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The Effect of Knot Size on Flexural Strength of Eucalyptus Grandis Structural Size Timber

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Abstract: This study investigated the effect of knot size on flexural strength of E. grandis. Sample trees were obtained from Uganda National Forestry Resources Research Institute's Eucalyptus grandis plantations at Kifu, Mukono district. Specimen preparation and testing was in accordance with ASTM D198 (2003). The effect of knot size on MOE and MOR were analyzed using linear regression analysis and ANOVA using Minitab software (version 14.0). Results showed that the mean MOE was 10,845.98 N/mm2 and mean MOR was 73.14 N/mm^2. There was a significant relationship between flexural strength and knot size; timbers with more knots had lower MOE and MOR. The findings point to the potential of using knot size and number in visual timber grading in timber yards of most developing countries. Although E. grandis is taken to be self pruning, there is need for early pruning as a silvicultural practice to minimize knotty wood.

Key words: Knots, MOE, MOR, flexural strength, timber, wood, defects

1. Introduction

In the past wood utilization in the tropics has been based on hardwood timber from a few well-known traditional species. However, with time due to the high demand and overharvesting of natural forests, the supply of quality timber from these species has dwindled [1]. To close the created demand gap, there has been shift to more available and fast growing plantation species particularly Eucalyptus grandis [2, 3]. At present E. grandis is available in several plantations in Uganda and can grow quickly with rotations of 8-15 years for the production of saw logs and large poles or even shorter for fuel wood and scaffoldings [4]. The increasing acreage for planted E. grandis coupled with its faster growth, the species is expected to help in addressing the demand for furniture and construction timber in the near future. However, being relatively new on the market not much empirical information is available about its appropriate utilization in different structural works. Wood properties often vary within the tree itself and among trees even within the same species. These differences could be attributed to the differential genetic makeup, age and agro geological factors such as soil type, climate and silvicultural practices employed during the growing period [5, 6]. Delayed pruning or not pruning growing timber trees in plantations results into timber with varying sizes of knots that may impact its structural strength. E. grandis is prone to growth defects particularly knots and irregular grain some of which are aggravated by the timing of silvicultural practices such as pruning. It has been reported in literature that the number, size, type and location of defects determine the load bearing ability of wood. The knotty core of a tree

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should be as small as possible and the size of the knotty core can be minimized by pruning of the trees at the right stage [7, 8]. In softwoods when a branch is removed from the bole of the tree, the sheath of the new growth will eventually cover the stub, producing knot free wood thereafter [9]. Such wood has markedly higher value than knotty wood for solid wood products and veneer because of increased strength and improved appearance. On the other hand, pruning does not necessarily result in higher quality or higher value timber in hardwood species [8, 10]. Although E. grandis usually exhibits good self-pruning properties, branch shedding in the lower parts of the stem only starts taking place 2-3 years after the branches dying. These branches give rise to sound knots of 50-60mm of their length from the pith, often with deep checks along the line of their own pith while their distal ends are usually dead and decayed. These knots usually occur in the juvenile wood, causing serious degrade on boards cut from the stem. Gross fractures are often present in association with the knots.

The conversion of tree stems into logs and consequently timber opens up live and dead portions of branches within the stem which become knots that lower product strength and stiffness of the timber [9]. In the timber value chain, knots are highly regarded as a major cause of lower product volume and value recovery from logs particularly if timber is for purposes of high structural strength requirements such as truss beams [11]. In sawn timber the knots usually develop checks during seasoning, which are signs of failure from a structural engineering point of view [12]. Since knots displace clear wood and result in grain distortion, they then have a strength reducing effect in timber [13]. Subsequently the value of timber for structural application is reduced due to presence of knots. Thus number, shape, size, location and type of knot are significant in deciding the grade of timber [14]. It has been reported that poor silvicultural practices such as lack of or under pruning in plantations result into timber with varying sizes of knots that impact its strength in various ways. Knots have long been recognized as a major strength reducing defect in timber [15].

