



Mechanical properties of Glued-laminated timber made up of mixed tropical wood species

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Comparative studies of three tropical wood species under compressive cyclic loading and moisture content changes

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Abstract: This paper deals with the experimental study devoted to cyclic compressive loading of three tropical species (*Aucoumea Klaineana* Pierre AKP, *Milicia Excelsa* ME and *Pterocarpus Soyauxii* PS) at different moisture content levels. According to the French requirement NF EN 408, 90 samples taken from these three species were dimensioned. The experimental campaign is compounded of static tests concerning 15 samples and cyclic tests performed on 75 samples. First, the samples are loaded into the static compressive test until their collapse, in order to obtain the mechanical characteristics of each species in terms of: (i) the modulus of elasticity, (ii) the maximal strength and (iii) the stress at the yield point. Then, each sample is loaded five times in cyclic compressive loading, following the paths of loading-unloading-reloading, at different moisture contents levels. The maximal load applied for each cycle corresponds to 10% of the collapse load of the AKP species. The results show a stiffening of the samples with the loading cycles. The stiffening is faster from the densest species to the least dense species, respectively. In addition, the phenomenon of densification, that occurs during the five loading cycles, is done with constancy of compressive strength in the three species.

Keywords: Tropical species; Effect of moisture content; cyclic compressive loading; compressive static tests.

Introduction

These last years, there are had a growing interest in the use of wood in the timber structures industry (Natterer 2004, Stevens 1990), this observation is valid for all the regions around the world (Kitek Kuzman and Sandberg 2018). In Gabon for example, this involved the valorisation and the harvesting of new types of wood species by reducing the pressure put into *Aucoumea Klaineana* Pierre (AKP). In fact, AKP appears today, with over 90% of the annual national production, as the most specie harvested and the most exploited. Indeed, in this country, during the 20th century, the production of AKP continued to increase with the continuous improvement of the wood machinery (pulling machine, dryer,...) and the increased harvesting surface areas (Medzegue et al. 2007, Peyrot 2008). In terms of volume in 2018, log production increased by 6% to more than 1.27 million m³, compared with 1.2 million m³ in September 2017. However, from the 1960s, we saw harvesting of new types of species called diverse woods. Among these species we have: *Milicia Excelsa* ME (so called Iroko) and *Pterocarpus Soyauxii* PS (Peyrot 2008, Mertens et al. 2007). The literature (Pambou Nziengui et al. 2017, Odounga et al. 2018) shows that these kind of species at 12% of the moisture content, for example, offer the better physical and mechanical properties as the AKP. So, for a better understand of their mechanical behaviour and their use in construction it is necessary to study them under complex mechanical loading and conditions. It is known that wood is a material whose mechanical properties (elastic, viscous, failure,...) are related to the conditions of environmental parameters such as the relative humidity and temperature (Eurocode 1 2005, Moutee 2006, Gerhards 1982, Ebrahimzadeh and Kubat 1993). This dependency is often linked with the variations of its moisture content and the intensity of the load applied (Mårtensson and Thelandersson 1990, Lenth and Kamke 2001, Moutee et al. 2005, Mukudai and Yata 1986, Navi and Girardet 2000). In the same case, the works of Gerhards (1982) show that many of the mechanical properties of wood reduce when its moisture content goes from 12% to 20%, below the fibre saturation point (FSP). These results have been also related by Guitard et al. (1987), through its analytical model to predict the module of elasticity for example which taking into account the variations of moisture content and the density of the sample studied. In addition, the interaction of moisture changes with mechanical loads can lead to excessive strains in wood structures (Redman et al. 2016, Manfoumbi Boussougou et al. 2014). Both precedent examples describe sufficiently the influence of moisture on the mechanical behaviour of wood material in structures.

The literature review shows also that the stresses on wood materials and timber structures are mainly due to the combined actions of mechanical and environmental effects (Eurocode 1 2005, Moutee 2006, Eurocode 5 2005). In fact, there are very specific processes used to describe the laws of mechanical behaviour of wood in interaction with environmental factors. Among these processes, we have different tests such as creep, bending, tensile, compression, torsion and shear tests. The aim of the use of these processes is to highlight the stress-strain relationships of the material tested. To these tests, we can add the cyclic tests, characterized by a mode of fatigue breakage which is just as important but rarely studied, especially on wood material (Pambou Nziengui et al. 2017, Nafa and Araar 2003), and even less so on tropical species. Also, Pambou and al. (2017) highlighted the study on the mechanical behaviour of AKP under cyclic compressive loading. This work has shown that the damage of AKP is most faster in cyclic compressive loading than in static compressive loading. On the another way, he has showed that the coupling of the number of loading cycles with the moisture content variations of the samples used, amplifies the latter's loss of mechanical performance under a variable load. The consideration of the gradual intensities on each loading cycle, made difficult the decoupling of the loading effects or the number of cycles on the behaviour of the studied samples. Nafa et al. (2003), on their side, worked on the damage to laminated timber beams submitted to cyclic torsional loading and showed also the effect of the load level on the behaviour and the durability of such structures. However, these papers related are not exhaustive to relate the mechanical behaviour of wood material under cyclic compressive loading but provide interesting information for understanding the impact of cyclic test in the wood behaviour in general.

