Original article

Influence of basic density and temperature on mechanical properties perpendicular to grain of ten wood tropical species

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Abstract – The influence of temperature on transverse mechanical properties of 10 tropical species in green condition was studied in radial compression (0 to 99 °C), transverse shear with longitudinal-radial shearing plane and rupture of the longitudinal-tangential plane (20 to 80 °C). Basic density ranged from 0.21 to 0.91 g cm^{-3}. Load-displacement curves were characterised by initial rigidity, yield stress, yield strain and strain energy at 20% strain level. The relation between each criterion and basic density was expressed by a power law. The dependency on temperature evidenced a sharp glassy transition, except for the fracture energy only slightly influenced by temperature. An empirical model allowed evaluating a transition temperature between 51 and 69 °C, depending on the species and the criterion, which was attributed to lignin. Detailed analysis of the apparent modulus in radial compression suggested that complex relaxation phenomena occur around 10 °C and that the rubbery state is not fully reached at 80 °C.

green wood / tropical wood / transverse mechanical properties / basic density / softening temperature

Résumé – Influence de l'infradensité et de la température sur les propriétés mécaniques transverses de dix bois tropicaux. L'influence de la température sur les propriétés mécaniques transverses du bois vert de 10 essences tropicales a été étudiée. Trois types d'essais ont été réalisés : compression radiale (entre 0 et 99 °C), cisaillement transverse suivant le plan longitudinal-radial et rupture dans le plan longitudinal-tangentiel (entre 20 et 80 °C). L'infradensité des essences est comprise entre 0,21 et 0,91 g cm^{-3}. Les courbes force-déplacement ont été caractérisées par la rigidité initiale, la contrainte de flambement, la déformation de flambement et l'énergie de déformation pour 20 % de déformation. La relation entre chaque critère et l'infradensité est exprimée par une loi puissance. La dépendance des critères avec la température met en évidence une transition vitreuse très prononcée, excepté pour l'énergie de rupture peu influencée par la température. Un modèle empirique permet d'évaluer une température de transition entre 51 et 69 °C, selon les essences et les critères. Ce phénomène est expliqué par la transition vitreuse des lignines. Une analyse détaillée du module radial apparent en compression suggère qu'un phénomène de relaxation complexe a lieu autour de 10 °C et que l'état caoutchoutique n'est pas complètement atteint à 80 °C.

bois vert / essences tropicales / propriétés mécaniques transverses / infradensité / température de transition vitreuse

1. INTRODUCTION

Improvement of basic knowledge on mechanical properties of tropical woods is of prime importance for the development of wood industry in French Guyana. Peeling and machining ability is usually correlated to basic density of woods [7]. Nevertheless, it seems that a detailed study of mechanical behaviour of green wood is prevailing to determine peeling and machining ability [10]. In particular, influence of temperature has to be taken into consideration [1, 8].

Veneer formation during slicing or rotary cutting is accompanied by a complex combination of radial compression, transverse shear and transverse splitting. Each of these mechanical actions is strongly depending on the steaming temperature applied to the log. Their simulation requires an improved knowledge of green wood rheology transversally to the fibres and it is of prime importance to understand the influence of temperature on each mechanical phenomenon. Moreover, experimental results about the effect of temperature on mechanical properties of wet wood provide important data for wood rheology, regardless of peeling and machining applications.

The complex behaviour of wood is related to its composite nature. Wood can be regarded as a superposition of an amorphous matrix composed of both lignin and hemicelluloses and a reinforcement of semi-crystalline fibres composed of cellulose.

Table I. Names and basic density of the species studied; names in bold will be used afterwards.

Scientific name	Local name	Density at 12% mc (g cm^{-3})	Standard deviation	Basic density (g cm^{-3})	Standard deviation
Parkia sp.	Dodomissinga	0.271	± 0.035	0.212	± 0.015
Virola surinamensis A.C. Smith	Yamamadou marécage	0.453	± 0.010	0.345	± 0.008
Vochysia sp.	Moutende Kouali	0.674	± 0.011	0.500	± 0.017
Ocotea rubra Mez.	Grignon blanc	0.732	± 0.045	0.590	± 0.025
Humiria balsamifera (Aublet) St Hil.	Bois rouge	0.818	± 0.037	0.581	± 0.028
Dicorynia guianensis Amsh.	Angélique	0.770	± 0.018	0.620	± 0.016
Humenolobium sp.	Saint-Martin jaune	0.752	± 0.031	0.650	± 0.017
Vouacapoua americana Aubl.	Wacapou	0.935	± 0.031	0.773	± 0.030
Tabebuia cf. capitala Sandw	Ebène verte	1.066	± 0.013	0.889	± 0.017
Bocoa prouacensis Aubl	Boco	1.178	± 0.033	0.909	± 0.006

Globally, mechanical properties of wood may be affected by glassy transition of each amorphous component, which is in turn influenced by temperature, moisture content and time scale of experiment. So experimental conditions are of prime importance to analyse the transitions observed.

In the present paper, mechanical tests perpendicular to grain on tropical species at different temperatures varying over a span of 0 to 99 °C are presented [2]. The samples were saturated with water, so moisture content can be considered as a fixed parameter. Various mechanical effects (stiffness, strength, deformation and energetic criteria) are chosen to describe load displacement curves from these tests. Evolution of each criterion is analysed respect to basic density and temperature.

2. MATERIALS AND METHODS

2.1. Testing machine and thermal regulation

Mechanical tests were performed on a universal testing machine (Classic of Wykeham Farrance England), on which three different load cells could be installed with capacity of 50 kN, 5 kN and 2 kN. Strain measurements were obtained using two displacement sensors (LVDT transducers) placed between the upper fixed platen and the moving one, the displacement being calculated as the average of both variations. Specimens and testing system were placed into a water bath controlled at constant temperature to within 0.1 °C using an electrical heating. To avoid a thermal drift of the load cell, an insulation system was installed.

It should be pointed out that we measured an apparent strain that is a superposition of the real strain of specimens and the elastic deformation of the frame, so we are dealing with apparent moduli.

2.2. Preparation of specimens for mechanical tests

Specimen were cut from tropical wood logs in the orthotropic directions, then placed in a vacuum cell for 30 minutes to fully saturate the wood, and kept soaked in water. Just before mechanical testing, the specimens with the shape of cubes were heated in water to the bath temperature in order to minimise the time needed to reach thermal equilibrium. *Table I* gives names, density at 12% wood moisture content and basic density of the Amazonian species used. Basic density is calculated as dried weight divided by saturated volume.

