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VARIATION IN MECHANICAL PROPERTIES WITHIN AND BETWEEN PLANTATION-GROWN *GMELINA ARBOREA* TREES

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ABSTRACT: Recent studies have shown that the material properties of Gmelina - a fast-growing hardwood species, are comparable with those of European-grown softwood species and are suitable for construction purposes. Information on the variation in the material properties which could aid the end use, such as sorting the logs with respect to end user requirement, is lacking. This work is an investigation into the variation of the mechanical properties along the height and between different Gmelina trees, to aid an efficient and effective end use of the material. 10 material properties were experimentally and statistically investigated. The results showed that the material properties of Gmelina do not vary along its height as much as is observed for other timber species. Between the trees, a variation range of 11 – 14 % was determined.

KEYWORDS: ANOVA, *Gmelina arborea*, Mechanical properties, Statistical analysis, Tropical timber species, Variation

1 INTRODUCTION

Gmelina arborea is a fast-growing tropical hardwood species which is capable of reaching a mean diameter at breast height of between 60 - 80 cm in 20 years [1]. It has a low cost of establishment, is suitable for paper and pulp and for making solid wood products, and has been described as a very promising tree species [2]. It has also become one of the most important plantation species in tropical areas due to its low cost of establishment and the fact that it can be developed extensively where it has never existed before [3]. Gmelina is not a threatened species and grows across different continents of the world. Recent studies on its mechanical properties and embedment strength, show that it has great potential for use as a construction material [4]. For an optimal use of the material in the construction industry however, a proper understanding of the variation of its strength properties along its height, and between different trees is required to provide valuable information to aid decisions on how to sort the logs in accordance with end-user requirements. For Gmelina however, this information is not yet available. This study aims at determining the variation in the mechanical properties between and within (along the height of) three Gmelina trees (see Figure 2) by means of experimental and statistical investigations.

2 MATERIALS AND METHODS

2.1 MATERIALS

The material used for this study was collected from three plantation grown *Gmelina arborea* trees obtain in Akure in southwestern Nigeria (see Figure 1).

Figure 1: *Map of Nigeria, showing Akure, the location where the materials were obtained (Map was obtained from Google).*

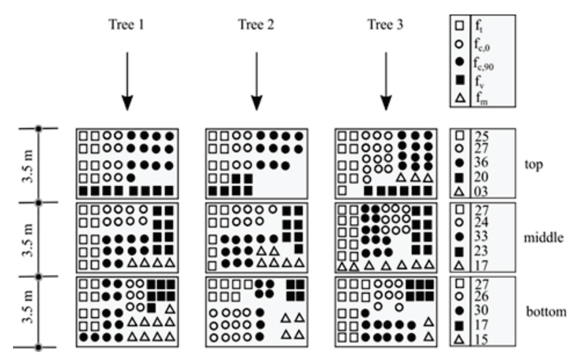

Figure 2: *Location and number of specimens tested.*

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2.2 METHODS

The collected specimens were prepared and tested in accordance with EN 408 [5], except for the tensile strength test, which was conducted in accordance with the German standard DIN 52188 [6]. The specimens for investigating the variation in the material properties between the trees were separated according to trees as trees 1, 2, and 3 while those for investigating the variation in the material properties along the height were separated according to location as top, middle, and bottom (see Figure 2). The number of specimens, the type of tests conducted, and the location from which the tested specimens were obtained, are all shown in Figure 2.

Details of the procedures leading to the experimental data shown in Table 1, are published in [4]. After obtaining the experimental data, statistical analyses such as the analysis of variance (ANOVA) and the Tukey HSD test were conducted on them using the R-programming language. The ANOVA was conducted to determine the variation in the various material properties along the height and between the trees, while the Tukey HSD test was conducted to determine further insights on the nature of the variations both within and between the trees.

