RELATIONSHIP BETWEEN MECHANICAL PROPERTIES AND SELECTED ANATOMICAL FEATURES OF NTHOLO (*PSEUDOLACHNOSTYLIS MAPROUNAEFOLIA*)

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UETIMANE JR E & ALI AC. 2011. Relationship between mechanical properties and selected anatomical features of ntholo (*Pseudolachnostylis maprounaefolia*). The anatomical features of the sapwood and heartwood of ntholo (*Pseudolachnostylis maprounaefolia*) were studied and interrelated with physico–mechanical properties. The samples were randomly taken from five trees irrespective of their position within the tree. The objective was to determine the mechanical properties of ntholo, a lesser-used species from Mozambique, and compare this species with the most used species in order to assess its end-use as well as to study the anatomy–property relationship through correlation and regression. Anatomical features were used to predict density and mechanical properties whereas density, to predict mechanical properties. There were notable differences between density and mechanical performance of sapwood and heartwood. The higher density of heartwood (1023.7 kg m^{-3}) compared with that of sapwood (758.9 kg m^{-3}) contributed to these differences. In terms of anatomy–property relationship, fibre length was the only anatomical trait which correlated with all measured properties and so density correlated with mechanical properties. Apart from modulus of elasticity (MOE) in sapwood having high predictive power, no other significant regression equations were observed for both sapwood and heartwood properties. Regression analyses showed that density alone was a poor predictor. Sapwood properties were mainly influenced by tissue proportions, whereas heartwood properties, by fibre dimensions and vessel.

Keywords: Density, fibre length, fibre wall thickness, hardness, static bending, vessel diameter

UETIMANE JR E & ALI AC. 2011. Hubungan antara ciri mekanik *Pseudolachnostylis maprounaefolia* dengan ciri anatomi terpilih. Ciri anatomi kayu gubal dan kayu teras *Pseudolachnostylis maprounaefolia* dikaji dan dihubungkaitkan dengan ciri fizikal dan mekaniknya. Sampel diambil secara rawak daripada lima batang pokok tanpa mengira kedudukan pada pokok. Kajian ini bertujuan untuk menentukan ciri mekanik *P. maprounaefolia*, satu spesies kurang digunakan dari Mozambique, dan membandingkannya dengan spesies kayu yang terkenal bagi menilai kegunaan akhirnya serta menyelidiki hubung kait antara anatomi dengan ciri kayu menggunakan korelasi dan regresi. Ciri anatomi digunakan untuk meramal ketumpatan dan ciri mekanik manakala ketumpatan digunakan untuk meramal ciri mekanik. Terdapat perbezaan yang jelas antara ketumpatan dengan prestasi mekanik kayu gubal dan kayu teras. Perbezaan ini disebabkan oleh ketumpatan yang lebih tinggi pada kayu teras (1023.7 kg m^{-3}) berbanding kayu gubal (758.9 kg m^{-3}). Dari segi hubung kait antara anatomi dengan ciri kayu, panjang gentian merupakan ciri anatomi tunggal yang berkorelasi dengan semua ciri yang dinilai. Jadi ketumpatan berkorelasi dengan ciri mekanik. Tiada persamaan regresi dapat meramal ciri kayu gubal dan kayu teras kecuali modulus kekenyalan (MOE) dalam kayu gubal. Analisis regresi menunjukkan bahawa ketumpatan ialah peramal yang lemah. Ciri kayu gubal banyak dipengaruhi oleh perkadaran tisu manakala ciri kayu teras pula dipengaruhi oleh dimensi gentian dan pembuluh.

INTRODUCTION

The growing use of wood, especially as engineering material, has been inspiring many researchers to model and predict its performance in service by means of its characteristics. Some wood features such as heartwood–sapwood, juvenile, mature and reaction woods are to some extent linked to specific properties. These features are usually used to predict how wood specimens behave in various applications. Unlike other materials in engineering use, wood is a biological material peculiarly known by its low strength–weight ratio and large intra–intertree variability in properties. The commonly known sources of wood variation include tree species, sample position within

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the log, growing conditions as well as genetic reasons (Barnett & Jeronimidis 2003, Bowyer et al. 2003).

