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Influence of the Age of Bamboo Culm and Its Vertical Position on the Technological Properties of Bamboo Fibers: A Case of *Bambusa vulgaris* Species from Cameroonian Culture

Joseph Loic Souck, Theodore Tchotang, Bienvenu Kenmeugne

Laboratory of Civil and Mechanical Engineering, National Advanced School of Engineering, Yaoundé 1 University, Yaoundé, Cameroon
Email: souckjosephloic@yahoo.fr

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Abstract

Due to their interesting properties, bamboo fibers are more and more used as reinforcements in polymer matrices as a substitute for synthetic fibers. For their future service life, it is important to understand their physical and mechanical behavior over time in order to control the aging phenomenon within this fiber. The paper analyzed the influence of the age of the bamboo thatch and the vertical position of the *Bambusa vulgaris* species cultivated in Cameroon on the physicomechanical properties of the fibers extracted from the thatch. Fibers were mechanically extracted from three bamboo culms aged respectively 3 years (BV3), 4 years (BV4) and 5 years (BV5). The culms were thus identified according to their number of ramifications, and were felled no abated for a total of three culms. A section of about one meter on each of the parts (lower part, middle part, upper part) of these three culms was made for the opposite technological studies. Each age was therefore represented by three portions of thatch, one from the upper part, one from the middle part and the last from the lower part of the thatch, all giving a total number of nine samples taken and marked BV3inf, BV3moy, BV3sup, BV4inf, BV4moy, BV4sup, BV5inf, BV5moy, BV5sup before handling in the laboratory. Physical (density, moisture absorption rate) and mechanical (tensile tests according to DIN EN ISO 13934-1, natural durability) characterizations were used to better understand the mechanisms of this influence. In view of all the results obtained, the fiber from the upper part of the 3-year-old thatch (BV3sup) is the one with the best characteristics and is recommended for a better elaboration of bamboo fiber composites: (Density: 0.83; Absorption rate 11.7%; Young's modulus: 7.4 GPa; Maximal stress: 64.3 MPa; Elongation at rupture: 1.1; Loss of mass natural durability: 7.63%).

Keywords

Fiber, Bamboo Culm, Characterization, Elaboration, Extraction

1. Introduction

Studies have been conducted for years on bio-composites with the aim of replacing traditional fibers, in particular glass fibers, with natural fibers. This impulse is motivated by the specific and interesting mechanical properties of natural fibers which allow considering perspectives of lightening on one hand and on the other hand to reduce the environmental impacts which lead to the use of resources of renewable origin. If we want to substitute these traditional fibers with natural fibers, we must place them in identical situations. They can therefore be exposed to severe conditions in service. These natural fibers are low-cost, low-density fibers and have specific properties, for example, they are biodegradable and non-abrasive [1].

Bamboo fibers are one of the alternatives to glass fibers due to their interesting mechanical and chemical properties. Bamboo is one of the last plant resources that has not been massively exploited and is one of the oldest building materials used by man [2]. Its cultivation in Cameroon is abundant and very diversified but its exploitation is limited [3]. In view of the ever-increasing availability of this resource, there is a growing interest in conducting scientific studies on the potential of bamboo fibers as a reinforcing material for polymer matrix composites. The problem that arises is that the information concerning the technological properties of this species is very insufficient or non-existent on a national scale.

These gaps in scientific knowledge on the technological properties of bamboo limit the possibility of using these materials. Consequently, the techniques of transformation are archaic and the use of bamboo especially at the industrial level is not very common in Cameroon, which is justified by the reduced number of companies and fields of use related to the bamboo sector. Hence the delay of Cameroon in terms of development of the bamboo sector compared to other foreign countries.

Many researchers have studied the development and characterization of natural fiber composites. There is little work in the literature on the influence of the age of the thatch from which the bamboo fibers are extracted on the technological properties of the said fibers and the plant reaches maturity in 3 years. The species *Bambusa vulgaris* is not widely known in the literature and is one of the three most important species in Cameroon due to its high growth rate [3]. Its main uses are in food, handicrafts and construction. It is important to know the aging mechanisms of fibers from this species in order to characterize their behavior as reinforcement in bio-composites. Bamboo fibers are extracted and used in their mature age in various applications, namely as reinforcements in bio-composites. Generally, for their use in various applications, no particular research is done to know if the bamboo stem used is the one with the most optimal properties in view of its age and size. So to fill this lack of information we undertook to look into the issue with regard to the species *Bambusa vulgaris* cultivated in Cameroon.