In addition, the coupling impact of cyclic loading and the variation of internal moisture content is not considered.

Moreover, when loading cyclically with a fairly low stress to a limited number of cycles, anyway a densification occurs on the loaded material (Kutnar et al. 2008). During this densification, the cellular structure of wood is permanently modified, giving a material with new properties (Blomberg and Persson 2004, Kutnar and Šernek 2007). One of the main factors influencing the mechanical and physical behaviour of densified wood is the amount and type of cell collapse. We are interested here, in the effects of the environmental factors (moisture content changes) in the mechanical behaviour of three tropical woods during the process of densification. Our study therefore deals with the problem of the mechanical behaviour of tropical woods, subjected to the combined actions of cyclic compressive loadings and changes in the internal moisture content of wood. The objective is to understand the behaviour in cyclic compressive loading of three hardwood species, namely Okume, Iroko and Padouk on which, the database present a very weak panel of information's but which nevertheless represent the most exploited species of Gabon. The first part of this article presents the experimental setup used, as well as the protocol adopted to conduct our study. The second part presents the results obtained during the experimental tests, namely: the results on the impact of the loading combined with moisture variations on the mechanical behaviour of our three species.

Material and methods

Wood specimens

Okume, whose scientific name is *Aucoumea klaineana* Pierre (AKP), is a species of the *Burseraceae* family, which is endemic in Congo Basin, from the coast to a line passing through Okondja in eastern of Gabon and between Mitzic and Oyem in northern of Gabon, at Cameroon, Congo and over almost the whole Equatorial Guinea region (Medzegue 2007). AKP is a fast-growing species that grows to a height of over 50 m and has a trunk diameter of up to 2 m. In Gabon, it is used mainly for the manufacture of plywood, but also for structures such as sliced veneer and multi-ply plates (Martin and Vernay 2016, Gérard et al. 1998, Gérard et al. 2004).

The term "Iroko" refers to the two species of the genus *Milicia* in the *Moraceae* family: *Milicia Excelsa* (ME) and *Milicia Regia*, which are very similar in morphology. *Milicia excelsa* is generally found on the African continent, from Guinea Bissau to Ethiopia, to Angola and Zimbabwe in a southerly direction; it is found particularly in Gabon. This tree reaches a maximum height of 45 to 50 m with a diameter of about 2.5 m. It was first used in Gabon for the construction of canoes, then for structures such as glued laminated posts and carpentry (Martin and Vernay 2016, Daïnou et al. 2012, Gérard et al. 1998).

Padouk of Africa is the commercial name of *Pterocarpus Soyauxii* Taub (PS) of the *Fabaceae* family, a species found in central and west Africa but whose optimal growing area is Gabon and Cameroun. It is suitable for carving, cabinet making but also for hydraulic work in immersed marine environments and shipbuilding. Moreover, with its very interesting resonance properties (very pure metallic resonance), it is also perfectly suitable for the manufacture of organs, pianos or other musical instruments. Padouk trees reach a height of nearly 50 m, with a diameter of about 60 to 100 cm and are free of branches up to about 30 m (Gérard et al. 1998, Martin and Vernay 2016, Gérard et al. 2004).

The choice of these three species is explained by the fact that in this study one of the objectives is to highlight the impact of density on the mechanical behaviour of wood. Hence the choice of a soft hardwood (Okoume), a medium hardwood (Iroko) and a heavy hardwood (Padouk) as classified by the CIRAD collection (Gérard et al. 1998 and 2004).

The Iroko and Padouk specimens used for our tests were taken in Libreville, from an open-air sawmill site, located between the Nkembo junction and the bus station interchange. On this site, a 3 m Padouk batten and a 2.5 m Iroko board were purchased for our work. As for the Okoume samples,

they were taken from the sample stock of the Laboratoire de Recherche et Valorisation du Matériau Bois (LaReVa Bois) at the Ecole Nationale des Eaux et Forêts (ENEF) of Gabon.

Type of specimens used

The dimensions of the wood specimens for the three species (Figure 1) are those given by the French standard NF EN 408 for a compression test, i.e. $20 \times 20 \times 60 \text{ mm}^3$. A total of 90 test pieces were obtained, with 30 specimens per species.

