the R.3.4.0. software package. The second campaign pertains to the cyclic compressive loading and was performed on 7 samples. These specimens were each gradually loaded 5 times in the elastic zone. In considering the fact that each sample held a specific MC, the first loading level was set at 30% of the maximum breaking strength of the driest specimen tested under the static compressive loading. Then, a 5,000-N increment was added at each subsequent loading level (Table 2). Each cycle combined a loading path and an unloading path (Figures 3 and 4). The transition time between the end of the unloading path of the previous cycle and the beginning of the loading path of the subsequent cycle was 2 minutes.

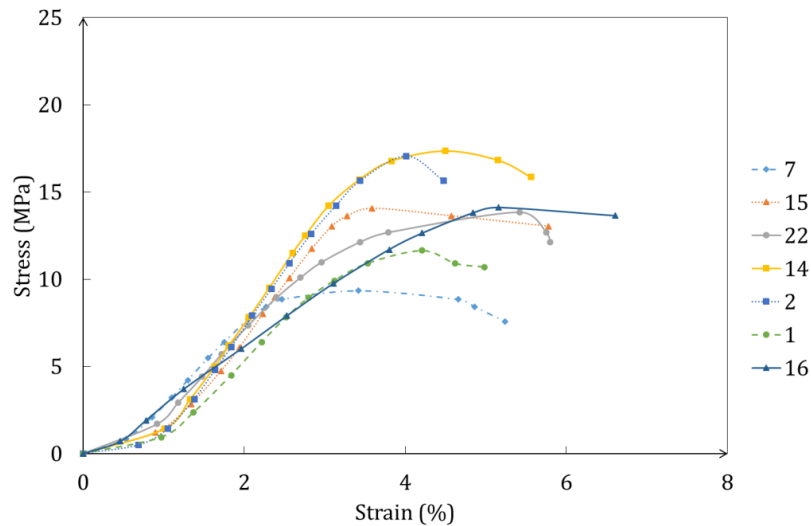
Table 2. Level of each selected loading cycle

Cycle no.	Load level (kN)
1	15.0
2	20.0
3	25.0
4	30.0
5	35.0

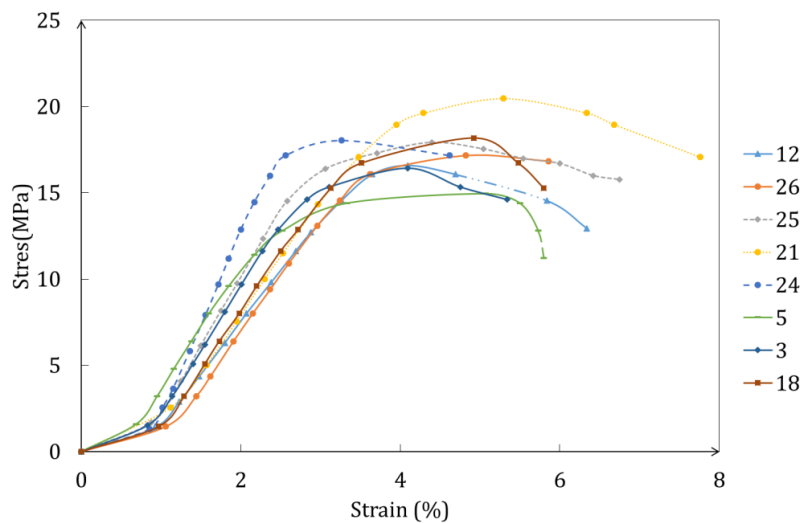
Results and discussion

Static compression

Figure 2 shows the evolution in the relationships between stress and strain of the specimens tested under a static compressive loading. The curves of these results have been divided into two groups: Figure 2a samples with an MC of above 30%, and Figure 2b specimens with an MC of below 30%.



a)



b)

Figure 2. Stress-strain relationships of samples with: a) MC > 30%, and b) MC < 30%

On each curve (Fig. 2) for the static loading, three different parts can be distinguished, namely: a linear part representing the reversible area where the modulus of elasticity (MOE) of AKP (see Table 3) is defined; a plastic area coinciding with the irreversible area; and a last part representing the specimen rupture area. According to these curves, the MOE and maximum stress (MS) of each *AKP* specimen tested at a different MC level have been calculated and presented in Table 3. The specimens from each of these two families of curves (i.e. with MC < 30% and with MC > 30%) follow practically

the same evolution. The choice of a 30% limit was made in accordance with the literature, as the fiber saturation point (FSP) value of *AKP* equals 30% (Medzegue 2007, Ndong Meye *et al.* 2015).

