5
Effect of moisture contents at room temperature and frozen conditions on the mechanical properties of Dendrocalamus giganteus (DG) bamboo

5.1. Introduction

Artificial and special synthetic fibres such as Rayon, Acetate, Polyester, Carbon fibres, Aramids and others can be produced with a definite range of properties. The properties of different natural fibres vary considerably depending on their structures, whether the fibres are taken from the plant stems, leaves or seed, and the quality of the plant's location. Depending on their origin, vegetable fibres can be grouped into hair, bast or hard fibres. Bast (hemp, jute, rattan) and hard fibres (bamboo, sisal, coir) have qualities that are most useful in composites [65]. In practically all cases, cellulose is the main component of vegetable fibres. The elementary unit of a cellulose macromolecule is anhydro-d-glucose, which contains three hydroxyl (-OH) groups. These hydroxyl groups form hydrogen bonds inside the macromolecule itself (intramolecular) and between other cellulose macromolecules (intermolecular) as well as with hydroxyl groups from moist air. Therefore, all vegetable fibres are hydrophilic in nature and their air dry moisture content can reach about 3-13% [44]. From a mechanical point of view the following parameters influence fibre properties [66, 67]: Fibre diameter; Size of the crystalline fibrils and non-crystalline regions; Spiral angle of fibrils; Supramolecular structure (e.g. degree of crystallinity); Degree of polymerization (DP); Crystal-structure (type of cellulose and defects); Orientation of the chains (non-crystallinecellulose, crystalline fibril); Void structure (content of pores, specific interface, size of pores). Also, moisture content has a great influence in natural fibres.

Bamboo of the species *Dendrocalamus giganteus (DG)* is one of the largest in the world. Its geometrical characteristics permit a classification of its structure as a very slender cylinder. The culm is characterized by: 400-550 mm long internodes which have a culm wall surrounding quite flat diaphragms; 150-250 mm diameter at the base; 10-25 mm in wall thickness and 30000-35000 mm tall [68]. The bamboo culm consists of a functional gradient distribution of vascular bundles and xylem, where the vascular bundle includes sheaths of fibres and sieve tubes (Figure 5.1b). As can be observed in the DG cross-section

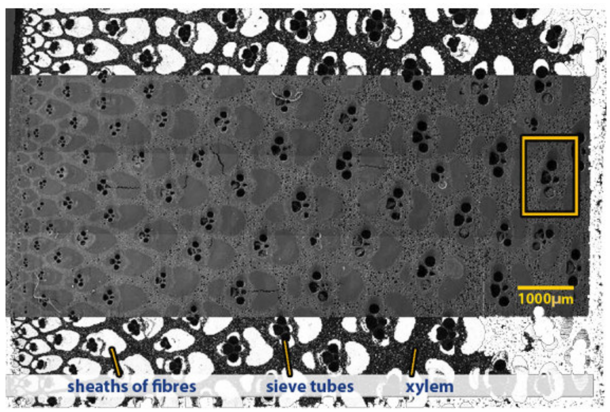
(Figure 5.1a) the vascular bundles change their geometrical characteristics and quantities of sheaths of fibres and sieve tubes. Scanning from the external to internal culm surface (left to right in Figure 5.1a) the first column of vascular bundles is composed of one sieve tube of 10-20 µm diameter, and one sheath of fibres with an average diameter of 345 µm. Also in this region lines of xylem are of 10-20 µm in width are observed. The vascular bundles in the last column include five sheaths of fibres, where three of them have average diameters of 210-250µm, one with an average diameter of 100-120 µm, and one with an average diameter of 350 µm. Also three sieve tubes with an average diameter of 210-230 µm and one tube 60-80 µm are present. The xylem lines in this region are 600-650 µm in width. This distribution and the mechanical resistance of the fibres provide a functional gradient of elastic modulus for the bamboo cross section.

The sheaths of fibres are the most important component that determines the mechanical properties of bamboo, and the xylem can transfer loads and take the role of a composite matrix. Therefore, in view of its macro-mechanical behaviour, bamboo is typically a unidirectional fibre reinforced bio-composite. Its unique direction, length of bamboo fibres and its microstructure characteristics, such as the volume fraction and the distribution of sheaths fibres optimize its mechanical properties as a composite material structure [47].

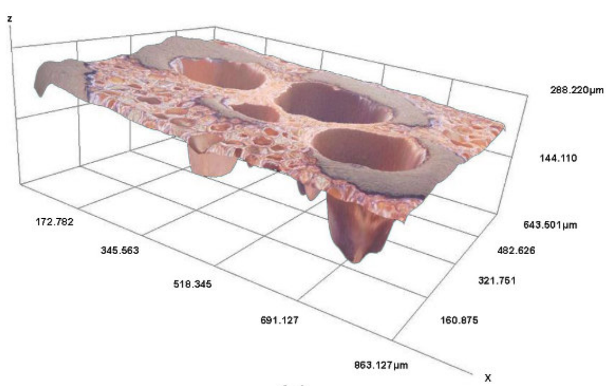
Dendrocalamus giganteus bamboo is one of the species with highest mechanical properties (as presented in this study) which can be applied in construction, energy field (structural parts of wind turbine blades), automotive field (car structures and panels) and for aviation (small aircraft). Few authors have investigated DG bamboo and its relevance in the use of composite materials. However, its use as an application in construction for concrete reinforcement has been reported by Ghavami [38]. Reinforcement of wood beams using laminated bamboo is reported by Lima and Dias [39]. Ghavami and Rodrigues [40] using digital image processing (DIP) methodology were able to establish the variation of the volume fraction of fibres of *Dendrocalamus giganteus* bamboo across its wall's thickness.

However, studies on the mechanical properties of DG bamboo layers (of the culm cross section) which showed the highest properties for engineering were not reported, also the effects of moisture content at room temperature and frozen condition on the bamboo's mechanical properties were not reported in the available scientific literature.

In this study, the tensile and compression properties on bamboo layers at different moisture content and the corresponding fibres volume fraction (V_f) and xylem tissue were measured on a large quantity of specimens. The properties of the bamboo's components and its failure were analyzed in detail and appropriate mathematical equations have been established. Further tensile and compression tests on a large quantity of frozen samples were performed. The results were compared and discussed with those tested with a variation of moisture content at room temperature.



a)



b)

Figure 5.1- (a) Transverse section of *Dendrocalamus giganteus (DG)* bamboo showing a decreasing distribution density of vascular bundles from the external to internal surface and the components of the culm wall (along the radial direction) (b) vascular bundle

5.2. Tensile properties

5.2.1. Experimental approach

A tensile test parallel to the grain was performed at three different fibre volume fractions (cutting the first three layers of 2 mm thick from the external to the internal surface of the culm wall cross-section, Figure 5.3). The fibre volume fraction (V_f) was also measured on the transverse section using DIP. 90 specimens at 2% moisture content were taken separately (45 of them were frozen to -18 ˚C in a freezer cabinet) 1035 specimens were immersed in distilled water to increase moisture content (for a maximum time of 167 days) with 360 of them frozen when they reached the moisture content required for testing. A digital moisture meter (Promtimeter MMS) was used to measure the percentage of the moisture content in the specimens. The DG bamboo used in the tests was 4 years old and sourced from plants growing at the Pontifical Catholic University of Rio de Janeiro (PUC-Rio), Brazil. After cutting, the bamboo culms were dried in situ in a vertical position for two weeks and then transported in 3000 mm long pieces to the University of Cambridge's engineering workshop to be stored at room temperature for 5 months (23˚C and 67% air humidity).

5.2.2. Experimental details

Specimens were taken from the internodes section 11, 12, 13 and 14 (height approximately 5000 mm to 7500 mm) with a culm wall thickness of about 15 mm. The culm sections were longitudinally split into 210 mm (L, longitudinal) x 5 mm (T, tangential) strips. They were then delaminated into 2 mm thick layers from the external to the internal surface of the culm walls, after the cortex and pith periphery were removed. 1125 specimens were prepared (375 for each V_f). The final shape, dimension and characteristics of the specimens for the tensile tests are shown in Figure 5.2. The dimensions of the effective experiment part (middle region) were 120 mm (L) x 5 mm (T) x 2 mm (R, radial). Using epoxy resin, 90 mm at each end of both sides of the specimen was reinforced by a 1 mm thick bamboo layer, taken from the internal surface of the bamboo culm (having the characteristics of being soft and highly flexible) to prevent crushing of the bamboo on the clamping region and to spread the tension along the fibres tested. The clamping region for the samples was 45 mm.

In order to obtain a high precision for the tensile strain, a C strain gauge sensor was installed on the effective experiment region. Tensile tests were performed on a computer-controlled testing machine (INSTRON 5500R). The specimens were loaded at a constant crosshead speed of 2 mm/min until failure. Tensile tests was performed on a total of 1125 specimens with 15 specimens being tested for each moisture content at both room temperature and frozen conditions (the frozen specimens were taken directly from the freezer and tested, still frozen). The test room temperature and humidity was 23˚C and 40% respectively.

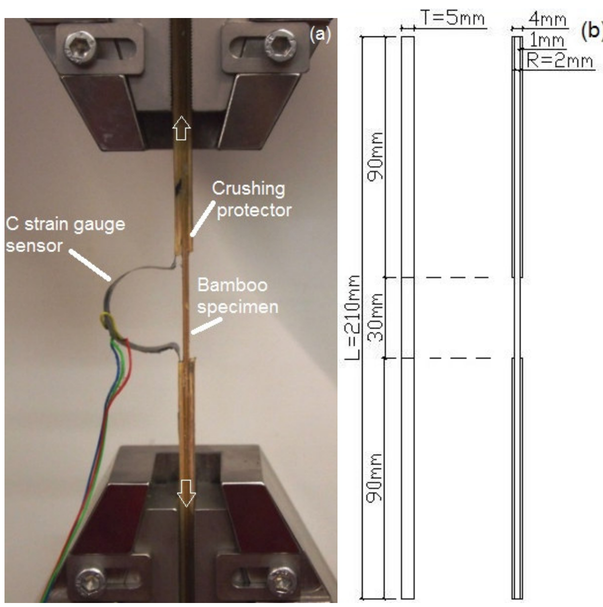


Figure 5.2- (a) Tensile test (b) bamboo specimen dimension

5.2.3. Fibre volume fraction (V_f) measurements

Samples were taken from each of the internodes that were used to prepare the experimental specimens. In order to estimate the value of V_f, the area of fibres (A_f) and the area of the first, second and third 2 mm layers from the external to the internal surface of the culm walls cross-section were measured (A_l) using DIP. Sections were observed under an optical microscope equipped with a digital camera linked to an image analysis system. Images were taken of the section and then they were treated to distinguish the sheaths of fibres from the xylem. The values of A_f / A_l were then measured by the image analysis software. Figure 5.3 shows an example of the images of each section of the samples located at the first, second and third 2 mm layers from the external to the internal surface of bamboo culm walls cross-section.

