Prediction of the Long-Term Mechanical Behaviour of Sapelli and Movingui

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Abstract -*Wood is a polymeric material. It deforms under the action of a mechanical stress (instantaneous strain). This strain increases with time, even with a constant mechanical stress: this is a creep. Therefore, a question arises: for how long will this creep be prejudicial to wood structure. The determination of duration before the breaking of wood material depends on long-term creep tests (about one hundred and fifty years). The long-term difficulty compels us to the time-temperature equivalence, which is an important principle of polymers. This principle stipulates that the behaviour of a polymer submitted to high temperature for short periods of time is equivalent to that of a polymer submitted to low temperature for long times [1]. Our aim in this work is based on the coupling of mechanic force and temperature. We are interested with the thermo-visco-elastic behaviour of two varieties of tropical woods: Sapelli of scientific name Entandrophragma cylindricum and Movingui scientifically called Distemonanthus benthamianus, carrying on four hour creeping test followed by sixteen hours recovering test on samples of 340mm long, 20mm wide and 20mm thick. Those tests were carried out in a controlled environment in temperature thanks to the variator-stabiliser of temperature mounted on a four-points bending. The series of isotherms of creep obtained has permitted to trace a master curve of each variety. The master curve, which is closer to the creep, has permitted to predict the long-term behaviour of each of the woods variety.*

Key Words: polymeric material, creep, equivalence principle time-temperature, thermo-visco-elastic

1. INTRODUCTION

In the current fight against greenhouse gases, wood material is regaining its place in building thanks to its low energetic expenditure for its use and the fact that it can fix carbon dioxide gas, recognised as a harmful factor to our environment. Buildings, mechanisms and assemblies done from this material, however show a be haviour often fragile and a variable limit resistance, difficult to guarantee. It is judicious to master better the link between the behaviour of wood material constructions and demands which are both environmental (moisture and temperature) and mechanical (long-term load).

Cameroon possesses in the great Congo basin the most threatened forest by pressure from both agriculture and logging companies. Since 1994, a new forest policy has recognised to indigenous communities the right to manage and exploit a portion of forests themselves. The global aim is to improve the participation of local populations in the preservation and management of forests, in order to increase their standard of living. But the local populations face difficulties when it comes to valorising structural wood. In fact, due to their insufficient financial and material capacities, the local populations do not have optimal access to diverse varieties of wood products such as beams, slats, bastings etc..., [2, 5]. To this lack of up to date equipments, is added the wrong knowledge of the relation of beam section, nature of wood variety and limit load, in order to make wood structures stay longer. The reduction of life span of wood structures due to a wrong dimensioning will not only accelerate deforestation, but also devalue wood material in front of other building materials.

The development of knowledge in term of wood rheology is fundamental to the modelisation and the improvement of behaviour laws which are at the origin of calculation codes for the dimensioning of wood structures. This work focuses on two points:

The first point shows the vegetal and experimental materials, their installation as well as the method used for the measure of the strain

The second presents the results, discussions and the comparison with the existing results, as well as the long-term prediction of the mechanical behaviour.

2. MATERIALS AND METHODS

2.1 Vegetal materials

Vegetal materials used for the work is constituted of wood varieties from Cameroon. Samples were obtained from two varieties: Sapelli and Movingui, respecting the NFB51008 norm; which recommends that for wood bending tests, the relation $l_{ut}/h = 14$; with l_{ut} the useful length of the sample and h its height [3, 10]. Therefore we have noticed based on the size of the testing machine $l_{ut} = 28$cm and a section of 2cmx2cm. For each essence, we have taken 15 pairs of samples, the pair being composed of a sample of length $l_{ut} = 28$cm and the other one called witness sample of length 2cm and of the same section and cut in the immediate surroundings of the first in the initial structure.

Among samples of length $l_{ut} = 28$cm, five serve to carry out the break up tests in order to determine the breaking load, while the rest permits to carry out creep tests. The witness sample serves to control the variation of humidity rate during the bending test. The arrangment of samples is indicated in figure1.