Table 3. Mechanical parameters of the specimens in static loading

	Specimen no.	MOE (kPa)	MS (MPa)
Specimens with MC < 30%	3	7.11	16.43
	5	9.60	14.95
	12	5.98	16.58
	18	7.03	18.18
	21	6.53	20.47
	24	10.66	18.03
	25	8.45	17.92
	26	6.88	17.16
Specimens with MC > 30%	1	4.70	11.64
	2	6.48	17.06
	7	5.00	9.34
	14	6.66	17.35
	15	6.34	14.06
	16	4.00	14.11
	22	5.81	13.84

Cyclic compressive loading

Figure 3 shows a representation of the typical curve of one cycle (both loading and unloading paths) obtained during the cyclic tests. The parameter ($l_i = PD$) denotes the residual amplitude of plastic strain; it is used to characterize and understand the mechanical behavior of the specimen for the duration of the cyclic compressive loading. This l_i parameter, as depicted in Figure 3, is equivalent to plastic strain.

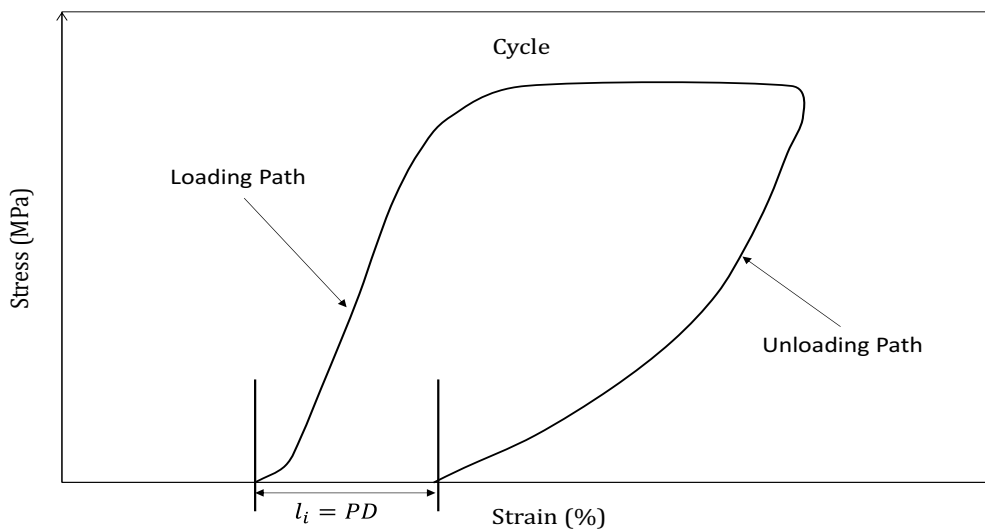


Figure 3. Diagram of a cycle and the various parameters studied in this work

Figure 4 displays the cyclic stress-strain relationships of *AKP* specimens with an MC of below 30% tested during the cyclic compressive loading, which is composed of loading, unloading and reloading

paths. This figure indicates nearly the same evolution in test specimen stress-strain curves. Each specimen curve may be divided into two parts in order to better understand the response of the specimen under the corresponding loading, i.e. an initial part with cycles exhibiting practically the same amplitude (permanent displacement, PD). This observation pertains to the first 3 loading cycles (Table 4). A second part, after the third cycle, contains an amplitude rise (Table 4), which could be explained by the fact that the linear limit (yield point) of the cyclic compressive test was exceeded. The first conclusion drawn is that a yield point exists during a cyclic longitudinal compressive test and after this point, the PD amplitude of each cycle increases with stress intensity.