2.3. Compression tests

Compression test device is described in *figure 1a*, in which the 50 kN load cell is used. Samples were 30 mm width cubes. Specimen from ten different species were compressed in the radial direction to
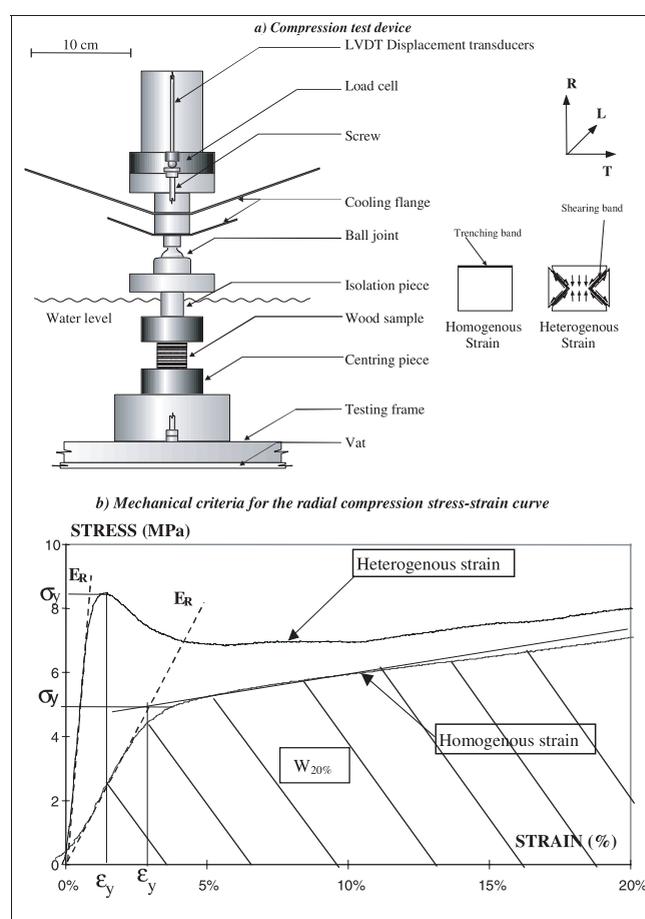
Figure 1. Radial compression tests: (a) compression tests apparatus; (b) radial compression stress-strain curves.

about 23% of their initial thickness over a temperature range of 0 to 99 °C at intervals of 5 °C. The displacement rate was 0.5 mm mn^{-1}, corresponding to a strain rate of 28×10^{-5} s^{-1}. Each test at one temperature for each wood species was repeated 3 times using 3 specimens cut from the same log.

Strain is calculated as displacement divided by initial height (R direction) of the sample; stress is calculated as load divided by samples surface perpendicular to loading direction (TL plane). R, T, L refer to the radial, tangential and longitudinal directions, respectively.
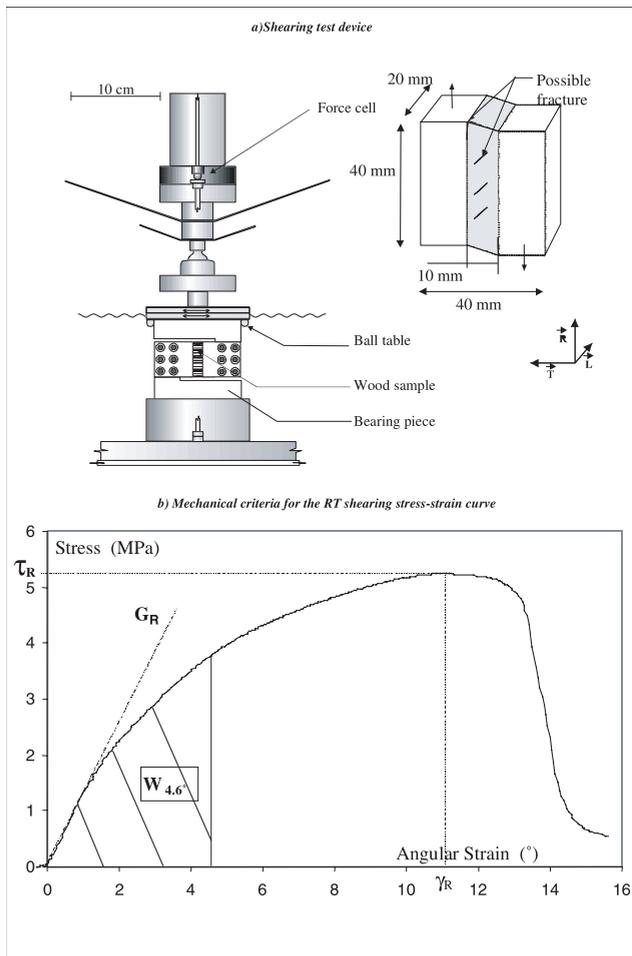
Figure 2. Rolling shear tests: (a) rolling shear tests apparatus; (b) RT shearing stress-strain curve.

Figure 3. Fracture toughness tests: (a) fracture test apparatus; (b) fracture force-displacement curve.
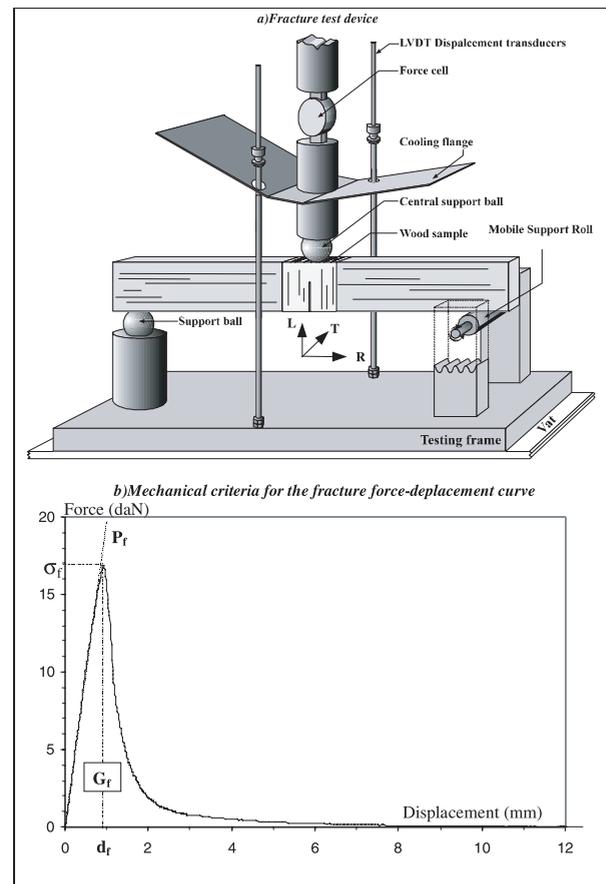
The stress-strain curves (*figure 1b*) obtained for a homogeneous strain first show a linear regime which is related to the elastic bending of the cell wall. This linear part is followed by a plateau of roughly constant load that is ascribed to the development of cell wall buckling. Finally, the load increases rapidly. It should be noticed that a second type of strain-stress curves exists when strain is heterogeneous. In this case shear bands occur and yield a fall of the load before the plateau.