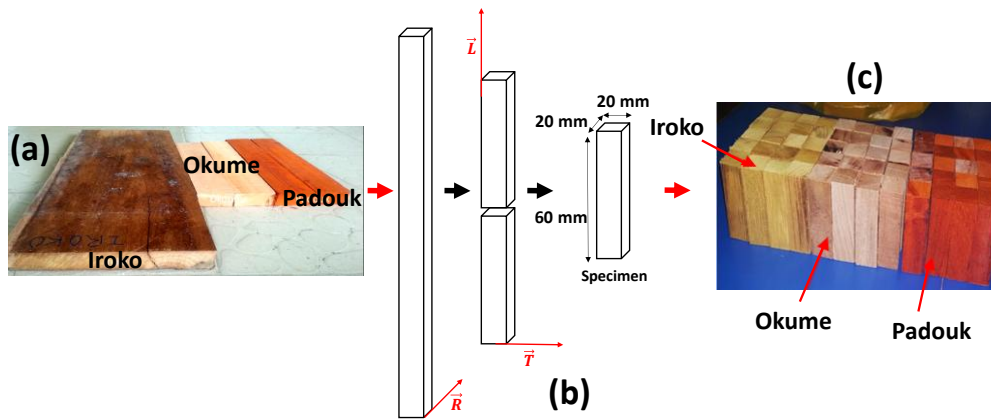


Figure 1. (a) Specimens of the species used, (b) Specimens cutting procedure; (c) specimens of the three topical species.

Sample preparation

The experimental device is compound of a "Universal testing machine" press, with a maximum load capacity of 100 kN and a computer equipped with a data acquisition system managed by the Datum 5.0 software. To humidify the specimens, we used tanks filled with water, in which the specimens were immersed.

Determining the intermediate dried weight (M_{oi})

Firstly, an intermediate dried weight (M_{oi}) was determined for each group of species and for all the specimens (Table 1). This M_{oi} is considered as the own dried weight of the specimen. Five specimens of each group of species were selected, for a total of 15 specimens and put in an oven set to be dried at a temperature of 103°C , as presented by Odounga *et al.* (2018). Figure 2 shows the kinetic of dried weight changes in the oven drying of the species measured over the time until the weights stabilized. There is a very rapid decrease (loss of moisture in the specimens as described by Moutee 2006, Moyne and Martin 1982) in the weight of the specimens of all three species after 6 hours of drying. The dry weight is reached when a stabilization (linear part of the curves see Figure 2) of the sample weight is observed.

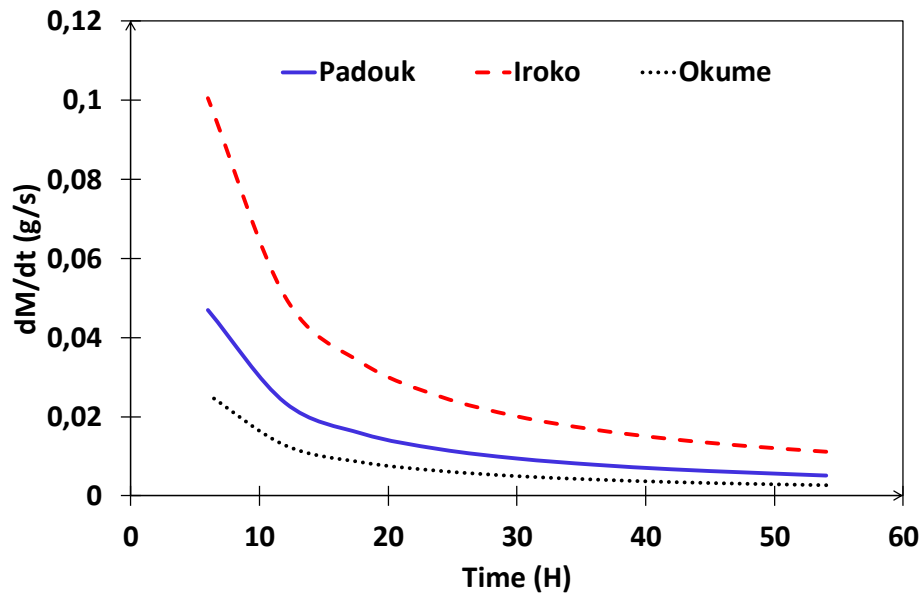


Figure 2. Changes to the average mass of the three species up to stabilisation

The weight value of the specimen, after it has stabilised in the oven, represents the own dried weight of the specimen. Finally, the intermediate dried weight (M_{oi}) of each species, which will be used to determine the MC, was obtained by calculated the average dried weight of the five specimens using the following Equation:

$$M_{oi} = (\sum_{j=1}^5 M_{oj})/5 \quad (1)$$

The results obtained from this calculation are shown in table 1 below.

Table 1. Means of intermediate anhydrous weight of the specimens obtained (mean \pm SD)

Specimens	Okume	Iroko	Padouk
M_{oi} (g)	9.91 \pm 0.29	9.66 \pm 0.39	15.89 \pm 1.37

Determining the moisture content (MC) of the specimen

Eight different levels of Moisture Content (MC) for the study of the specimens were arrested: 10%, 15%, 25%, 30%, 35%, 40%, 60% and 90%. To have these different levels of MC, the specimens were firstly put in tanks filled with water, for their saturation, during six weeks for the *AKP* and *ME* specimens and eight weeks for the *PS* specimens. Then, the results of the M_{oi} (see Table 1) calculated for each species were used to determine the moisture content (MC) of each specimen studied by coupling the empirical method of the determination of the MC. The method consists by drying naturally the specimens saturated until the corresponding MC found. In this case, the intermediate dried weight (M_{oi}) for each species calculated, is considered as the dried weight of the

$$MC (\%) = [(M_H - M_{oi})/M_{oi}] \times 100 \quad (2)$$

specimen tested, then for each species the following equation is used:

Where: M_H is the weight of the specimen at humidity H and M_{oi} the intermediate dried weight for each species.