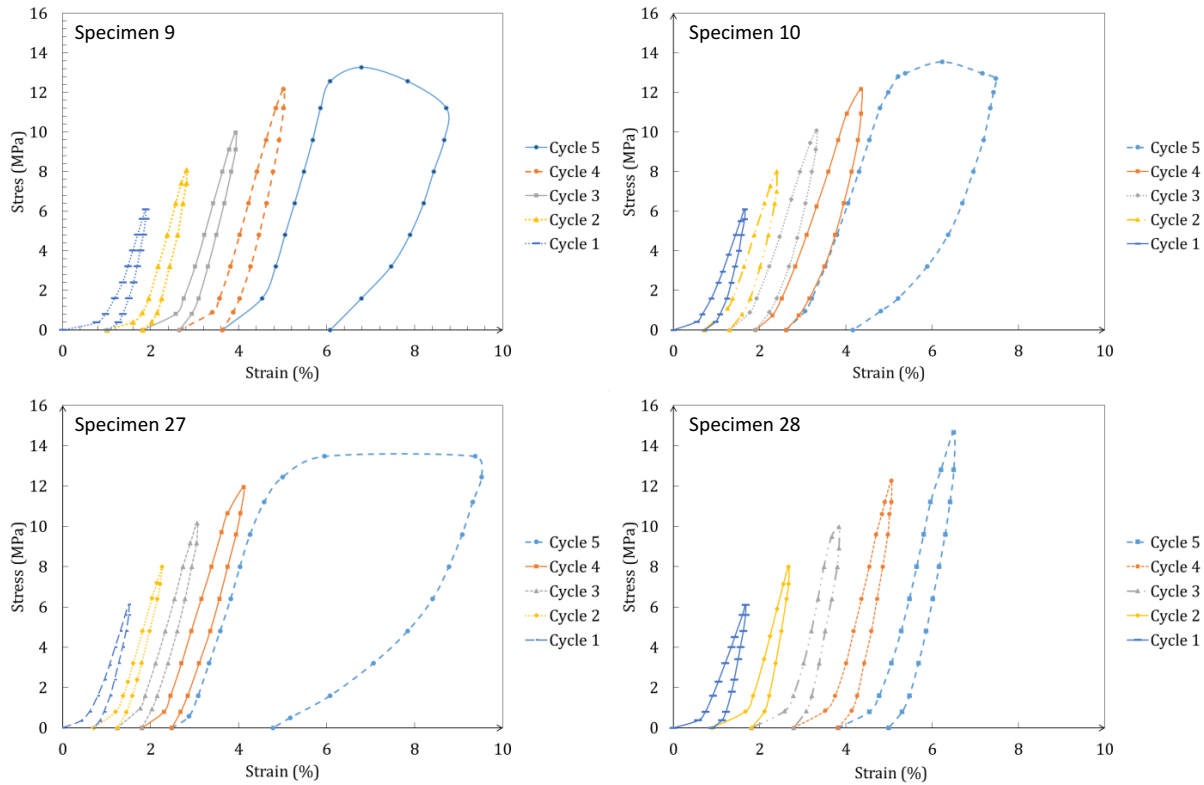


Figure 4 . Cyclic stress-strain evolution curves for specimens with an MC below 30%

Figure 5 shows the cyclic stress-strain evolution curves for specimens with an MC above 30%. Despite the fact that the MC of specimens in this group exceeds FSP, the result is practically the same in both groups (specimens with MC values of below 30% and above 30%). Based on the evolution of each curve, it can be concluded that the fact each specimen's MC value lies above or below the FSP value has no real impact on the *AKP* behavior in a cyclic longitudinal compressive test.