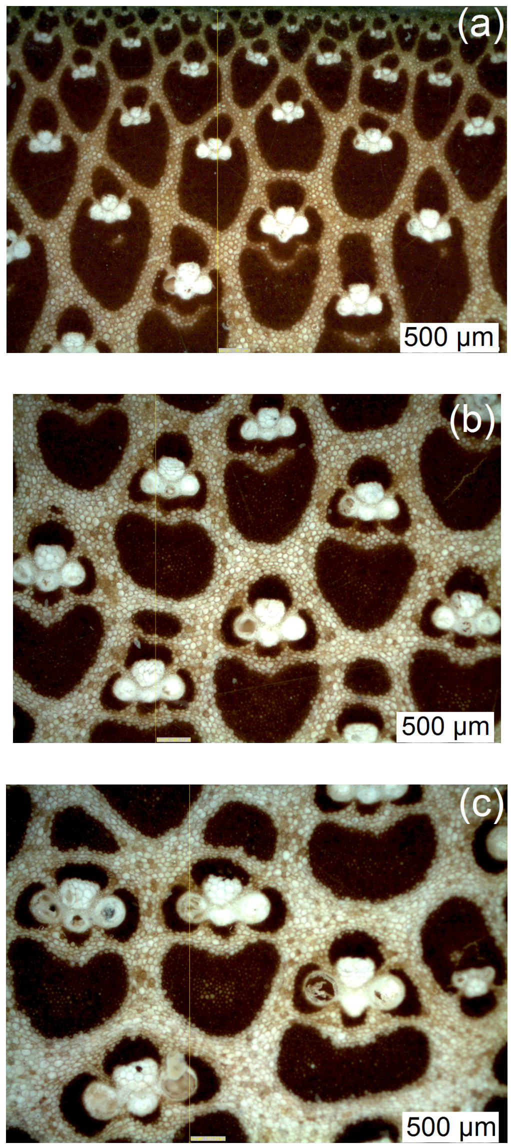


Figure 5.3- Images used for definitions of fibre volume fraction (V_f,) (a-c) areas of the first, second and third 2 mm layers from the external to internal surface bamboo culm where the corresponding values of V_f were 57.4%, 52.3% and 47.4% respectively

5.2.3. Results and discussion

5.2.3.1. Moisture absorption

To understand the effect of moisture content on the mechanical properties of bamboo DG the specimens were prepared and submerged in distilled water at normal conditions and at 23˚C. To measure the moisture content (after absorption) at different V_f (57.4%, 52.3% and 47.4%), the bamboo specimens were stored in three groups separately for 167 days. Afterwards, at defined time intervals the change in moisture content caused by the water up take was monitored on seven samples (randomly chosen) from each group by a moisture meter (Promtimeter MMS), with precautions taken to remove the surface moisture by wiping the samples before metering. The moisture absorption data results show that the kinetics of absorption, and the moisture content at equilibrium distinctly increase with increasing V_f as shown in Figure 5.4 (fitted curves on average results). In this figure moisture content is plotted against time for the bamboo specimens. It can be observed that initially, there is almost a linear increase in the equilibrium moisture content, leading gradually to a constant saturation level. Specimens with 57.4%, 52.3% and 47.4% fibre volume fraction reached 85% moisture content at 80 days, 125 days and 167 days respectively. The fact that moisture content gradually increases and then becomes almost constant leads to the conclusion that the mechanism of moisture change is different beyond the saturation time.

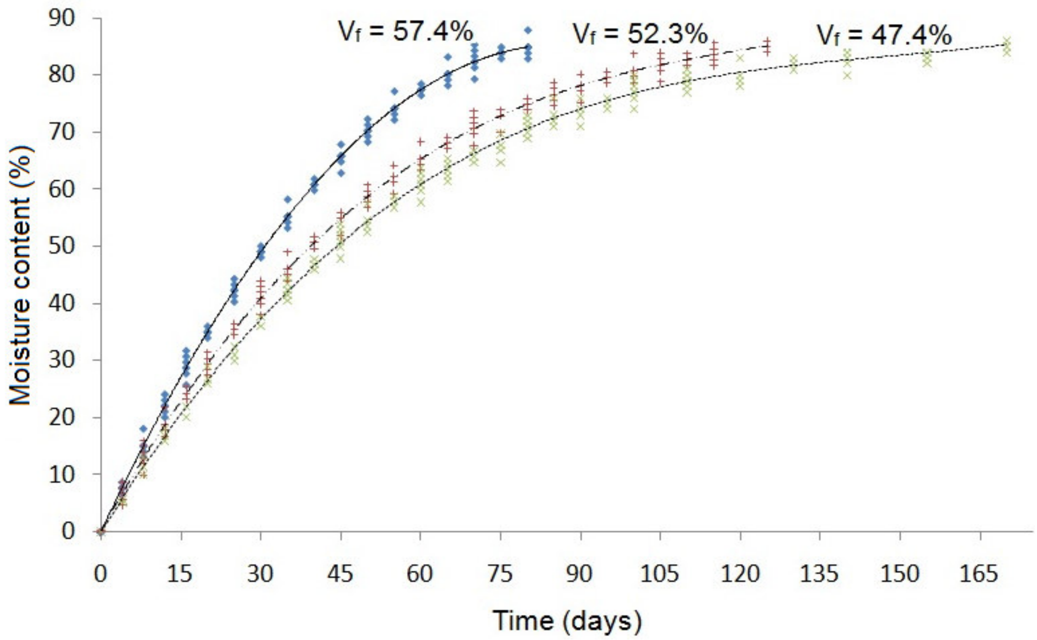
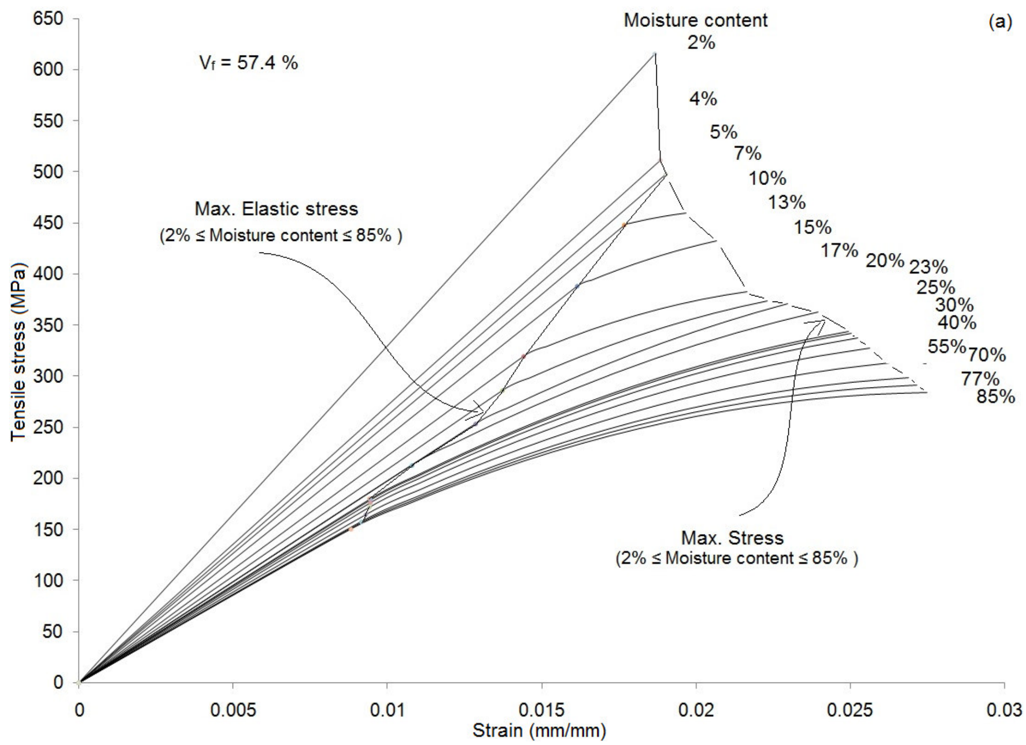


Figure 5.4-Moisture contents of the first, second and third 2 mm layer (V_f, 57.4%, 52.3% and 47.4% respectively) from the external to the internal surface of the DG bamboo culm

5.2.3.2. Moisture content effects on tensile stress-strain

The tensile stress–strain curves of DG bamboo layers (V_f , 57.4%, 52.3% and 47.4%) containing different levels of moisture content are shown in Figure 5.5. The samples containing V_f 57.4%, 52.3% and 47.4% failed showing linear stress-train from the beginning of loading to the breaking point when the level of moisture content was lower than 5%, 4% and 3% respectively. It was shown that the modulus and tensile strength decreased because of the plasticization effect resulting from the absorption of water. The specimen containing moisture content up to 13% showed evidence of only a small amount of necking. However, the necking decreased as the moisture content increased. The samples containing moisture content between 23% and 85% did not exhibit any appreciable necking. With variation in moisture level content the stress–strain behaviour of the DG bamboo samples can be grouped into three types: Elastic, with increasing stress till failure (~ up to 4.5% moisture); Elastic and plastic, where stress is increased smoothly after the elastic region till failure (~ 4.5% to 15% moisture); Elastic and extremely plastic with the stress level maintaining relatively constant till failure (~ above 15% moisture). As shown in Figure 5.5 these three behaviours are more delimited for V_f 52.3% and 47.4%.

In conventional composites it has been shown that the water particles deteriorate the interface bonding between the matrix and its reinforcement. Therefore it is possible that a similar effect may occur between bamboo fibres and the xylem (matrix) resulting in the loss of strength, elasticity and further deformation. Consequently the stress–strain curve becomes flatter until the specimen breaks.



