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MECHANICAL AND PHYSICAL CHARACTERIZATION OF COMPOSITE BAMBOO-GUADUA PRODUCTS: PLASTIGUADUA.

Hector F. Archila[1], Caori P. Takeuchi[2], David J. A. Trujillo[3]

ABSTRACT: The bamboo species *Guadua angustifolia Kunth* (Guadua) was subjected to different fibre extraction processes, chemically treated and used in combination with a set range of polymers to form various composite materials. Novel technologies and artisan methods for veneer production and fibre extraction were explored. Extensive experimental work was undertaken on the composites manufacture, mixes and arrangements to form flat sheets. Physical and mechanical properties of these sheets were assessed on two material configurations: Plastiguadua-L and Plastiguadua-P. The former was a laminated material with 70% by weight of thin veneers of Guadua and 30% thermoset polyester resin. The latter had a 1:1 ratio by weight of short fibre bundles and resin content respectively. For the mechanical characterization, bending, tensile and impact-Izod tests were undertaken. Rockwell hardness, UV, condensation and water absorption were carried out to assess their physical properties. Values obtained for the elastic properties of Plastiguadua-L were lower than those of Plastiguadua-P, whilst strength values showed the opposite response for both bending, tension and impact. Bending and tensile modulus of elasticity for the former were 3.96 GPa and 2.21 GPa respectively, and 4.61 GPa and 2.38 GPa respectively for the latter. Tensile and impact strength values obtained were 38.3 MPa and 20.73 MPa respectively for Plastiguadua-L and 157 J/m and 55 J/m respectively for Plastiguadua-P. Improved resistance to degradation was observed through the UV/condensation test on samples embedded on resin when compared to those with none or slight preservation treatments. Overall, the research project showcased a range of products manufactured by mixing different forms of Guadua fibres and mats with polymers and assessed the mechanical and physical features of two of them. The project focused on a holistic approach to the use and manufacture of bamboo products for engineering applications and as potential substitutes for wood applications.

KEYWORDS: Bamboo, *Guadua angustifolia Kunth*, composite materials, mechanical properties.

1 INTRODUCTION

Bamboo resources were listed by FAO (Food and Agriculture Organization of the United Nations) as Non Wood Forest Products (NWFP) on its last forest resources assessment [1]. Bamboo's self-renewability, high biomass production and fast growth rate offer key environmental advantages together with a high carbon sequestration above and below ground –which has been compared to that of fast growing trees- [2]. Among other bamboos *Guadua angustifolia Kunth* (Guadua) a species endemic to South and Central America has the highest tonnage of carbon fixed per hectare, per year with the lowest rotation period [3]. Guadua is widely used for construction and the utilization of round culms for one and two storey buildings have been standardized under building codes in countries such as Colombia and Peru. Engineered bamboo and Guadua products such as glue laminated beams and cross laminated panels are also under development and seeking standardization [4]. However, either during traditional construction with round culms or manufacturing of engineered Guadua products with rectangular strips, about 40% of the material is discarded due to natural defects and irregularities in diameter, thickness or length [5]–[7]. When possible part of the remaining material is used to power furnaces, but usually it becomes waste. Therefore, Guadua features such as its high fibre content and high tensile strength are not fully exploited. With the aim of tackling these issues and exploring different alternatives and more efficient ways for converting raw Guadua into standardized products with improved characteristics the present research project was set at the National University of Colombia (Universidad Nacional de Colombia). The composite materials developed used the high strength of Guadua fibres as reinforcement in combination with polymeric matrixes to provide embedment and protection against weather, bio-deterioration, humidity and insects

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attack. Various techniques of fibre extraction, modification and arrangement were explored together with different manufacturing technologies. Physical and mechanical properties of some of the developed products were also assessed following NTC (Colombian Technical Norm) and ASTM (American Society for testing and Materials) standards.