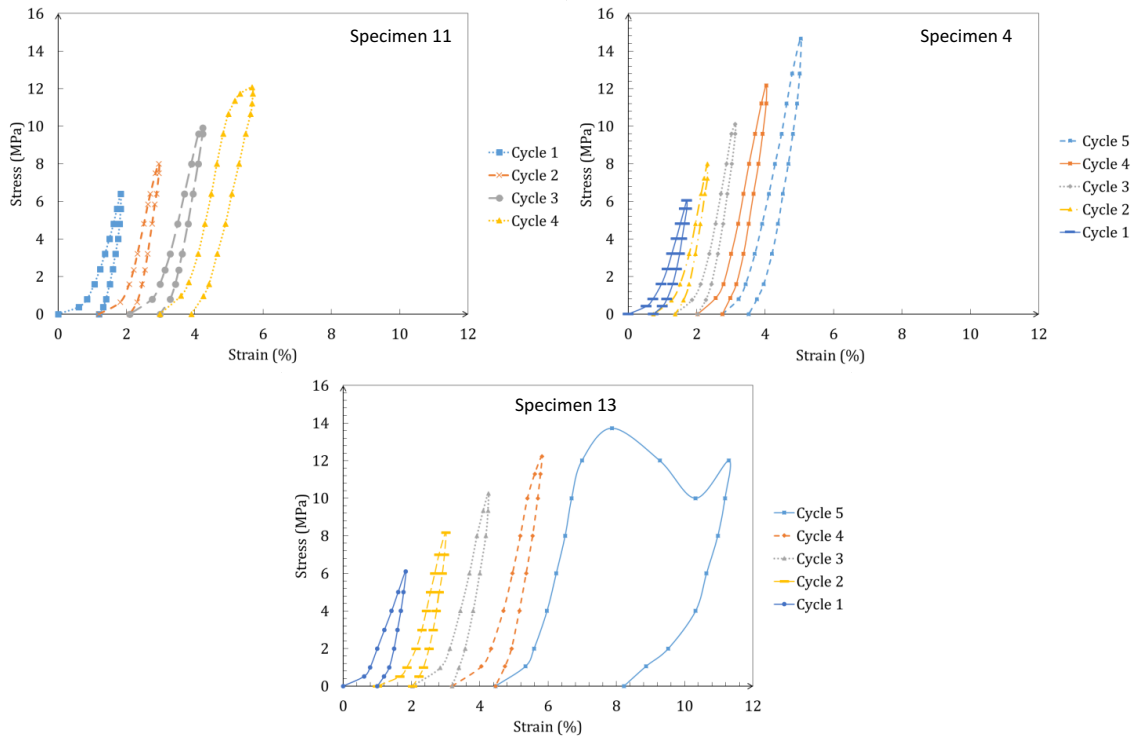


Figure 5. Cyclic stress-strain evolution curves for specimens with an MC above 30%

Comparison and statistical analysis between the PD amplitudes

Table 4 shows the comparisons and results derived between the PD amplitudes of each cycle for each specimen. The previous tests conducted on the permanent displacement amplitudes of each cycle (Table 4) indicate that for 71% of all specimens studied, a significant difference exists between the amplitudes after a number of cycles. For all 7 *AKP* specimens loaded, the PD amplitude in 57% of the samples changes after the third cycle, and 14% after the fourth cycle. According to Ikogou *et al.* (2016), on the basis of these aforementioned tests, a cyclic compressive limit for *AKP* is generated experimentally.

Table 4. Comparisons between the PD amplitudes of each loading cycle

	Specimen no.	L_1/L_2	L_2/L_3	L_3/L_4	L_4/L_5
Specimens with MC > 30%	4	0.84	0.82	0.79	0.74
	11	0.76	0.86	0.38	-
	13	0.78	0.93	0.76	0.09
Specimens with MC < 30%	9	1.00	0.84	0.62	0.14
	10	0.79	0.87	0.66	0.22
	27	0.85	0.72	0.65	0.09
	28	0.84	0.96	0.80	0.70
	Mean	0.84	0.86	0.66	0.33
	SD	0.05	0.05	0.10	0.26

In Table 4, L_i represents the permanent displacement amplitude of each cycle i . According to Table 4 and the comparisons drawn between amplitudes (L_i/L_{i+1}), no significant differences exist between amplitudes L_1, L_2 and L_3 ($SD = 0.5$), yet a difference does appear after the third cycle (L_3/L_4 ; $SD = 0.10$).

SD: Standard deviation

Influence of MC and number of cycles on the AKP behavior

Figure 6 shows the relationship between MOE and MC of *AKP* for a static compressive loading. The MOE decreases as MC rises. For specimens with an MC < 30%, little dispersion is found between their MOE values, but beyond an MC > 30% their MOE values become more widely dispersed.

