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Correlation between chemical compounds and mechanical response in culms of two different ages of *Guadua angustifolia* Kunth

Correlación entre composición química y respuesta mecánica
para dos edades de culmos de bambú *Guadua angustifolia* Kunth

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ABSTRACT

Wet chemical analysis was used to determine carbohydrate structural contents, as well as ash and extractive contents on four *Guadua Angustifolia* Kunth forms (f. Cebolla, f. Macana, f. Rayada Amarilla and f. Castilla) with two different growth ages (young and mature). Soluble and insoluble fiber content was determined by using AOAC 985.29 method. Bending tests were conducted in a universal testing machine following ASTM D143 standard method in order to determine modulus of rupture (MOR). Finally, a correlation between contents of chemical compounds and bending behavior (MOR modulus) was carried out with SPSS Statistical Package, version 7.0, obtaining Pearson's coefficient correlation and showing the relationship between soluble fibers and bending response for mature *Guadua* culms.

KEY WORDS: bamboo culms, Chemical composition, Fiber Content, Modulus of Rupture, Mechanical properties.

RESUMEN

Mediante un análisis químico, se determinó el contenido de carbohidratos estructurales, contenido de cenizas y el contenido de extractivos de cuatro formas de *Guadua Angustifolia* Kunth (f. Rayada Amarilla, f. Macana, f. Cebolla y f. Castilla), en dos edades de crecimiento diferente (joven y madura). Se determinó el contenido de fibra soluble e insoluble mediante el método oficial AOAC 985.29. Se realizaron ensayos de flexión, siguiendo el método estándar ASTM D143, para determinar el módulo de ruptura (MOR) en las cuatro variedades de *Guadua*. Por último, se realizó una correlación mediante el paquete estadístico SPSS versión 7, entre el contenido de compuestos químicos y la respuesta de flexión, obteniendo el coeficiente de correlación de Pearson. Se encontró una correlación entre el contenido de fibra soluble e insoluble y la respuesta de flexión (MOR) en las *Guaduas* con mayor edad de crecimiento (maduras).

PALABRAS CLAVE: tallos de bambú, composición química, contenido de fibra, módulo de ruptura, propiedades mecánicas.

INTRODUCTION

Bamboo is a fast growing plant (Porterfield, 1928; Liese and Hamburg, 1987), which grows naturally in all continents except Europe; however, most species are found in Asia Pacific and South America (Liese and Hamburg, 1987; Bystriakova *et al.*, 2003; Chaomao *et al.*, 2004). Some species can tolerate temperatures between 40 °C and 50 °C, whereas others can withstand snow or even temperatures of severe frost. Bamboo plays an essential role in the daily lives of millions of people in subtropical and tropical regions; even in some countries like Japan, bamboo has become an important natural material and it is widely used for many purposes. There are many bamboo species; one of the most important species that grows in Central and South America is called *Guadua*; this bamboo species is higher and thicker than Asian bamboo species.

All bamboo species are composite natural materials, whose culms are a vertical consecutive arrangement of nodes and internodes and their properties are mainly determined by their anatomy and chemical composition (Liese and Hamburg, 1987; Ghavami and Marinho, 2005). The total bamboo culm comprises about 50% parenchyma, 40% fibers, and 10% conducting tissue (Liese, 1998), some percentage variations exist according to species, however, all of them have a unique distribution pattern within a culm. The distribution pattern consists of long-fiber aligned cellulose embedded into a lignin and hemicellulose matrix; these fibers do not have a homogeneous content within the bamboo culm and it has been recorded that the fibers increase from the inner to the outer wall (Grosser and Liese, 1971), as well as from bottom to top and this distribution affects the mechanical behavior (Mohan and Mohana, 2007; Gyansah *et al.*, 2010). It is well known that the fibers in Asian bamboo culms are grouped into cup shapes of around 1,5 mm to 4,5 mm-long conductive tissue (Porterfield, 1928). This arrangement is quite characteristic of various bamboo species, including *Guadua*. Knowledge of Asian bamboo fibers has permitted using these fibers mainly in pulp paper and textile industries (Ning y Yang, 2007; Oda,

2003; Hammett *et al.*, 2005); nevertheless, nowadays bamboo fibers have become an important alternative in the research of reinforced composite materials with natural fibers (Ghavami, 2005). That knowledge permits finding in this plant a good material for several necessities like housing, food, furniture, toys, apparel, and paper, among others.