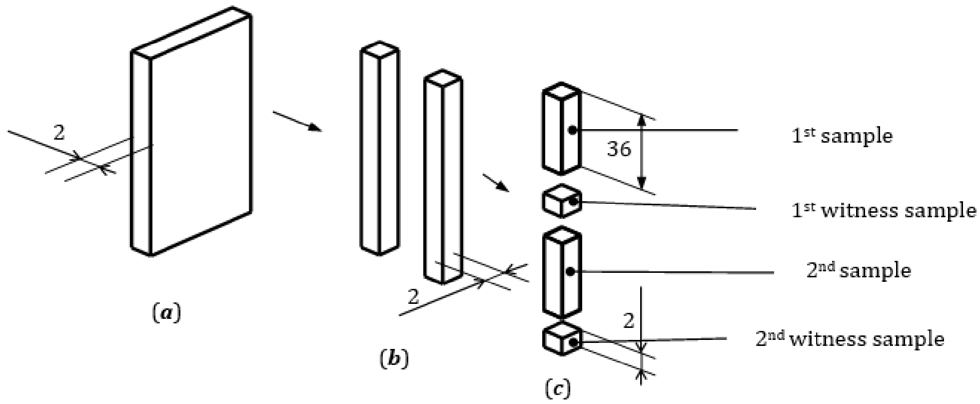
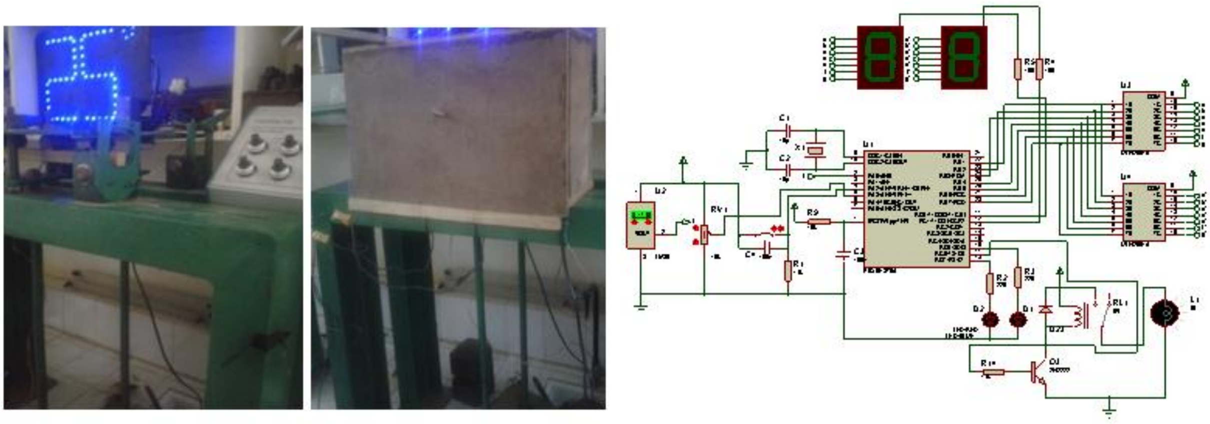


Fig -1: Illustration of samples orientation, and dimensioning in the diagram (a) and the ruler (b) as well as their numbering (c) for each variety.

2.2 Experimental materials

- The oven: In the process of determining water content in wood, we have used an oven to dry the sample in order to obtain an anhydrous mass. A sensitive weighing machine is associated to this experiment. It helps in weighing the sample after conditioned in the laboratory and the sample after passing in the oven.