In general, wood property is mainly explained by its specific cell arrangements, i.e. its wood anatomy. The structure–property relationship has been researched for decades and it has gone as far as ultrastructure and nanotechnology approaches where a single fibre is tested for its mechanical behaviour (Salmén & Burget 2009). Along the way, several studies have shown correlations between wood mechanical properties and selected anatomical features (Ezell 1979, Leclercq 1980, Ifju & McLain 1983, Zhang & Zhong 1992, Ocloo & Laing 2003, Rahman et al. 2005, Eriksson 2008). Apart from wood strength, other properties such as the acoustic quality of wood have also been related to wood anatomy (Brancheriau et al. 2006a, b, Buksnowitz & Teischinger 2007). However, most of the studies examined mainly softwood and hardwood from temperate zones. Very few structure–property analyses on tropical hardwood species have been produced (Ocloo & Laing 2003) and to a great extent nearly nothing on the wood structure and properties of the lesser-known/used tropical hardwood species can be found (Uetimane Jr et al. 2009).

With regard to wood mechanical strength, the arrangement and proportions of ground tissues in hardwood species (axial and ray parenchyma, fibres and vessels) play a central role (Barnett & Jeronimidis 2003, Bowyer et al. 2003). Thus, the specialised function in the xylem and larger volume of thick-walled fibres will usually lead to high wood strength. More specifically, cell wall thickness of the fibres and their fractional volume are known to influence wood density, a parameter generally associated with mechanical strength of hardwood species (Ocloo & Laing 2003, Salmén & Burget 2009).

Recently, comprehensive studies on properties of lesser-used wood species from Mozambique were published (Ali et al. 2008, Uetimane Jr et al. 2009, Uetimane Jr et al. 2010). This paper is part of the referred studies and aims to provide the main mechanical properties of ntholo (*Pseudolachnostylis maprounaefolia*) and compare this species with the most traded Mozambican wood species to assess its end-uses. This study also analysed the relationship between wood anatomy and physico–mechanical properties.

MATERIALS AND METHODS

Sampling and physico–mechanical properties

Wood samples were taken randomly from five trees of ntholo irrespective of their position within each tree stem. The growing conditions, tree sampling and features were described in Uetimane Jr et al. (2009).

A total of 21 samples (20 × 20 × 400 mm) representing sapwood and another 21 consisting of heartwood were prepared. This was done to reflect the routine operations in sawmills in Mozambique whereby the sawn timber is usually sorted out to either sapwood or heartwood boards. The samples were cut from logs (averaging 30 cm in diameter) which had sapwood content ranging from 25% at the bottom up to 82% at the top. The samples were conditioned to 12% moisture content (MC) prior to testing and the preparation followed physical and mechanical tests recommended by the International Standards Organisation. The mechanical properties were tested using Universal wood testing machine according to ISO standards:

(1) Density at 12% MC (D_{12}) (ISO 3131:1975)
(2) Static hardness (perpendicular and parallel to grain—ISO 3350:1975)
(3) Compression stress (parallel to grain—ISO 3787:1975 and perpendicular to grain—ISO 3132:1975)
(4) Static bending strength (modulus of elasticity (MOE)—ISO 3349:1975 and modulus of rupture (MOR)—ISO 3133:1975)
(5) Tensile strength parallel to grain (ISO 3345: 1975)
(6) Impact bending strength (ISO 3348:1975)

Anatomical description

For all samples, small blocks close to the failure point (about 1 cm^3 each) were taken, autoclaved in 10% glycerine for 1 hour and subsequently sectioned (20–40 μm thick) using microtome sledge. The sections were stained either with glycerol or 1% safranin (transverse sections). For fibre dimensions, the blocks were delignified and macerated by treatment in 1:1 mixture of 100% acetic acid (CH_3COOH) and H_2O_2 at 60 °C for 18 hours (Wise et al. 1946). Measurements were made using Image-Pro Plus. Anatomical descriptions followed terminology and procedures from IAWA Hardwood List (IAWA Committee 1989). The anatomical features studied were fibre dimensions/morphology (length, wall thickness and diameter), vessel features (diameter and number of vessels/mm^2) and ground tissue composition (% fibres, % parenchyma including rays and % vessels).