The useful life of bamboo as a plant is around three years and it is possible to find different applications, which are correlated with its age. Young culms are commonly used in food, while the older bamboo culms are used as construction building material (Van der Lugt *et al.*, 2006), but in some applications such as textile, pulp paper, and handicrafts among others, bamboo culm age does not matter. Another important aspect to determine uses for bamboo species is related to their chemical composition. Fiber content and chemical composition has been studied on Asian and Japanese bamboo species and their variation with age and height have also been determined by different authors (Liese and Weiner, 1996; Low *et al.*, 2006; Lybeer and Koch, 2005) and these studies have permitted to consider this type of bamboo as an alternative in biomass research and its application (Scurlock *et al.*, 2000). Despite, all the information about Asian and Japanese bamboo species, *Guadua* has not been studied in detail and no reports exist of its chemical composition or its mechanical behavior.

OBJECTIVE

The objective of this work is to present a complete chemical composition of four *Guadua* bamboo culms to increase future research areas with this kind of bamboo. Moreover, the present work seeks to provide results from a regression analysis between chemical composition and bending behavior.

MATERIALS AND METHODS

Description of samples

Bamboo samples came from an experimental field located in Armenia, Quindío (Central region of Colombia). All



the specimens were oven dried at 40 °C for 8 h to reduce moisture content and decrease microorganism proliferation. The culms of these kinds of bamboo are hollow in the center and the distance between the internal to external wall is on average 1,5 cm; the *Guadua* bamboo culms are separated by nodes and internodes, as shown in figure 1. In this work, bamboo samples were taken from the bottom culm and were classify as mature for culms with 4 years and young for culms with 2 years.

Wet chemical composition analysis

All bamboo samples were analyzed by using standard biomass analysis by the National Renewable Energy Laboratory (NREL) with laboratory analytical procedures (LAPs) for whole biomass analysis, as listed:

- NREL/TP-510-42620 Preparation of Samples for Composition Analysis
- NREL/TP-510-42619 Determination of Extractives in Biomass
- NREL/TP-510-42622 Determination of Ash in Biomass
- NREL/TP-510-42618 Determination of Structural Carbohydrates and Lignin in Biomass

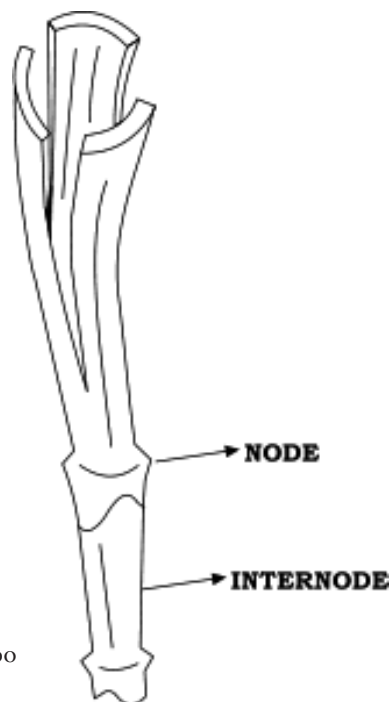


FIGURE 1. *Guadua* Bamboo Culms.

US National Institute of Standards and Technology (NIST) Bagasse Standard Reference Material # 8491 was analyzed with each batch of bamboo samples, as a quality-assurance reference for determination of extractives, lignin, and carbohydrates. Aqueous and ethanolic extractions were performed in duplicate on the milled, homogenized samples. Each extractive-free sample was analyzed in duplicate for lignin and carbohydrate content, giving a total of four separate determinations for each bamboo sample. Direct measurement of the protein content in these samples was not performed, but the protein content can be estimated from the nitrogen elemental analysis (Phillips, 1939) and varies only slightly with age in the range of 1,4% - 3,8%

Soluble and Insoluble Fiber content

Insoluble fiber determination was performed by using the standard Method AOAC 985.29 (AOAC, 2000). All measurements were done in triplicate.

Bending test

The bamboo samples were tested by following the ASTM D143-94 (ASTM, 2007) standard test method, modified accordingly, to accommodate the specific characteristics of the bamboo specimens, in a universal machine (INSTRON 4401). The load was applied on the transverse surface with a crosshead speed of 0,5 mm/min (Fig. 2). The specimens were cut as strips and its size was set at 160-mm length and 10-mm width, and thickness was determined with each culm thickness. The Modulus of Rupture (MOR) was obtained in triplicate for each bamboo sample.

