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The Relationship Between Fibre Characteristics and Pulp-sheet Properties of *Leucaena leucocephala* (Lam.) De Wit

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Abstract: This study investigates the relationships between fibre characteristics and pulp-sheet properties of 5-year old trees of *Leucaena leucocephala* grown under intensively managed alley cropping. Wood chips were subjected to soda pulping in a laboratory-scale digester while slivers were macerated for fibre analysis. Multiple regression equations involving fibre characteristics and their morphological indices were determined to predict the pulp-sheet properties of *Leucaena leucocephala* at three different freeness levels. Cell-wall thickness and fibre length had the greatest influence on the strength properties of the unbeaten pulp. After beating their influences were largely evident as indices of their derived morphology. However, the regression equations showed that it is not possible to fully categorize the performance of pulp-sheet properties based on a single morphological factor. All the fibre features considered were found to influence the pulp sheet of *Leucaena leucocephala.*

Key words: Fibre dimensions · pulpsheet properties · relationship · *Leucaena leucocephala*

INTRODUCTION

The successful conversion of pulp into a marketable product depends on the original fibre characteristics and the response of the fibre to the processing variables. Because of the great variety of wood types, the physical properties of a piece of paper from one species will often vary markedly from similar piece from another species although processing conditions may have been identical. Thus, analysis of fibre characteristics such as fibre length, fibre diameter, lumen width, cell-wall thickness and their derived morphological factors became important in estimating pulp quality of fibre [1-3]. One of the first fibre properties related to strength properties was fibre length. Several investigators found that extensibility of the bonding sites is a function of the fibre length [4, 5]. This led to the conclusion that hardwood pulps are lower in paper strength because of their shorter fibres than those of softwoods with longer fibres. Other anatomical features like lumen size and cell wall thickness affect the rigidity and strength properties of the papers made from the fibres [6]. Fibres with large lumen and thin walls tend to flatten to ribbons during papermaking with enhanced inter-fibre bonding between fibres and consequently having good strength characteristics [7, 8].

With the wood-fibre-crisis envisaged by experts and the need to meet future fibre supply [9], occasioned by the ever increasing demand for pulp and paper products globally, it become imperative to beam search light on lesser used wood species with the aim of screening them for pulp and paper making. *Leucaena leucocephala* fall in this category. The fibre characterization and chemical analysis suggests that Leucaena is among the best tropical hardwood for papermaking [10]

The present study investigates the fibre characteristics and pulp-sheet properties of *Leucaena leucocephala* with the aim of predicting the performance of pulp-sheets based on its fibres and soda pulp quality.

MATERIALS AND METHOD

Ten 5-year old *Leucaena leucocephala* trees grown under intensively managed alley cropping system at International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria were used for this study.

Billets of 20cm in length were obtained from base, middle and top portions. From each billet a disc of 5.0cm thickness was cut and used for fibre analysis while the remaining billets were chipped for pulping.

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Fibre Analysis: Fibre length, lumen width, cell-wall thickness and their derived morphologies were measured in stem cross section. Wood slivers parallel to the grain were taken from each annual ring and macerated in a 1:2 (v/v) mixture of 10% acetic acid and 30% hydrogen peroxide at 100±2°C for 4 hours. Fibre dimensions were measured in swollen condition using Rheichert visopan microscope. The mean fibre characteristics with their derived, morphologies are presented in Table 1.

Pulping Experiments: Pulping experiments were carried out at the chemical Engineering Department, Obafemi Awolowo University, Ile-Ife, Nigeria. All the 15.0cm billets from each tree were chipped into 3 cm x 1cm size. The wood chips were pulped using soda method. Pulping was performed in a 5-L transversely rotatory autoclave. For each cooking cycle, liquor to wood ratio and cooking time was kept constant at 3-l/kg and 3 hours respectively. During cooking, the digester was de-gassed for a period of 10 minutes at every 1-hour interval. After each cook, 20 minutes gas down period was allowed before the black liquor was ejected. All pulps were disintegrated and washed with cooled distilled water on a standard size 1 mm x 1 mm netted sieve. The cooking parameters are shown below:

Bone dry weight of wood:	1000 g
Liquor ratio:	3:1
NaOH concentration	5%
Temperature	170°C
Time to maximum	60 mins.
Time at maximum	180 mins.
Gas down period	20 mins.