2 MATERIALS AND METHODS

Extensive experimental work was undertaken on the preparation, transformation and manufacture of composite materials using *Guadua angustifolia Kunth* as fibre reinforcement. Thermoset polymers, natural latex, polystyrene and polyurethane were used in combination with Guadua fibres, mats and veneers. The objective of carrying out these combinations was to assess the potential of using various forms of Guadua with diverse matrix mixes to develop new fibre reinforced composites (GFRC) and applications. Figure 1 shows some of the alternatives explored and products obtained.

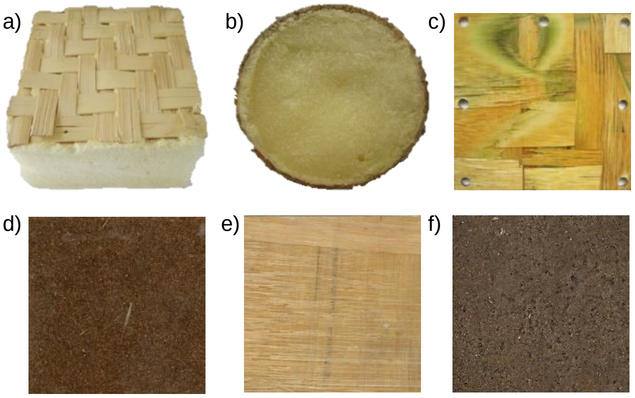
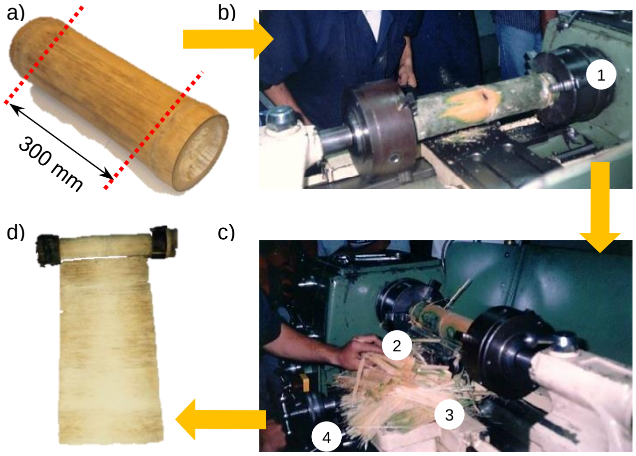


Figure 1. a) Sandwich of woven Guadua faces and polyurethane core; b) Guadua veneer tube with polyurethane core; c) Guadua strands embedded on epoxy resin; d) Guadua saw-dust embedded on polyester resin (Plastiguadua-D); e) Cross laminated Guadua veneers embedded on polyester resin (Plastiguadua-L) and f) Guadua fibres embedded on natural latex.

Two of the developed GFRC were selected for characterizing their mechanical properties: Plastiguadua-L and Plastiguadua-P and subjected to a detailed testing programme. Samples of Plastiguadua-L and P were submitted to three point bending test, tensile test, Izod-impact test and Rockwell hardness. Additionally water absorption and UV and condensation test were undertaken on some of the samples.

2.1 MANUFACTURE OF PLASTIGUADUA-L

Plastiguadua-L s a flat FRC laminate composed of Guadua veneers embedded on a polyester resin. Guadua veneers were extracted mechanically following a technique developed by the technological centre for design and innovation at SENA (Servicio Nacional de Aprendizaje) Dos Quebradas in Colombia. This technique consisted of slicing thin veneers off green culms sections of Guadua placed on the rotatory axis of a metalworking lathe. A 300 mm sharp stainless steel blade positioned parallel to the rotation axis of the lathe and tangentially to the round culms peeled off the material. The speed of the lathe was set to 30 rpm and the advance of the blade was controlled manually. Continuous veneers of thickness 1.5±0.8 mm were obtained using sections of Guadua between two nodes; sections including nodes are fairly discontinuous due the change on the direction of the fibres at the nodes. Figure 2 illustrates the process followed and equipment used.



1.Head of lathe (rotatory axis); 2.Blade; 3.Peeled off material; 4.Mechanism to control the advance of the blade.

Figure 2. Manufacturing process of Guadua veneers; a) Piece of round Guadua; b) Off-cut of round culm between lathe rotating heads; c) Advance of the blade removing the outer-most layer of Guadua d) Final result.