Much of the literature focuses on the study of wood fibers and the aging of composites reinforced with these fibers [4]. S. Jin *et al.* [5] studied the influence of relative humidity aging on the mechanical properties of hemp fibers in order to characterize the behavior of virgin and aged hemp fibers using micro-tensile tests. He noticed a 33% decrease in stiffness and break stress during relative humidity aging, while the breaking strain increased threefold in four weeks.

It is important to master the natural aging phenomena within the bamboo fiber (*Bambusa vulgaris*) cultivated in Cameroon according to the age and the vertical position of the culm where they are extracted in order to know the consequences on the technological properties.

2. Experimental Materials and Conditions

2.1. Origin and Obtaining of Bamboo Fibers

The species of bamboo used has the scientific name *Bambusa vulgaris*. Its cellulose content is relatively high and its micro fibrillar angle is low [6]. Its cultivation is very diversified in Cameroon, especially in the coastal regions of south and central Cameroon. The anatomy of the bamboo plant is shown in **Figure 1**. Thatch is the stem of bamboo. It is usually hollow, and consists of different boxes separated by diaphragms forming the nodes.

The culm samples were collected from the center region of Cameroon, in the Nkolnda area. This collection site was chosen because of the abundant presence of cultivated bamboo species.

The obtaining of *Bambusa vulgaris* fibers is done through several steps of various choices.

- The first step is the recognition of the *Bambusa vulgaris* stem by visual observation, the color of its thatch is usually green covered with medium diameter

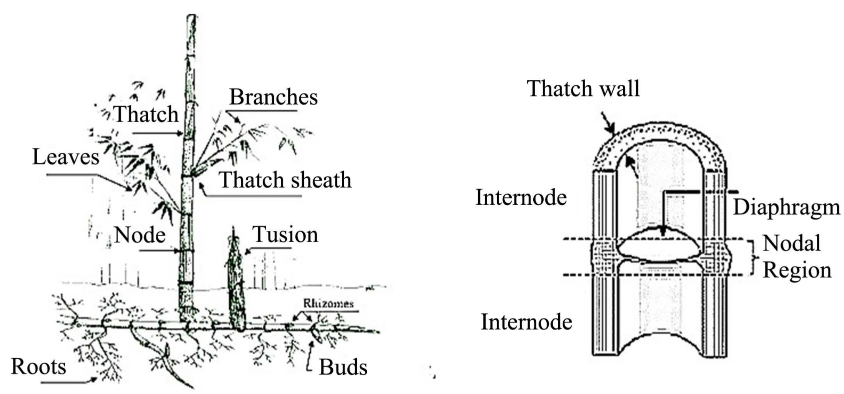

Figure 1. Anatomy of the bamboo plant [7].

hairs [8].

- The second is the recognition and cutting of mature stubble. This was done by the method recommended by Wei-Chih Lin [8]. According to this method, each year, one more branch develops along the thatch. The age of the thatch is therefore given by the number of branches that have developed on it (**Figure 2**). A culm is then considered mature if it has at least three sympodic branches [8].

The culms of 3 years, 4 years, and 5 years noted respectively BV3, BV4 and BV5, were thus identified according to their number of ramifications, and were abbatated for a total of three culms. A section of about one meter on each of the parts (lower part, middle part, upper part) of these three culms was made for the opposite technological studies. Each age was therefore represented by three portions of thatch, one from the upper part, one from the middle part and the last from the lower part of the thatch (**Figure 3**), all giving a total number of nine samples taken and marked BV3inf, BV3moy, BV3sup, BV4inf, BV4moy, BV4sup, BV5inf, BV5moy, BV5sup before handling in the laboratory.

The fibers were extracted manually (no chemical or thermal extraction) from the cut bamboo thatch and then peeled to get flat pieces of 0.5 to 1 mm thick which are later divided into fine fibers with a sharp knife. Then the fibers are placed in an oven at a temperature of 80˚C for 5 h to remove the contained moisture. The fibers were extracted from the three culms BV3, BV4, BV5 shown in **Figure 4** from left to right.