The influence of knots on mechanical properties of timber is mainly attributed to interruption of wood fibres and displacement of clear wood. To stress the impact of knot location Sinha et al. (2012) noted that knots that occur near the ends of the beam do not weaken it since these are less stressed areas within [16]. Consequently, knots reduce the grade of lumber because of its negative effects on mechanical properties. Zziwa et al. (2009) noted that E. grandis is among those species with limited timber strength research studies [17]. This implies that its strength properties need to be investigated to guide structural application. It is known that presence of knots in wood affects its strength [11]; however, there is paucity of documented information on the extent to which knots affect the flexural strength properties of plantation grown E. grandis. Bending strength is one of the negatively affected strength properties by the occurrence of knots and of course the impact depends on their size and position in the structural timber [18]. Therefore determining the effect of knots on the flexural strength of wood could provide the much needed knowledge to guide appropriate timber selection and utilization. In essence, structural failure and wood waste could be avoided. To this end therefore, this study investigated the effect of knot size and number on the Modulus of Elasticity (MOE) and Modulus of Rupture (MOR) of structural size timber of E. grandis.

2. Materials and Methods

2.1 Sample Preparation

Sample trees were obtained from the Uganda National Forestry Resources Research Institute's (NaFORRI) E. grandis plantations in Kifu, Mukono District. Kifu is located in Mukono District, in the lake shores of central Uganda. Kifu lies at an altitude

0o48' and longitude 32o46'E and elevation of 1250 m above sea level. The specimens were prepared according to ASTM D198 (2003) [19]. The specimens were stacked and air dried in the shade while monitoring possible drying defects. The specimens were planed to 50 mm width, 50 mm depth and 1000 mm length. Then the specimens were visually graded on the basis of visible knots (Fig. 1) as evidence of a common grade for study. Two visual grades (one with specimens containing visible knots and one without) were considered, each containing 30 test specimens. The number of knots within the mid span of the test specimen was counted, their average diameters determined (Fig. 2 and Eq. (1)) and recorded for computation of knot area by approximating knots to circles.

The MOR of the test specimens was determined using Eq. (1):

$$D_{mean} = \frac{D_1 + D_2}{2} \tag{1}$$

Where: D_{mean} is the mean diameter of the knot.

Knot area was determined using Eq. (2):

$$D_{mean} = \frac{\Pi D_{mean}^{2}}{4} \tag{2}$$

2.2 Determination of Flexural Strength

ASTM D 198 (2003) standard test methods of static tests of lumber in structural sizes were adopted in determination of MOR. In principle, this involved the determination of maximum load required to cause rupture of test structural specimens (measuring 50 mm × 50 mm × 1000 mm) and estimation of stress at this load. Specimens were subjected to uniform loading using a Universal Testing Machine, Olsen Tinius (Fig. 3). The load was applied to the radial surfaces of test pieces midway between the supports using four-point loading. The loading speed was 6 mm per minute to ensure rupture of structural specimens in 1.5±0.5 minutes from the start of loading.

The MOR of the test specimens was determined using Eq. (3):

$$MOR = \frac{1.5 P_{\max} L}{bh^2} \tag{3}$$

Where: P_{max} is the breaking load in Newtons; L is the distance from supports in mm; b is the breadth of the test piece in mm; and h is the depth of the specimen in mm.

MOE was calculated according to Bowyer (2003) using Eq. (4):

$$MOE = \frac{PL^3}{48ID} \tag{4}$$

Where: P is concentrated centre load (Newtons); D is deflection at mid span (mm) due to P; L is the span (mm) and I is moment of inertia as given by Eq. (5):

Fig. 1 Test specimens with visible knots.

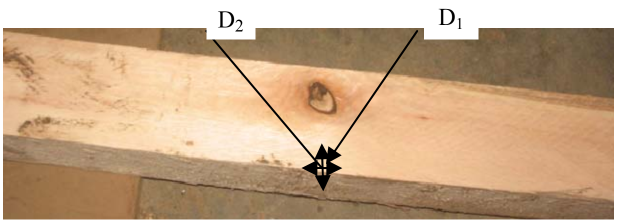


Fig. 2 Determination of average knot diameter.