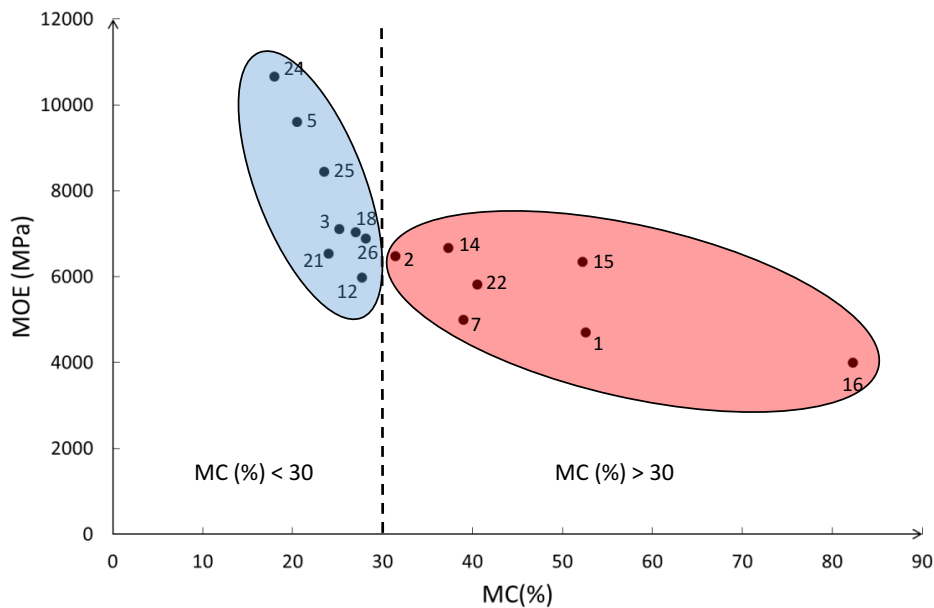


Figure 6. Evolution of MOE vs. MC of *AKP* specimens tested under static loading

To justify these results, static analyses have been performed on these two groups (specimens with MC < 30% and with MC > 30%). Figure 7 shows the linear regression plots of both groups. For the first one (MC < 30%), the correlation test analysis clearly demonstrates a strong correlation ($p < 0.001$; $r = -0.917$) between the MOE and MC of the specimens. To the same extent, the simple static linear regression test also indicates a strong relationship ($R^2 = 0.841$) between MOE and MC for this group. For the second group (MC > 30%), the correlation test shows a low correlation ($p < 0.055$; $r = 0.749$) between specimen MOE and MC, yet with a relationship between MOE and MC not clearly established. The simple linear regression test for this group (MC > 30%) corroborates this limited impact ($R^2 = 0.474$) of MC on MOE. This impact can be explained by the fact that an MC = 30% lies above the FSP of *AKP*. This statement is justified by the dispersion of MOE values around the FSP of *AKP* ($26\% < FSP < 30\%$). On the basis of this result, an impact is generated on the MC variation in the *AKP* behavior, but this behavioral impact differs from FSP, either below or above.

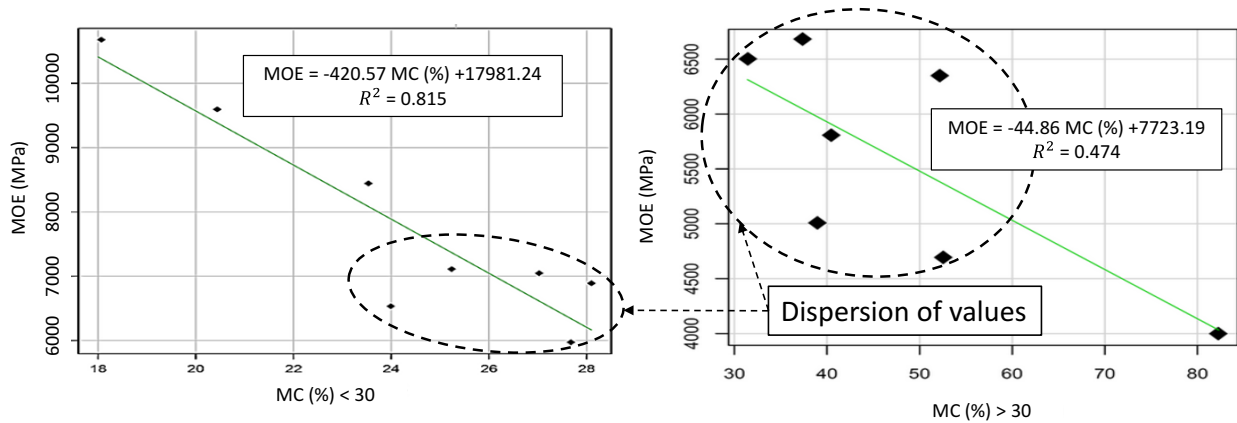


Figure 7. Linear regression plot between the MOE obtained on each specimen loaded in statics and its MC