Statistical analysis

Each sample of ntholo was individually used to measure the static bending strength (MOE and MOR), D_{12}, static Brinell hardness (BH) and compression stress (CS). The experiment was carried out separately for the sapwood and heartwood samples. The physico–mechanical properties were related to their corresponding anatomical features in an attempt to gain insight into their inter-relationships through correlation analysis and regressions analysis (partial least squares (PLS) and simple linear regression) using statistical software Minitab 15. PLS was used to deal with multicollinearity observed between some anatomical features which were assumed as independent variables (Table 1). Tensile strength and impact bending properties were not inter-related with anatomical features but were reported along with other mechanical properties for comparative purposes with commonly used species from Mozambique.

The response variables for Y are the physico–mechanical properties (D_{12}, MOE, MOR, BH and CS). Since the predictors were measured in different scales, the regression coefficients were standardised. Essentially, apart from prediction, PLS analysis is also aimed at identifying key anatomical features over which the measured properties are largely dependent, providing their regression coefficients from the pool of X variables as follows:

$$Y = X1 + X2 + X3 + X4 + X5 + X6 + X7 + X8$$

where

Y = physical or mechanical properties (D_{12}, MOE, MOR, BH and CS)
X1 = % fibres
X2 = % vessels
X3 = % parenchyma tissue (rays included)
X4 = number of vessels/mm^2
X5 = vessel diameter
X6 = fibre length
X7 = fibre diameter
X8 = fibre wall thickness

Table 1 Multicollinearity between some anatomical features

Anatomical feature		Heartwood							
		X1	X2	X3	X4	X5	X6	X7	X8
X1	% Fibres	1							
X2	% Vessels	0.018	1						
X3	% Parenchyma (rays included)	-0.939*	-0.361	1					
X4	Vessel/mm^2	0.104	0.491*	-0.266	1				
X5	Vessel diameter	-0.171	-0.328	0.272	-0.377	1			
X6	Fibre wall thickness	-0.26	0.24	0.159	-0.149	0.269	1		
X7	Fibre diameter	0.043	0.451*	-0.196	0.582	-0.43	0.275	1	
X8	Fibre length	0.031	-0.029	-0.019	-0.329	0.188	0.507*	0.18	1
		Sapwood							
X1	% Fibres	1							
X2	% Vessels	-0.384	1						
X3	% Parenchyma (rays included)	-0.819*	-0.214	1					
X4	Vessel/mm^2	-0.296	0.692*	-0.116	1				
X5	Vessel diameter	0.077	0.073	-0.127	-0.134	1			
X6	Fibre wall thickness	-0.056	-0.031	0.078	0.114	-0.14	1		
X7	Fibre diameter	-0.028	0.139	-0.09	-0.063	0.203	-0.01	1	
X8	Fibre length	0.146	-0.329	0.05	-0.735*	0.122	-0.43	0.27	1

* Significant correlation coefficients at p = 0.05

In PLS, the key predictors in the model (regression equations) were identified according to the magnitude of their standardised regression coefficients. Only statistically significant PLS regression equations were assessed for their predictive ability using the "leave-one out cross validation" method.

Through simple linear regression analysis, ntholo density was used as independent variable to predict each mechanical property for practical reasons. Since correlation analysis describes only the association between variables, a separate discussion on correlation and regressions (PLS and simple linear regression) is presented. In both regression analyses, a cause–effect (anatomy–property) was sought and therefore predictive regression equations highlighting the key predictors were presented, whereas the correlation analysis was intended to quantify and discuss how well two subsets of variables related to each other.

RESULTS AND DISCUSSION

Density and selected mechanical properties of ntholo

Apart from deposition of chemicals (extractives and other secondary metabolites), the cellular morphology of wood remains almost unchanged during conversion of sapwood to heartwood (Bowyer et al. 2003). Therefore, generally within the same species, no considerable differences between mechanical strength of heartwood and sapwood are expected. Ntholo is an exception (Table 2). The difference between sapwood and heartwood densities is partly associated with the amount of extractives embedded in heartwood vessels and parenchyma cells (Cuvilas 2009, Uetimane Jr et al. 2009). Thus, the resulting differences between strength properties of sapwood and heartwood are likely to be explained by density due to its widely known effect on some mechanical properties (Armstrong et al. 1984, Grabner et al. 2005).

Ali et al. (2008) pointed out the need to identify potential substitutes for the decreasing stock of Mozambican main and well-known commercial wood species such as chanfuta (*Afzelia quanzensis*), umbila (*Pterocarpus angolensis*) and jambire (*Milletia stuhlmanii*). The mechanical properties of ntholo are compared with those of well known wood species (Table 3).