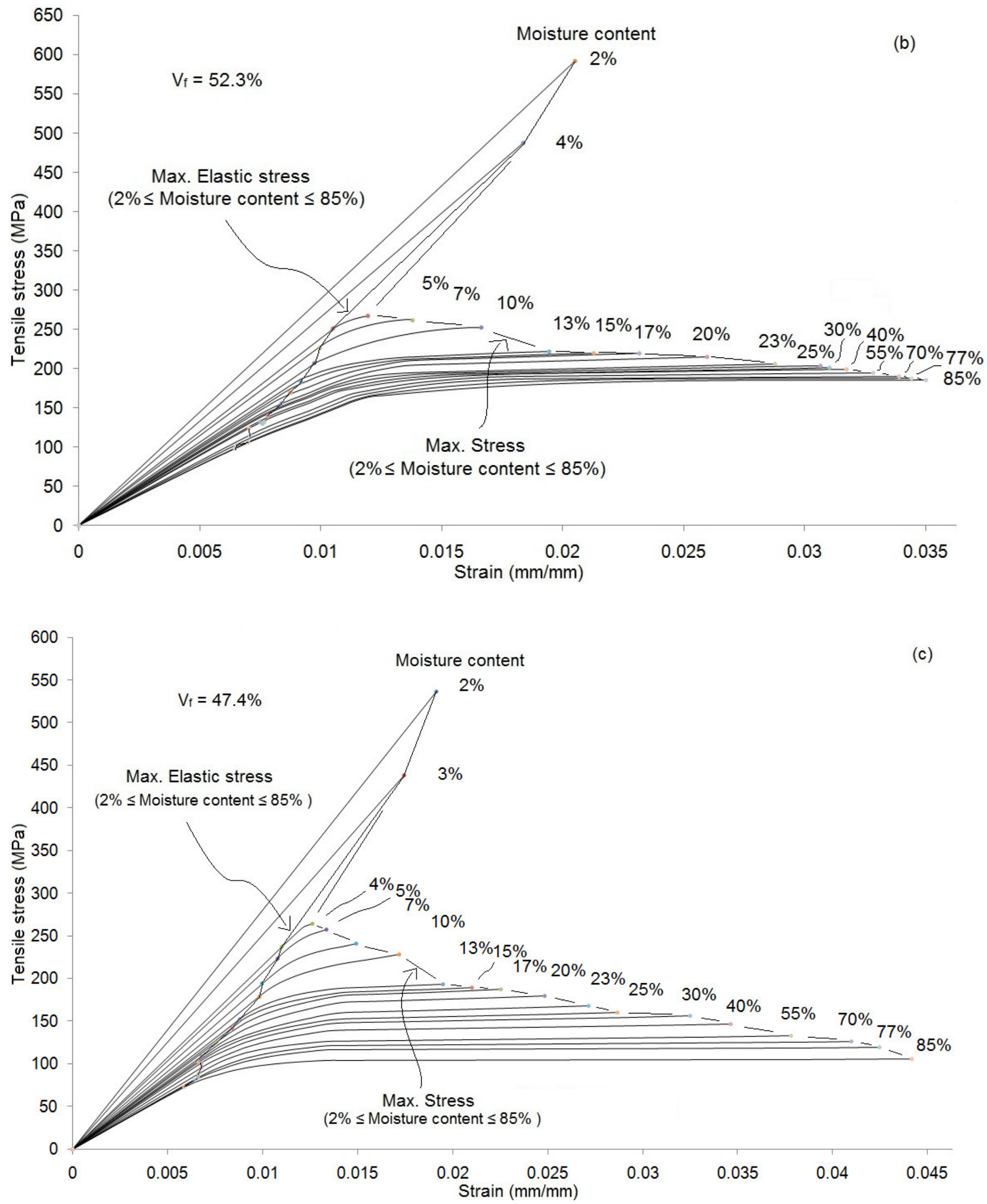


Figure 5.5- Tensile stress-strain curves for samples containing V_f (a) 57.4% (b) 52.3% and (c) 47.4% at moisture content between 2% and 85%

5.2.3.3. Moisture content effects on tensile modulus of elasticity (TMOE)

The tensile modulus of elasticity (TMOE) was defined from the initial linear part of the stress-strain curves. In general, the moisture content effects on TMOE on DG bamboo layers are independent of V_f studied as shown in Figure 5.6. Therefore the modulus variation for all of them can be classified in four regions, where three are following an accentuated decreasing logarithmic curve and one a gently decreasing linear function. Figure 5.6 shows the modulus variation due to the absorption of water. Considering the TMOE of 2% moisture content as initial reference, the reduction in the modulus at the limit of the first region (~ 4.5% moisture content) is approximately 20.5% (average value). If the moisture content is increased up to 10% (second region) the reduction of the modulus is approximately 28.4%. At the end of the third region (23% moisture content) the increase in moisture content causes a considerable reduction in the modulus of elasticity (approximately, 41.5%). In the last region the variation of the modulus is nearly the same (moisture content more than 23%), since the water particles almost become homogeneous inside the material.

The modulus of elasticity against moisture content (Figure 5.6) shows a similar change as shown in the tensile strength (presented later). It decreases with increasing moisture content as attributed to the action of water as a softener for bamboo polymers which is similar to the data for wood and paper materials [69].

From the results the TMOE of DG bamboo on the layers with V_f 57.4%, 52.3% and 47.4% can be calculated using the following equation if the moisture content is considered (with an average standard deviation presented in Table 5.1):

2%≤ Moisture content < 23% (V_f equal to 57.4%, 52.3% and 47.4%, respectively)

$$\text{TMOE (GPa)} = -4.534 \ln (M_c (\%)) + 34.558 \quad (5.1)$$

$$\text{TMOE (GPa)} = -4.849 \ln (M_c (\%)) + 32.388 \quad (5.2)$$

$$\text{TMOE (GPa)} = -4.8 \ln (M_c (\%)) + 30.124 \quad (5.3)$$

23%≤ Moisture content ≤ 85 (V_f equal to 57.4%, 52.3% and 47.4%, respectively)

$$\text{TMOE (GPa)} = -0.04\, M_c (\%) + 20.151 \quad (5.4)$$

$$\text{TMOE (GPa)} = -0.0387\, M_c (\%) + 18.446 \quad (5.5)$$

$$\text{TMOE (GPa)} = -0.0491\, M_c (\%) + 16.76 \quad (5.6)$$

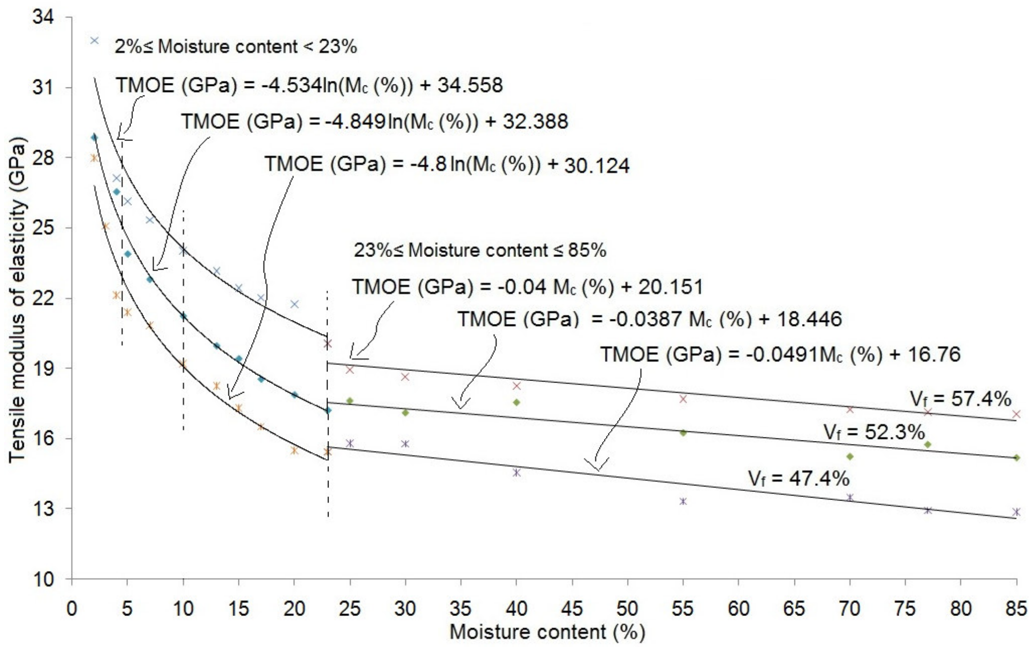


Figure 5.6- Tensile modulus of elasticity-moisture content curves for samples containing V_f 57.4%, 52.3% and 47.4% at moisture content between 2% and 85%

5.2.3.4. Moisture content effects on tensile stress

In Figure 5.7 the relationship between the tensile strength and moisture content is shown. The tensile strength is affected by the moisture content in a similar tendency for all V_f studied. There is a sharp decrease up to approximately 23% moisture content and a smooth linear decrease after that. As presented in Figure 5.7 the differences between the maximum elastic strength and maximum strength at failure decreases as V_f is decreasing. These differences are 150.5 MPa, 78.2 MPa and 48.3 MPa for V_f 57.4%, 52.3% and 47.4% respectively (average at the linear zone). The results show that the increase of moisture content on a dry DG bamboo leads to a plastic region effect on the material's behaviours for the stress-strain curves, where the limit of moisture content for only elastic response are approximately 5%, 4% and 3% for V_f 57.4%, 52.3% and 47.4% respectively, as can be observed in Figure 5.7.

It seems that the absorbed moisture up to approximately 10% has far greater effect on the maximum elastic tensile strength and maximum tensile strength; about 70.2%, 42.7% and 42.6% of the strength at 2% remain for V_f 57.4%, 52.3% and 47.4% respectively. From 23% of moisture content, where the maximum tensile strength is 56.7%, 34.7% and 31.3% of the strength at 2% for V_f 57.4%, 52.3% and 47.4% (respectively) the effect of moisture content variation does not cause considerable reductions. The reduction of mechanical properties can be attributed to the plasticization of matrix, plasticization of fibres, reduction of fibre/matrix interfacial adhesion and reducing mechanical interlocking friction between the fibres and matrix due to the water absorption.