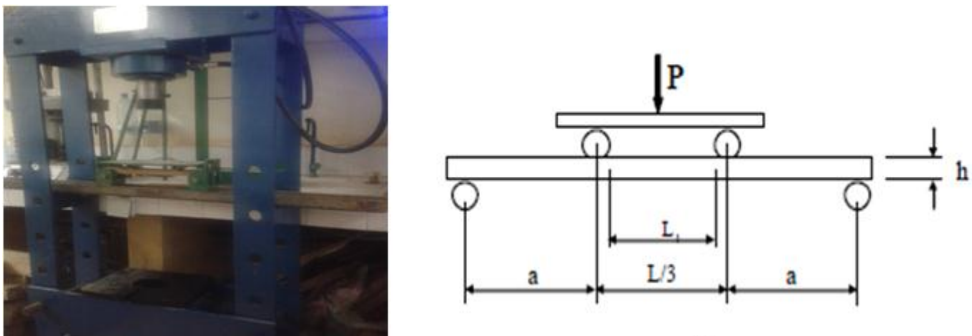
- The constant temperature enclosure: A covering lid, made in three layers: the first with flexi glass, the second with wood and the third with polystyrene was realised. It will be placed upon the testing machine containing the sample in four-point bending with the idea of minimising the exchange of temperature with the ambient milieu (laboratory) as indicated in figure 2(b). Inside the lid, six resistors of 20Ω/100watt are mounted in series and installed in the way of standardising the temperature in the enclosure. A detector of temperature of type LM35 is also mounted in the lid, near the wood sample. This constant temperature enclosure provided with the two components connected to the stabiliser-dimmer of temperature supports experiments in temperatures from 23℃ to 99℃ . It should be noted that the only electronic equipments present in the enclosure during the experiment are the strain gauges, the LM35 detector and the six resistors.



(a) (b) (c)

Fig -2*:* testing machine with sample mounted (a), enclosure and machine mounted together (b). Schematic diagram of stabiliser-dimmer of temperature(c).

- Hydraulic press type DMY with mounted four point bending device: The bending device was conceived for samples of 340mm long and 20mmx20mm thick. The sample is loaded systematically in four-point bending as represented in figure 3.

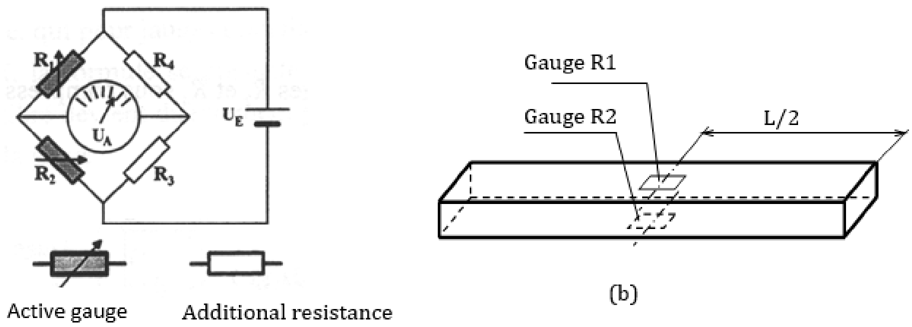


(b)

(a)

Fig -3: Hydraulic press type DMY (a) Schematic representation of a four-point bending (b)

The sample receives mechanical actions on simply supported made up of steel cylinder which permits to minimize local punching. One of the supports of the ends is mobile and rotating and the other one fix. Movements out of the bending plan of samples are prevented. The stress is applied by the pressure of the hydraulic press in the case of the determination of the breaking load and by the marked masses (load less than 0.35x P where P is the breaking load) for creep and recovery [1, 4]. The strain created is measured by electrical gauges connected to an extensometry bridge which directly gives the small strain in µm /m (figure4).



(b)

(a)

Fig-4: (a) Mounting of gauges in half bridge of Wheatstone, (b) pasting of gauges

2.3 Measures of deformations

Modern metrology has been able to make two main types of sensor deformation in order to indirectly determine the elasticity of materials.

For our tests, we have used a strain gauge of type BF-120-25AA-F of resistance R= 120,0±0,1and of gauge factor kj=2,0±1%. We have used a Chinese glue of type Oskasum to paste those gauges on the central part of the sample.