The three principal traded species in Mozambique are interchangeably used for almost the same purpose such as furniture, flooring, window frames and doors. The suitability of ntholo for window frames and doors has been reported to be satisfactory (Ali et al. 2010). However, in this paper the focus is to assess the performance of ntholo in strength-demanding applications. Therefore, in comparative terms, ntholo is a far heavier timber compared with the local commercial species and can hardly be recommended for furniture but probably suitable for flooring due to its hardness. In terms of bending strength (MOE and MOR), ntholo was superior to the other commercial species but weaker with regard to compressive stresses applied parallel to grain. Based on the

Table 2 Density and main mechanical properties of ntholo

Property	Sapwood					Heartwood				
	Min	Max	Average	SD	CV (%)	Min	Max	Average	SD	CV (%)
D_{12} (kg m^{-3})	654.67	803.5	758.90	38.55	5.08	942.4	1019	1023.7	43.10	4.21
MOE (N mm^{-2})	7914	13020	10326.70	1359	13.16	11454	22252	17263	3560.1	20.62
MOR (N mm^{-2})	63.53	129.8	100.89	16.3	16.16	73.31	144	119.24	15.53	13.03
Comp parallel (N mm^{-2})	33.02	59.29	52.09	5.64	10.82	31.39	64.42	55.68	8.19	14.71
Comp perp (N mm^{-2})	13.32	15.77	14.55	0.77	5.29	19.07	33.64	27.54	4.29	15.59
Tensile strength (N mm^{-2})	21.59	76.54	50.61	14.13	28	23.48	103.49	78.62	18.75	24
Brinell hardness parallel	3.71	7.24	5.51	0.89	16.08	4.96	8.97	7.21	1.07	14.81
Brinell hardness perp	2.35	3.15	2.88	0.24	8.31	3.71	5.68	4.32	0.51	11.74
Impact bending (kJ mm^{-2})	35.55	207.6	121.22	50.71	41.83	45.81	144.57	81.46	35.18	43.19

n = 21 sapwood and heartwood samples each; comp = compression, perp = perpendicular mechanical performance, rather than replacing the present commercial species, it seems that ntholo timber can satisfactorily complement the available options as wood species with recognised high strength.

Correlation between anatomical features and physico–mechanical properties of ntholo

Full correlation analysis relating anatomical features with selected mechanical properties is summarised in Table 4.

Density and mechanical properties

Ntholo wood density was significantly correlated with some of the tested mechanical properties. For example, the densities of both heartwood and sapwood samples were positively and significantly correlated to static bending with the exception of heartwood samples that yielded non-significant negative correlation with MOE (Table 4). Unlike heartwood samples, MOE and MOR of sapwood showed significant positive correlation between themselves ($r = 0.735$; $p = 0.00$). Similar interrelationships have been reported for Finnish birches (Heräjärvi 2004) and *Petersianthus macrocarpus*, a lesser-used hardwood from Ghana (Poku et al. 2001). Sapwood samples subjected to compression tests perpendicular to grain produced the only significant negative correlation with density (Table 4), suggesting that even denser ntholo sapwood was not likely to sustain high compressive stresses in this direction, probably due to the presence of radial and adjacent non-encrusted vessels. In terms of hardness, ntholo heartwood samples tested perpendicular to grain were significantly and positively correlated to density (Table 4). Probably, this was due to the fact the extractive-filled heartwood vessels made this direction denser compared with the lesser dense sapwood caused by empty vessels. Four Argentinean hardwood species of the genus *Proposis* and one *Acacia* revealed similar interrelationship as ntholo. Unlike ntholo, the compression stress and density of Argentinean hardwoods were reported as positively correlated (Pometti et al. 2009).

Anatomical features and density

Despite rather weak coefficients of determination, some significant correlations between anatomical features and corresponding properties were observed. For instance, density was positively correlated with the fractional volume of parenchyma tissue and the length of the fibres (Table 4). More specifically, ntholo heartwood density was partly associated with the amount of parenchyma tissue (including rays), whereas the density of sapwood was proportional to the length of the fibres. Indeed, ray proportion has been reported as positively correlated to density in other hardwoods species such as oak, beech and teak (Taylor 1969, Fujiwara 1992, Rahman et al. 2005). In this aspect, ntholo heartwood ray parenchyma cells constitute the bulk of the total volume of parenchyma tissue (Uetimane Jr et al. 2009).