The ANOVA, being a process of testing for the similarity or difference between two or more groups of data by testing the means of the different groups, is done under the null hypothesis H_0 that the sample means are equal, or do not have significant differences. The result of this test is generally given in terms of the F-statistic (f-value), which is then compared with critical f-values obtained from statistical tables. The null hypothesis is true if the calculated or observed f-value ($F_{observed}$) from a set of data is less than the corresponding critical f-value ($F_{critical}$) from statistical tables. Since this is a relatively complex calculation, its result from the R programming language is given both as the f-value as well as the p-value (an evidence in support of the null hypothesis). Considering a significance level (α-value) of 0.05, p-values > 0.05 would mean that there is no significant difference in the sample means of the set of data tested. P-value < 0.05 means that the means of the tested group of data are different. In such cases, the Tukey HSD test (conducted under the null hypothesis that the means of the various groups are equal) is carried out by determining the q-statistic. This is then compared with critical q-statistic values of the studentized range distribution, to uncover the source of the difference in the tested data. Using the R-programming language, the results are also given as p-values, which can be interpreted as already explained.

Ten material properties including the tensile strength ($f_{t,0}$), compressive strength parallel to the grain ($f_{c,0}$), compressive strength perpendicular to the grain ($f_{c,90}$) shear strength (f_v), bending strength (f_m), density (ρ) the elastic moduli in tension ($E_{t,0}$), bending (E_m) compression parallel ($E_{c,0}$) and the MoE in compression perpendicular to the grain ($E_{c,90}$) were all investigated in the study and the results obtained are presented and discussed in Section 3.

3 RESULTS

3.1 EXPERIMENTAL RESULTS

Results of the complete experimental investigations are shown in Table 1.

Table 1: *Experimental results*

Material property	Minimum (MPa)	Maximum (MPa)	Mean (MPa)
$f_{t,0}$	36.89	98.72	67.91
$f_{c,0}$	23.88	41.38	34.02
$f_{c,90}$	3.97	9.53	4.51
f_v	3.91	7.83	6.30
f_m	29.79	72.73	55.64
E_t	7,855	18,888	11,840
$E_{c,0}$	6,321	21,051	11,027
$E_{c,90}$	161.00	701.00	419.42
E_m	9,446	15,540	12,340
ρ *(kg/m³)*	387.00	528.00	452.00

3.2 STATISTICAL ANALYSIS RESULTS: WITHIN-TREE VARIATION

The ANOVA results for the within-tree variation are shown in Table 2 and those for the between-tree variation, are shown in Table 4.

Table 2: *ANOVA results for within-tree variation*

Material Property	Within tree variation		
	$F_{observed}$	$F_{critical}$	p-value
$f_{t,0}$	2.902	3.129	0.061
$f_{c,0}$	10.02	3.131	< 0.01
$f_{c,90}$	2.428	3.102	0.093
f_v	3.316	3.102	0.044
f_m	1.595	3.302	0.219
$E_{t,0}$	0.298	3.149	0.744
$E_{c,0}$	0.146	3.130	0.865
$E_{c,90}$	1.418	3.149	0.248
E_m	0.358	3.133	0.702
ρ	3.985	3.000	0.020

The result in Table 2 shows that apart from the $f_{c,0}$, f_v, and ρ, whose p-values < 0.05, the material properties of the Gmelina trees considered in this study do not vary along the height. This findings agree with those of [7] who reported no variation in the MoE in bending, bending strength and in the compressive strength parallel to the grain of Blackwood grown in Portugal.

The variation along the height of Gmelina determined in Table 2 for $f_{c,o}$, f_v, and density also agrees with [8] who reported a variation in density and compressive strength parallel to the grain along the height of beech wood. The nature of the variation determined for these material properties along the height of Gmelina, was further investigated by comparing the mean value of one of the groups (e.g., the top) with the mean value from each of the other groups (middle and bottom respectively), using

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the Tukey HSD test. The result of this is shown in Table 3. In Table 3, the results of the Tukey test are shown in the first three columns, while the mean material property values obtained from the different parts of the trees are presented and compared in the other columns.