To increase the sensitivity and eliminate undesired effects, two gauges are mounted on the active sample as indicated on the figure 4 b. The gauges are connected to a bridge of extensometry DELTALAB 616, so as to make a half bridge of Wheatstone (figure 4 a) which is most appropriate circuit to measure slight variations of electrical resistance**.**

Before the application of a deformation, the bridge is adjusted by the variation of resistances, so that the output voltage UA vanishes:

$$\frac{R_1}{R_2} = \frac{R_2}{R_3} = r \quad (1)$$

The variations ΔR_i of R_i from the deformation of gauges cause an imbalance and the off coming tension UA becomes:

$$U_A = \frac{r}{(1+r)^2} U_E . \text{kj} . \frac{(\varepsilon_1 - \varepsilon_2)}{1 + \frac{r}{1+r}\left(\frac{R_1+R_2}{Z_m}\right) + NL} \quad (2)$$

where the term of non linearity is :

$$\text{NL} = \frac{\text{kj}}{1+r}[\varepsilon_1 + \varepsilon_2] \quad (3)$$

U_E is the input voltage and Z_m the impedance of the reading instruments.

The non linearity is nil (deformation ε_1 and ε_2 being equal in module but of opposite signs). Neglecting the report $\frac{R}{Z_m}$(for Z_m>>R) and because initially the gauges have the same resistance (r=1), the output voltage is:

$$U_A \cong \frac{U_E}{4} . \text{kj} . (\varepsilon_1 - \varepsilon_2) \quad (4)$$

It should be noted that the output voltage UA of the half bridge does not depend only on the mechanical deformation of gauges1 and 2. In fact, the two gauges are exposed to the same temperature ΔT; therefore the same thermal equation (4) and based on the disposition of the gauges on the sample; we obtain the expression of the deformation:

$$\varepsilon = \frac{2U_A}{\text{kj}.U_E} \quad (5)$$

Modelisation of the sample during the creep:

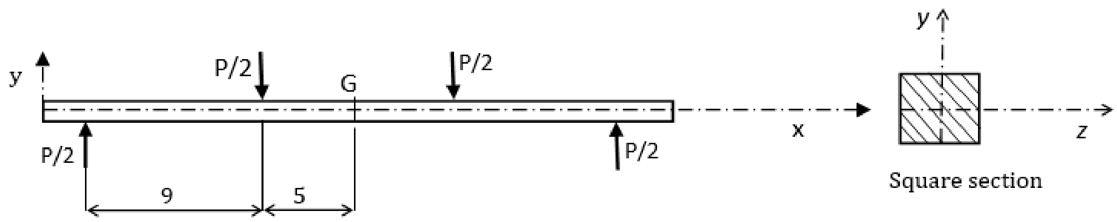


Fig-5*:* Modelisation of forces on the sample

By sectioning the beam in G and applying the fundamental principle of statistics, we obtain:

$$mf_z = 4{,}5P \quad (6)$$

The balance of the moments in the right section passing through G gives:

$$\sigma_0 = \frac{mf_z}{I_{Gz}/_\vartheta} \tag{7}$$

with

$$I_{Gz}/_\vartheta = \frac{a^3}{6} \tag{8}$$

where a is the dimension of the right section of the beam

By combining the three preceding relations, we obtain the expression of the normal strain in the middle of the sample where the deformation gauges are placed:

$$\sigma_0 = \frac{27P}{a^3} \tag{9}$$

σ_0 being the strain resulting from the charged P applied perpendicularly to the average line. The elastic complacency of the material in the direction of its neutral line is given by:

$$J_{(t)} = \frac{\varepsilon_{(t)}}{\sigma_0} = \frac{a^3}{27P}.\varepsilon_{(t)} \tag{10}$$

where $\varepsilon_{(t)}$ is the deformation of the moment t.

Formulae obtained in (5) en (10) permit to trace creep and recovery curves respectively.

The difficulty encountered during the test lie in the control of the temperature and the stability of the installation after the bridge balancing.

3. RESULTS AND DISCUSSIONS

3.1 Water content of the two essences

Before proceeding to the creep of the samples, it was worth mastering their water content, which influences on the physical and mechanical properties of wood. We have weighed five witness samples for each essence. After seventy two hours, we have weighed the samples again, and the results are in table 1. The double weighing has permitted to calculate the water content of each essence.