Four criteria are used to describe load-displacement curves:

– one stiffness criterion, E_R, which is the slope of the initial linear part of the curve; this parameter can be defined as an apparent radial stiffness;

– one strength criterion, named yield stress (σ_y), which is defined as the maximum stress before the crushing zone (heterogeneous strain) or the stress at the intersection between the linear approximation of the plateau and the first linear part (homogeneous test), where ε_y is the associated deformation;

– one energetic criterion, $W_{20\%}$, derived from the area below the curve until 20% deformation of the sample.

2.4. Rolling shear tests

Shearing tests were performed over a temperature range of 25 °C to 80 °C at intervals of 5 °C. Test device is shown in *figure 2a*, in which the 5 kN load cell is used.

Samples dimensions were 20 mm in the longitudinal direction, 40 mm in the radial and 40 mm in the tangential one. The sample was clamped between rugged metal plates allowing the deformation of a 40×10 mm^2 central zone in a parallelogram shape. The shearing plane was RL, the loading rate was 0.5 mm mn^{-1}, corresponding to a strain rate of 5×10^{-3} s^{-1}. The maximum shearing angle was 16.7°. Insofar as it is not a proper shearing test leading to a correct shearing modulus, we have to do with apparent radial shearing modulus G_R. Shearing angle is calculated as inverse tangent of displacement divided by 10 mm (T dimension of the shearing zone). Stress is calculated as load divided by 40×20 mm^2 (RL plane of the shearing zone).

Referring to the curve of stress against shearing angle (*figure 2b*), four criteria can be defined. G_R the stiffness criterion, is calculated as the slope of the first linear part. The strength criterion (τ_R), derived from the maximum load value, γ_R is the associated angular deformation. An energetic criterion ($W_{4.6°}$) is calculated from the area below the curve until a global angular deformation of 4.6°.

2.5. Fracture toughness tests

The tenacity test as proposed by Gustafssonn [6] is a three points bending test of a pre-notched sample called SENB (Single Edge Notched specimen in Bending). Samples dimensions were 40 mm in the longitudinal direction, 40 mm in the radial and 24 mm in the tangential. Temperature was varying from 25 °C to 80 °C at intervals of
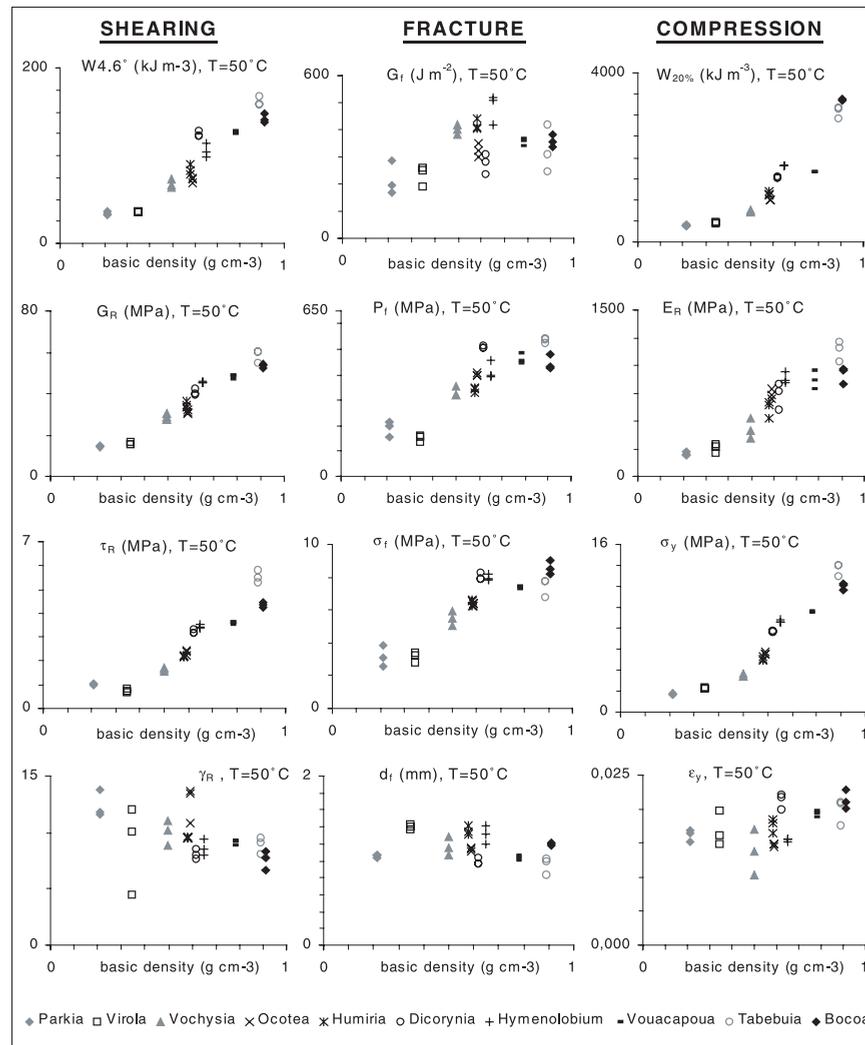
Figure 4. Evolution of mechanical criteria from radial compression test, shearing test and fracture test respect to basic density for T = 50 °C.

5 °C. Wet samples were glued to side arms made of *Diplotropis purpurea* (high density guyanese wood) using a special glue for wet wood SUMITAK 242A from Daiichi Kogyo Seiyaku, Japan, obtained through the courtesy of Pr. Kawai from Kyoto University. The initial crack of 24 mm long in the L direction was performed by sawing. *Figure 3a* illustrates this fracture test, when the 2 kN load cell was used. The rupture occurs is the longitudinal-tangential plane. Displacement rate was 0.3 mm mn^{-1} until displacement reaches 3 mm, then the displacement rate was set to 2 mm mn^{-1}.