Figures 8 and 9 also present the impact of MC on *AKP* specimen behavior. During the first loading cycle (Fig. 8), we note a decrease in MOE as MC increases. This state is in agreement with the relationship obtained in Figure 6 for static loading, but after the first cycle, MOE increases (Fig. 8) despite the fact that MC is increasing. This state has been explained by Sandberg *et al.* (2013), and also observed by others authors (Kutnar *et al.* 2015), who showed that compressing wood in the transverse direction reduces the void volume of lumens in the wood material and increases wood density. Density however is correlated with MOE (Dwianto *et al.* 1998, Wei Xu 2007); a wood density increase is of benefit to the wood MOE. This conclusion can be also observed for the *AKP* specimens tested herein. The fact that MC is increasing exerts no real influence on the cyclic compression behavior of *AKP*, according to Figure 8, yet this offers a critical view of the variation in MOE vs. number of cycles (Fig. 10). Let's remark that the *AKP* aging rate in cyclic compression depends on the MC history of the specimen.

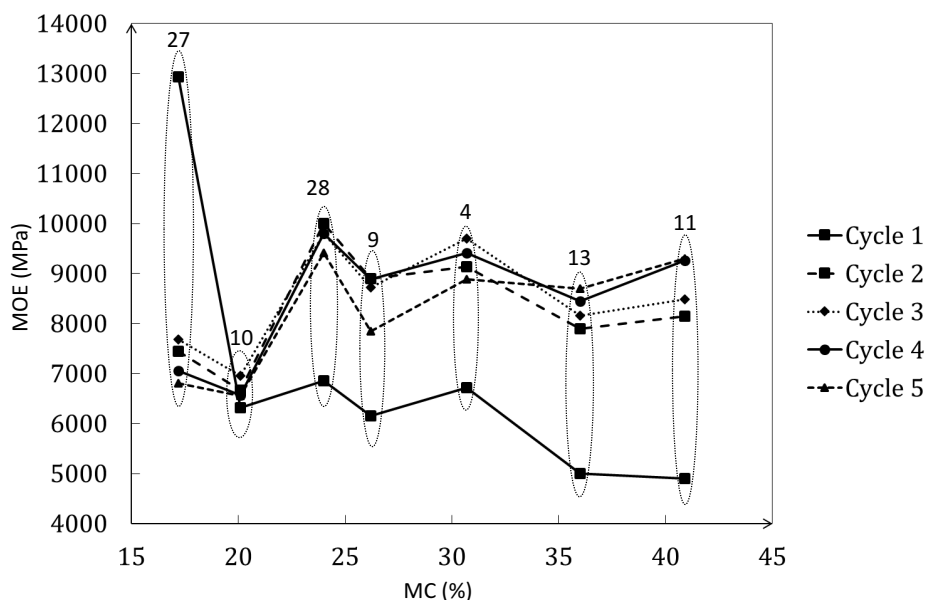


Figure 8. Evolution of MOE vs. MC at different cycles for each *AKP* specimen under study