Table -1: Water content of the two samples before the beginning of the creep

Essences	Sapelli					movingui				
No of the sample	S_{T4}	S_{T12}	S_{T7}	S_{T9}	S_{T6}	M_{T8}	M_{T4}	M_{T15}	M_{T2}	M_{T7}
Mass at the content H (%)	4.91	4.97	4.61	5.28	4.77	6.18	5.99	6.94	6.25	6.38
Anhydrious mass	4.26	4.23	3.95	4.49	4.17	5.56	5.39	6.02	5.42	5.54
Water content of the sample	15.25	17.49	16.70	17.59	14.38	11.15	11.13	15.28	15.31	15.16
Water content of the essence	**16.28%**					**13.60%**				

3.2 Determination of the breaking loads of the two essences of wood.

After exposing the samples in the mechanical laboratory for week, we have used a machine made of hydraulic press type DMY (figure 3a) to determine the breaking loads of the two essences of wood.

For each essence, we have progressively increased the pressure until the breaking of the different samples. The results of the tests are shown in table 2. Taking Pr the pressure read on the manometer, the breaking load is given by the formula:

$$P = \frac{\pi . d^2 . P_I}{4 . g} \quad (11)$$

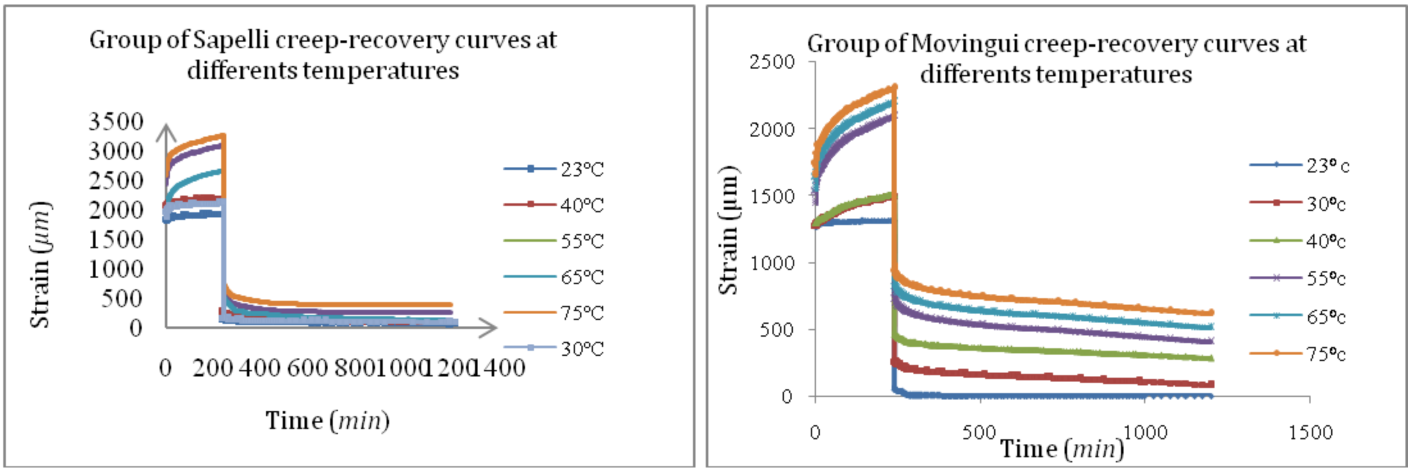
Table -2: Breaking load of the two essences of wood

Essences	Breaking loads of the samples				Average breaking loads
Sapelli	S_{10}	S_{11}	S_{12}	S_{13}	$P_{sapelli}$ = **224.25kg** to16.28% humidity
	222	223	225	227	
Movingui	M_{10}	M_{11}	M_{12}	M_{13}	$P_{Movingui}$ = **293kg** to13.60% humidity
	299	285	287	301	

The analyses of these results show a rapprochement of the breaking loads with those obtained by SALES [3].

3.3 Creeps and recovering of the two essences of wood

The two electrical gauges have been connected to the Extensometry Bridge DELTALAB ET 616. The bridge has been connected to a computer to record then deformations of the two essences as well as their display depending on duration



(a) (b)

Chart-1: Group of curves of creep-recovering of Sapelli (a), Movingui (b) at different temperatures

In order to visualise the effect of the temperature, we have superimposed the curves of creep-recovering at different temperatures on the same graph. Two graphs have been represented.