Anatomical features and static bending strength

The elasticity and the maximum stress supported by a wood sample under central loading in static mode are usually expressed as MOE and MOR respectively. Table 4 shows that the elasticity of

Table 3 Comparison of ntholo mechanical properties with other species at 12% MC

Property	Ntholo	*Pterocarpus angolensis* [a]	*Afzelia quanzensis* [a]	*Milletia stuhlmanii* [a]
MOE ($N\ mm^{-2}$)	17263	8200	13100	13600
MOR ($N\ mm^{-2}$)	119.2	82	108	112
Impact bending ($kJ\ mm^{-2}$)	81.5	57.1	79.2	69.0
Hardness parallel to grain	7.21[b]	5500 [c]	8229 [c]	7251[c]
Compression parallel to grain ($N\ mm^{-2}$)	55.68	50.00	–	69.00
Density 12% MC ($kg\ m^{-3}$)	1024	590	670	990

a = Takawira-Nyenya 2005, Lemmens 2008; b = Brinell hardness; c = Janka hardness; MOE = modulus of elasticity, MOR = modulus of rupture; MC = moisture content

Table 4 Correlation between selected anatomical features and measured physico–mechanical properties

Anatomical feature	Density (12% MC)		Mechanical property: Static bending – MOE		Static bending – MOR		Compression strength – Paral to grain		Compression strength – Perp to grain		Brinell hardness – Paral to grain		Brinell hardness – Perp to grain	
	SW	HW	SW	HW	SW	HW	SW	HW	SW	HW	SW	HW	SW	HW
X1	0.325	-0.338	0.314	0.214	0.527*	0.063	-0.228	-0.029	-0.372	0.166	0.282	0.150	-0.355	-0.198
X2	-0.411	-0.396	-0.072	0.187	-0.014	0.277	0.037	-0.046	0.342	-0.382	-0.021	0.076	0.002	-0.257
X3	-0.089	0.451*	-0.288	0.264	-0.549*	0.154	0.219	0.043	0.182	-0.023	-0.285	-0.167	0.375	0.273
X4	-0.414	-0.167	-0.390	0.293	-0. 200	0.025	0.083	0.029	0.409	-0.068	-0.034	0.024	-0.037	-0.104
X5	-0.190	0.094	-0.187	0.208	0.041	0.363	-0.074	-0.062	-0.073	0.066	-0.559*	0.295	-0.428	-0.215
X6	0.457*	-0.180	0.697*	0.268	0.471*	0.259	-0.127	-0.610*	-0.521*	-0.425	0.243	0.013	-0.015	-0.449*
X7	0.048	-0.168	0.117	0.530*	0.159	0.374	0.295	-0.347	-0.164	-0.501*	0.090	-0.230	0.087	-0.317
X8	-0.296	0.142	-0.488*	0.021	-0.284	0.098	0.232	-0.447*	0.155	-0.307	-0.192	0.098	0.142	-0.103
Density (12% MC)	1	1	0.486*	-0.256	0.463*	0.520*	-0.119	0.201	-0.697*	0.298	0.226	0.307	-0.102	0.561*

* Significant correlation coefficient at $p = 0.05$
SW = sapwood, HW = heartwood, X1 = % fibres, X2 = % vessels, X3 = % parenchyma tissue (rays included), X4 = number of vessels/mm^2, X5 = vessel diameter, X6 = fibre length, X7 = fibre diameter, X8 = fibre wall thickness; paral = parallel, perp = perpendicular

ntholo is mainly associated with fibre dimensions. Ntholo sapwood MOE was positively correlated to fibre length but inversely proportional to samples with thick-walled fibres. On the other hand, high values of ntholo heartwood MOE seemed to be associated with the presence of fibres with large diameters. In relation to MOR, only sapwood samples showed significant correlation with anatomical features. High fractional volume of fibres and longer fibres were positively correlated to MOR, whereas large volume of parenchyma tissue produced low MOR. This interrelationship can be explained by the specialised roles of each tissue in the xylem (Barnett & Jeronimidis 2003, Bowyer et al. 2003).