The Guadua veneers were immersed in 8% NaOH (Caustic soda) solution in a water bath at room temperature for 48 hours, with the aim of preparing the surface of the material and improving veneer-matrix interface. Caustic soda treatment has proved to improve fibre-matrix adhesion and compatibility and to remove impurities from the fibre surface [8]. Subsequently, the veneers were rinsed thoroughly in water and left to dry at room temperature before being put in an oven at 105ºC for 24 hours. Following drying, the veneers were impregnated on resin, arranged at 0º and 90º on a 1 m x 0.30 m mould and vertical pressure was applied. A two components Palatal® polyester resin supplied by BASF Química Colombia S.A. was used for the lamination. The amount of resin utilized accounted for one third of the total dried weight of the final product. Once the resin set, pressure was removed and the panel was left to cure for a period of 20 days at room temperature, before machining and testing. The final result can be seen on Figure 1e.

2.2 MANUFACTURE OF PLASTIGUADUA-P

Plastiguadua-P used short fibre bundles mixed with polyester resin to form flat sheets of GFRC. Discontinuous material left from the manufacture process of Guadua veneers was subjected to chemical modification with Caustic soda. This contributed to the separation of fibres, dissolved the lignin that bonds them and improved fibre-matrix interface. The material was immersed in 8% caustic soda solution in a water bath at room temperature for 10 days. Subsequently, the fibre bundles obtained were manually selected, washed several times, left to dry at room temperature and oven dried at 105ºC for 6 hours.

A flat sheet of Plastiguadua-P with thickness 10±0.5 mm was manufactured to facilitate the production of testing samples (Figure 1d). A 1:1 mix of Palatal® polyester resin and fibre of Guadua was casted on a 1 m x 0.30 m mould. Vertical pressure was applied until the resin set, and the panel was left to cure for a period of 20 days at room temperature, before machining and testing.

3 ASSESSMENT OF PLASTIGUADUA’s P & L PROPERTIES

With the aim of assessing the characteristic mechanical and physical properties of the two developed GFRC’s (Plastiguadua P and L), a testing programme was carried out using NTC (Norma Técnica Colombiana) and ASTM (American Society for testing and Materials) standards. The former are the Colombian standards for materials testing and are homologated with the ASTM. Table 1 shows the details of the testing protocol, number of specimens and the standards used.

Table 1. Mechanical and physical testing programme.

Test	Material	No.	Standard
Bending (three point)	Plastiguadua P	5	NTC 1769 (ASTM D790)*
	Plastiguadua L	5	
Tensile	Plastiguadua P	5	NTC 595
	Plastiguadua L	5	
Izod-impact	Plastiguadua P	5	ASTM D256
	Plastiguadua L	5	
Rockwell hardness	Plastiguadua P	1	ASTM D785
	Plastiguadua L	1	
UVB/Condensation	Various	8	ASTM G154-00
Water absorption	Plastiguadua P	3	ASTM D570

*Homologated with ASTM

3.1.1 Three point bending test

Specimens of Plastiguadua P and Plastiguadua L were subjected to a three point bending test to failure following the guidelines of NTC 1769 (1982). The dimensions of the samples and the test set-up can be observed in Figure 3. A ratio length (L) to depth (d) of about 16 was maintained Relative humidity and temperature during the test were 50% and 23ºC, respectively.

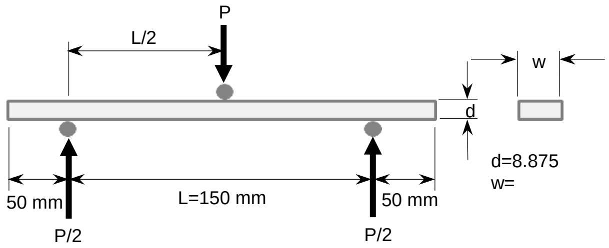


Figure 3. Three point bending test dimensions and set-up.