Stress and strain are calculated as if it was a beam tested in three points flexion with a section of 16 (R) × 24 (T) mm^2 and a length of 240 mm.

The criteria used to describe the load-displacement curve obtained are (*figure 3b*):

– one stiffness criterion, P_f, calculated from the initial linear part;

– one strength criterion, σ_f, the maximum stress before cracking, where d_f is the associated displacement;

– one energetic criterion, G_f, which is calculated from the area below the complete load-displacement curve.

2.6. Summary of tests and mechanical criteria measured

test	temperature range (°C)	number of wood species tested	maximum strain	strain rate s^{-1}	criteria C
radial compression	0 to 99	10	23%	28 × 10^{-5}	E_R, σ_y, ε_y, $W_{20\%}$
radial shearing	25 to 80	10	16.7°	5 × 10^{-3}	G_R, τ_R, γ_R, $W_{4.6}$
fracture	25 to 80	10	until fracture		P_f, σ_f, d_f, G_f

Generally speaking, C will represent any criteria.

2.7. Processing of rough data

Since displacement is measured between the fixed crosshead and the moving platen, strain is a superposition of the real strain of specimens and the elastic deformation of the frame. Compression tests without wood specimen lead to the rigidity of the frame at each temperature. So elastic deformation of frame can be calculated and
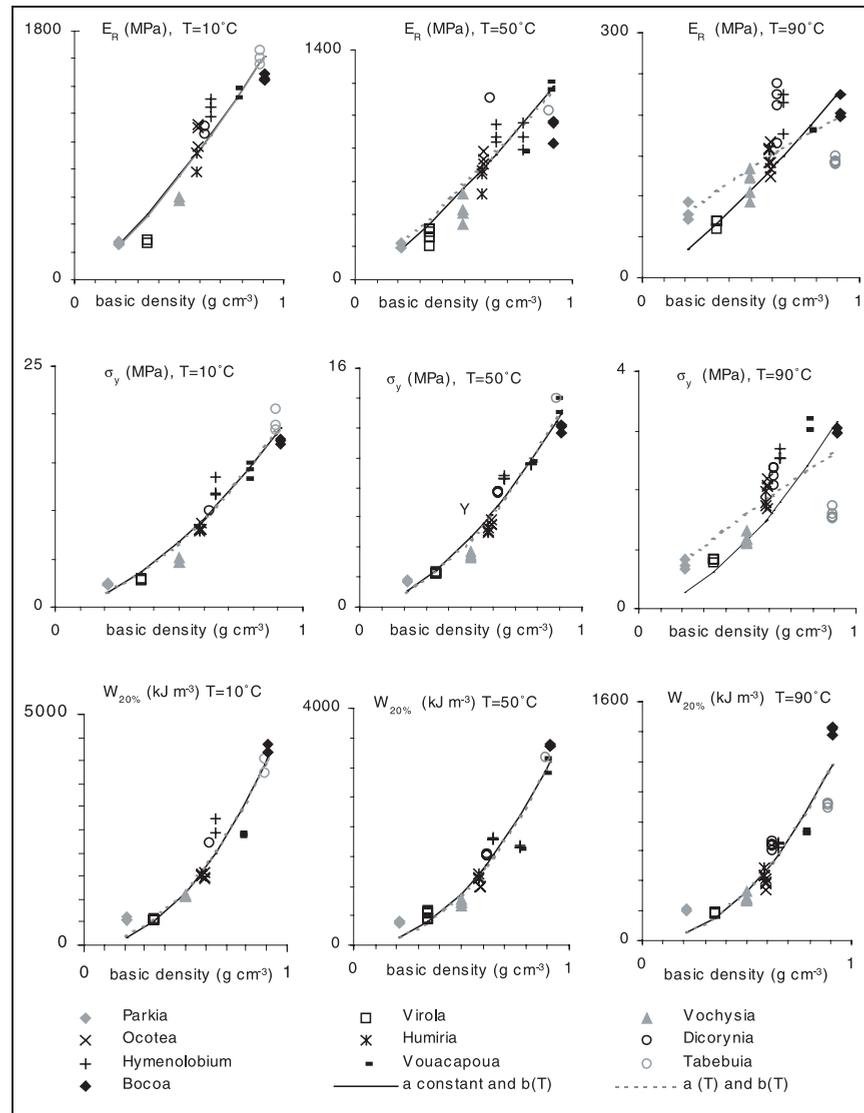
Figure 5. Evolution of mechanical criteria from compression test (E_R, σ_y and $W_{20\%}$) respect to basic density for three temperatures. Solid lines represent theoretical laws.

subtracted from the total displacement in order to calculate the specimen displacement.

3. RESULTS AND ANALYSIS

3.1. Influence of species

Only deformation criteria (ε_y, γ_R and d_f) are slightly dependent on basic density. Otherwise, we observed a strong correlation between mechanical criteria and basic density. An illustration of the evolution of every mechanical criteria respect to basic density at one temperature is given in *figure 4*.

In order to find a model which could represent the relation between mechanical criteria and basic density, we first focus our attention on mechanical criteria from radial compression tests. As temperature range is larger in compression tests, we assume that a model which would be relevant for compression criteria, could be applied to shearing and fracture criteria.

As shown by Guitard [5], the relation between criteria and basic density may be expressed in a general way by: $C = \beta \times x^{\alpha}$. Here C is any mechanical criteria from compression test (E_R, σ_y and $W_{20\%}$) and x is the basic density. The parameters α and β depend on wood species, but the question concerns the dependence between α, β and temperature. We tried two solutions to fit the model on experimental data:

– case 1: α and β both depend on temperature;

– case 2: α is constant and β depends on temperature.

It seems that these two solutions are not very different (*figure 5*). Comparison between determination coefficients calculated using case 1 and case 2 (*table II*) leads to the conclusion that both solutions are relevant. In order to get the simplest expression of the model, case 2 (α constant and β dependant on temperature) is chosen.

The power law presented previously is used to model the relation between criteria from shearing test (G_R, τ_R and $W_{4.6°}$),

Table II. Values of the parameters in case 1 and case 2 calculated for three criteria (E_R, σ_y and $W_{20\%}$). R^2 is the determination coefficient.