From the results the tensile stress of DG bamboo on the layers with V_f 57.4%, 52.3% and 47.4% can be calculated using the following equation if the moisture content is considered (see Table 5.1 for standard deviation at different moisture content):

For maximum elastic stress (V_f equal to 57.4%, 52.3% and 47.4%, respectively):

2%≤ Moisture content < 23%;

$$\sigma_{TE}\ (MPa) = 664.84\ e^{-0.056\ Mc\ (\%)} \quad (5.7)$$

$$\sigma_{TE}\ (MPa) = 853.61(M_c\ (\%))^{-0.601} \quad (5.8)$$

$$\sigma_{TE}\ (MPa) = 714.42\ (M_c\ (\%))^{-0.618} \quad (5.9)$$

23%≤ Moisture content ≤ 85;

$$\sigma_{TE}\ (MPa) = -0.4704\ M_c\ (\%) + 190.47 \quad (5.10)$$

$$\sigma_{TE}\ (MPa) = -0.5828\ M_c\ (\%) + 147.3 \quad (5.11)$$

$$\sigma_{TE}\ (MPa) = -0.5191\ M_c\ (\%) + 116.59 \quad (5.12)$$

For maximum stress (V_f equal to 57.4%, 52.3% and 47.4%, respectively):

$$\sigma_T\ (MPa) = -99.38\ \ln\ (M_c\ (\%)) + 653.03 \quad (5\% \leq \text{Moisture content} < 23\%) \quad (5.13)$$

$$\sigma_T\ (MPa) = 576.29\ (M_c\ (\%))^{-0.344} \quad (4\% \leq \text{Moisture content} < 23\%) \quad (5.14)$$

$$\sigma_T\ (MPa) = 514.33\ (M_c\ (\%))^{-0.365} \quad (3\% \leq \text{Moisture content} < 23\%) \quad (5.15)$$

23%≤ Moisture content ≤ 85;

$$\sigma_T\ (MPa) = -0.9733\ M_c\ (\%) + 366.45 \quad (5.16)$$

$$\sigma_T\ (MPa) = -0.2986\ M_c\ (\%) + 210.67 \quad (5.17)$$

σ_T (MPa)= -0.9158 M_c (%) + 183.27 (5.18)

5.2.3.5. Effect of frozen moisture on tensile stress

The study on the moisture content under frozen conditions is also of interest in the investigation of the structural parts of wind turbine blades, particularly in regions where the climate or winter period is cold. Also aviation experiences the same environment challenges. Hence the following investigation can prove to be very useful. As discussed earlier there is degradation in the mechanical property of DG bamboo when its moisture content is increased. This is also true for sub-zero conditions, and the effect of moisture under frozen conditions can similarly be investigated. In this case the measure of mechanical behaviour is observed in the context of tensile stress. So, the effect of moisture content on tensile stress values were recorded for both plain and frozen specimens under the same level of moisture content, and plotted in Figure 5.7.

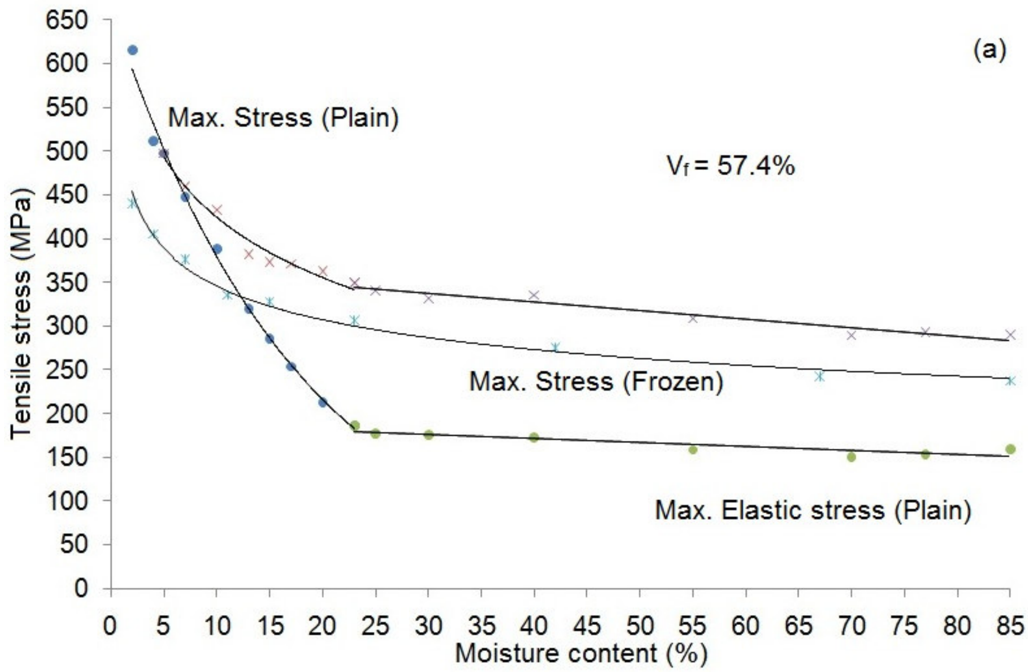
As shown in the figure (Figure 5.7), with the exception of the DG bamboo layer with V_f equal to 57.4% the effect of frozen moisture content up to approximately 4% is very accentuated. At 2% frozen moisture content the tensile strength for V_f 52.3% and 47.4% is 37% and 29.4% respectively of their correspondent strength at plain conditions (for V_f 57.4% it is 71.6%). However, it is observed in the results as given in Figure 5.7 that the tensile stress of all V_f studied with frozen moisture was lower than the maximum stress of plain specimens with the same moisture content. This may be due to the increase in swelling stresses, due to the volume expansion of moisture during freezing leading to damage of the xylem tissue that works as a matrix transferring tensions. The big difference between the specimens with V_f 57.4% and the other two at 2% frozen moisture may be because of the existence of more xylem in the specimens, which results in more deformation and the release of extra residual bonding between the fibres and matrix.

From the results the tensile stress of DG bamboo on the layers with V_f 57.4%, 52.3% and 47.4% can be calculated using the following equations if the frozen moisture content is considered (see Table 5.1 for standard deviation at different frozen moisture content): For maximum frozen stress to V_f equal to 57.4%, 52.3% and 47.4%, respectively (2%≤ Moisture content ≤ 85%):

σ_{TF} (MPa) = 510.78 (M_c (%))$^{-0.17}$ (5.19)

σ_{TF} (MPa) = -19.22 ln (M_c (%)) + 229.96 (5.20)

σ_{TF} (MPa) = 186.83 (M_c (%))$^{-0.198}$ (5.21)



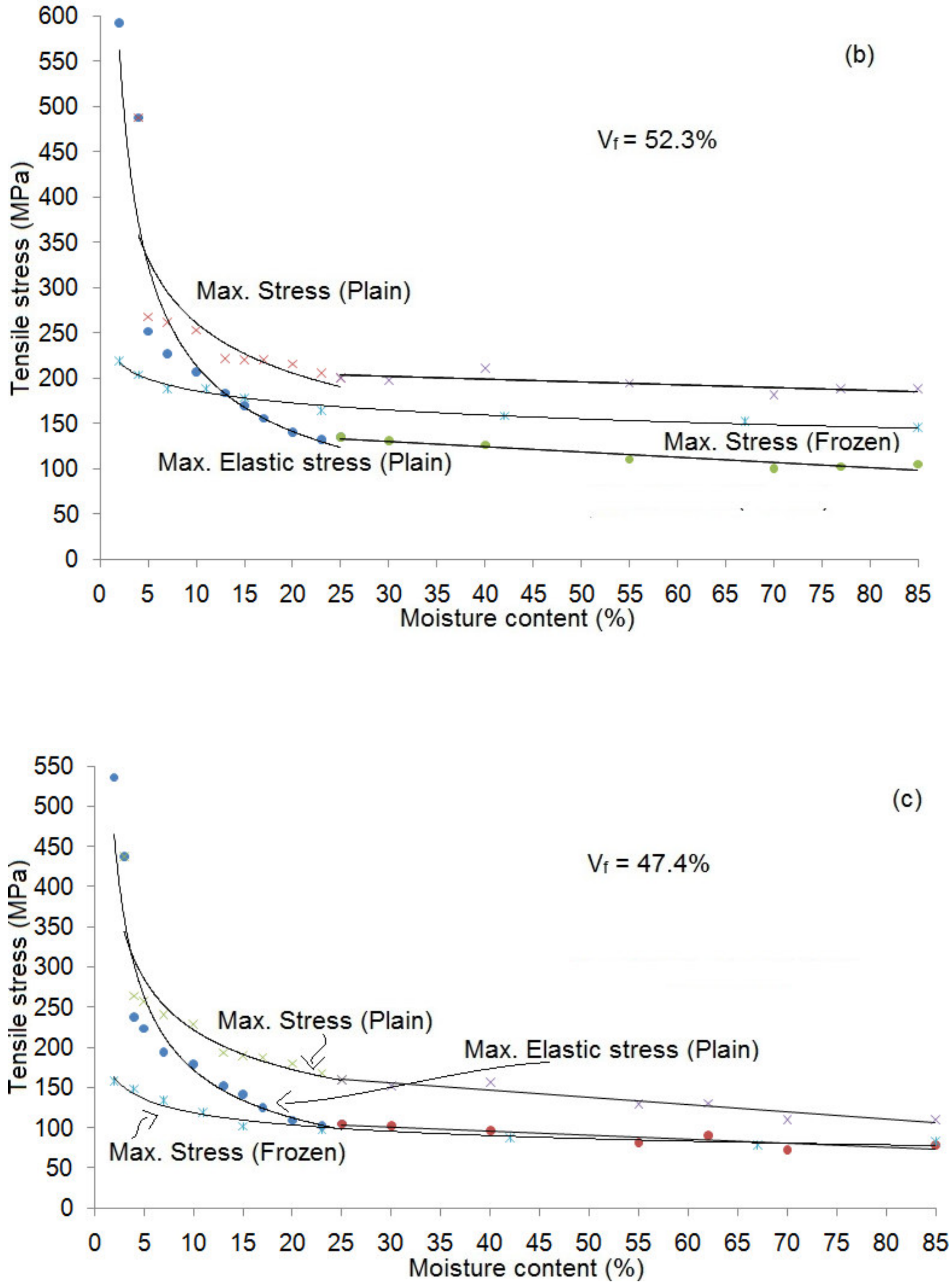


Figure 5.7- Tensile stress-moisture content curves for samples containing (a) V_f 57.4% (b) 52.3% and (c) 47.4% at plain and frozen moisture content between 2% and 85%

5.2.3.6. Fibre tensile strength and TMOE estimation

The bamboo culm wall can be considered as a unidirectional long fibre reinforced composite as its fibres are longitudinally oriented between the nodes. Therefore, in view of mechanical behaviour, the bamboo culm can be simplified as a composite of a parallel connection model composed of two elements, i.e., fibres and which is assumed as matrix. According to the parallel connection model, loads on the composite should be shared by the two elements, i.e., bamboo fibres and xylem, and the strains of the two elements are equal. Thus, the following equations can be deduced [70]:

$$\sigma_c = \sigma_f V_f + \sigma_x V_x = \sigma_f V_f + \sigma_x (1 - V_f) \quad (5.22)$$

$$E_c = E_f V_f + E_x V_x = E_f V_f + E_x (1 - V_f) \quad (5.23)$$

Where σ_c, E_c, σ_f, E_f, σ_x and E_x were noted as tensile stress and the corresponding TMOE on the transverse section of the bamboo culm specimen, fibre and xylem, respectively. V_f and V_x are the volume fractions of fibre and xylem ($V_f + V_x = 1$).The variation of V_f of the culm wall along the radial direction on the region considered in this study was established (Figure 5.3). Figure 5.5 shows some *σ*–□ curves measured on the bamboo culm (layers, 2 mm thick) with different V_f values, considering only the results for moisture content 2% as *σ*–□ were entirely linear. Positive linear relationships were found between V_f with tensile strength and TMOE, respectively. As shown in Figure 5.8 and Eqs. 5.24 and 5.25 (average values of 45 specimens).

$$\sigma_c = 791.62\, V_f + 166.64 \quad (5.24)$$

$$E_c = 51.218\, V_f + 3.16 \quad (5.25)$$

According to Eqs. 5.22 and 5.23, the tensile strength and TMOE of fibre and xylem were estimated as σ_f = 958.3 MPa, E_f = 54.4 GPa, σ_x = 166.6 MPa and E_x = 3.1GPa, respectively. This estimation suggests the high potential for reinforcement applications of the DG bamboo fibres.