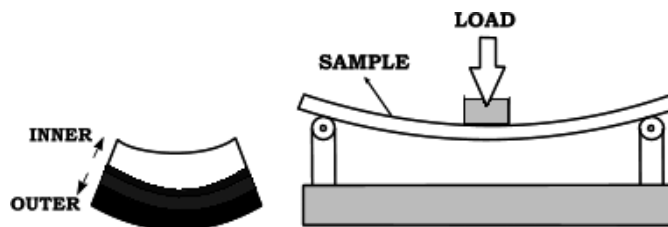


FIGURE 2. Load applied in *Guadua* bamboo culms.

Regression

Statistical analysis was performed with the STATGRAPHICS 5.1 Plus Statistical Package to obtain Pearson's correlation coefficient. Five variables were used and the multiple linear regression analysis was made among Insoluble Fiber, Soluble Fiber, Lignin, Cellulose, and Hemicellulose with the MOR.

RESULTS

Chemical composition

Table 1 shows the complete wet chemical analysis (soluble fiber) of all the *Guadua* bamboo specimens in mature and young culms. Total mass for all specimens is close to 90% or above, indicating that the analysis was complete and no significant biomass fractions were lost. The direct protein measurement was not performed, but protein content could be obtained by nitrogen element analysis and did not have significant variation (Phillips, 1939). Higuchi (1957) measured chemical composition for different kinds of Asian bamboos and found a similar chemical composition to *Guadua* bamboo chemical composition. Scurlock *et al.* (2000) reported a wet chemical composition analysis for a Japanese bamboo; these results are close in value to *Guadua* bamboo chemical composition analysis.

Lignin content values for *Guadua* are between 23% and 27%; meanwhile, Scurlock reported a range between 24% and 37% for softwoods (Scurlock *et al.*, 2000), suggesting that *Guadua* bamboo has similar physical pro-

perties and can be used as conventional softwood. On the other hand, a Cellulose content of 37% - 44% and a hemicellulose content of 13% - 20% for *Guadua* bamboo could be compared to cellulosic biomass feedstock with a content of 35% - 50% for cellulose and 10% - 40% for hemicellulose (McKendry, 2002). It placed *Guadua* bamboo as natural material comparable to biomass feedstock in which its high cellulose/hemicellulose content could be used for ethanol and paper production.

Soluble and Insoluble fiber

Soluble and Insoluble fiber are the total fiber content and each is made up of complex carbohydrates, including cellulose, hemicellulose, and lignin (Selvendran, 1984). The fiber content was determined for all samples in mature and young culms. Figure 3 shows the insoluble and soluble total fiber content per specimen. It is possible to see that for all samples the main fiber content is insoluble fiber.

From the ANOVA statistical analysis, it is possible to establish that the insoluble and soluble fiber content for some varieties do not have significant differences. It is also possible to see that, in general, the insoluble fiber content exhibit a small decrease in samples with age, while soluble fiber exhibit a high increases with age. Total fiber content is an important test that provides information related to each *Guadua* bamboo variety and it is possible to establish the potential uses of this kind of bamboo. The results shown in this figure correspond to five measurements per specimen.

TABLE 1. Wet chemical composition analysis in *Guadua* Bamboo samples on two different ages.

	AGE	ASH	EXT ET	LIGNIN	GLUCOSE	XILOSE	ARABI-	MANOSE	Total
Macana	Young	2,68	1,92	23,06	47,80	15,85	2,18	0	93,50
	Mature	0,92	2,33	20,21	47,43	18,08	2,61	0	91,60
Cebolla	Young	2,56	1,66	27,75	49,17	15,64	2,15	0	98,93
	Mature	2,30	1,92	25,41	45,83	13,34	1,61	0	90,41
Rayada	Young	1,86	2,17	24,33	52,49	14,14	1,91	0	96,90
	Mature	1,43	3,08	22,13	48,41	13,06	1,74	0	89,85
Castilla	Young	2,93	1,42	26,33	50,26	15,85	2,22	0	99,01
	Mature	1,44	2,46	23,86	46,30	14,24	1,89	0	90,19
NIST Baggase		3,33	2,29	25	41,16	22,58	2,75	0	97,11