Within-tree variation in the compressive strength parallel to the grain – $f_{c,0}$

Table 2, shows the results of comparing the strengths of one part of the trees (e.g., the top), with the other parts (middle or bottom respectively) to determine the part or parts of the tree that are different from the others. Based on the data in Table 2, one sees that there is no statistical significance in the compressive strength parallel to the grain obtained from the top and bottom parts of the trees.

A comparison between the middle and bottom parts as well as the top and the middle parts, as shown in Table 3, are seen to be statistically significant (p-values < 0.05). Furthermore, the differences of the mean strength values between the middle and bottom as well as the top and middle parts are respectively 8 % and 14 %, while that between the top and bottom part is 5 %. A look at the mean values, shows that the compressive strength parallel to the grain obtained at the middle parts of the trees, is smaller than those obtained from the top and bottom parts. This shows that the difference in the strength values detected by the ANOVA, is due to the strength obtained from the middle part of the trees. The variation in compressive strength along the height (as shown in Table 3) is thus a slight reduction in the strength from the bottom to the middle and then a slight increase from the middle to the top.

Table 3: *Within-tree Tukey HSD test results*

Material Property	Parts tested	p-values.	Mean values (MPa)			Bottom / Middle	Top / Bottom	Top / Middle
			Top	Middle	Bottom			
$f_{c,0}$	Middle-Bottom	0.0008	35.88	31.60	34.23	1.08	1.05	1.14
	Top -Bottom	0.1945						
	Top-Middle	0.0219						
f_v	Middle-Bottom	0.1663	5.92	6.70	6.13	0.91	0.97	0.88
	Top-Bottom	0.7995						
	Top-Middle	0.0497						
ρ	Middle-Bottom	0.0835	448	450	458	1.02	0.98	1.00
	Top-Bottom	0.0216						
	Top-Middle	0.8476						

Within-tree variation in shear strength parallel to the grain - f_v

On the variation of the shear strength, Table 3 shows that there is no variation in the shear strength obtained from the middle and bottom parts of the trees as well as those obtained from the top and bottom parts (all having p-values > 0.05). However, comparison of results obtained between the top and middle parts is seen to be statistically significant, with a p-value of approximately 0.05. This shows that the difference detected in the ANOVA test for the shear strength tests, is due to the results obtained from the middle part of the trees, whose mean values as seen in Table 3 are relatively higher. Based on data in Table 3 however, the difference in the mean values obtained from the top and the middle parts is 12 %. The variation in shear strength is seen to increase slightly from the bottom to the middle, and then reduces slightly from the middle towards the top.

Within-tree variation in the density values

No statistical difference was determined in the density values between the top and the middle parts of the trees as well as between the middle and bottom parts of the trees. A comparison between the top and bottom parts however, showed to be statistically significant (having a p-value of 0.0216, which is < 0.05). Looking at the mean density values in Table 3, one sees that the mean density obtained from the bottom part of the trees is comparatively higher than those obtained from the middle and top parts, respectively. This shows that the difference in the density values identified by the ANOVA, is owed to the value from the bottom part of the trees. It can also be seen that the mean density value at the middle is higher than that at the top. This implies that the density values as considered in this study, fall slightly with increase in height. Although studies by different researchers as compiled in [9] show exceptions with differing along the height of different wood species, it can be understood from the formation and growth of wood in trees, as well as the influence and presence of juvenile wood up the trunk that the heaviest wood should be at the base of the tree, with a gradual decrease in density up the trunk [10]. Other density variation patterns discussed in [9] are inconsistent

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with this rule and are not within the scope of discussion of the current study. The results (slight reduction of density with height) obtained in this study for the variation of density along the height of Gmelina, was also reported by Lamb [11] for Gmelina, as well as by other researchers [7], [8], [12] for other tree species.

3.3 STATISTICAL ANALYSIS RESULTS: BETWEEN-TREE VARIATION

Results of the between tree variation in the Gmelina trees examined in this study are shown in Table 4 and Table 5. The data in Table 4, shows that there is no variation in the shear strength, the bending strength, and the MoE in compression parallel to the grain between the Gmelina trees considered in this study, whereas the other material properties showed to vary between the trees. The nature of the variation in the mechanical properties between the trees as determined from the Tukey HSD test are detailed in Table 5 and discussed in the sections that follow.