Fig. 3 The universal testing machine.

$$I = \frac{bh^3}{12} \tag{5}$$

Where: b is the breadth of the test piece in mm and h is the depth of the specimen in mm.

2.3 Data Analysis

Descriptive statistics were used to summarize the measured data into arithmetic mean and standard deviation of the strength values. In addition regression analysis was used to establish and quantify the effect of knots size and number on flexural strength (MOE and MOR) of E. grandis. Analysis of variance (one-way ANOVA) was used to determine the variation in MOR and MOE with knot area. All analysis was done at 95% confidence level ($p = 0.005$) using Mintab software version 14.0.

3. Results and Discussion

Table 1 shows the mean and standard deviation of MOE and MOR of E. grandis with and without visible knots. As would be expected, results show lower mean values for E. grandis with visible knots.

On the basis of the mean flexural strength values, E. grandis with visible knots is suitable for light construction work whereas timbers without visible knots are recommended for medium construction (Table 2). The MOR was low due to displacement of clear wood by the knots, the fibres around the knot being distorted causing cross grain especially around inter-grown knots and discontinuity of wood fibres leading to stress concentration [18]. However, it should be noted that small knots located along the neutral plane of the structural specimens increase their strength by tending to prevent longitudinal shearing and failure [12].

3.1 Impact of Knot Area on MOE and MOR

ANOVA showed a statistically significant ($P < 0.05$) relationship between flexural strength (MOR and MOE) and knot area of E. grandis (Tables 3 & 4).

Table 1 Mean of MOE and MOR of *E. Grandis* with and without visible knots.

Variable	Specimens with visible knots		Specimens without visible knots	
	Mean	Standard Deviation	Mean	Standard Deviation
MOE (N/mm^2)	10,845.98	2,565.4	14,161.18	3,349.09
MOR (N/mm^2)	73.14	20.84	85.72	27.21

Table 2 Classification of timber structures according to MOR and MOE.

	Classification	**MOR (N/mm^2)**	**MOE (N/mm^2)**
Kityo and Plumptre (1997)	Heavy classification	≥133	≥14700
	Medium construction	89-132	9900-14700
	Light construction	39-88	6860-9800
This study	Specimens with visible knots	73.14^{**}	10845.98^{**}
	Specimens without visible knots	85.72^{**}	14161.18^{**}

Table 3 Influence of Knot Area on MOE

Source	DF	SS	MS	F	P
Factor	1	1625502242	1625502242	465.70	0.000
Error	58	202447641	3490477		
Total	59	1827949882			
Level	N	Mean	SD		
MOE (N/mm^2)	30	10846	2609		
Knot Area (mm^2)	30	436	415		

Table 4 Impact of Knot Area on MOR.

Source	DF	SS	MS	F	P
Factor	1	1975413	1975413	22.84	0.000
Error	58	5017427	86507		
Total	59	6992841			
Level	N	Mean	SD		
MOR (N/mm^2)	30	73.1	21.2		
Knot Area (mm^2)	30	436.0	415.4		

3.2 Effect of Number of Knots on the MOE and MOR

There was a statistically significant ($P < 0.05$) relationship between knot area and flexural strength of structural timber of E. grandis (Tables 5 & 6). Koman et al. (2013) established that higher number of knots and the corresponding higher knot area ratios in structural timber were strongly correlated to reduced MOE and MOE values with the reduction sometimes reaching almost 40-50% [20]; thus rendering some timber materials unfit for structural applications with relatively higher strength requirements.