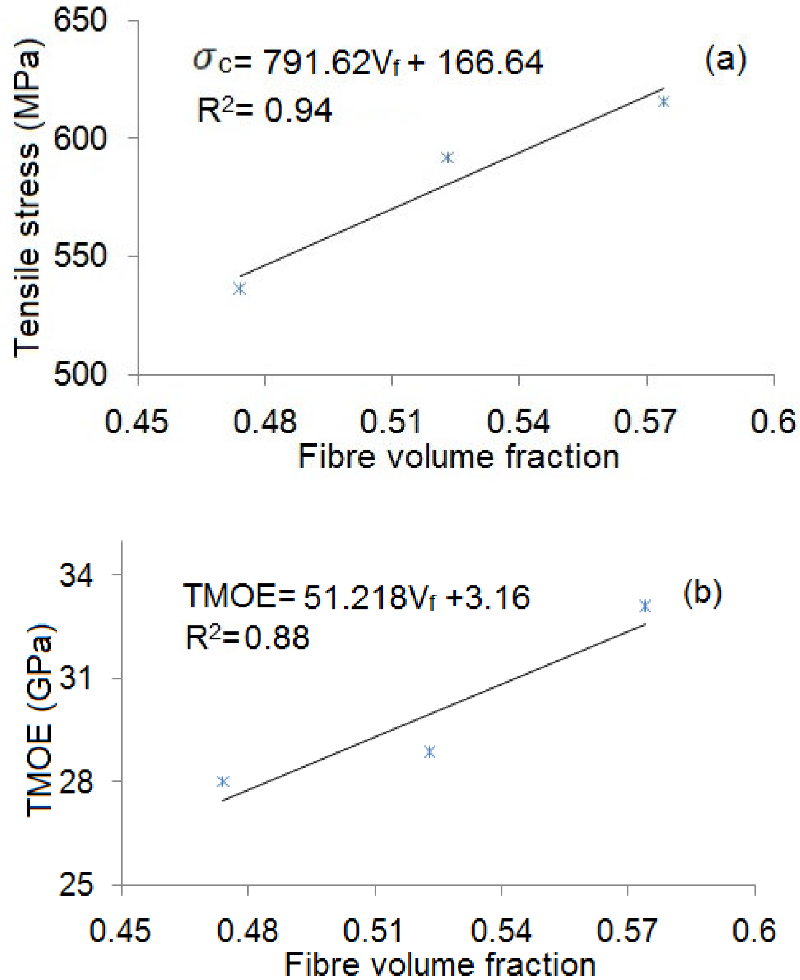


Figure 5.8- Relationship between (a) fibre volume fraction (V_f) and bamboo tensile strength and (b) TMOE

Table 5.1- Average results of tensile test

Moisture content (%)	**Number of samples**	**Average Max. Tensile stress (MPa)**	**Average Max. Elastic Tensile stress (MPa)**	**Average TMOE (GPa)**	**Standard deviation (respectively)**		
V_f =57.4%	Room temperature						
2	15	615.55	615.55	33.00	26.77	25.49	4.25
4	15	511.23	511.23	27.14	24.36	24.79	4.81
5	15	497.31	497.31	26.13	22.63	21.33	4.42

7	15	459.04	447.77	25.33	20.61	18.88	4.35
10	15	432.27	387.96	24.02	24.17	24.11	5.90
13	15	382.59	319.62	23.16	26.32	22.05	6.89
15	15	373.47	286.05	22.43	25.92	20.54	7.06
17	15	370.98	253.72	22.02	24.11	27.41	4.65
20	15	362.42	212.98	21.73	24.91	26.07	5.56
23	15	349.03	185.67	20.07	26.00	22.08	5.67
25	15	340.49	177.38	18.94	23.20	26.83	6.97
30	15	331.79	175.42	18.65	22.82	26.16	4.90
40	15	335.17	172.68	18.24	23.17	23.78	4.34
55	15	308.57	158.66	17.69	23.72	27.45	6.50
70	15	289.27	150.50	17.24	26.10	26.97	7.47
77	15	293.12	153.76	17.14	26.56	25.83	6.93
85	15	290.00	159.19	17.04	25.72	19.28	4.49
V_f =52.3%							
2	15	591.85	591.85	28.87	26.12	24.92	4.31
4	15	487.50	487.50	26.55	26.72	26.98	5.51
5	15	267.62	251.31	23.89	24.57	23.31	4.23
7	15	261.29	226.77	22.81	21.68	19.89	3.53
10	15	253.02	206.96	21.24	24.06	24.02	5.56
13	15	221.90	183.42	19.96	26.82	23.85	4.54
15	15	219.79	169.88	19.41	23.99	21.47	3.78
17	15	219.80	155.40	18.54	23.74	28.74	6.65

20	15	215.38	140.02	17.87	25.87	26.60	7.50
23	15	205.46	132.28	17.21	26.42	21.20	4.44
25	15	199.99	134.50	17.63	22.33	26.18	5.32
30	15	197.67	130.50	17.11	21.96	25.63	5.37
40	15	210.63	126.35	17.56	24.09	26.18	6.08
55	15	194.01	110.21	16.24	23.35	26.76	4.16
70	15	181.85	99.93	15.22	26.46	25.17	5.87
77	15	188.42	102.20	15.74	27.48	25.22	5.63
85	15	188.07	104.74	15.17	25.16	20.60	4.52
V_f =47.4%							
2	15	536.17	536.17	28.00	27.47	27.24	5.10
3	15	437.90	437.90	25.08	27.76	26.63	6.21
4	15	264.08	237.23	22.13	26.81	27.10	5.79
5	15	257.18	223.31	21.41	25.10	23.68	5.18
7	15	240.85	193.77	20.84	19.96	18.17	3.83
10	15	228.21	178.96	19.19	22.70	22.66	6.31
13	15	193.39	152.42	18.25	27.40	23.83	5.90
15	15	189.10	141.88	17.31	24.54	21.17	4.95
17	15	187.11	125.40	16.51	21.93	28.06	5.05
20	15	179.96	109.02	15.50	27.22	26.95	5.92
23	15	167.59	102.28	15.44	26.74	20.18	3.84
25	15	159.57	104.50	15.80	21.09	27.07	5.56
30	15	151.79	102.69	15.78	20.63	28.17	6.51
40	15	156.00	96.77	14.54	22.15	25.58	6.32

55	15	129.51	81.55	13.32	21.39	27.84	5.33
62	15	130.43	89.96	13.50	23.01	17.83	4.73
70	15	109.74	72.21	12.94	27.01	25.30	5.82
85	15	109.76	77.95	12.88	27.43	19.32	5.89
	Frozen conditions						
		Average Max. Tensile stress (MPa)			Standard deviation		
	V_f =	57.4%	52.3%	47.4%	57.4%	52.3%	47.4%
2	15	440.65	219.22	157.79	25.64	28.15	19.34
4	15	405.17	203.44	148.08	22.89	26.81	22.91
7	15	376.67	187.82	133.88	23.03	21.88	22.90
11	15	335.57	187.99	118.90	19.99	23.39	25.39
15	15	328.17	178.04	101.75	23.56	26.18	26.39
23	15	305.89	163.91	97.24	24.91	24.84	26.09
42	15	275.21	158.10	87.08	23.82	26.77	25.43
67	15	242.78	151.91	78.57	25.43	28.30	21.95
85	15	237.27	145.37	83.30	26.14	24.95	24.47

5.2.3.7. Tensile failure

Figure 5.9 shows a typical failure region of three specimens with different V_f (57.4%, 52.3% and 47.4%) and below 7% moisture content; and a typical failure region of all specimens with moisture content above 7%, which is similar to the failure of all those with a frozen moisture content for V_f 57.4%, 52.3% and 47.4% (where the three V_f studied do not show clear differences). The failure surface of all specimens below the 7% moisture content had split along the longitudinal direction. Increasing the region together with V_f (Figure 5.9) which mean that the specimens had high toughness. When the moisture content is more than 7%, the fibres and the matrix split before the composite failure as the moisture content debilitates the xylem. The region of debonding (fibre/matrix) presented before failure increase together with moisture content of the specimen. Finally the fibres split along the longitudinal direction (Figure 5.9d).

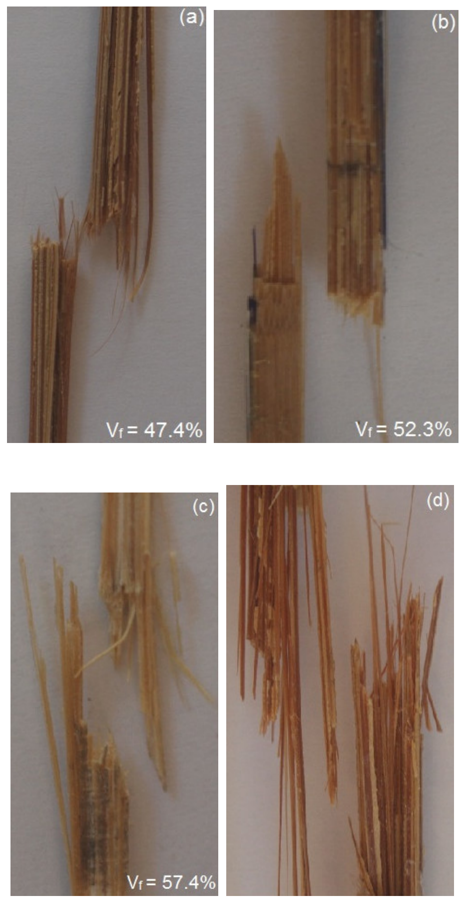


Figure 5.9- Typical tensile fracture of: (a-c) 3 specimens with different V_f and moisture content below 7% and (d) specimens with moisture content over 7%

5.3. Compression properties

5.3.1. Experimental approach

A compression test parallel to the grain was performed at three different fibre volume fractions (cutting the first three layers of 2mm thick from the external to the internal surface of the culm wall cross-section, Figure 5.3). The fibre volume fraction (V_f) was also measured on the transverse section using DIP. 90 specimens at 2% moisture content were taken separately (45 of them were frizzing). 1035 specimens were immersed in distilled water to increase moisture content (for a maximum time of 167 days) with 360 of them frizzing when they reached the moisture content required for testing. A digital moisture meter (Promtimeter MMS) was used to measure the percentage of the moisture content in the specimens. The DG bamboo used in the tests was 4 years old and sourced from plants growing at the Pontifical Catholic University of Rio de Janeiro (PUC-Rio), Brazil. After cutting, the bamboo culms were dried in situ in a vertical position for two weeks and then transported in 3000 mm long pieces to the University of Cambridge's engineering workshop stored at room temperature for 5 months (23˚C and 67% air humidity).