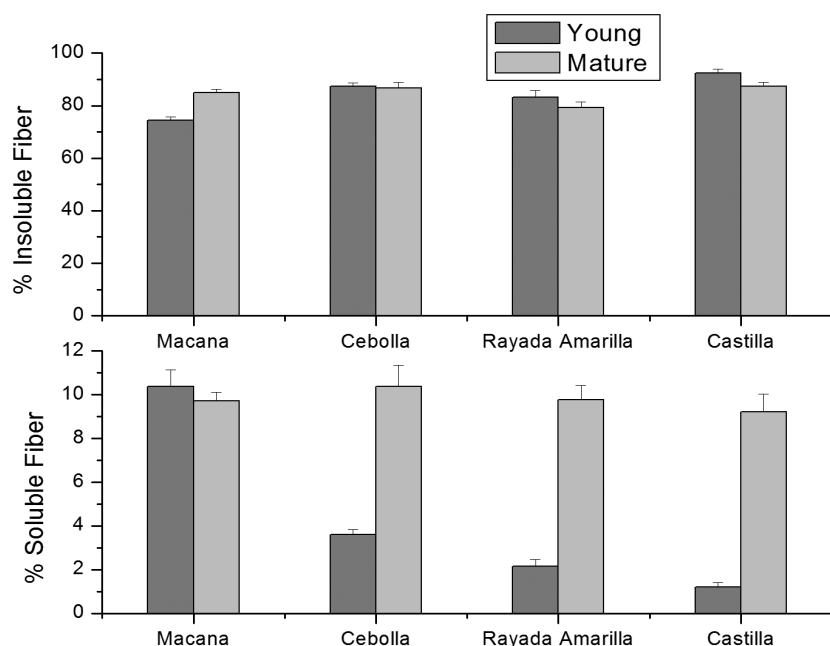


FIGURE 3. Fiber content for *Guadua* bamboo culms young (red) and mature (green).

Bending test

Failure of test specimens is associated to a common failure mode known as local crushing and this was identified in all specimens tested (Chung and Yu, 2000). Typical load deflection curves were obtained, as shown in figure 4.

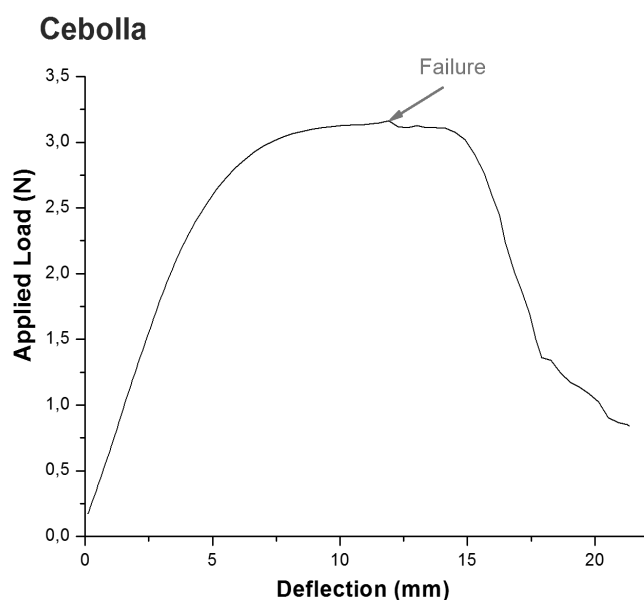


FIGURE 4. Deflection curve to *Guadua* bamboo culm.

Table 2 shows the MOR in each bamboo sample for mature and young culms; from the ANOVA statistical analysis, it is possible to establish that the MOR does not have significant differences in young culms. Decreased MOR with age is noted in most varieties; this decrease is above 50%. These results agree with those reported by Correal and Arbelaez (2010) who found that for *Guadua Angustifolia* Kunt all mechanical properties including MOR have a correlation with age; they showed that these mechanical properties decrease in old culms. In addition, variations in the chemical components could be correlated to the mechanical behavior (Sánchez-Echeverri *et al.*, 2010). The results shown in Table 2 correspond to three measurements per specimen.

TABLE 2. Rupture modulus (MOR) for each bamboo samples Young and mature culms.

	Modulus of Rupture MOR (N/mm ²)	
	YOUNG	MATURE
Macana	96,87 ± 3,1 ^a	43,73 ± 2,1 ^c
Cebolla	127,39 ± 6,4 ^a	123,64 ± 6,2 ^a
Rayada Amarilla	104,65 ± 7,2 ^a	141,71 ± 5,3 ^a
Castilla	102,27 ± 5,1 ^a	80,37 ± 3,4 ^b

Test were performed in triplicate. Mean ± SD values followed by the same letter in each column are not significantly different (P < 0,05).