Results and discussions

Static compression loading

Static compression tests were first performed on 5 specimens for each species to mechanically characterise them. Thus, by using these tests, we could determine the maximum stress at the collapse point and the module of elasticity (MOE) of each species for the static compressive test. Figure 3 shows the stress-strain relationships taken from the compressive static tests performed on the specimens of the species of *AKP* (Figure 3a), *ME* (Figure 3b) and *PS* (Figure 3c) at $12 \pm 2\%$ MC. According to the literature (Guitard and Gachet 2004, Manfoumbi Boussougou et al. 2014, Moutee 2006) it is known that two main sections can be identified on these stress-strain curves, i.e.: a linear part corresponding to the elastic zone and a parabolic shaped part corresponding to the plastic zone (Figure 3). The analysis of the different curves obtained during these static compression tests enabled us to determine the mechanical properties of our three species.

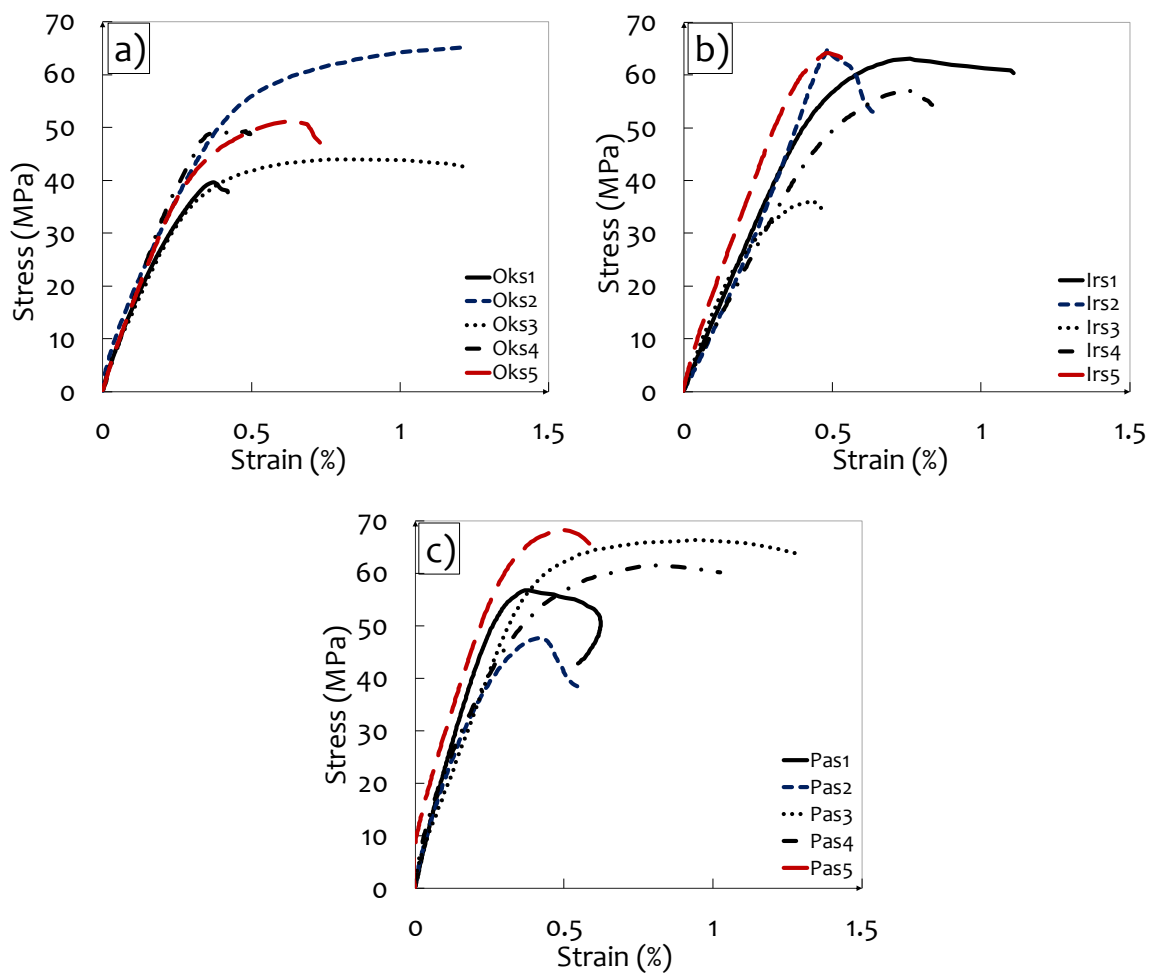


Figure 3. Typical stress-strain curves of compressive static tests performed on the specimens: (a) Okume, (b) Iroko and (c) Padouk

Tables 2 shows the main physical and mechanical results obtained after the compressive static test on the specimens of the three species studied. The values presented in this table, represent the mean \pm standard deviation for each parameter calculated.