Since MOE is a measure of the stiffness or rigidity of a structural member under load, knots provide an easy route to premature failure in a structure or beam because they lead to grain disturbance and interruption of fibre continuity and in the process reduce flexural strength [21]. For structural purposes, knots lower the grade of lumber because of their negative effects on MOE [15]. Dead knots were observed to cause premature failure amongst the structural specimens (Fig. 4). This concurs with Mohan and Venkatachalapathy (2012) who noted that knots contribute to cracking, warping and cleavability of timber thereby weakening timber and lowering its value for practical purposes. The effect of the knots is to reduce the difference between the fibre stress at

Table 5 Effect of knot number on MOE.

Source	DF	SS	MS	F	P
Factor	1	1764073731	1764073731	518.21	0.000
Error	58		197443258	3404194	
Total	59		1961516989		
Level	N	Mean	SD		
MOE (N/mm^2)	30	10846	2609		
No. of knots	30	1	1		

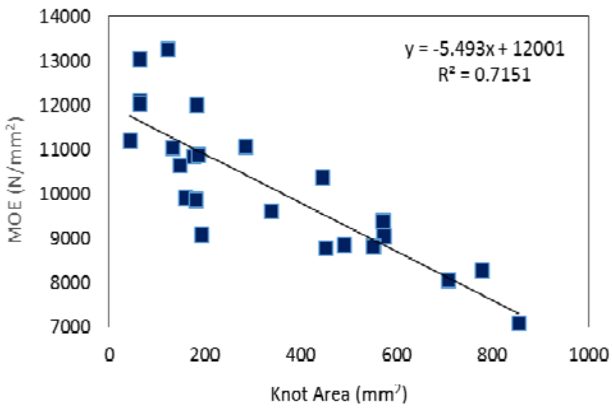
Table 6 Effect of number of knots on MOR

Source	DF	SS	MS	F	P
Factor	1	77209	77209	343.31	0.000
Error	58	13044	225		
Total	59	90254			
Level	N	Mean	SD		
MOR (N/mm^2)	30	73.14	21.20		
No. of knots	30	1.40	0.67		

Fig. 4 Failure under flexural loading often occurs at a knot position.

elastic limit and the MOR of structural timber, hence breaking strength is very susceptible to defects especially knots (Fig. 3).

Linear regression analysis showed a weak relationship between knot area and flexural properties (MOE and MOR). This is in agreement with Koman et al. (2013) who noted that presence of knots can significantly limit the utilization of wood materials as a



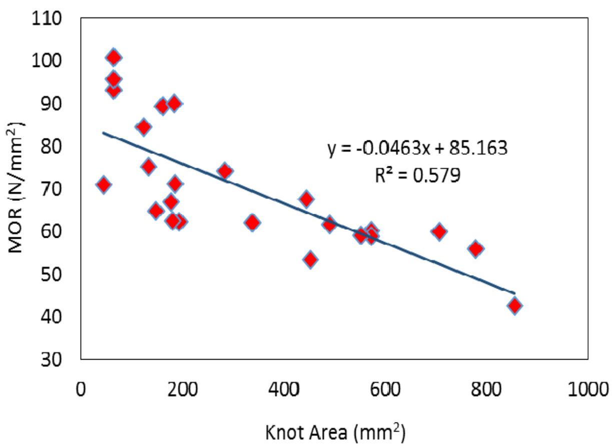


Fig. 5 Relationship between MOE and Knot Area.

result of its negative impact on density, MOE and MOR of timber [20].

As expected regression analysis results show an inverse relationship between flexural strength and knot area ratio with MOE affected more than MOR. Thus knot size and number have a significant negative impact on the flexural strength of E. grandis. This is in agreement with Zhong et al. (2012) who also noted that knots critically affect the bending properties of wood [22].

4. Conclusion

A negative flexural strength reducing effect was confirmed by the study particularly that knot size and number have a significant negative impact on the flexural strength of E. grandis timber. The findings point to the potential of using knot size and number in visual timber grading in timber yards of most developing countries. Although E. grandis is taken to be self-pruning, there is need for early pruning as a silvicultural practice to minimize knotty wood. It is recommended that knot areas be used a critical consideration in structural timber grading.

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