An Instron 5586 test machine fitted with a 5kN load cell applied vertical load at the specimen midpoint through a 5 mm roller. The specimen was supported on two rollers of the same diameter and the speed of the test was 0.06 mm/sec. Test was conducted to failure and the maximum deflection was reported. Load and deformation at midpoint were recorded and elastic modulus (MOE) and yield strength values were calculated for both specimens (Plastiguadua P and L). These values are presented in Table 2.

Table 2. Results of three point bending test on Plastiguadua’s P and L specimens.

Specimen	width* (mm)	depth* (mm)	MOE* (GPa)	Yield strength (MPa)	Max. defl. (%)
Plastiguadua P	13.05 ±0.41	10.46 ±0.03	4.61 ±0.37	31.3 ±2.1	1.54
Plastiguadua L	13.15 ±0.35	8.87 ±0.03	3.96 ±0.49	74.1 ±11.5	3.59

* average; defl. = deflection

Samples of Plastiguadua-L showed a more ductile failure than those of Plastiguadua-P (Figure 4); the former withstood twice more deformation and doubled the strength at yield when compared to the latter. However, the elastic values in bending for Plastiguadua-P are 15% higher than those of Plastiguadua-L.

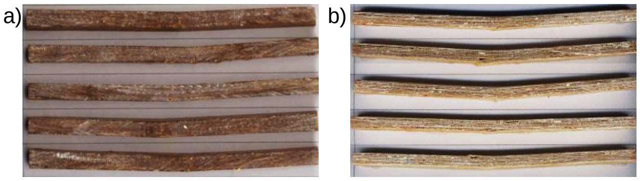


Figure 4. Samples after bending test: a) Plastiguadua-P. b) Plastiguadua-L

These differences on the ability to dissipate energy and withstand load can be explained by the arrangement and configuration of the composites. The higher content of resin in Plastiguadua-P makes it more brittle than Plastiguadua-L, which benefits from its 0-90º lamination and higher fibre content.

3.1.2 Tension test

Plastiguadua-L and Plastiguadua-P samples were subjected to longitudinal tensile test with the aim of assessing their mechanical properties. The test followed NTC 595 (1996) testing protocols and tension modulus of elasticity and tension strength were calculated. Five Type-I samples for each specimen were prepared following the standard procedures and conditioned at a temperature of 23±2ºC and relative humidity of 50±10% for 254 hours before testing.

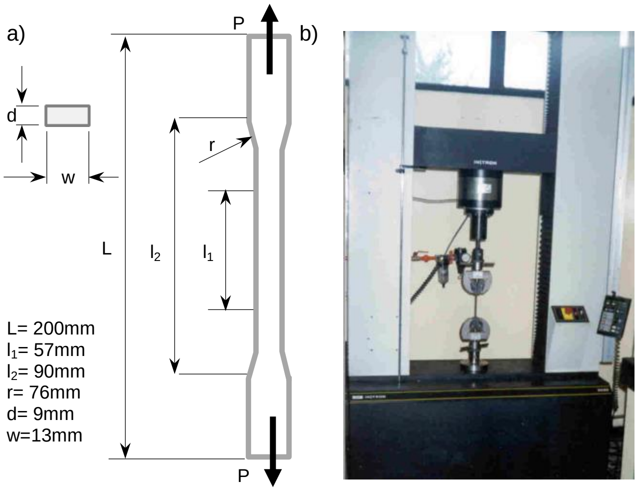


Figure 5. Longitudinal tensile test, a) Type I sample. b) testing machine and test set-up.

The sample was held by self-aligning jaws mounted on an Instron 5586 test machine fitted with a 5kN load cell. The speed of the test was 0.08 mm/sec. Figure 5 illustrates the dimensions of the sample and the test equipment used.

Table 3. Results of the longitudinal tensile test on Plastiguadua's P and L specimens.

Specimen	MOE* (GPa)	Tensile strength* (MPa)	Elongation at failure. (%)
Plastiguadua P	2.38±0.14	20.73 ±4.28	1.0±0.2
Plastiguadua L	2.21±0.13	38.3±4.32	2.2±0.3

* average

The mechanical response of both set of specimens under tension was fairly similar to the results obtained from the bending test. The elastic values for Plastiguadua-L were lower than those of Plastiguadua-P by about 8%, whilst for the former the tensile strength values were superior by a factor of 2 compared to the latter. Hence, the elongation at failure for samples of Plastiguadua-L was about twice the result of Plastiguadua-P. Table 3 contains the elastic and strength values obtained from testing.