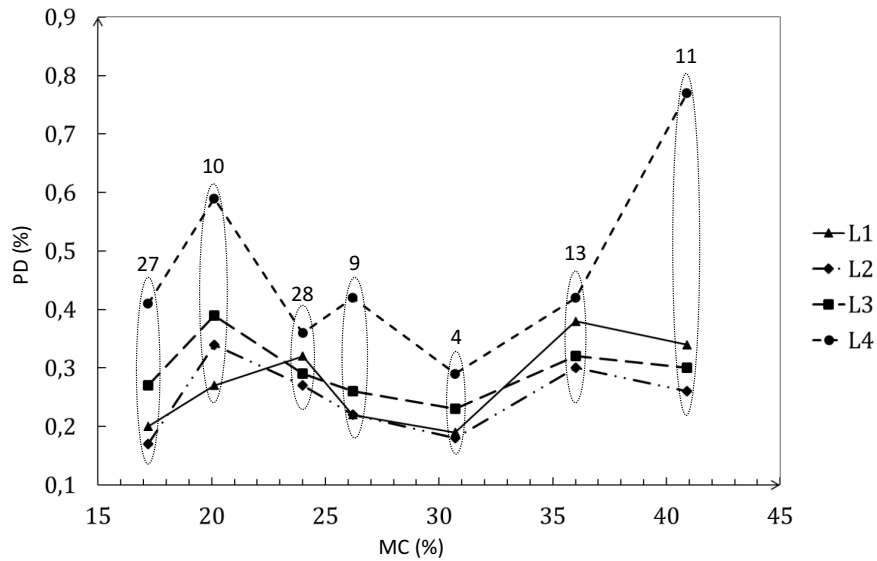


Figure 9. PD evolution with MC variations and number of cycles

The stiffness of *AKP* decreases with a rise in MC (Fig. 10) under cyclic compressive loading. This rate of decrease is fast for the specimen, which has an MC < 30%, and slow for the specimens with an MC > 30%. This phenomenon is called plasticization and can be explained by the fact that when wood absorbs water, it becomes more flexible. Figures 9 and 10 show the impact of the evolution in number of cycles (or the impact of intensity). According to these figures, the PD amplitude increases with stress intensity (Fig. 9). The first three cycles overlap; this state confirms the hypothesis given in Figures 8 and 9 and Table 4, i.e. an elasticity limit exists for a cyclic loading. According to Figure 9, let's also observe a linear correspondence between the stress history and the strain history for a progressive cyclic response. In this case, a progressive cyclic load is applied on the specimens in order to produce a material response up until failure.

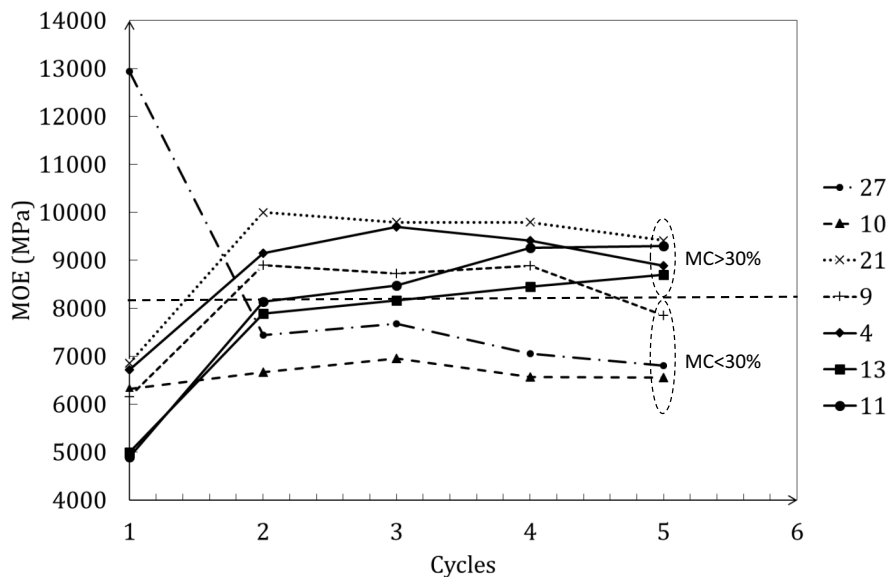


Figure 10. Evolution of MOE vs. number of cycles in each specimen

On the basis of these results, we can state the hypothesis that for a progressive cyclic compressive loading before failure, two areas are found: an elastic one of the cyclic compressive loading of *AKP*, and a plastic one of the cyclic compressive loading. The elastic area of *AKP* in cyclic compressive loading is considered herein as the part where the mechanical properties of *AKP* have not considerably changed, but the plastic area is the part where its mechanical properties have changed to a noticeable extent. As noted regarding this research work, a boundary is present between these two parts, and this boundary can be considered as the yield point of *AKP* in cyclic compressive loading.

Conclusion

The purpose of this work has been to study the impact of moisture content (MC), coupled with static and cyclic compressive loadings on the mechanical behavior of *Aucoumea Klaineana Pierre (AKP)*. Results show that as with major wood species, As MC increases, it decreases the *AKP* strength. This result is valid for both types of compressive loading (i.e. static and cyclic) and for each specimen. In addition, the number of loading cycles exerts an impact on the mechanical behavior of *AKP*; this impact is perceptible beyond a cyclic limit that could be defined as a cycle yield point of *AKP* under a cyclic compressive loading. These main results also reveal that coupling the number of loading cycles with the variation in *AKP* moisture content amplifies the loss of *AKP* mechanical performance under loading. This work was specifically focused on an experimental study of the effects of MC variation combined with progressive cyclic compressive loading. In the upcoming work, it will be necessary to develop a predictive experimental mechano-sorptive behavioral model of *AKP* load-unload-reload under a cyclic compressive loading. Moreover, the analytical and numerical cyclic models that take viscoelastic aspects into account will be proposed in order to simulate the behavior of tropical species under complex loading processes.

Acknowledgments

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