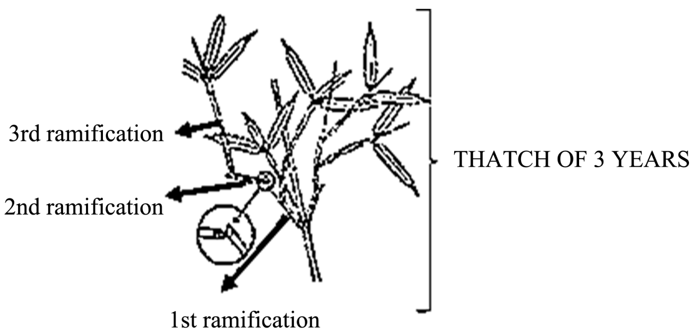

Figure 2. Age distinction by branching [8].

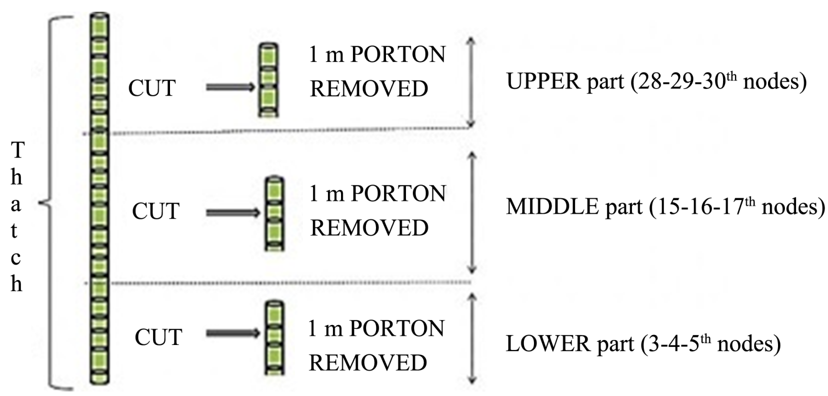

Figure 3. Parts of the bamboo stems taken [8].

Figure 4. Stems from where the fibers were extracted: BV3, BV4 and BV5.

2.2. Density

Density is a physical property, the first to be determined to qualify a material. It is an important parameter to measure and has a great influence on drying. A material with a high density, therefore heavy, is made up of thick-walled cells with small-diameter cell voids. The circulation of water inside it, and therefore its drying, will be more difficult than in a light material made up of thin-walled cells with cell voids of large diameter [9].

The equipment used consisted of a graduated test tube, a nut, electronic balance with an accuracy of 0.01 g and a caliper with an accuracy of 0.01 mm.

The procedure was as follows: the fibers of each type are first extracted and then three packages of fibers of each type are weighed with the balance. In a 250 mL beaker, water is first introduced and the V1 graduation is taken after stabilization. Then a nut is introduced and the V2 graduation is read once more. The nut is taken out and the fibers are weighted in the nut, the whole is introduced in water and the V3 graduation is read. The volume of the fibers is given by the difference between V3 and V2.

2.3. Water Absorption Rates

It is the percentage of water absorption in the fiber. For this purpose we used an electric scale and a container. First, the fibers are weighed and then they are left in water for 24 hours and weighed again. The absorption rate is given by

$$\text{absorption rate} = \frac{\text{initial fiber mass}}{\text{final mass}} * 100 \tag{1}$$

2.4. Bamboo Fiber Tensile Tests

It is the test used to determine the main mechanical characteristics of the fibers. It consists in subjecting the fibers to a progressive tensile stress until they break. The tensile tests are carried out at the center of scientific and technical services in Food, Packaging, Environment and Textile (Celabor) in Herve in Belgium on a tensile machine "Zwick" with a force cell of 10 kN (precision = 0.01/N). The tests are carried out with an imposed displacement speed of 100 mm/min, controlled by a computer. The method used is the conventional tensile test. The bamboo fiber is glued on a paper to ensure its linearity and placed between the fixed and mobile jaws of the mechanism. The central unit collects the data from to the rupture force with the elongation.