- Group of creeps-recoveries of Sapelli (a)

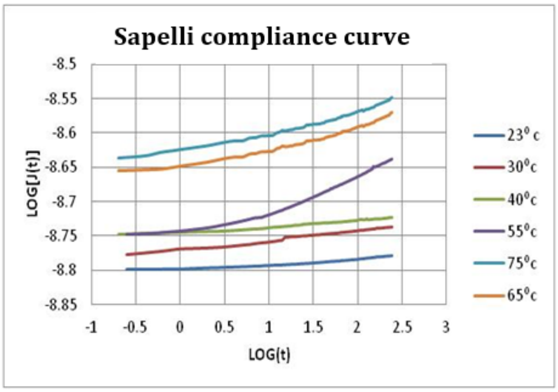
- Group of creeps-recoveries of Movingui (b)

On the two graphs, we can observed an instantly or long term increase of deformation with the increase of temperature. The decrease of the strength of the wood when the temperature increases goes along the line with the relation between the mechanical property of wood and the change of temperature according to Bodig and Jayne [5, 8, 9].

The two graphs equally show the influence of the temperature on the recovery. When the temperature increases, the instant or long-term recovery also increases.

3.4 Long term prediction: drawing of the master curve

In order to determine complacencies of wood materials on a large time scale, we have drawn a master curve of each essence based on the series creeps isotherms.



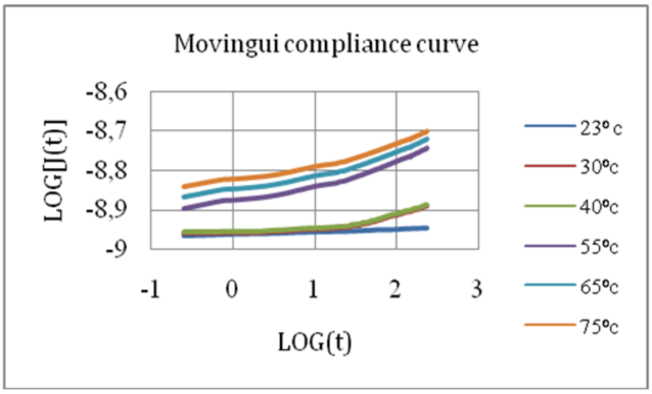


Chart-2: Isotherm of viscoelastic compliance of Sapelli (a), Movingui (b)

We have coincided the curve at 30^{0}c with that obtained at 23^{0}c. This is possible with the shifting of the curve at 30^{0}c following both the time axis [horizontal shift factor a_{T30-23}] and complacencies axis.

In the same way, we have shifted the other curve to obtain the coincidence. The results of the superimpositions have led to the master curves of chart 3 and 4.