Correlations

Table 3 shows Pearson's coefficient correlation between MOR and the chemical composition in each *Guadua* bamboo sample for mature and young culms. The bold number shows a highly significant Pearson's coefficient correlation with $p < 0,05$. These results indicated that only exists an inverse correlation among MOR and cellulose and hemicellulose content for mature culms, while young culms do not have any correlation. Genet, *et al.* (2005) related cellulose content with mechanical properties, they found a positive correlation between tensile strength and Cellulose, however; they did not separate Cellulose and Hemicellulose and that positive correlation is influenced by the high stiffness in the longitudinal direction of the cellulose fibers (Persson, 2000), nevertheless; there are no published data about bending behavior and chemical compounds content for transversal direction for those materials or *Guadua*. It is interesting that results shown here are against others previously published, despite there are not results presented specifically for *Guadua*, some results for materials composed mainly by cellulose, hemicellulose and lignin (fibrous ligno-cellulosic materials) as leaves and roots increase their mechanical properties with cellulose content (Angeles *et al.*, 2010; Genet *et al.*, 2005).

TABLE 3. Pearson coefficient correlation between chemical composition and Rupture modulus (MOR).

	Pearson coefficient correlation (<i>r</i>)	
	MOR YOUNG	MOR MATURE
Cellulose	0,7913	-0,6269
Hemicellulose	-0,0661	-0,8427
Lignin	0,4677	-0,2926
Soluble fiber	0,1654	0,2333
Insoluble fiber	0,3994	-0,4365

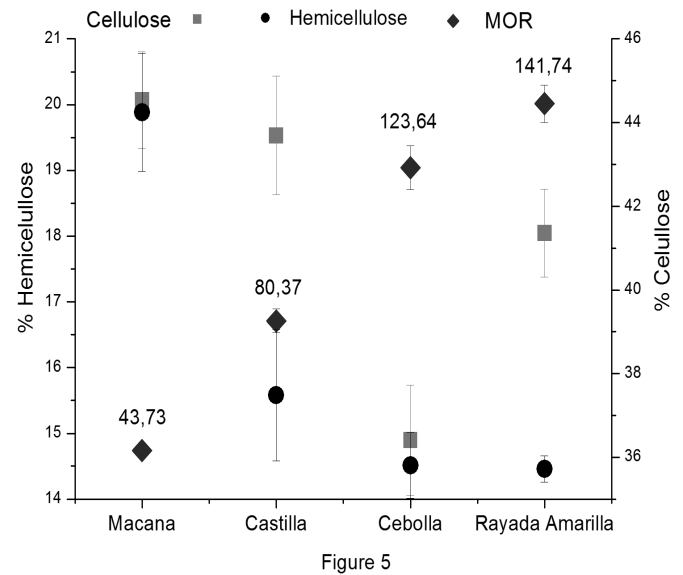


FIGURE 5. Chemical compounds and Rupture modulus for Mature *Guadua* bamboo culms.

Figure 5 shows cellulose, hemicellulose content, and MOR for mature *Guadua* bamboo culms. The MOR is influenced by content of cellulose and hemicellulose as expected in a composite material.

CONCLUSIONS

Wet chemical analysis (soluble fiber) for *Guadua* bamboo culms can be compared to results found for other kinds of Asian and Japanese bamboos, which currently have important applications. Although there is a variation in both soluble and insoluble fiber content with age, the variation in insoluble fiber is not significant, however; for the two *Guadua* ages analyzed, the main fiber content is insoluble fiber. The main chemical compounds that have an influence in the mechanical properties are Cellulose, Hemicellulose and Lignin whose elastic properties were described by Davalos-Sotelo (2005); for *Guadua* these were the main compounds found.

The hemicellulose and cellulose content has inverse proportionality with MOR for mature culms. As is well known, Cellulose fibers has a longitudinal orientation and hence Hemicellulose, which is a polysaccharide linked to cellulose also has the same general orientation;



the distribution ratio in these two principal compounds will have an effect in the bending behavior which was tested in transversal direction. The inverse correlation could be explained due the low stiffness strength of cellulose and hemicellulose on radial direction (Persson, 2000), hence a high content of both components results in a low MOR. Knowledge of chemical and mechanical properties and their relationship in *Guadua* bamboo is a base to develop studies with this plant and generate potential applications.

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