From the measured force/displacement data at each instant of a tensile test, we calculate the following:

Maximum stress

$$\sigma_{max} = \frac{F_{max}}{S_0} \tag{2}$$

Fracture stress

$$\sigma_r = \frac{F_r}{S_0} \tag{3}$$

Young's modulus

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} \tag{4}$$

where:

- σ: stress in Mpa;
- F: force in N;
- S_0: initial section fiber mm^2;
- ε: Deformation in %.

2.5. Natural Durability Test

The natural durability of a material, in a given use, is its capacity, more or less great, to remain intact of any deterioration proper to the material during the time of use which is required for the work or this material intervenes [10]. It is an important technological property because it characterizes the ability of the material, here bamboo, to resist the attack of biological agents of alteration, thus its service life under a given condition of use [8].

The test is carried out in a natural environment on exposed ground (permanent contact with the ground or a source of humidity and exposure to the action of the weather). This test, illustrated on the **Figure 5** is called "graveyard test" [11]. It consists of placing the bamboo specimens on exposed ground and then evaluating the state of weathering of these specimens after six (6) months of experimentation. The alterations are the harmful and irreversible effects caused by the biological agents during the experimentation. They are mainly the loss of mass, the degradation of the color, and the formation of holes or galleries of variable dimensions oriented in the direction of the fibers.

Figure 5. Graveyard test [11].

The initial mass of each specimen was measured before the durability test. After the characterization of their initial state, each specimen was placed on the experimental field according to the method of Ashaari and Mamat [12], that is to say with a spacing between the specimens equal to 300 mm and a sinking of half of its total length in the ground. The durability test in service lasted 6 months in the locality of Nkolnda in Yaoundé. After 6 months of exposure the final masses of each type of bamboo were measured in order to deduce the mass loss Δm by the relation.

$$\Delta m = \frac{m_i - m_f}{m_f} \times 100 \tag{5}$$

where m_i is the initial mass and m_f final mass after exposition

After the calculation of mass loss, the investigation continued to deducing the natural durability of each species studied, taking the mass loss as an indicator defining the natural durability. To do this, the evaluation grid of natural durability developed by Beauchêne [13] was used. This grid maps the mass loss in percentage with the attached natural durability (Table 1).

3. Results and Interpretations

3.1. Density of Fibers

The results in Figure 6 and Figure 7 show that the three ages of *Bambusa vulgaris* studied are as a whole as dense as the average of natural fibers used as reinforcing material for polymer matrix composites: the density of each culm is the average of each of the densities of its three same-age samples.

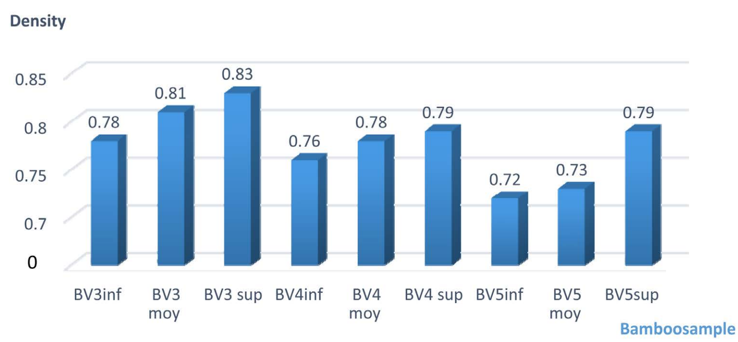

Figure 6. Density according to the vertical position of the internodes and by age of the stem.

Table 1. Quantitative evaluation grid for natural sustainability [13].