5.3.2. Experimental details

Specimens were taken from the internodes section 11, 12, 13 and 14 (height approximately 5000 mm to 7500 mm) with a culm wall thickness of about 15 mm. The culm section were longitudinally split into 300 mm (H, height) x 6 mm (T, tangential) strips. Then, they were delaminated in a 2 mm thickness of outer to the inner part of the culm walls (after the cortex and pith periphery were removed). Bonding with epoxy resin and compressing together 3 bamboo sheets with the same fibre volume fraction during 2 days the cube were created splitting longitudinally into 6 mm (h, specimen height). 1125 specimens were prepared (375 for each V_f). The final shape, dimension and characteristics of the specimens for compression tests are shown in Figure 5.10. The dimension of the specimen cube was 6 mm (h) x 6 mm (T) x 6 mm (three 2 mm thick radial sheet of bamboo, R). Using PRESI P255U machine and 150 µm sandpaper the compressing area were polished to guarantee a flat surface and parallelism between them. In order to obtain high precision, the specimens were aliened with the INSTRON 5500R machine central axis using thin light line and a computer-controlled testing machine. The specimens were loaded at a constant crosshead speed of 2 mm/min until failure. Compressive tests were performed on a total of 1125 specimens, considering 15 specimens for each moisture content at both room temperature and frozen conditions. The test room temperature and humidity was 23˚C and 40% respectability.

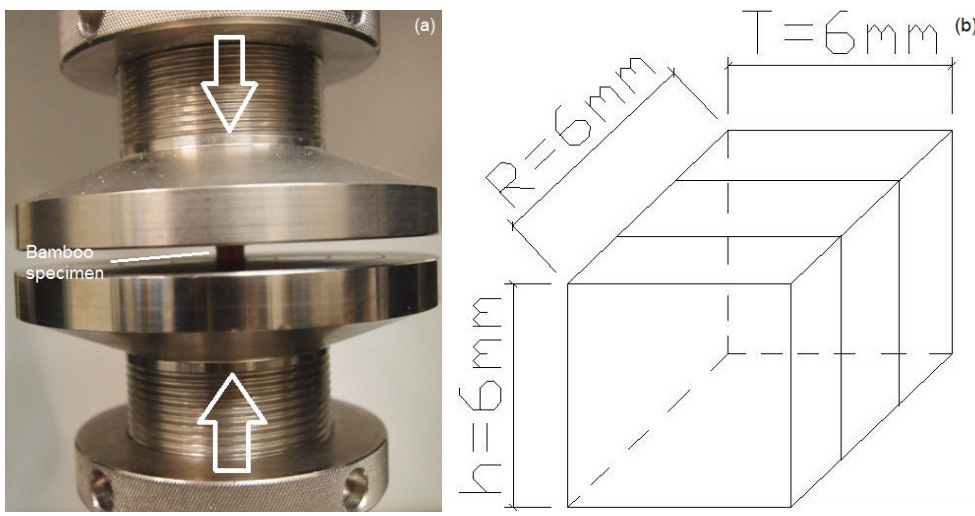


Figure 5.10- (a) Compression test (b) bamboo specimen dimension

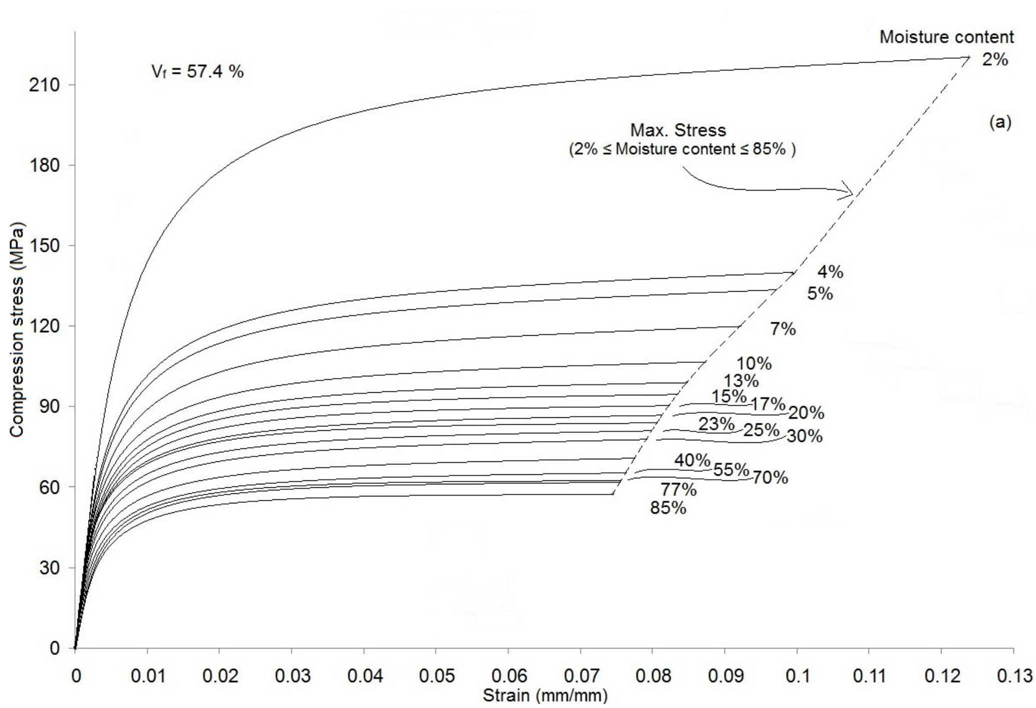
5.3.3. Results and discussion

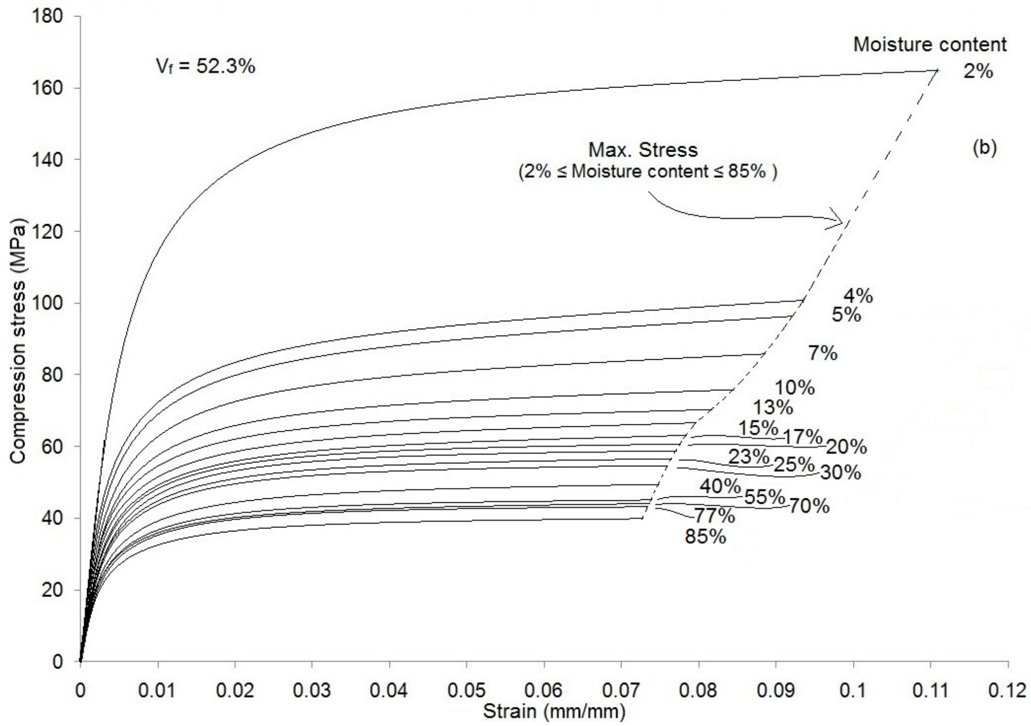
5.3.3.1. Moisture content effects on compression stress-strain

The stress–strain curves of DG bamboo layers (V_f , 57.4%, 52.3% and 47.4%) containing different levels of moisture content are shown in Figure 5.11. The modulus and tensile strength are found to be decreased because of the plasticization effect that overcomes by the absorption of water dealing an expansion of xylem (matrix) producing micro breaks in the material. Can be observed for all V_f studied that exist a considerable reduction on the maximum strain from 2% to 4% moister content.

The strain at maximum compressive stress decreases when the moisture content is increased. The compressive stress-strain curves of DG bamboo for all V_f studied can be classified in three regions: the initial region showing increasing stress, the middle region increasing stress but loosing stiffness more evidentially and the final region with the stress level maintaining almost constant but with large strain till the sample failure (average maximum compressive tress and standard deviation presented in Table 5.2).

As in conventional composites, the water particles deteriorate the interface bonding between the matrix and reinforcement. Therefore, it can be concluded that similar effect may occur between the bamboo fibres and the xylem (matrix) resulting in the loss of strength, stiffness and strain that permits the fibres and matrix to work together. Considering the characteristics of DG bamboo at 2% moisture content the average coefficient of variation of maximum compression strength, modulus of elasticity and strain at rupture when the moisture content is increased to 85% are 73.9%, 45.4% and 39.9% (V_f 57.4%), 75.8%, 36% and 30.5% (V_f 52.3%) and 69.1%, 55.2% and 29.6% (V_f 47.4%) respectively.