T (°C)	E_R (case 1)		E_R (case 2)		σ_y (case 1)		σ_y (case 2)		$W_{20\%}$ (case 1)		$W_{20\%}$ (case 2)	
	α	β	α	β	α	β	α	β	α	β	α	β
0	1.39	1971	1.28	1905	1.82	24.0	1.70	23,3	2,14	5207	2.13	5201
5	1.29	1830		1823	1.77	23.1		22,8	2,15	5216		5164
10	1.28	1018		1018	1.76	22.2		21,9	2,09	4990		5002
15	1.32	1813		1793	1.75	21.5		21,3	2,08	4811		4827
20	1.39	1807		1744	1.76	21.2		20,9	2,08	4718		4730
25	1.24	1728		1752	1.73	20.7		20,6	2,09	4899		4913
30	1.19	1611		1657	1.67	19.6		19.8	2.07	4710		4734
35	1.29	1686		1680	1.77	19.3		19.0	2.12	4497		4496
40	1.22	1536		1563	1.69	17.9		18.0	2.09	4322		4333
45	1.27	1452		1454	1.71	16.5		16.5	2.11	4021		4022
50	1.17	1281		1328	1.79	15.6		15.2	2.21	3811		3774
55	1.19	1146		1175	1.69	13.4		13.4	2.22	3569		3531
60	1.49	1096		1035	1.63	11.6		11.9	2.25	3286		3243
65	1.60	912		833	1.36	8.5		9.4	2.23	2858		2821
70	1.31	611		606	1.26	6.9		7.9	2.25	2557		2517
75	0.82	366		424	1.11	5.5		6.4	2.23	2201		2175
80	0.89	311		351	1.06	4.5		5.4	2.24	1932		1908
85	0.82	273		319	0.96	3.6		4.5	2.09	1613		1614
90	0.64	209		259	0.85	2.9		3.7	2.13	1446		1441
95	0.75	183		217	0.88	2.6		3.2	2.09	1264		1263
99	0.89	194		220	1.00	2.6		3.2	2.09	1204		1200
R^2	0.904		0.902		0.960		0.958		0.945		0.944	

Table III. Values of the parameters calculated for criteria from shearing and fracture tests. R^2 is the determination coefficient.

T (°C)	G_R		τ_R		$W_{4.6°}$		P_f		σ_f		G_f	
	α	β	α	β	α	β	α	β	α	β	α	β
25	1.05	75.2	1.35	6.6	1.10	211	0.64	745	0.67	11.0	0.42	417.2
30		74.0		6.6		204		703		10.4		399.5
35		71.0		6.4		194		687		10.4		403.4
40		67.6		6.1		186		637		10.1		391.9
45		65.8		5.8		178		601		9.6		424.6
50		62.3		5.4		165		534		9.2		428.8
55		58.2		4.8		149		474		8.5		412.0
60		52.4		4.2		131		426		7.9		441.5
65		44.7		3.6		111		368		7.2		461.4
70		35.2		3.0		89		313		6.3		442.5
75		29.3		2.6		74		254		5.5		445.7
80		24.1		2.3		62		204		4.7		175.3
R^2	0.903		0.875		0.971		0.676		0.736		0.351	

fracture test (P_f, σ_f and G_f) and basic density. The parameters α and β are calculated to adjust the theoretical law to experimental data (*table III*).

Correlation between G_f and basic density is less strong than other criteria ($R^2 = 0.351$ whereas R^2 is higher than 0.6 in other cases).

### 3.2. Influence of temperature on mechanical criteria

The curves representing the evolution of each mechanical criterion in function of temperature show the same typical relaxation pattern except for G_f. It is interesting to note that criteria representing deformation (ε_y, γ_R and d_f) increase with temperature whereas other criteria decrease. One wood species (Dicorynia) is chosen to give an illustration of this observation and mechanical criteria from the different tests are plotted as a function of temperature in *figure 6*.

The curves of E_R, G_R, P_f, σ_y, τ_R, σ_R, $W_{20\%}$ and $W_{4.6°}$ in function of temperature are typical of a viscoelastic material [3]. Globally, each of these criteria varies in function of temperature in the same way. At low temperatures this type of criterion is roughly constant (glassy region), then it decreases drastically around 55 °C (glassy transition), finally it tends to be again roughly constant (rubbery plateau). Nevertheless, it
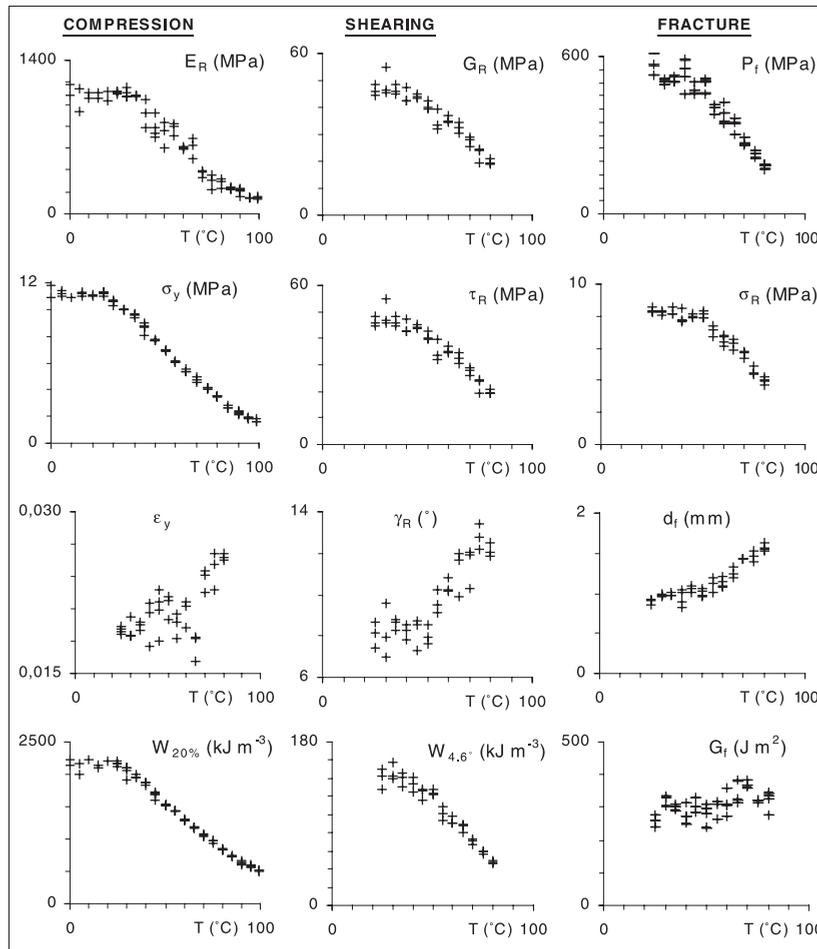
Figure 6. Evolution of the twelve mechanical criteria in function of temperature for one wood species (*Dicorynia*). Each cross represents one value of the three repetitions.
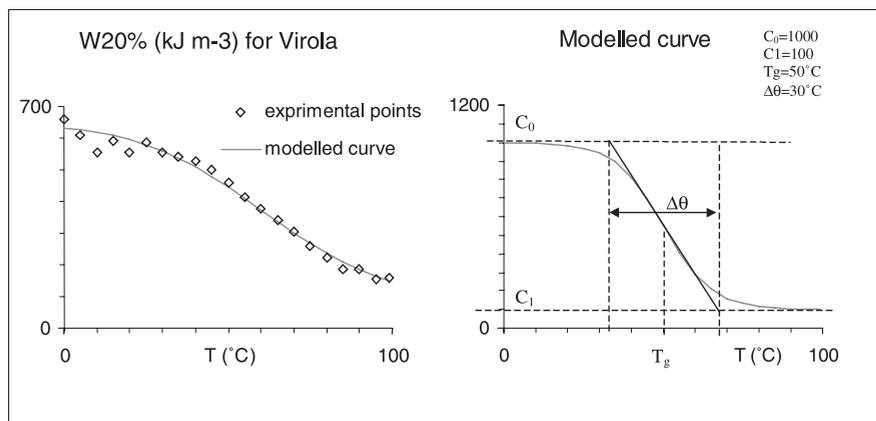