3.1.3 Impact Izod test

Impact Izod test was undertaken on notched samples of specimens P and L of Plastiguadua. This test assesses the energy required to break a notched vertically cantilevered sample with a single swing of a pendulum with a set mass.

The resulting impact energy was measured for five samples per specimen and the material's impact resistance was calculated as the ratio of impact energy to thickness (t) expressed in joules per meter (J/m). Test procedure and sample preparation followed the ASTM D256 (1993) standard; type A samples specified by the standard were machined to the dimensions detailed in Figure 6b and conditioned prior to test at 42% relative humidity and 23ºC temperature for 42 hours. Individual samples clamped to the base of the test fixture (Figure 6a) were impacted on their notched face by a 5ft/lb (6.77 J) striker fitted to the pendulum. The distance between the base and the line of initial contact was set to 22.0±0.05mm.

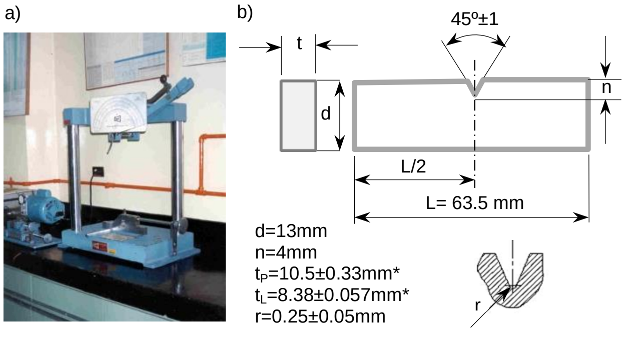


Figure 6. a) Impact test fixture. b) Notch Izod Impact test sample. *d_P and d_L are the dimensions for Plastiguadua-P and Plastiguadua-L respectively.

Table 4 shows the calculated results of the test in both specimens and the type failure occurred in the samples.

Table 4. Results and images of the Notched Izod Impact test.

	Plastiguadua P	Plastiguadua L
Izod notched Type A samples (ASTM D256)		
Sample thickness (mm)	10.5±0.33	8.38±0.057
Impact resistance* (J/m)	55±8	157±36
Failure type	C	P

* average

As can be seen on Table 4, all the samples per each specimen had the same failure mode. Samples of Plastiguadua-P experienced a C (complete break) type failure whilst those of Plastiguadua-L had a P type failure (partial break) as defined by the ASTM D256 [9]. In Plastiguadua-L the fractured distance between the notch and the opposite side is at least 90% keeping hold of part of the material without acting as a hinge.

Overall, Plastiguadua-L samples underwent a ductile failure whilst Plastiguadua-P experienced a brittle failure. The former had a higher capacity of propagating the fracture energy transferred by the pendulum striker (about threefold); this is due to the higher ratio fibre to matrix (7:3) in these samples and their cross laminated fibre arrangement (0-90º).

3.1.4 Hardness Rockwell test

The standard ASTM D785 (1989) for assessing the Rockwell hardness of composite materials was used to measure the hardness of specimens L and P of Plastiguadua. Six samples per specimen were tested using a Wilson Rockwell hardness tester Series 600. Samples with an average thickness of 10.6 mm were subjected to loads between 10 and 60 kg for 10 seconds (Rockwell scale R). The diameter of the indenter was 12.7 mm. Procedure A of the standard was followed and the test was conducted at temperature and relative humidity of 23ºC and 50%, respectively.

Table 5. Rockwell hardness test results for Specimens P and L of Plastiguadua

Specimen	ASTM Proced.	Rockwell scale	Sample thickness (mm)	Rockwell hardness*
Plastiguadua P	A	R	10.6	123.1±1.79
Plastiguadua L	A	R	10.6	52.3±8.29

* average

As can be seen on Table 5 specimens with the highest content of resin and the lowest of fibre (Plastiguadua-P) showed the highest results of Rockwell hardness. These values for Plastiguadua-L were about half of Plastiguadua-P values.