Table 4: *ANOVA results for the between-tree variation*

Material Property	Between tree variation		
	$F_{observed}$	$F_{critical}$	p-value
$f_{t,0}$	3.261	3.129	0.044
$f_{c,0}$	6.119	3.131	0.003
$f_{c,90}$	11.93	3.102	< 0.01
f_v	2.905	3.102	0.064
f_m	0.461	3.302	0.635
E_t	15.83	3.149	< 0.01
$E_{c,0}$	2.626	3.130	0.079
$E_{c,90}$	3.641	3.149	0.030
E_m	19.13	3.133	< 0.01
ρ	3.225	3.000	0.041

Table 5: *Between tree Tukey HSD test results*

Material property	Trees compared	p-values	Mean values (MPa)			Tree 1 / Tree 2	Tree 1 / Tree 3	Tree 2 / Tree 3
			Tree 1	Tree 2	Tree 3			
$f_{t,0}$	T2 - T1	0.0507						
	T3 - T1	0.1171	73.13	64.29	66.33	1.14	1.10	0.97
	T3 - T2	0.8304						
$f_{c,0}$	T2 - T1	0.0624						
	T3 - T1	0.0024	36.13	33.72	32.64	1.07	1.11	1.03
	T3 - T2	0.5072						
$f_{c,90}$	T2 - T1	< 0.01						
	T3 - T1	0.2809	3.96	5.33	4.38	0.74	0.90	1.22
	T3 - T2	0.0037						
$E_{t,0}$	T2 - T1	< 0.01						
	T3 - T1	0.995	12,775	9828	12,831	1.30	1.00	0.77
	T3 - T2	< 0.01						
$E_{c,90}$	T2 - T1	0.0509						
	T3 - T1	0.9993	387	499.93	385.5	0.77	1.00	1.30
	T3 - T2	0.0509						
E_m	T2 - T1	0.9959						
	T3 - T1	< 0.01	11,475	11,435	13,849	1.00	0.83	0.83
	T3 - T2	< 0.01						
ρ	T2 - T1	0.9699						
	T3 - T1	0.0967	455	456	447	1.00	1.02	1.02
	T3 - T2	0.0638						

Between-tree variation in the strength properties

The between tree variation in tensile strength as obtained by the Tukey HSD test and as presented in Table 5, shows no variation between the trees (p-values > 0.05 for all cases). Though different from the ANOVA results, this can be attributed to the level of sensitivity of the tests used. Considering that for all cases, the ANOVA has been proven to be very robust [13], the maximum difference detected by the ANOVA in the between-trees tensile strength (based on the mean tree values), as shown in column 7 of Table 5, is 14 %. This shows that the maximum difference was obtained by comparing the values from trees 1 and 2. Following the same procedure applied for determining the sources of differences in the material properties along the height of the trees, one sees that the maximum difference in the compressive strength parallel to the grain between the trees is 11 %, stemming from tree 1. Considering the compressive strengths perpendicular to the grain, the maximum variation (26 %) between the trees was obtained from comparing trees 1 and tree 2. From the mean values presented in Table 5, this can easily be understood as stemming from tree 2. In general, the variation in the strength properties (both within and between the Gmelina trees species considered in this study) falls between 11 % to 14 %. The exception to this, is the compressive strength perpendicular to the grain which, although did not vary within the trees, showed a maximum variation between the trees of 26 %. It can thus, be firmly stated that for the materials considered in this study, the compressive strength perpendicular to the grain, between the trees, was the most varied.

Between-tree variation in the elastic moduli values

A comparison between trees 1 and 3 as well as trees 2 and 3 as shown in Table 5, shows that there is a significant variation in the MoE in bending between the trees. This difference however, is 17 % and agrees with the 16.9 % reported in [14] for Blackwood. The value (30 %) obtained for the MoE in compression perpendicular to the grain and for the MoE in tension, is seen to be the highest of all variations observed in this study for Gmelina.