Figure 7. Illustration of the model of evolution of one criterion respect to temperature.

seems that the softening phenomenon is not completed at 80 °C. Regarding the experimental conditions, the drastic change of mechanical properties can be brought about by the glassy transition of one of the polymeric constituent of wood: lignin [4, 9]. Nevertheless, one should not forget that wood is a polymeric composite and so it presents a multitransition viscoelastic behaviour.

The fact that the energetic criterion G_f from fracture test is not related to temperature is important for the prediction of crack propagation. In simulation of crack propagation, G_f can be taken as constant.

In order to present the effect of temperature on every criteria, it was suggested to measure softening temperature on graphs. The curves of criterion in function of temperature were
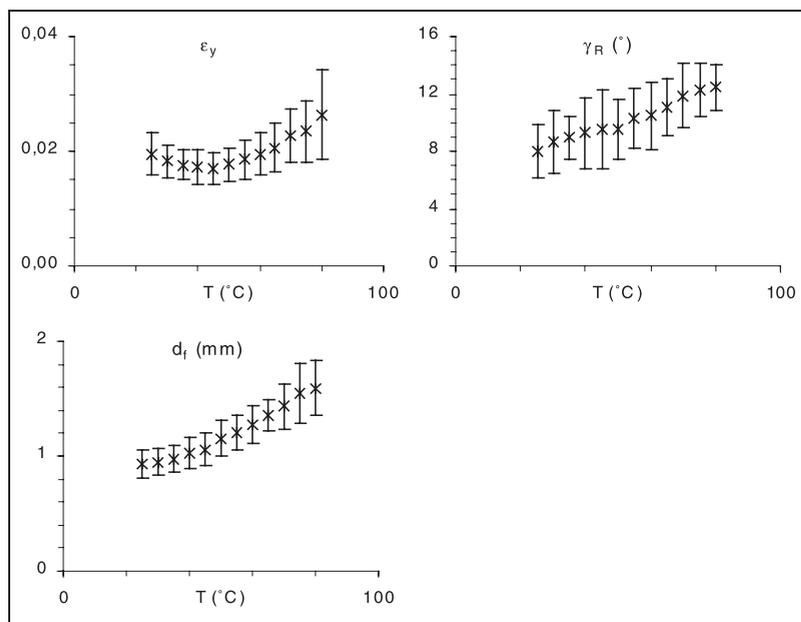
Figure 8. Evolution of ε_y, γ_R (°) and d_f (mm) in function of temperature. Crosses represent the average value on ten wood species, vertical lines show the standard deviation.

Table IV. Values of the softening parameters calculated from the evolution of three mechanical criteria from radial compression tests (E_R, σ_y and $W_{20\%}$) in function of temperature for each species.

	E_R			σ_y			$W_{20\%}$		
Species	T_g (°C)	$\Delta\theta$ (°C)	C_0/C_1	T_g (°C)	$\Delta\theta$ (°C)	C_0/C_1	T_g (°C)	$\Delta\theta$ (°C)	C_0/C_1
Parkia	69	73.1	10.3	61	85.4	10.4	55	98.4	8.7
Virola	62	66.0	15.0	64	68.4	9.7	61	79.3	8.5
Vochysia	53	37.1	7.4	56	68.8	9.9	54	60.9	5.7
Ocotea	57	48.6	14.5	57	78.8	10.2	58	82.2	9.2
Humiria	58	41.5	8.3	46	91.1	12.8	60	65.9	6.2
Dicorynia	60	50.4	10.9	60	64.1	13.7	59	63.1	5.4
Hymenolobium	60	45.0	9.7	58	49.4	6.9	57	49.4	5.2
Vouacapoua	57	40.8	9.0	57	74.3	13.9	56	65.2	4.7
Tabebuia	57	40.0	16.6	57	53.4	31.0	65	59.5	11.7
Bocoa	54	52.8	13.5	54	63.8	15.7	64	77.9	7.5

not smooth enough to allow a precise measure of softening temperature of relaxation phenomena. The following mathematical expression was used to describe the curves:

$$C = \frac{C_0 + C_1}{2} - \frac{C_0 - C_1}{2}\tanh\left(2\frac{T - T_g}{\Delta\theta}\right)$$

where C is the criterion measured (except G_f), C_0 and C_1 the limits at low and high temperature, T the temperature, T_g the temperature at the inflexion point and $\Delta\theta$ the variation of temperature required for C to decrease from C_1 to C_0 (*figure 7*).

The three main parameters calculated from this expression are T_g, which corresponds to the softening temperature, $\Delta\theta$ which gives an illustration of the spread of the relaxation phenomenon and the ratio C_1 over C_0 which gives the amplitude of the phenomenon. Values of these softening parameters are given in *table IV*, *table V* and *table VI* for each mechanical

parameters. *Table VII* gives an average value of these parameters for each mechanical criteria C.