Loss of mass (%)	Natural durability state
[0; 5[	Highly durable
[5; 10[	Durable
[10; 20[	Moderately durable
[20; 30[	Not very durable
More than 30%	unsustainable

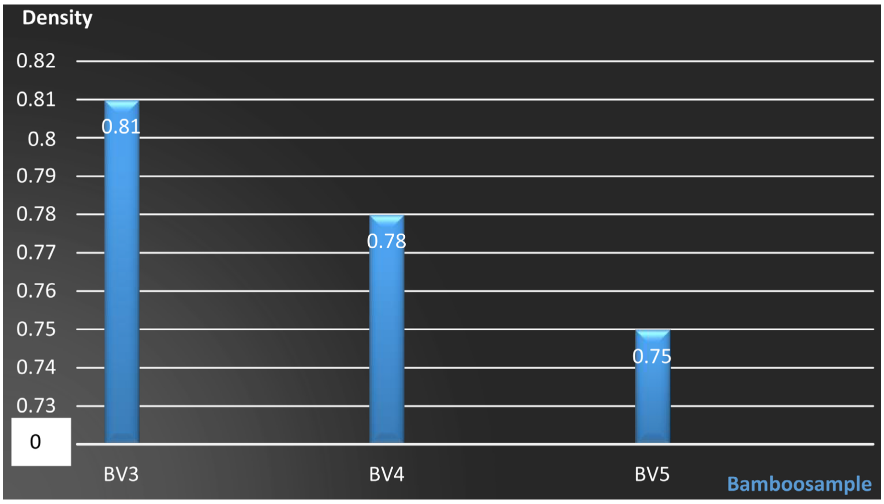

Figure 7. Density by age of the stem.

These results mean that BV3 is heavier than the other two. The density depends on the vertical position of the internodes. The density of the upper samples is higher than that of the lower ones, which means that the walls of the upper parts of each culm are thicker than the middle and lower parts.

Overall the age of the culms does not have much influence on the dimensional stability of bamboo fibers *Bambusa vulgaris* but its density decreases with the age of the fiber culm.

3.2. Water Absorption Rate

The three ages of fibers have very close moisture absorption rates. The results found are as follows Table 2.

It is observed that the absorption rate varies in a decreasing way with the age of the thatch of bamboo fiber *Bambusa vulgaris*. The fibers from the 3 years old thatch retain more water than the others.

3.3. Bamboo Fiber Tensile Tests

Figure 8 shows the appearance of the stress-strain curves of the different specimens of each type of thatch. It can be seen that the fiber behavior is quasi-linear for the majority of the specimens.

To be used as reinforcement in polymer matrices, natural fibers must have good mechanical characteristics.

The results of the tensile tests of types of fibers are noted on the following Table 3.

Fibers from the upper part of BV3 have the highest Young's modulus (7.4 GPa) while those from the middle part of BV5 have the lowest value (2.1 GPa).

The highest maximum stress is from the upper part of BV3 (64.3 MPa) while the lowest is from the middle part of BV5 (12.5 MPa). In general, we note a decrease in the mechanical characteristics of *Bambusa vulgaris* fibers with the age of the thatch. The stress and stiffness decreases due to the weakening of the links between molecules with time, which leads to a decohesion between the components, especially those linked to hemicellulose and cellulose, but an increase in deformation is observed, which is essentially due to plasticization within the fiber.

Table 2. Results of the three-stem absorption test.