Anatomical features and compression strength

Fibre dimensions seemed to play the main role and were all negatively correlated for both directions (Table 4). When compression forces were applied parallel to grain, heartwood samples with long fibres and thin wall could not resist high compressive stresses. This is predictable as fibres bearing such dimensions (long and thin wall) have less sectional area to support loads in any direction. However, the present study showed that longer fibres had thick walls (Table 1). In the opposite direction (perpendicular to grain), negative correlations were observed for both wood sections against fibre dimensions. Sapwood samples characterised by longer fibres resisted less to the applied stresses, whereas unexpectedly the heartwood samples with wide fibre diameters failed easily. Heartwood fibre diameter was positively correlated with vessel density (Table 1). Since ntholo vessels occurred in radial multiples (Uetimane Jr et al. 2009, Figure 1), more weak longitudinal radial area was available which might not support high stresses over the vessel radial walls (perpendicular to grain). Decreasing maximum stress of wood loaded in radial direction with increasing vessel area has been reported by Müller et al. (2003).

Anatomical features and Brinell hardness

In a broad sense, the hardness represents the capacity of a given material to withstand indentation (Bowyer et al. 2003). In the direction parallel to grain, sapwood samples were negatively correlated with Brinell hardness

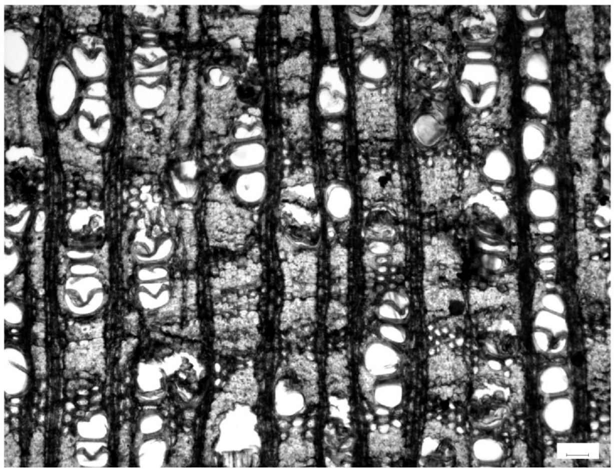

Figure 1 Ntholo sapwood cross-section displaying vessels in multiple radial

values (reflecting large dented area) due to the presence of adjacent non-encrusted vessels (Table 4). Empty wood vessels expose weak points of wood to any opposing force (Akachuku 1985, Ocloo & Laing 2003). In the direction perpendicular to grain, a single significant negative correlation was observed in heartwood where apparently samples with short fibres yielded high values of hardness, i.e. small dented sectional area.

Predicting physico–mechanical properties from anatomical features through partial least square and simple linear regressions

The regression was carried out twofold: PLS and simple linear regression. Unlike correlation, the regression analysis was conducted to provide models explaining important predictor variables (PLS) as well as to predict tested properties from density (simple linear regression). PLS regression analysis is devoted to select/identify key variables (main anatomical features) exerting large influence on measured properties. Table 5 compiles regression equations highlighting key predictor variables in the model.

Sapwood and heartwood

With the exception of MOE sapwood, all PLS equations were not significant (Table 5). Apart from hardness parallel to grain, the remaining tested sapwood properties seemed by far to be controlled by tissue proportions (X1, X2 and X3; Table 5) and were negatively related to them.

Since MOE of the sapwood produced the only significant regression equation, its predictive ability was evaluated through leave-one out cross validation method. The results showed that the actual MOE and the new value generated from the model were fairly close. Thus, the regression model can be regarded as reliable as demonstrated in Figure 2.

No significant regression equation was observed for heartwood properties. Nevertheless, PLS analysis suggested that density was negatively affected by vessel proportion and positively affected by fibre wall thickness. In fact, despite containing extractives, ntholo heartwood vessels still contribute to void spaces in the xylem, but thicker fibre walls imply more cell wall material with reduced cell lumina. Both anatomical features have been previously reported by several authors as key factors controlling density (Ezell 1979, Leclercq 1980, Zhang & Zhong 1992).

In terms of bending strength, MOR seems not to have very clear leading factors, although fibre diameters along with the number of vessels/mm^2 have relatively larger coefficients. Slightly more evident key predictors are detectable in MOE, i.e. the fibre dimensions (Table 5).

The compression stress parallel to grain is apparently negatively controlled by a single anatomical feature, namely, the fibre length. This supports previous discussion regarding the correlation between fibre length and compression parallel to grain (Tables 4 and 5). In contrast, apart from fibre length, compression perpendicular to grain was also controlled by fibre diameter, % vessels and the number of vessels/mm^2 . This is in accordance with earlier correlation analysis involving the referred variables (Tables 4 and 5).