Deformation criteria (ε_y, γ_R and d_f) are studied separately. It was shown previously that they are almost independent of wood species, so we can work on the average value on the ten species. *Figure 8* presents the evolution of average values of ε_y, γ_R and d_f in function of temperature.

Deformation criterion from compression test (ε_y), first decreases slightly from 1.9% to 1.7% between 25 and 45 °C and then increases until 2.6%. The value of γ_R increases from 8° to 12.5° while temperature increases from 25 to 80 °C, demonstrating that wood is more ductile at high temperature. The evolution of d_f is similar: d_f increases from 1 to 1.8 mm. A model can be applied to the evolution of γ_R and d_f using the following theoretical law:

$$C = \frac{C_0 + C_1}{2} - \frac{C_0 - C_1}{2}\tanh\left(2\frac{T - T_g}{\Delta\theta}\right)$$

where the parameters are the same as previously.

Table V. Values of the softening parameters calculated from the evolution of three mechanical criteria from rolling shear tests (G_R, τ_R and $W_{4.6°}$) in function of temperature for each species.

Species	G_R			τ_R			$W_{4.6°}$		
	T_g (°C)	$\Delta\theta$ (°C)	C_0/C_1	T_g (°C)	$\Delta\theta$ (°C)	C_0/C_1	T_g (°C)	$\Delta\theta$ (°C)	C_0/C_1
Parkia	62	37.5	3.4	62	48.1	2.6	62	47.5	4.1
Virola	64	38.7	4.4	58	43.6	2.9	60	46.7	4.4
Vochysia	59	48.4	7.1	53	43.4	2.7	51	57.6	7.0
Ocotea	58	56	4.0	56	47.7	3.5	54	61	5.8
Humiria	61	36.2	4.3	58	48.7	4.4	60	42.1	4.5
Dicorynia	63	45.8	3.6	57	46.7	3.7	61	42.7	4.6
Hymenolobium	62	36.6	4.7	58	40.8	4.0	59	45.2	5.6
Vouacapoua	61	43.6	4.1	58	46.2	3.7	58	44.3	4.7
Tabebuia	60	33.6	4.9	59	30.6	3.9	58	34.6	5.6
Bocoa	65	27.1	4.7	59	32.2	3.3	64	30.5	4.4

Table VI. Values of the softening parameters calculated from the evolution of two mechanical criteria from fracture toughness tests (P_f and σ_f) in function of temperature for each species.

Species	Pf			σ_f		
	T_g (°C)	$\Delta\theta$ (°C)	C_0/C_1	T_g (°C)	$\Delta\theta$ (°C)	C_0/C_1
Parkia	60	43.5	3.4	60	39.3	2.3
Virola	58	61.7	2.3	61	45.9	1.7
Vochysia	54	44.3	3.5	59	48.4	3.0
Ocotea	54	39.9	3.3	61	43.6	2.8
Humiria	54	37.8	5.0	57	44.5	4.0
Dicorynia	62	57.9	6.2	63	37.1	2.3
Hymenolobium	54	54	8.6	63	51	3.0
Vouacapoua	61	47.8	7.5	61	56.5	2.6
Tabebuia	56	45.9	10.7	59	47.2	4.8
Bocoa	58	47.5	6.6	60	38.8	2.8

Table VII. Average values of the parameters for each mechanical criteria C, the mean is calculated on the 10 species, "sd" represents the standard deviation.

Test	C	Tg (°C)	sd	$\Delta\theta$ (°C)	sd	C_0/C_1	sd
Radial compression	E_R	**58.4**	3.47	**40.3**	7.50	**7.5**	2.35
	σ_y	**57.4**	2.91	**52.4**	9.66	**6.1**	2.00
	$W_{20\%}$	**57.8**	4.34	**60.2**	5.55	**4.9**	0.87
Radial shearing	G_R	**61.5**	2.17	**40.3**	8.26	**4.5**	1.02
	τ_R	**57.8**	2.30	**42.8**	6.48	**3.5**	0.64
	$W_{4,6°}$	**58.7**	3.80	**45.2**	9.16	**5.0**	0.97
Fracture	P_f	**57.1**	3.14	**48.0**	7.69	**5.7**	2.72
	σ_f	**60.4**	1.84	**45.2**	5.96	**2.9**	0.86

Table VIII gives the values of the parameters calculated from this model for γ_R and d_f. These parameters are in the same range as those calculated from others criteria.

Values of T_g calculated from the evolution of each criterion respect to temperature are quite close. Nevertheless, two criteria have higher values for T_g: G_R and σ_f. This difference can be accounted for by a superposition of tension and compression strain during the shearing and fracture tests. Both $\Delta\theta$ and C_0/C_1 present an important variation from criterion to criterion.

The outcome of these observations is that softening temperature seems to be independent of mechanical criteria studied, whereas spread and amplitude of the softening behaviour are affected by them. These observations lead to the focus on one mechanical test to study the softening behaviour and one criterion. Compression test and E_R are selected.

3.3. Detailed study of one mechanical criterion: E_R from compression test

To go further in the investigations, we studied the influence of species on one criterion: E_R measured from compression tests. *Figure 9* presents the evolution of E_R in function of temperature for each wood species.

Table VIII. Values of the softening parameters calculated from the evolution of two deformation criteria γ_R and d_f.

| γR			df		
T_g (°C)	$\Delta\theta$ (°C)	C_0/C_1	T_g (°C)	$\Delta\theta$ (°C)	C_0/C_1
62	57	1.7	60	38	1.8

Examining the curves E_R in function of temperature, it seems that many species (especially Humiria and Bocoa) have a first inflexion point around 5 °C. This phenomenon may be accounted for by a secondary transition of lignin or by a glassy transition of hemicelluloses.