3.1.5 Physical tests

In order to assess weathering effects produced by sunlight and rain exposure during usage, samples of transformed Guadua (non-treated and treated with NaOH) and the developed Guadua-based composites were subjected to UV light/condensation and water absorption tests. UV and condensation test followed the ASTM G154-00a standard whilst ASTM D570 was used for the water absorption test.

Specimens for the fluorescent UV/condensation test were exposed to alternated four hour cycles of UV-B (short wave ultraviolet B) light and condensation. An Atlas UV instrument was fitted with a Sunlamp 313nm (nanometers) and the total exposure of the samples was 50 hours. The UV-B cycles were run at 60ºC, approximate wavelength of 310nm and typical irradiance of 0.63 W/m^2/nm. Temperature during condensation cycles was set to 50 ºC. This UV/condensation procedure corresponded to the cycle type 2 specified by the ASTM standard (Practice G53). Changes in colour and appearance of the samples in comparison to the unexposed ones are reported in Table 6 and can be observed in Figure 7.

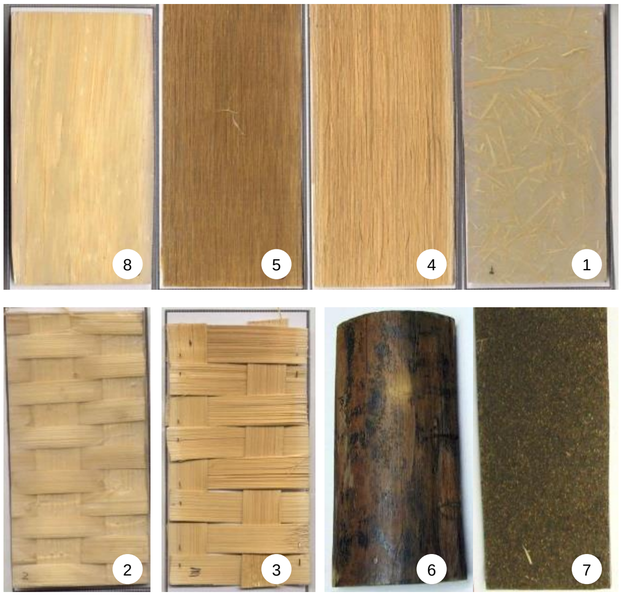


Figure 7. Samples after UV exposure test (key on Table 6)

Water absorption test was carried out following ASTM D570-98 standard. Prior to test, Plastiguadua-P’ samples (random short fibre/polyester - 50:50) were conditioned in an oven (Ternolyne OU 35135) at 50±3ºC for 24 hours, cooled in a desiccator and weighed to the nearest 0.001g (conditioned weight). Subsequently, the samples were placed in a container of distilled water at a constant temperature of 23±1ºC for 24 hours. Once removed from the container, the samples were wiped off to remove the excess of water on the surface and weighed again to the nearest 0.001g (reconditioned weight).

Table 6. Result of UV/condensation and water absorption tests.

No.	Specimen	Changes after UV exposure	Water absorption (%)
1	Plastiguadua-P’	Slightly yellow	5.279 ±0.402*
2	Plastiguadua-W (woven mat)	None	-
3	Woven Guadua mat	Slightly yellow	-
4	Guadua veneer (non-treated)	Slightly yellow	-
5	Guadua veneer treated with caustic soda (NaOH)	Slightly brown	-
6	Smoked treated Guadua	None	-
7	Plastiguadua-D (saw-dust)	None	-
8	Plastiguadua-L	Slightly yellow	-

* average

Results of the accelerated weathering exposure tests conducted and images of the samples after the same test are presented in Table 6 and Figure 7, respectively.

4 DISCUSSION

Table 7 shows the results obtained from the mechanical testing programme undertaken on Plastiguadua-L and Plastiguadua-P specimens. Values from other studies are also listed with the aim of comparing the results.