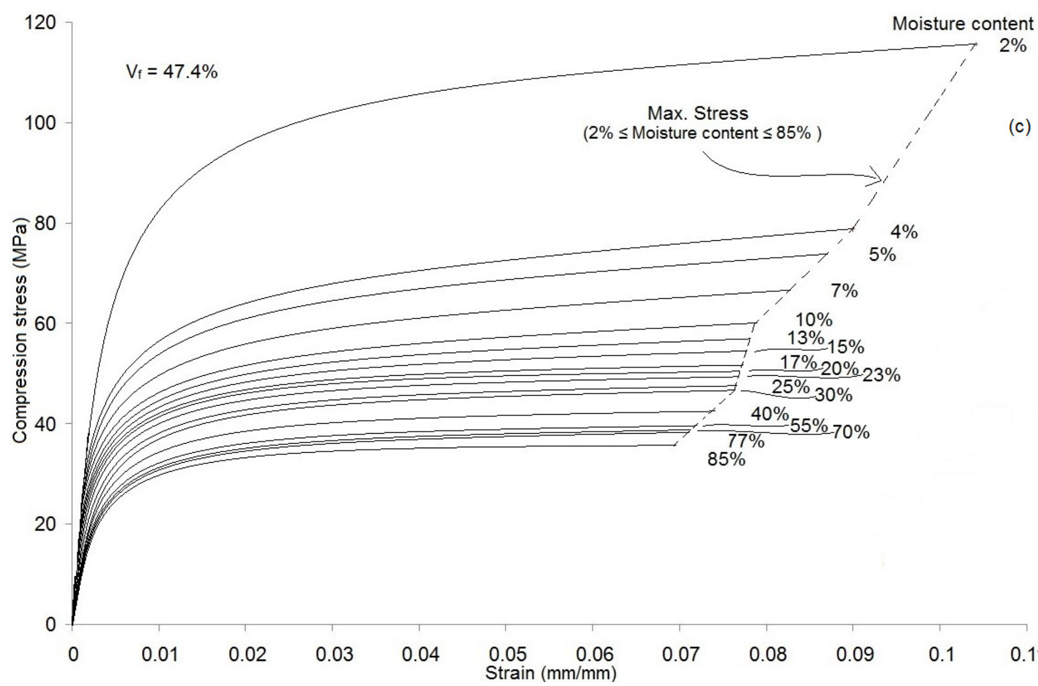


Figure 5.11- Compression stress-strain curves for samples containing V_f 57.4% (a) 52.3% (b) and 47.4% (c) at moisture content between 2% and 85%

5.3.3.2. Moisture content effects on compression stress

In Figure 5.12 the relationship between the compressive strength and moisture content is shown. The compressive strength is affected by the moisture content in a similar tendency for all V_f studied. Therefore the maximum compressive strength reduction for all of them can be classified in four regions based on the inclination of the curve.

Considering the compressive strength of 2% moisture content as an initial reference, the reduction in the strength at the limit of the first region (~ 5% moisture content) is approximately 39% (average value). Increasing the moisture content up to 23% (second region) the reduction of the strength is approximately 61.1%. At the end of the third region (40% moisture content) the increase of moisture content causes a considerable reduction in the compressive strength by 66.9%. In the last region (moisture content more than 40%) the variation of the strength is lower and the strength is nearly constant, since the water particles almost become homogeneous inside the material. The compressive strength against moisture content shows a similar change as the tensile strength (Figure 5.7). It decreases with increasing moisture content is attributed to the action of water as a softener of bamboo polymers (similar to data for wood and paper materials [69]).

From the results the compressive stress of DG bamboo on the layers with V_f 57.4%, 52.3% and 47.4% can be calculated using the following equation if the moisture content is considered (see Table 5.2 for standard deviation at different moisture content):

Maximum compressive stress to V_f equal to 57.4%, 52.3% and 47.4%, respectively (2%≤ Moisture content ≤ 85%):

$$\sigma_c \text{ (MPa)} = 232.92 \, (M_c \text{ (\%)})^{-0.323} \quad (5.26)$$

$$\sigma_c \text{ (MPa)} = 172.99 \, (M_c \text{ (\%)})^{-0.34} \quad (5.27)$$

$$\sigma_c \text{ (MPa)} = 120.62 \, (M_c \text{ (\%)})^{-0.282} \quad (5.28)$$

5.3.3.3. Effect of frozen moisture on compression stress

Studying moisture content of bamboo under frozen conditions is also interesting to investigate especially in the context of the structural parts where the climate or winter period is cold. This is also relevant to the wind energy field (bamboo wind turbine blades) and aviation industry that often experiences such an environment during their voyage. Hence the following investigation can prove to be very useful in those conditions.

As discussed earlier there is degradation in the mechanical property of DG bamboo when its moisture content is increased. This is also true for sub-zero conditions, and the effect of moisture under frozen conditions can similarly be investigated. In this case the measure of mechanical behaviour is observed in the context of compression stress. So, the effect of moisture content on compression stress values were recorded for both plain and frozen under the same level of moisture content, and these are plotted in Figure 5.12. The figure illustrates in the DG bamboo layers with V_f and the effect of frozen moisture content till approximately 25% is accentuated. However, this effect at 2% frozen moisture content on compression strength for V_f 57.4% , 52.3% and 47.4% is sharp, decreasing in relation to plain DG bamboo compression strength of 51.7%, 65.8% and 68.8% respectively.

It is observed in the results (Figure 5.12) that the compression stress of all V_f studied with frozen moisture was lower than the maximum stress of plain specimens with the same moisture content. This may due to the increase in swelling stresses, due to the volume expansion of moisture during freezing. This leads to damage in the xylem tissue that works as a matrix (maintaining the fibres together and transferring tensions). As showed before the difference between plain and frozen moisture content at 2% for V_f 52.3% and 47.4% are higher than for V_f 57.4%. This may be due to the existence of more xylem, resulting in more deformation and releasing extra residual bonding between fibre/matrix.

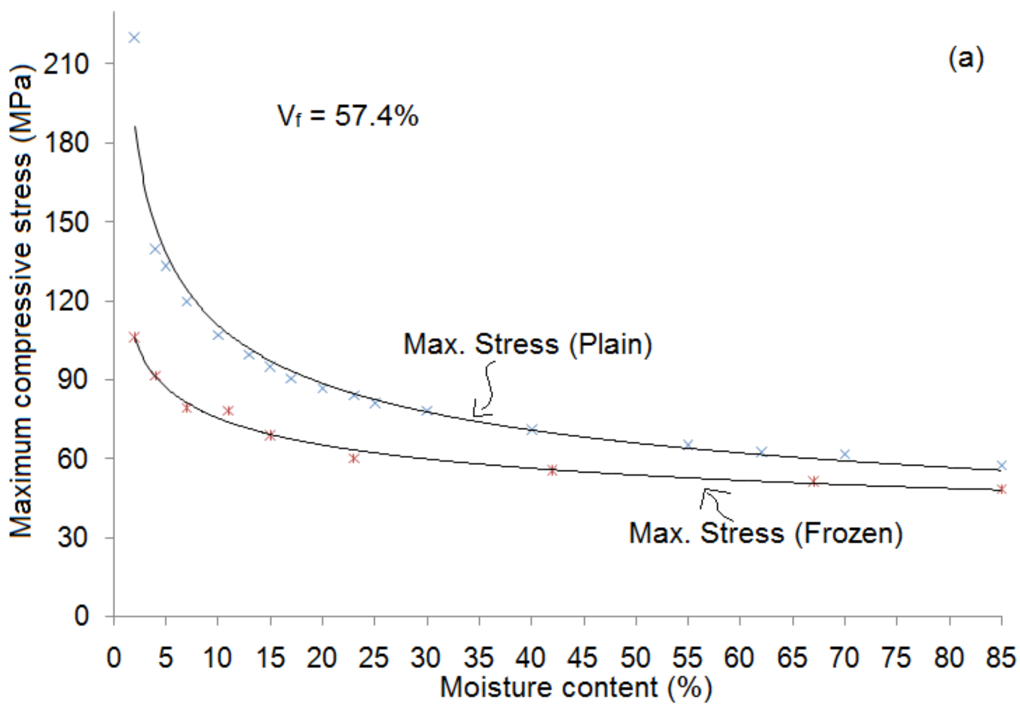
From the results the maximum compressive stress of DG bamboo on the layers with V_f 57.4%, 52.3% and 47.4% can be calculated using the following equation if the frozen moisture content is considered (see Table 5.2 for standard deviation at different frozen moisture content):

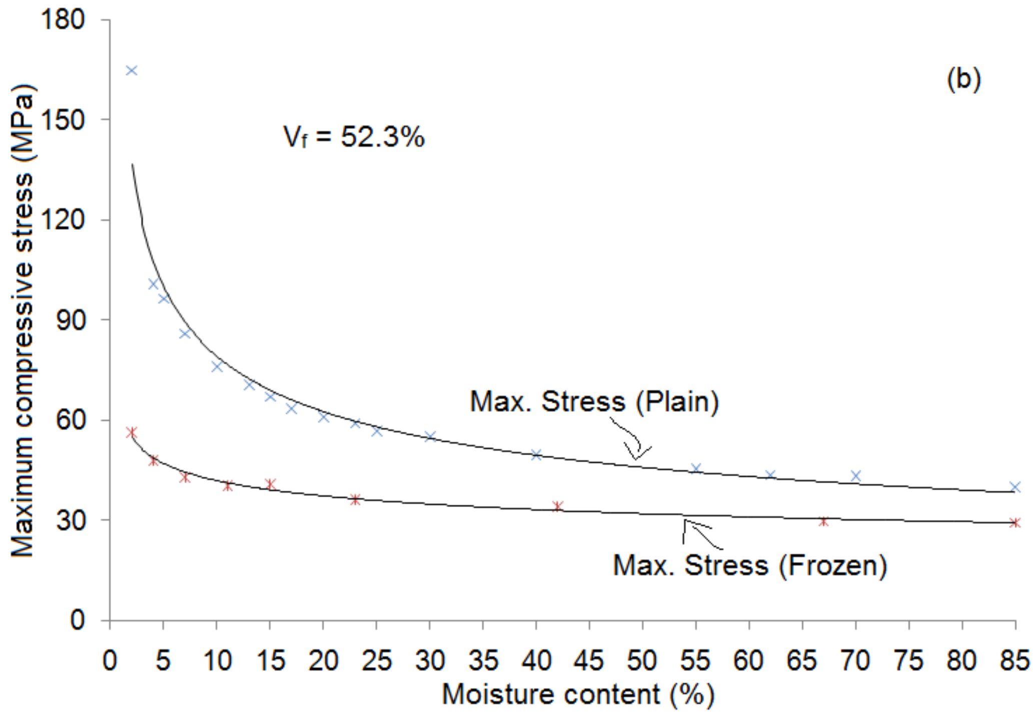
Maximum compressive stress to V_f equal to 57.4%, 52.3% and 47.4%, respectively (2%≤ Moisture content ≤ 85%):

σ_{CF} (MPa) = 122.42 (M_c (%))$^{-0.211}$ (5.29)

σ_{CF} (MPa) = 61.591 (M_c (%))$^{-0.168}$ (5.30)

σ_{CF} (MPa) = 42.964 (M_c (%))$^{-0.229}$ (5.31)