Applying the mathematical law presented in the previous paragraph to the evolution of E_R with respect to temperature, three softening parameters were calculated for each species: T_g, C_0/C_1 and $\Delta\theta$. From *table IV*, we observed that the softening temperature, T_g, varies from one wood species to the other between 54 °C and 65 °C. The glassy transition seems to depend on the wood species studied. The following question raises: what could be the structural parameters which handle the relaxation phenomenon?
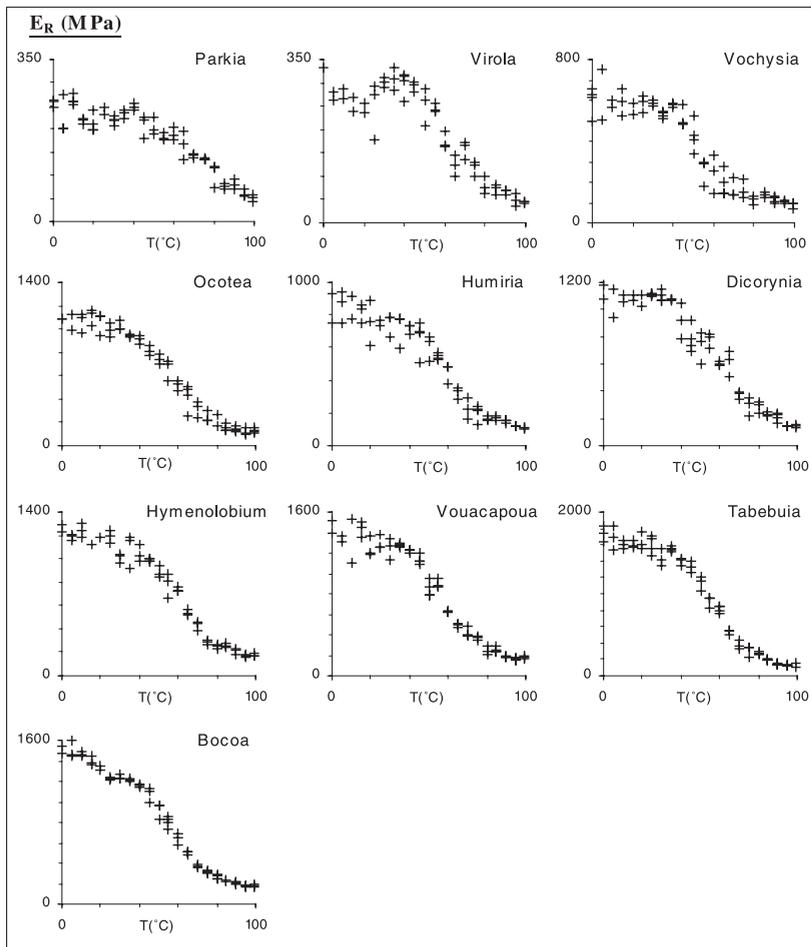
E$_R$ (MPa)

Figure 9. Evolution of E$_R$ (MPa) from compression test in function of temperature for each wood species. Single cross represents one value of the three repetitions.
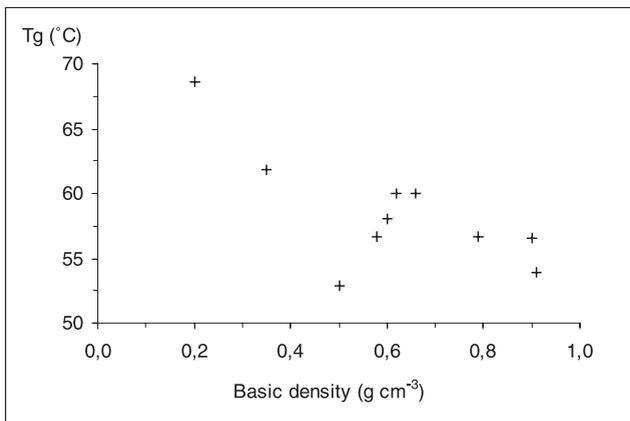
Figure 10. Evolution of T$_g$ in function of basic density.
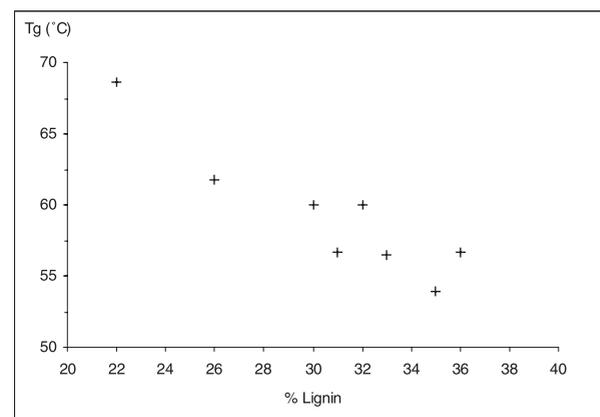
Figure 11. Evolution of T$_g$ in function of lignin percentage.

First it is suggested that basic density could explain the differences between wood species. Referring to the plot of T$_g$ as a function of basic density (*figure 10*), it appears that softening occurs at higher temperature for species with lower basic density. For basic density over 0.5 g cm^{-3}, this parameter seems not to influence T$_g$.

Nevertheless, we wonder if the basic density is the relevant parameter to explain differences between softening behaviour of wood species. It can be hypothesised that differences between species may be ascribed to chemical composition of wood. Looking at a data-base from CIRAD, we know the lignin composition of eight of the ten Guyanese species tested.

Referring to *figure 11*, T_g and the percentage of lignin seem correlated.

Unfortunately, it appears that the choice of these wood species is not neutral. Actually, it exists a relation between basic density and lignin percentage of these species, so we can not conclude about influence of chemical composition on softening behaviour.

4. CONCLUSION

These mechanical tests have provided numerous data about transverse mechanical behaviour of ten tropical species under water-saturated conditions. Mechanical properties were studied through three kinds of test: radial compression, transverse shearing and transverse fracture toughness. Influence of both basic density and temperature was highlighted.

All mechanical criteria, except deformation criteria depend on wood species. The relation between these criteria (C) and basic density can be expressed by the following power law: $C = \beta \times x^{\alpha}$. The parameter α varies between 1.3 to 2.1 for compression, 1 to 1.3 for shearing and 0.4 to 0.7 for fracture toughness, according to criteria inside the test.

The influence of temperature on transverse properties of water-saturated samples of tropical wood was clearly noticed. Softening phenomena were observed on mainly all the criteria except for deformation criteria and G_f. This last remark is coherent with classical analysis of crack propagation. Deformation criteria increase with temperature which shows that wood is more ductile when temperature increases. Other criteria depend on temperature following law like:

$$C = \frac{C_1 + C_0}{2} - \frac{C_1 - C_0}{2}\tanh\left(2\frac{T - T_g}{\Delta\theta}\right).$$

The softening temperature, T_g, corresponding to the inflexion point of the curve, is varying between 54 °C and 65 °C, depending more on wood species than on mechanical criteria.

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