Between-tree variation in the Density values

Considering the density variation between the trees, data in Table 5 strongly declares no between-tree density variation. This is validated by the fact that for all the cases compared, the p-values were consistently above the limits of 0.05. The maximum difference in density computed between the trees as seen in columns 8 and 9 of Table 5 is 2 % and confirms that the mean density values obtained for the different trees as presented in Table 5 are within the same range. It can thenceforth be conclusively stated that the density of Gmelina as considered in this study does not vary between the trees. Any difference between the Tukey HSD and ANOVA tests would be due to the difference in the level of sensitivity of the different tests.

4 FINDINGS

Using 10 material properties which were experimentally determined from different parts of three Gmelina trees obtained from Southwestern Nigeria, this study has shown that at 95 % confidence level:

i. There is no consideration variation in the tensile strength, compressive strength perpendicular to the grain, bending strength, MoE in tension, MoE in compression parallel to the grain, MoE in compression perpendicular to the grain, and the MoE in bending along the height of the Gmelina sample considered in this study.

ii. The compressive strength of Gmelina parallel to the grain ($f_{c,0}$) varies along the height; with mean values from the middle parts being 8 % and 14 % lower than those from the bottom and top parts, respectively.

iii. Even though the shear strength varies with height, no difference was determined for the middle and the bottom parts as well as for the top and the bottom parts, respectively. A comparison between the top and the middle parts however, showed to be statistically significant. This difference (in terms of the mean shear strength values) was observed to be 12 %.

iv. Variation in the shear and compressive strength parallel to the grain along the height of Gmelina as obtained in this study, ranged between 11 % and 14 %, and was the same as was obtained between the trees for the tensile and compressive strength parallel to the grain. The only exception was the compressive strength perpendicular to the grain whose variation between the trees was obtained to be 26 %.

v. The shear strength, bending strength, MoE in compression parallel to the grain and density did not vary between the trees considered in this study, whereas the other material properties did vary.

vi. The density variation within and between Gmelina trees is constant at 2 %. The variation along the height is a slight reduction with increase in height of the trees. No statistical significance was determined for the top and middle parts of the trees. However, a comparison between the other parts showed to be statistically significant. Considering the mean density values, the variation between the bottom and the middle parts and that between the top and the bottom parts are respectively 2 % and 3 %. This variation in the density as seen, does not influence the variation in the mechanical properties. This is because the variation pattern exhibited by the density data (slight reduction from the bottom to the top) is quite different from that exhibited by the mechanical properties (compressive strength parallel to the grain and the shear strength) which varied along the height. The variation pattern observed for the density in this study, agrees with that reported for Gmelina in [11].

vii. The variation in the MoE in bending between the trees is 17 % and agrees with 16.9 % reported in the literature for Blackwood [7].

viii. The mechanical properties of Gmelina as considered in this study (except for the shear and compressive strengths parallel to the grain which vary along its height), are not location dependent as is the case with some wood species. The

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overall variation (combined variation both within and between the trees) of Gmelina is less than is obtainable for spruce (*Picea abies*) and pine (*Pinus sylvestri*) grown in Europe. The nature of the variation along the height of Gmelina would be useful in aiding end users on how to optimally and profitable apply Gmelina trunks for practical use.

5 CONCLUSION

This study has discussed the variation in the material properties between and within three plantation - grown *Gmelina arborea* trees obtained from Akure, in southwestern Nigeria, thus contributing to existing research efforts on the characterization and use of Gmelina as a construction material. Having elaborated on how the various material properties vary within and between the trees that were investigated, the study has presented information that would be useful in facilitating an efficient and optimal use of the material for effective applications. Further areas of research on Gmelina as a structural material are its long-term behaviour under load and temperature, determination of applicable modification and deformation factors for the timber, and similar investigations using materials from different sites to complement the results reported both in the current as well as previous studies.

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