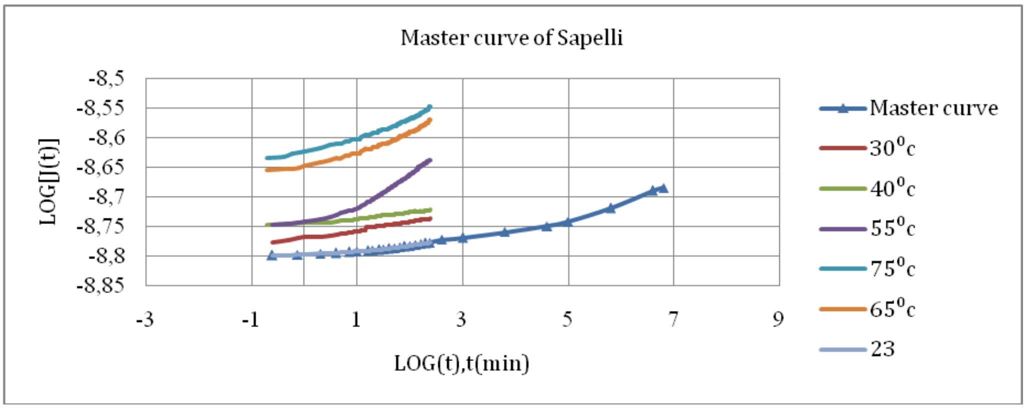


Chart-3: Master curve of Sapelli

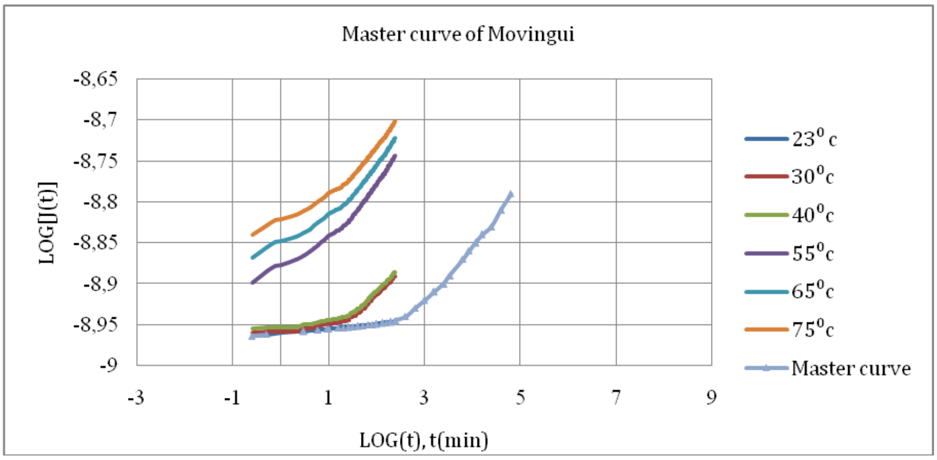
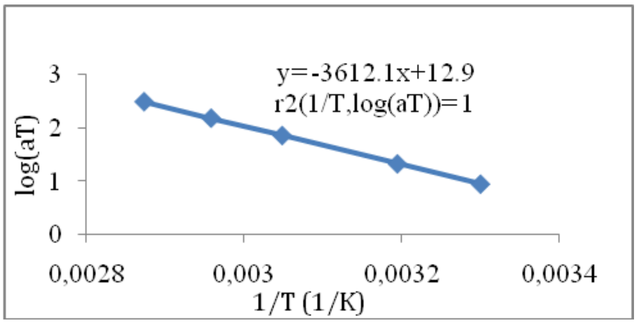
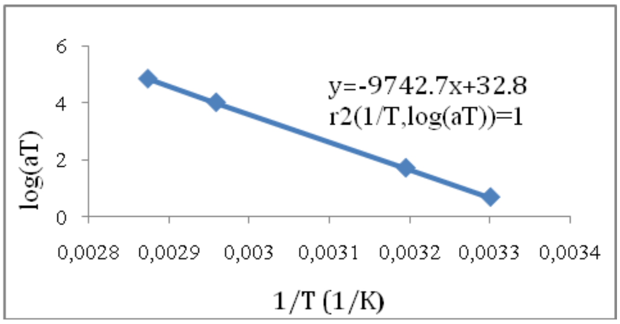


Chart -4: Master curve of Movingui.





(a) (b)

Chart-5: Linear regression of horizontal shift factor of Movingui(a), Sapelli(b)

From chart 5(a and b), one can note that there is a strong correlation (r^2=1) between the horizontal shift factor and the reverse of temperature. This indicates a linear relation of type Arrhenuis:

$$\log a_T = \frac{\Delta H}{2.303R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right) \quad (12)$$

From this linear regression between log(a_T) and 1/T, and considering the Arrhenuis relation [4, 6, 10], we determine the formula of wood essences activation energy:

$$\Delta H = 2.303R.tg\alpha \quad (13)$$

where tgα is the regression line and R the constant of perfect gases. We find 44.56kcal/mol for Sapelli and 16.52kcal/mol for Movingui.