Table 2. Physical and mechanical parameters of three species

Species	Size (mm)			MC (%)	M (g)	ρ (g/cm ³)	MOE (GPa)	MS (MPa)
	L	e _{moy}	h _{moy}					
<i>AKP</i>	61.32±0.40	19.83±0.23	19.56±0.16	12.46±0.26	11.14±0.03	0.46±0.01	12.77±2.50	49.35±9.52
<i>ME</i>	60.84±0.06	19.49±0.11	19.56±0.16	12.20±0.87	12.9±0.07	0.56±0.01	13.09±1.57	57.10±1.21
<i>PS</i>	61.45±0.31	19.84±0.33	20.11±0.42	12.12±0.23	17.83±0.034	0.72±0.02	17.48±2.30	60.08±8.32

As expected, we see in Table 2 that Padouk is the species with the highest maximum stress at break point in static compression, followed respectively by Iroko and Okume. This is easily explained by their respective densities. Padouk being the densest species with 0.72 ± 0.02 of density, its maximum stress at break point is therefore the highest, followed respectively by Iroko and Okume (with respective densities of 0.56 ± 0.01 and 0.46 ± 0.01). This observation is also valid for the MOE, Padouk still having the highest MOE value, followed by Iroko and Okume. The MOE values obtained experimentally differ from those obtained in the literature (Gérard et al. 2004, Gérard et al. 1998) by 23%, 2% and 7% respectively for the Okume, Iroko and Padouk specimens. Likewise, the maximum stresses differ by 27%, 5% and 8% respectively for the Okume, Iroko and Padouk specimens. These differences between our experimental values and those from the literature can be explained in part by the origin of the species from which the specimens were taken. Indeed, several studies have shown that depending on their biological origins, the characteristics of wood materials can vary between species, within the same species and within the same tree (Medzegue et al. 2007, Pâques 1996, Guitard and Gachet 2004, Almeida 2006, Charron et al. 2003). An investigation on the results obtained in this part, for the two species Okume and Iroko, shows a difference near to 18% of their respective mean density which is weak compared to that showed in the literature (31% for the density between the two species). The main explanation could be the origin of the region where the species studied were cut or the times of the log exposure in the lumberyard.

Cyclic compression loading

For each species studied, five compression loading cycles parallel to the fibres at a constant stress level, i.e. 10% of the maximum stress at the Okume break point, were carried out. This maximal loading was arrested because one of the goals of this study is to perform the test, for each specimen, in the elastic domain of the material. The reason for the choice of this loading is that compared to the two other species studied (Iroko and Padouk), Okume presents by taking into account the literature investigations and our results the weakest physical and mechanical characteristics. Figure 4 shows the general behaviour of the stress-strain curves for the Okume, Iroko and Padouk specimens obtained after the cyclic compression tests, at 10% of MC (Fig. 6a), 25% of MC (Figure 4b), 30% of MC (Figure 4c) and 60% of MC (Figure 4d).