Age	Absorption rate
BV3	11.7%
BV4	10.3%
BV5	8.4%

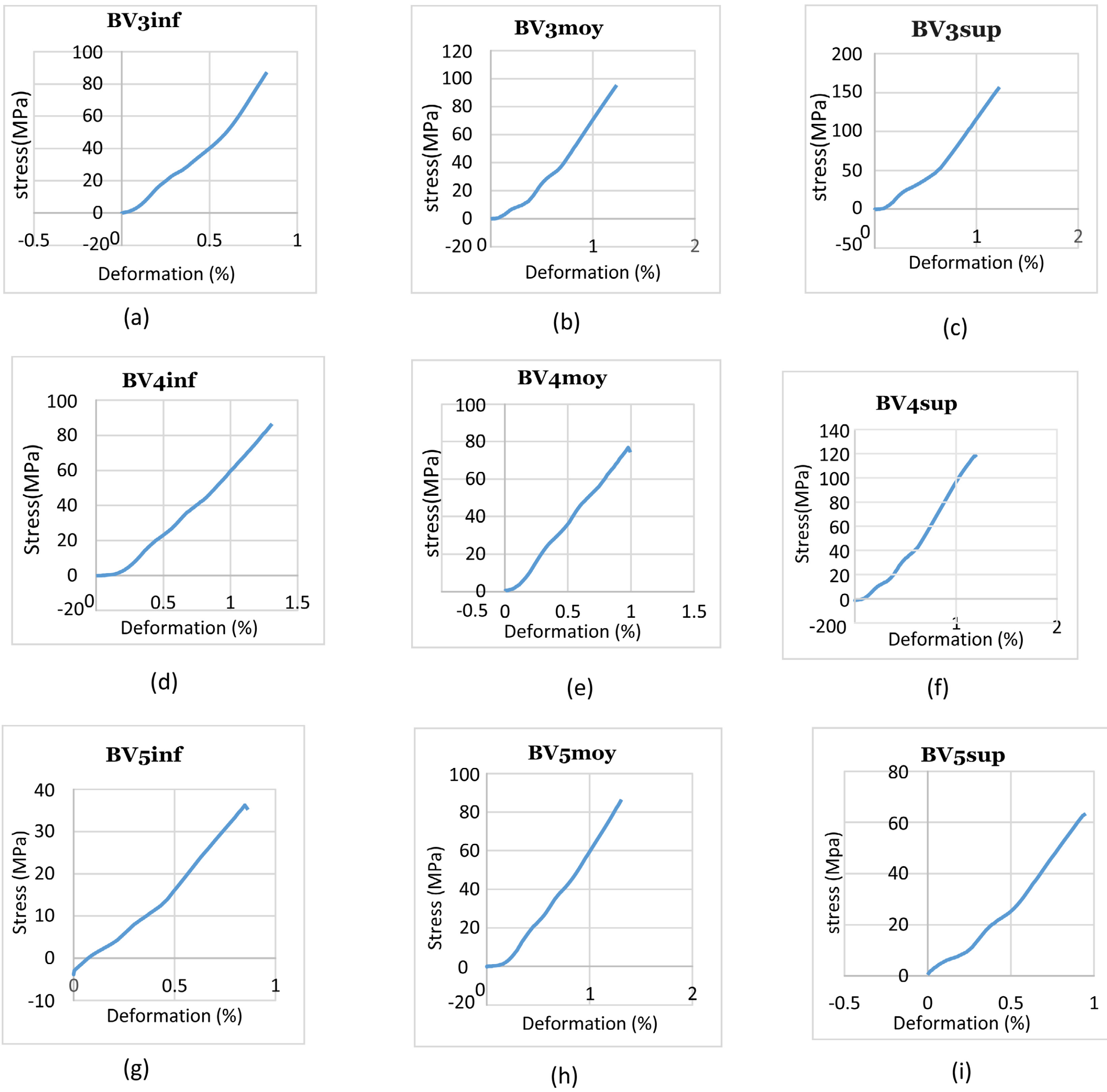

Figure 8. Stress—Deformation.

3.4. Natural Durability

The samples have known some major modifications after the 6 months of exposure, in particular concerning the discoloration and some small holes of small dimensions on the surface of the samples. Figure 9 shows for example the bamboo samples BV3 before and after the test.

The calculation of mass loss is shown in Figure 10.

All three materials were found to be of durable quality based on the evaluation grid in Table 1, except for the 5-year-old top thatch samples, which were in the moderately durable range. The 3-year-old thatch fibers from the upper part are, however, more durable than the other samples and therefore more resistant to biological attack.

Summary of results obtained

In view of all the results obtained in Table 4, the fiber from the upper part of the 3-year-old thatch (BV3sup) is the one with the best characteristics.

Table 3. Fiber tensile results.

fibers	E (GPa)	σm (MPa)	εr (%)
BV3inf	4.1 ± 0.5	35.6 ±6.7	0.9 ± 0.1
BV3moy	4.9 ± 0.4	38.3 ± 4.2	1.3 ± 0.1
BV3sup	7.4 ± 0.3	64.3 ± 1.7	1.1 ± 0.1
BV4inf	2.2 ± 0.4	36.2 ± 3.3	1.3 ± 0.1
BV4moy	2.6 ± 0.2	34.3 ± 3.5	0.9 ± 0.1
BV4sup	5.4 ± 0.2	50.9 ± 5.7	1.3 ± 0.1
BV5inf	4.2 ± 0.6	16.5 ± 5.6	0.7 ± 0.1
BV5moy	2.1 ± 0.5	12.5 ± 2.9	0.9 ± 0.1
BV5sup	5.7 ± 0.5	25.4 ± 3.3	1 ± 0.1

Table 4. Summary of results.