Extrapolation of the deformation

Having had the curve log-log of the complacency, we have deducted that of J=f(t) representing the master curve. Approaching the two master curves by a two parameters power function for the Sapelli and three parameters for the Movingui, we have obtained:

- For the Sapelli:

$$J(t) = J_0\left(1 + at^b\right) \quad (14)$$

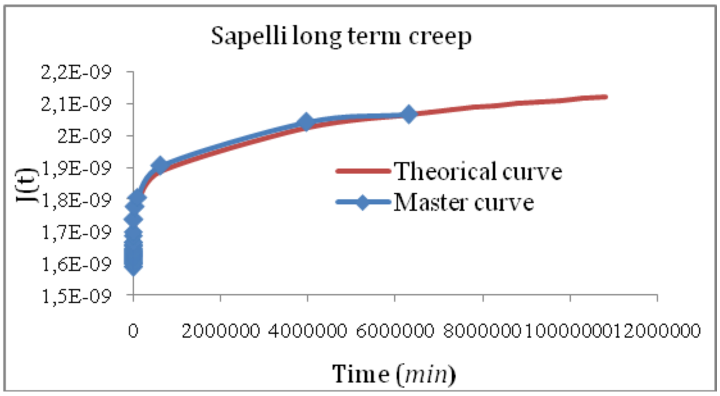
with a = 0.01365 and b = 0.199 representing the creep cinetic factor.

- For the Movingui:

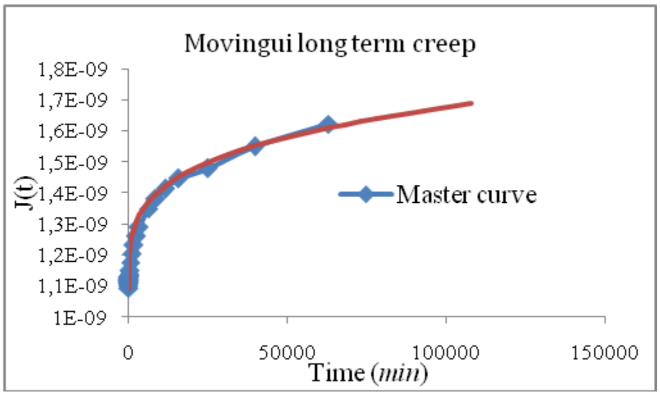
$$J(t) = J_0\left[\left(1 + \frac{c}{J_0}\right) + at^b\right] \quad (15)$$

where a=0.0315, b=0.25 and c=2e-11

With the determination of these model parameters, we have traced (chart 6 a and b) the theoretical curve (red colour), the most representative of the creep function for each essence. This theoretical curve permits to extrapolate long-term deformation.



(a)



(b)

Chart-6: Power model of long-term creep of Movingui (a) Power model of long-term creep of Sapelli (b)

4. CONCLUSIONS

The objective of our work is the study of the long-term behaviour of tropical wood essences, particularly Sapelli and Movingui; and their modelisation under the effect of mechanical forces and variations of temperatures. Other parameters such as humidity and different couplings between solicitation, temperature and humidity, though influencing on the behaviour of wood are not considered in this work.

For the work, a four-point bending device has been chosen to carry on the experiments of creep-recovery.Those tests have been conducted with small sizes samples (340mmx20mmx20mm) to limit water content in the thickness. The measuring of the superficial strain has been done with electrical strain gauges pasted on the interior and exterior surfaces of the sample mounted in a Wheatstone half-bridge.

Creep-recovery tests were carried out on a period of four hours for the creep and sixteen hours for the recovery, and at different temperature levels (23^0c, 30^0c, 40^0c, 55^0c, 65^0c, 75^0c). To that effect, we put in place an experimental apparatus to analyse the creep in controlled thermal conditions, using a four-point bending device in a enclosure with a steady and controlled temperature.

The results of creep-recovery tests in constant thermal conditions have shown the increase of longitudinal deformation when the temperature increases wood essence less rigid when the temperature increases.

Results have also shown a total recovery for loads inferior to one third of the breaking load. However, we have observed a residual deformation when the temperature increases. We have also noticed that the creep is more important when the temperature is high and that recovery is slow or partial.

With the time-temperature principle, we have obtained the long-term behaviour of Sapelli and Movingui. The results obtained from this theory have permitted to compare with the real deformation tested in the laboratory. From this comparison on a higher number of samples, we have obtained new results of the modelisation of long-term behaviour of the two essences of wood, in order to predict their long-term behaviour when they are used.

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