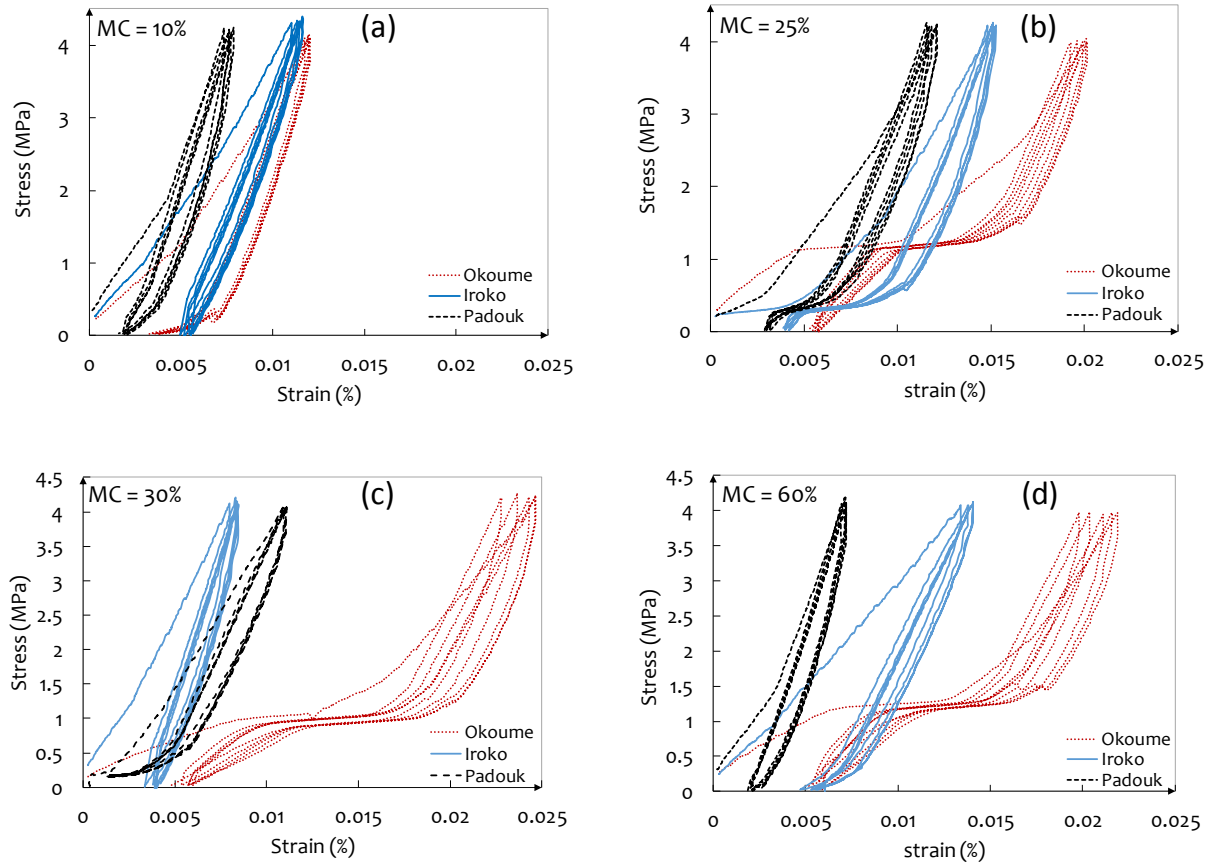


Figure 4. Typical stress-strain curves of cyclic compression specimens

The actual discussion will essentially focus, on these four level of MC. This choice is justifying by the fact that, by taking into account the literature (Odounga *et al.* 2018), we can consider two domains of the hygroscopic behaviour of wood: (i) the mechanical behaviour of the wood with MC located before the FSP and (ii) the mechanical behaviour of the wood with the MC located after FSP. It appears at each MC level of the specimens, that for the three species, the loading path differs from the unloading path. In other words, Okoume, Iroko and Padouk present hysteresis at unloading during the different cycles. These hysteresis phenomena can be explained by the fact that our materials are not perfectly elastic (Fozao *et al.* 2014). We also observe on these curves (Figure 4) that after the first loading cycle, the strain does not return to its initial level after the unloading path. This highlights the existence of the residual permanent strain that appeared in the first loading cycle, despite the low intensity of the force used (Pambou Nziengui *et al.* 2017). However, the residual permanent strain observed during the first loading cycle remains constant in the following cycles. Everything happens as if the specimen had adapted to the stress exerted.

Impact of loading combined with variations in moisture content (MC) on strain amplitude

The histograms in Figure 5 show the change in deformation of the specimen after each cycle at different MC levels.