Table 7.

Composite material (matrix- fibre)	Fibre content wt. (%)	Yield strength (MPa)	MOE bending (GPa)	MOE tension (GPa)	Tensile strength (MPa)	ε_{max} tension (%)	Impact strength (J/m)
Plastiguadua-P	50	31.3 ±2.1	4.61 ±0.37	2.38 ±0.14	20.73 ±4.28	1.0 ±0.2	55 ±8
Plastiguadua-L	70	74.1 ±11.5	3.96 ±0.49	2.21 ±0.13	38.3 ±4.32	2.2 ±0.3	157 ±36
Polyester-fiberglass wastes [11]	30	-	-	1.9 ±0.1	26.2 ±1.8	1.9 ±0.3	122.9 ±7.9
	50	-	-	0.1 ±0.0	3.2 ±0.4	8.6 ±0.8	385.8 ±0.8
Polyester-Sisal [12]	30 (unid)	-	-	-	-	-	51
Polyester-malva [12]	30 (unid)	-	-	-	-	-	408
Polypropylene (PP)-flax [12]	30	-	-	5 ±0.4	-	2.7 ±1.5	-
PolyL lactic acid (PLA)-flax [13]	30	-	-	8.3 ±0.6	-	1.0 ±0.2	-
CNSL-Hemp [14]	(unid)	-	-	29.79 ±1.93	83.29 ±15.45	0.45 ±0.11	-

CNSL (cashew nut shell liquid); ε_{max} (elongation at break); **unid** (unidirectional)

Overall, the values obtained for the elastic properties of Plastiguadua-L are lower than those of Plastiguadua-P, whilst strength values showed the opposite response for both bending, tension and impact. This behaviour is observed on the characteristic ductile mode of failure of samples L in comparison to the more brittle response of Plastiguadua-P samples and is mainly due to the higher content and the controlled orientation of fibres in Plastiguadua-L specimens (0º/90º).

The particularly low values of modulus of elasticity and the prolonged zone of plastic deformation exemplifies the low strain-rate dependence of composites reinforced with natural fibres [10] and specifically of Plastiguadua-L. It can also be observed that higher fibre content increases the ability of the GFRC to dissipate energy and Plastiguadua-L's impact strength. By contrast, Rockwell hardness values increased with the increase on matrix material. Correspondingly, UV/condensation test also showed better results on samples embedded on resin than those with none or slight preservation treatments.

The UVB light and condensation procedure triggers rapid failure in polymeric materials, but results are not well suited to real sunlight conditions. Although UVB degrades the material in a shorter period of time, the 313nm peak weave-length is not appropriate for sunlight simulation and its effects are regarded to aging process not occurring outdoors.

5 CONCLUSIONS

The versatility and viability of bamboo species *Guadua angustifolia Kunth* for structural applications was showcased by the development of multiple Guadua fibre reinforced composites (GFRC) such as Plastiguadua-P and Plastiguadua-L and their specific mechanical and physical testing. Although, limitations were encountered during their manufacture, this research served as the basis for further investigation on the development of engineered bamboo products [4].

High embodied energy on the extraction process of fibre bundles and veneers for manufacturing Plastiguadua-P and L was observed; however, waste product material from current lamination processes (between 40 and 50% of the bulk material) could be converted into by-products with improved physical and mechanical properties. Further investigation into less labour-intensive fibre extraction processes, chemical treatments applied to the fibre to improve interface and the use of bio-resins is required for the development of innovative, sustainable and commercially viable products of Guadua.

Although resin embedment of GFRC showed good results in terms of weathering resistance, oil derived matrix products score negatively on Life Cycle Assessments, have some harmful effects on human health (VOC) and increase the overall cost of final products. Technologies such as acetylation and densification used on timber to modify the cell structure and improve its physical and mechanical properties could be applied to Guadua and bamboos in general. These can contribute to tackle common issues associated with the use of bamboo such as bio-deterioration, natural irregularity and short life span.

Overall, new ways for efficiently using the material together with composite materials technologies need to be investigated if Guadua is to become a mainstream and substitute product to timber.

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