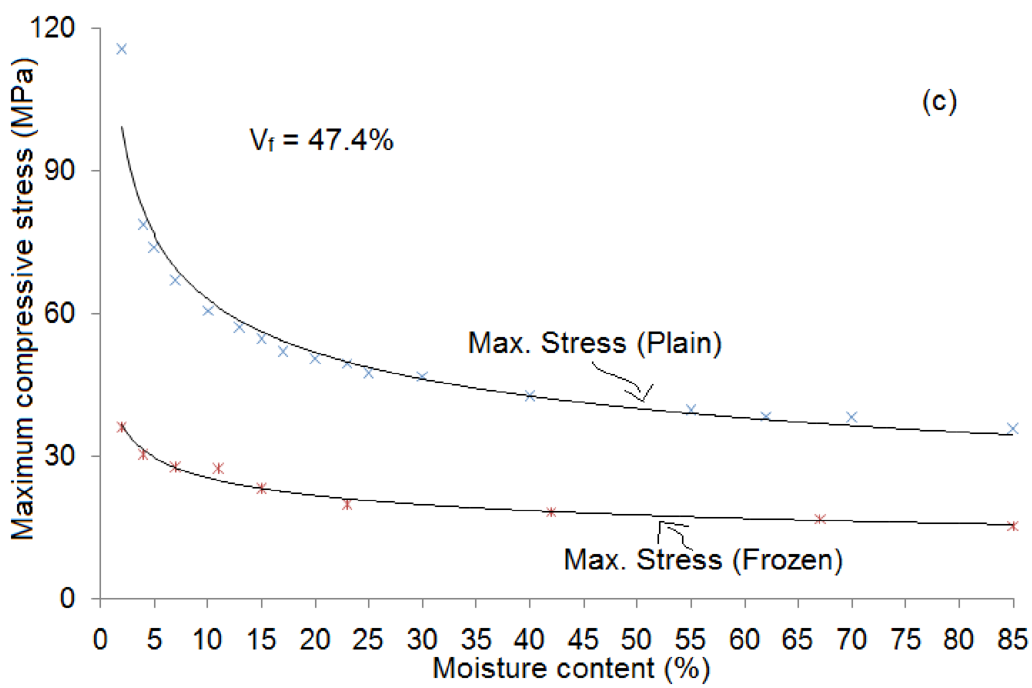


Figure 5.12- Maximum compressive stress-moisture content curves for samples containing V_f 57.4% (a) 52.3% (b) and 47.4% (c) at plain and frozen moisture content between 2% and 85%

Table 5.2- Average results of compression test

Moisture content (%)	**Number of samples**	**Average Max. Compressive stress (MPa)**			**Standard deviation**		
		V_f =57.4%	V_f =52.3%	V_f =47.4%	V_f =57.4%	V_f =52.3%	V_f =47.4%
		Room temperature					
2	15	220.22	164.89	115.61	7.77	7.90	7.76
4	15	139.77	100.83	78.76	4.99	5.62	5.61
5	15	133.43	96.48	73.94	4.72	5.05	5.49
7	15	119.77	85.86	67.01	6.49	6.96	7.18
10	15	106.97	76.03	60.52	5.34	6.00	7.32
13	15	99.47	70.56	57.16	5.21	6.02	7.07
15	15	94.89	67.04	54.69	4.16	4.60	6.64
17	15	90.41	63.46	51.96	5.13	6.05	8.57
20	15	86.81	60.98	50.51	5.51	6.56	6.75
23	15	83.97	59.07	49.43	6.08	6.17	8.42
25	15	81.03	56.67	47.50	5.38	5.89	6.54
30	15	78.14	54.92	46.70	6.29	7.08	8.45
40	15	71.05	49.53	42.65	5.55	5.29	7.88
55	15	65.15	45.36	39.74	5.55	6.53	5.94
62	15	62.64	43.48	38.28	6.66	6.37	6.55
70	15	61.74	43.18	38.19	5.54	5.45	6.56
85	15	57.51	39.88	35.68	5.58	6.35	7.46
		Frozen conditions					
2	15	106.33	56.31	36.06	14.09	2.33	4.77
4	15	91.45	48.00	30.29	10.79	4.62	2.76

7	15	79.32	42.85	27.74	10.71	3.94	3.95
11	15	78.20	40.23	27.46	7.85	2.40	4.42
15	15	68.71	40.88	23.23	7.09	3.07	3.93
23	15	60.18	36.15	19.81	4.96	5.99	2.60
42	15	55.44	34.06	18.17	7.53	6.09	3.30
67	15	51.19	29.61	16.74	7.03	6.13	2.67
85	15	48.44	29.27	15.21	7.98	6.27	3.20

5.3.3.4. Compression failure

Figure 5.13 shows: a typical failure of three specimens with different V_f (57.4%, 52.3% and 47.4%) and below 5% moisture content; A typical failure of all specimens with moisture content above 5%, which is similar to the failure of all frozen moisture content for V_f 57.4%, 52.3% and 47.4% (where the three V_f studied do not show clear differences). The failure form of all specimens was split (fibre/matrix) transversally of fibres. This separation is more clear when the V_f decrease and also when moisture content is increased. This results shows that in compression stress the degradation of xylem is more sensitive than tensile stress in the general behaviour of the composite material. The region of debonding (fibre/matrix) presented before failure increase together with moisture content of the specimen.

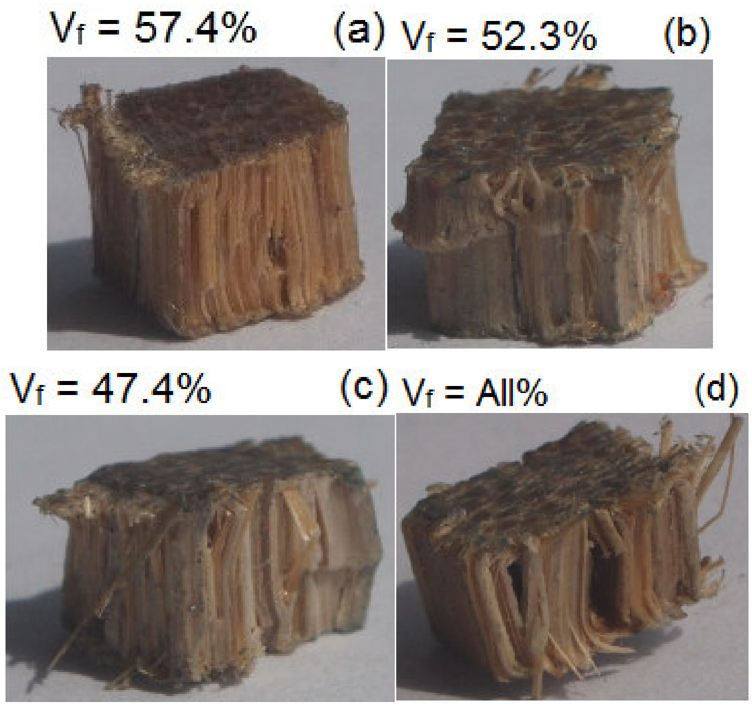


Figure 5.13-Typical compression failure of: (a-c) 3 specimens with different V_f and moisture content below 5% (d) specimens with moisture content over 5%

5.4. Conclusion

The kinetics of absorption and the moisture content at equilibrium distinctly increase with increasing V_f on the DG bamboo layers. The fact that moisture content gradually increases and then becomes almost constant leads to the conclusion that the mechanism of moisture change in bamboo is different beyond the saturation time.

The increase of water particles weakens the bamboo polymers deteriorating the interface bonding between the DG bamboo fibres and the xylem (matrix) resulting in the loss of strength, modulus of elasticity and further deformation. The tensile stress-strain behaviour of the DG bamboo layers can be grouped into elastic (~ up to 4.5% moisture), elastic and plastic (between ~ 4.5% to 15% moisture) and elastic and extremely plastic (~ above 15% moisture).

In general, the moisture content effects on TMOE of the DG bamboo layers are independent of V_f studied (57.4%, 52.3% and 47.4%) and can be represented by an accentuated decreasing logarithmic curve up to 23% moisture content, where the average reduction in the modulus of elasticity is approximately

41.5% of the TMOE at 2% moisture content. Above 23% moisture content a gently decreasing linear function represents the decreasing of TMOE.

The tensile and compression strength is affected by the moisture content in a similar tendency for all V_f studied. There is a sharp decrease up to approximately 23% moisture content and a smooth linear decrease after that. In tension, the limit of moisture content for an only elastic response are approximately 5%, 4% and 3% for V_f 57.4%, 52.3% and 47.4% respectively.

In tension, moisture content up to approximately 10% has far greater effect on the maximum elastic tensile strength and maximum tensile strength; about 70.2%, 42.7% and 42.6% of the strength at 2% remain for V_f 57.4%, 52.3% and 47.4% respectively. From 23% of moisture content, where the maximum tensile strength is 56.7%, 34.7% and 31.3% of the strength at 2% for V_f 57.4%, 52.3% and 47.4% (respectively) the effect of moisture content variation does not cause considerable reductions.

The tensile and compression strength of all layers studied with frozen moisture content was lower than the maximum stress of plain specimens with the same moisture content. This may be due to the increase in swelling stresses, due to the volume expansion of moisture during freezing leading to the damage of the xylem tissue that works as a matrix transferring tensions.

In tension, with the exception of the DG bamboo layer with V_f equal to 57.4% the effect of frozen moisture content up to approximately 4% is very accentuated. At 2% frozen moisture content the tensile strength for V_f 52.3% and 47.4% is 37% and 29.4% respectively of their correspondent strength at plain conditions (for V_f 57.4% it is 71.6%).

In tension, the failure surface of all specimens below the 7% moisture content was split along the longitudinal direction. Increasing the region together with V_f , which means that the specimens had high toughness. When the moisture content is more than 7%, the fibres and the matrix split before reaching composite failure.

In tension and compression failure, the region of debonding (fibre/matrix) presented before failure increased together with the moisture content of the specimen. But the results show that in compression stress the degradation of xylem is more sensitive than tensile stress in the general behaviour of the composite material.

According to the tensile test results at 2% moisture content (plain) the strength and TMOE of DG bamboo fibre were estimated as 958.3 MPa and 54.4 GPa respectively concluding that a specific procedure to obtain bamboo fibres without losing its mechanical properties needs to be researched.

The compressive stress-strain curves of DG bamboo for all V_f studied can be divided in three regions: the initial region showing increasing stress, the middle region increasing stress but loosing stiffness more evidentially and the final region with the stress level maintaining almost constant but with large strain till the sample failure.

The results show that *Dendrocalamus giganteus (DG)* bamboo layers with highest fibres volume fraction (V_f) and moisture content up to ~ 2% (preferentially) can be applied in composite materials for engineering purposes that require high tension and compression properties.