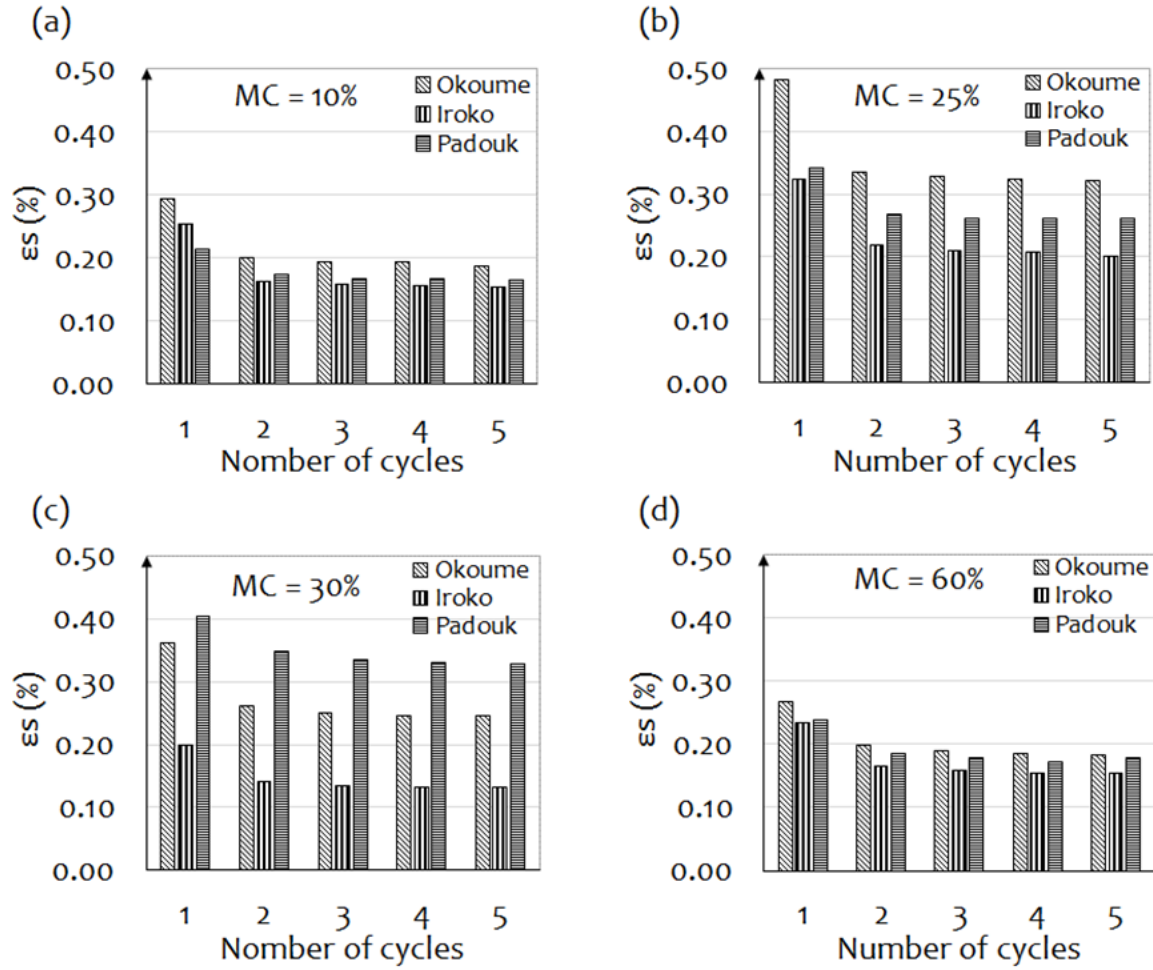


Figure 5. Comparison of the amplitudes of strain of the five loading cycles on the Okoume, Iroko and Padouk specimens

A coupling and a closer observation of the stress-strain curves in Figure 4 and the histograms of Figure 5 shows a decrease in the strain amplitude (ϵ_s) with the number of loading cycles. Between the first and fifth loading cycles, a regression of ϵ_s of 0.11%, 0.10% and 0.05% for the Okoume, Iroko and Padouk respectively at 10% moisture (Figure 5a). At 25% moisture (Figure 5b), the regression is 0.16%, 0.12% and 0.08% for the Okoume, Iroko and Padouk respectively. At 30% moisture (Figure 5c), it is 0.12%, 0.07% and 0.08% for the Okoume, Iroko and Padouk respectively. Finally, at 60% moisture (Figure 5d), the regression is 0.08% for the Okoume and Iroko, 0.06% for the Padouk. In other words, there is specimen strain during the loading cycle despite the low intensity of the load used. This regression of ϵ_s can be explained by the densification phenomenon that appears during the different loading cycles (Kutnar et al. 2015, Blomberg and Persson 2004). Indeed, just as in the drying process, the cell wall is compacted and the mass of the ligneous substance in a given volume increases during the different loading cycles (Kutnar et al. 2015, Segovia et al. 2013). This has the consequence of stiffening the specimens and thus reducing the strain in the following cycles. Also, the change in behaviour between the Iroko and Padouk specimens observed in the second loading cycle (Figures 4a, 4b, 4c, 4d) suggests that the densification observed occurs earlier in the Padouk specimens compared to the Iroko specimens. This regression of the strain amplitude can also be explained by the accommodation effect (Nguyen 2014). Indeed, after the first loading cycle, we have the specimen adapts to the stress imposed which can cause the stabilization of the strain observed in the following cycles.

For each cycle, we have plotted the changes to the strain amplitude with different moisture levels. Figure 6 shows the change in ϵ_s at each loading cycle as a function of each moisture level for the specimens tested.