Fibers	E (GPa)	σm (MPa)	density	Δm (%)	Absorption rate
BV3inf	4.1 ± 0.5	35.6 ±6.7	0.78	7.91	
BV3moy	4.9 ± 0.4	38.3 ± 4.2	0.81	7.78	**11.7**
BV3sup	**7.4 ± 0.3**	**64.3 ± 1.7**	0.83	7.63	
BV4inf	2.2 ± 0.4	36.2 ± 3.3	0.76	9.88	
BV4moy	2.6 ± 0.2	34.3 ± 3.5	0.78	9.86	10.3
BV4sup	5.4 ± 0.2	50.9 ± 5.7	0.79	9.39	
BV5inf	4.2 ± 0.6	16.5 ± 5.6	0.72	10.26	
BV5moy	2.1 ± 0.5	12.5 ± 2.9	0.73	9.83	8.4
BV5sup	5.7 ± 0.5	25.4 ± 3.3	0.79	8.88	

Figure 9. BV3 before and after natural durability test.

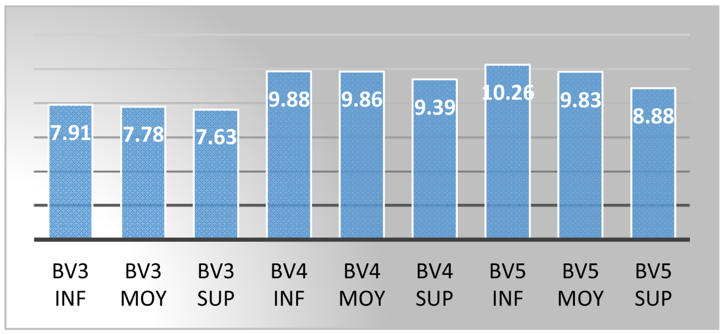

Figure 10. Loss of mass %.

Density: 0.83;
Absorption rate: 11.7%;
Young's modulus: 7.4 GPa;
Maximal stress: 64.3 MPa;
Elongation at rupture: 1.1;
Loss of mass natural durability: 7.63 %.

4. Conclusions

The substitution of traditional fibers with natural fibers in polymer matrices is an issue that is intensifying over the years. Our study focused on bamboo fibers from the Cameroonian culture, in this case, the *Bambusa vulgaris* species which is very abundant and matures after 3 years. It was thus important for us to know the influence of the age of the thatch from which the fibers are extracted and its vertical position on the physical and mechanical properties of these fibers. We used a thatch of 3 years of age (BV3), 4 years (BV4) and 5 years (BV5) according to the method recommended by Wei-Chih Lin to extract manually (neither chemical compounds nor temperature) the bamboo fibers. A section of about one meter on each of the parts (lower part, middle part, upper part) of these three culms was made for the opposite technological studies. Each age was therefore represented by three portions of thatch, one from the upper part, one from the middle part and the last from the lower part of the thatch, all giving a total number of nine samples taken and marked BV3inf, BV3moy, BV3sup, BV4inf, BV4moy, BV4sup, BV5inf, BV5moy, BV5sup before handling in the laboratory. It appears from the tests carried out that age has a decreasing influence on the physical properties such as density and moisture absorption rate. The mechanical properties of the three types of fibers were also studied. A decrease in Young's modulus and maximum stress but an increase in strain at break was noted. A natural durability test was also performed and classified the three types of bamboo fibers is generally durable. The fiber from the upper part of the 3-year-old thatch (BV3sup) is the one with the best characteristics and is recommended for a better elaboration of bamboo fiber composites: (Density: 0.83; Absorption rate 11.7%; Young's modulus: 7.4 GPa; Maximal stress: 64.3 MPa; Elongation at rupture: 1.1; Loss of mass natural durability: 7.63%).

In view of all the results obtained, the parts of a bamboo stem do not all have the same properties. The physicomechanical properties of bamboo depend also on the age of the culm.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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