Pulp analysis: Pulp yield expressed as percentage of the oven dry weight of the chips was determined together with rejects proportion. Kappa number measurement was determined as specified in the laboratory tests manual of Iwopin pulp and Paper Company. Pulp freeness was tested using Schoper Riegler Freeness tester according to (Tappi, 1985). It was expressed as the rate at which water drained from a suspension of 3g of pulp in 1 litre water. Consistency, which is a function of the percentage of dry pulp in water, was determined using [12]. Both freeness and consistency determination was carried out at 6.3^{OSR} (unbeaten pulp), 51^{OSR} and 75^{OSR} degree of freeness. The mean results are presented in Table 3.

Table 1: Fibre characteristics of *Leucaena lencocephala* wood

Fibre dimensions	Value
Fibre length (L) µm	652.00
Fibre diameter µm	15.67
Cell-wall thickness µm	2.90
Lumen width (d) cm	9.87
Runkel ratio (2^w/d)	0.59
Flexibility ratio (d/D)	0.63
Slenderness ratio (L/D)	41.61
Wall rigidity (w/D)	0.19

Table 2: Pulp yields and kappa number of soda pulp of *Leucaena leucocephala*

Parameter	Value
Chemical consumption (%)	35.00
Kappa number	23.60
Screened yield (%)	48.00
Rejects (%)	0.06
Total yield (%)	48.06

Table 3: Pulp-sheet properties of soda pulp of *Leucaena leucocephala* wood at different freeness levels

Paper properties	Freeness levels (°SR)		
	Unbeaten pulp(6.3)	51.00	75.00
Burst (g/cm^2)	7.20	16.79	16.96
Tear (g/gm^2)	87.30	124.90	140.60
Breaking length (m)	765.90	21.84	2672.40
Stretch (%)	0.49	1.27	1.87

^{O}SR means schopper riegler freeness

Handsheet preparation and testing: The pulp was beaten in a laboratory valley beater according to (Tappi 1988). All the handsheets made at the three level of freeness were tested for burst, tear, breaking length and stretch.

Statistical analysis: Multiple regression analysis was used to establish the relationships between the fibre characteristics and pulpsheet properties at the 3-level of freeness.

RESULTS AND DISCUSSION

Fibre dimension: Mean fibre length and cell wall thickness were 0.65mm and 2.9µm respectively while Runkel ratio, flexibility and slenderness were 0.59, 0.63 and 42:1 as shown in Table 1. These values are lower than those obtained for eucalyptus species by (Kibblewhite, *et al*., 2000; Jorge, *et al*., 2000; Igartua, *et al*., 2005; Veenin, *et al*., 2005; Monteoliva, *et al*., 2005) and trembling aspen by (Fujiwara and Yang, 2000). According to (Oluwadare, 1998), these values are of acceptable range for hardwoods

Table 4: Multiple regression equations for unbeaten pulp of *Leucaena leucocephala*

Equations		Predictors	Standard co-efficients	Individual variance R^2	Multiple R^2	Standard error
		Freeness				
A		Constant	a. 47.668			
	X_1	Reciprocate of wall thickness (1/2w)	b_1-1.354	0.553		
	X_2	Square of Slendernes ratio $(L/D)^2$	b_2 2.729	0.284		
	X_3	Runkel ratio (2w/l)	b_3 2.831	0.285		
	X_4	Wall rigidity (w/D)	b_4-1.008	0.227	0.551	1.757
B		Breaking length				
		Constant	a. 14.20.176			
	X_1	Reciprocal of cell-wall (1/2w)	b_1-0.589	0.553		
	X_2	Fibre length	b_2-0.589	0.423		
	X_3	Lumen width	b_3 0.183	0.135	0.551	139.727
C		Burst factor				
		Constant	a. 4.359			
	X_1	Reciprocal of cell-wall thickness (1/2w)	b_1 0.959	0.247		
	X_2	Flexibility ratio (d/D)	b_2-0.598	0.161		
	X_3	Fibre length	b_3 0.537	0.268	0.381	2.212
D		Tear factor				
		Constant	a. 108.189			
	X_1	Slenderness ratio (L/D)	b_1 0.130	0.451		
	X_2	Fibre length	b_2 0.11	0.411		
	X_3	Reciprocal of cell-wall thickness (1/2w)	b_3.-0.491	0.589	0.393	4.122
E		Stretch				
		Constant	a.-0.573			
	X_1	Fibre length	b_1-0.331	0.564		
	X_2	Reciprocal of cell-wall thickness (1/2w)	b_2 0.573	0.697		
	X_3	Wall rigidity (w/D)	b_3-0.046	0.121	0.580	6.272E-02

Equation type: $y = a + b_1x_1 + b_2x_2 \ldots b_nx_n$. where y = Pulp properties desired and x_1, x_2 … = Independent variables (Fibre characteristic).

for papermaking. The Runkel ratio is typical of most temperate species like Populus and Caribbean pine, which produces good quality paper. The morphological indices are fairly good except that the slenderness is low compare to temperate softwood.