Such as in MOE, hardness parallel to grain is mainly influenced by fibre dimensions and vessel diameter. In the opposite direction (perpendicular to grain), both fibre diameter and number of vessels/mm^2 are the key variables. Using multiple regression equations, Leclercq (1980) reported the same anatomical features as exerting strong effect upon these mechanical stresses.

Table 5 PLS regression equations highlighting key anatomical predictors

Property	Sapwood	p
D_{12}	0.269X6 + 0.071X7 – 0.25X8 – 667.41X3 – 414.54X2 – 706X1 – 0.033X4 – 0.31X5	0.498
MOE	0.68X6 – 0.09X7 – 0.27X8 – 1335X3 – 828.31X2 – 1412.25X1 – 0.16X4 – 0.44X5	0.009*
MOR	0.74X6 – 0.06X7 – 0.02X8 – 1003.98X3 – 622.96X2 – 1061.73X1 + 0.27X4 – 0.12X5	0.120
Comp parallel	0.37X7 – 0.24X6 – 0.02X8 – 1578.54X3 – 980X2 – 1670.56X1 – 0.17X4 – 0.19X5	0.821
Comp perpendicular	-0.687X6 – 0.06X7 – 0.126X8 – 262.3X3 – 162.53X2 – 277.8X1 – 0.38X4 – 0.058X5	0.533
Hardness parallel	0.38X6 + 0.14X7 – 0.06X8 + 1176.57X3 + 730.47X2 +1245.35X1 + 0.29X4 – 0.58X5	0.110
Hardness perpendicular	0.186X7 – 0.264X6 – 0.043X8 – 725.74X3 – 450.24X2 – 768.025X1 – 0.50X4 – 0.522X5	0.578
Property	**Heartwood**	**p**
D_{12}	0.35X6 – 0.11X7 + 0.51X8 + 0.20X3 – 0.51X2 – 0.031X1 + 0.086X4 – 0.224X5	0.282
MOE	0.329X6 + 0.583X7 – 0.363X8 – 0.055X3 + 0.028X2 + 0.049X1 + 0.017X4 + 0.116X5	0.312
MOR	-0.20X6 – 0.36X7 + 0.15X8 + 0.03X3 – 0.233X2 + 0.045X1 + 0.361X4 + 0.206X5	0.526
Comp parallel	-0.50X6 – 0.19X7 – 0.19X8 – 0.0001X3 + 0.12X2 – 0.04X1 – 0.114X4 – 0.005X5	0.233
Comp perpendicular	-0.33X6 – 0.61X7+ 0.28X8 – 0.031X3 – 0.421X2 + 0.189X1 + 0.333X4 – 0.182X5	0.129
Hardness parallel	-0.49X6 – 0.47X7 + 0.51X8 + 0.132X3 – 0.36X2 – 0.007X1 + 0.08X4 – 0.589X5	0.077
Hardness perpendicular	0.05X6 – 0.46X7 + 0.20X8 – 0.131X3 + 0.102X2 + 0.103X1 + 0.339X4 + 0.246X5	0.722

X1 = % fibres, X2 = % vessels, X3 = % parenchyma tissue (rays included), X4 = number of vessels/mm^2, X5 = vessel diameter, X6 = fibre length, X7 = fibre diameter, X8 = fibre wall thickness; *significant PLS regression at p = 0.05; comp = compression

Prediction of mechanical properties from density

Unlike some hardwood species, ntholo density was a poor predictor at least for the tested mechanical properties since all the observed r^2 (coefficient of determination) were very low (Table 6).

In comparative terms, only ntholo sapwood density produced the largest r^2 with significant regression equation to predict compression stress perpendicular to grain. The sapwood bending strength (MOE and MOR) produced significant regression equations ($p < 0.05$), but very low r^2, i.e. the model described only less than 20% of bending strength variance. Heartwood density produced slightly higher coefficient of determination ($r^2 = 23.2$, $p < 0.05$) for MOE. Sapwood density could not predict hardness at all, whereas heartwood density could at least weakly predict hardness perpendicular to grain ($r^2 = 27.9$, $p < 0.05$). Thus, in general both heartwood and sapwood densities were weak predictors for some of the tested mechanical properties. In contrast Bektaş et al. (2002) reported relatively higher r^2 ranging from 50 to 56% for Turkish beeches (*Fagus orientalis*) in linear regression equations relating density with the same mechanical properties. On the other hand, density of other diffuse-porous hardwoods such as *Populus cathayana, Populus tomentosa* and *Castanopsis fargesii* was reported as poor predictor for the same mechanical properties (Zhang 1997). The poor predictability of ntholo density was probably due to random sampling of specimens as well as tree intrinsic features with regard to density variability.