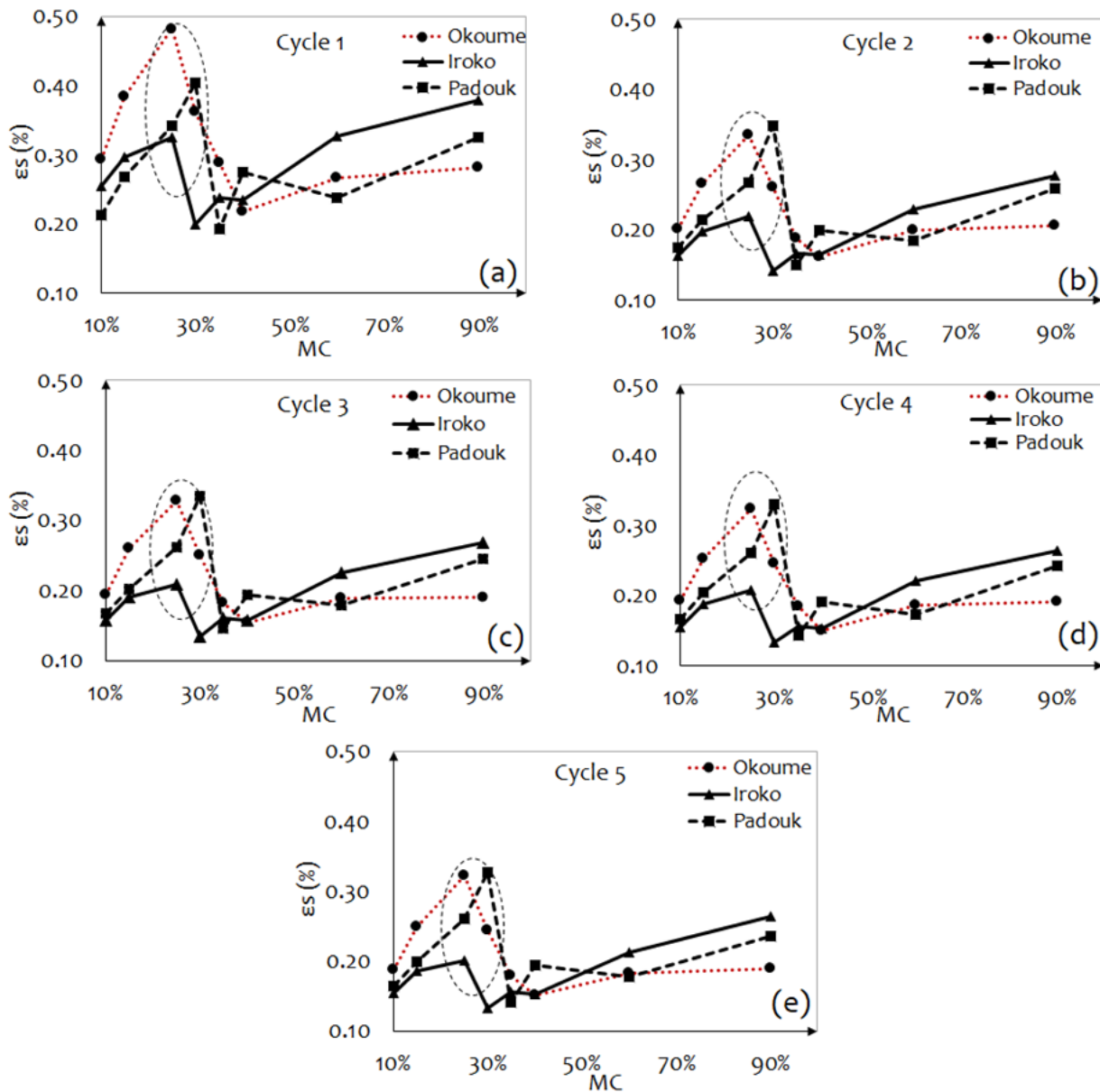


Figure 6. Effects on the strain amplitude (ϵ_s) for Iroko, Okume and Padouk specimens by the moisture levels. The ellipses represent the zone of the hygroscopic domain of our three species.

In general, for the three species, we observed an increase in strain amplitude at each cycle up to a certain moisture level close to 30% (Figures 6a, 6b, 6c, 6d, and 6e). This increase in ϵ_s could be explain by the rise of moisture content which lead the softening of the test pieces. Indeed, the change in moisture content deeply affects the balance of the elastic constants of the wood, especially where the moisture content is in the hygroscopic domain (Dinh 2011, Gerhards 1982, Moutee et al. 2005). Thus, the increase in humidity causes a decrease in the rigidity of the specimens. This decrease in the rigidity has the effect of increasing the specimen strains during loading. However, Figure 6 also shows that the increase in strain as with moisture levels rise is not continuous. There is a discontinuity due to the FSP, the point from which the MC level becomes too large to judge the effect of the stress. It is therefore more than likely that the area where this change of variation occurs matches the FSP domain of our three species. The ellipse observed on each of

the curves in Figure 6 thus shows the FSP domain. Finally, it should be said that these results are fairly consistent with the data in the literature, which indicates FSP at around 30%, 25% and 21% moisture respectively for the Okume, Iroko and Padouk specimens (Gérard et al. 2004, Gérard et al. 1998, Medzegue et al. 2007).

Conclusion

The objective of this study was to perform a comparative study to highlight the impact of cyclic compressive loading combined with variations in moisture content, on the mechanical behaviour of three tropical species. The species chosen including a soft hardwood (Okume), a medium hardwood (Iroko) and a heavy hardwood (Padouk). The dimensions of the wood specimens for the three species are those set down in French standard NF EN 408 for a compression test, i.e. $20 \times 20 \times 60$ mm.

The cyclic tests carried out, in the elastic domain made it possible, firstly, to highlight the emergence of a constant residual permanent strain in the specimens of the three species during the different loading cycles. In other words, the strains generated during the loading are not fully absorbed when unloaded. Hysteresis is then observed during unloading. In the other way, these cyclic tests carried out with a constant load level and at different moisture levels made it possible to show that there is a densification (or a crushing) of the specimens which occurs with the loading cycles, thus causing the regression of the strain. In addition, they show that the crushing observed is faster respectively from the densest species (Padouk) to the least dense species (Iroko and Okume respectively) in the dry state (here at 10% of MC). This trend tends to change in the FSP domain where the impact of moisture content coupled with loading becomes less and less important.

For future work, in order to better evaluate the resistance of our three species subjected to cyclic stress in compression; it would be interesting to increase the number of loading cycles. It would be interesting to also perform fatigue tests in compression. It would also be interesting to perform cyclic bending tests to understand the behaviour of structures such as bridges. The results obtained in this section highlight also the necessity to sampling directly in the forest our specimens studied.

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