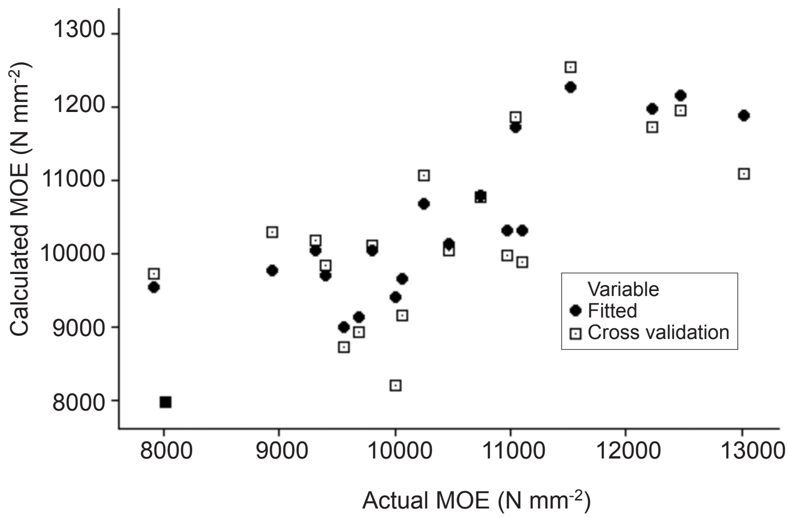

Figure 2 Predictive ability for MOE of the sapwood model using leave-one out cross validation method

Table 6 Simple linear equations to predict mechanical properties from density

Mechanical property	Simple linear regression equation					
	Sapwood	r^2 adj (%)	p	Heartwood	r^2 adj (%)	p
MOE	$17.1D_{12} - 2679$	19.4	0.03	$0.187D_{12} - 72.7$	23.2	0.016
MOR	$0.196D_{12} - 47.7$	17.1	0.04	$38880 - 21.1D_{12}$	1.6	0.263
Compression parallel	$57.8 - 0.04D_{12}$	0.0	0.61	$0.0646D_{12} - 36.6$	0.0	0.382
Compression perpendicular	$115 - 0.142D_{12}$	45.8	0.001	$0.0821D_{12} - 70.9$	4.1	0.189
Brinell hardness parallel	$0.005D_{12} + 1.57$	0.0	0.338	$0.00762D_{12} - 0.59$	4.7	0.175
Brinell hardness perpendicular	$3.36 - 0.00063D_{12}$	0.0	0.67	$0.0066D_{12} - 2.44$	27.9	0.008

D_{12} = density at 12% MC, r^2 adj (%) = adjusted coefficient of determination, MOE = modulus of elasticity, MOR = modulus of rupture

CONCLUSIONS

Ntholo is a heavier timber with relatively higher mechanical strength compared with the well known commercial timber species from Mozambique. Rather than replacing the commercial species, ntholo is proposed to be included in the small group of heavy timbers available in Mozambique. Based on the mechanical properties of ntholo, it seems suitable for flooring, window frames and doors.

Fibre length was the only anatomical feature significantly correlated with all tested physico–mechanical properties of ntholo. Density also showed the same trend. In contrast, the number of vessels/mm^2 and % vessels were not significantly correlated to any of the measured properties but seemed to be key anatomical features for predictions under PLS.

Apart from sapwood MOE, the remaining sapwood PLS regression equations were not significant. However, according to PLS equations, all tested properties of ntholo sapwood were greatly influenced by tissue proportions. In general, ntholo heartwood properties were characterised by more levelled anatomical predictors for the tested mechanical properties, although invariably fibre dimensions and vessel features seemed to be the key variables. Based on observed r^2 from simple linear regression, both sapwood and heartwood densities were weak predictors for the tested mechanical properties. Nevertheless, given some observed significant correlations with tested properties, it is expected that they can roughly provide good indication when selecting material for designated end-uses.

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