Pulp yields and paper properties: The Kappa number was 23.6 with screened yield of 48.0% and rejects of 0. 06% (Table 2). This value is slightly higher than kraft pulp yield of between 42.5-47.7% obtained by (Khristova, *et al*., 1988) for same species from Sudan. The paper properties also compared favourably well with kraft pulp sheet with burst index of 7.2 g/cm^2, tear 87.3 g/gm^2 breaking length of 766m and stretch of 0.49% for unbeaten pulp. However, these properties increased tremendously as drainability increased to 51 and 75°SR with burst of 16.8, tear 125, breaking length 2.2km and stretch of 1.27% at 51°SR while 17 g/cm^2, 141 g/gm^2 2.7km and 1.87% was obtained at 75°SR (Table 3). These values show that good quality paper of high strength value could be obtained from soda pulp of *Leucaena leucocephala.*

Fibre characteristics and pulp sheet interrelationships: The freeness of the unbeaten pulp was found to be 6.3. The dominant factor affecting freeness at this level is cell-wall thickness, which alone accounted for 55.3%. The

Table 5: Multiple regression equation for pulp-sheet properties at 51^{OSR} of freeness

Equations		Standard predictors	Individual co-efficients	Multiple variance R^2	Standard R^2	Error
		Breaking length				
A		Constant a. 241.868				
	X_1	Square of Slenderness ratio (L/D)	b_1-0.658	0.173		
	X_2	Reciprocal of wall thickness (1/2w)	b_2 0.342	0.296		
	X_3	Wall rigidity (w/D)	B_3 0.816	0.199	0.149	78.162
B		Burst factor				
		Constant	a. 24.026			
	X_1	Flexibility ratio (d/D)	b_1-0.440	0.332		
	X_2	Slenderness ratio (L/D)	b_2 0.423	0.077		
	X_3	Fibre length b_3 0.363	0.025	0.122	0.691	
C		Tear factor				
		Constant	a. 41.321			
	X_1	Fibre length	b_1 0.153	0.225		
	X_2	Runkel ratio	b_2-2.649	0.130		
	X_3	L2 x (1/2W)	b_3 0.128	0.056		
	X_4	Wall rigidity (w/D)	b_4 2.893	0.258	0.444	7.463
D		Stretch				
		Constant	a.-8.166			
	X_1	Fibre length	b_1 0.405	0.267		
	X_2	Wall rigidity (w/D)	b_2 2.114	0.355		
	X_3	Flexibility ratio (d/D)	b_3.1.846	0.245	407	0.122

Equation type: $y = a+b_1x_1 + b_2x_2 \dots b_nx_n$. where y = Pulp properties desired and $x_1, x_2 \dots x_n$ = Independent variables (Fibre characteristic)

lumen to diameter ratio accounted for 28.4%. The multiple regression analysis involving these variables with Runkel ratio and wall rigidity accounted for 55.1% of the total variation (Table 4). At this level, the fibres has not achieved great entanglement thus, the cohesion between the fibres is low. The mean breaking length was low (788.9 m). It was found that 55.3 and 42.3% of the variations were attributed to cell-wall thickness and fibre length. Multiple regressions involving these variables with lumen width accounted for 38.1% with standard error estimate of 139.727. Similar results were obtained for burst factor and stretch of the unbeaten pulp with R^2 of 24.7 and 69.7, 26.8 and 56.4% attributed to cell-wall thickness and fibre length in each case (Table 4). The prediction equation for tear factor in Table 4 also compared well to those of other sheet properties. Cell-wall thickness alone accounted for 58.9% of the total variation while fibre length and slenderness ratio contributed 41.1 and 45.1% respectively. The influence exerted by cell-wall thickness and fibre length of the unbeaten pulp reflects low fibre-to-fibre bonding. According to (Dinwoodie, 1965), if fibres are not bonded together in a continuous sequence, the sheet will develop weak spots making it liable to failure under small load.

Meanwhile, when beating was increased to 51^{OSR} freeness, the dependence of individual fibres was lessened. Fibre interactions became a dominant factor. Therefore, after beating interactions between morphological indices occurs. Multiple regression analysis showed that fibre flexibility, reciprocal of cell-wall thickness and wall rigidity accounted for 17.3, 29.6 and 19.9% of the total variations in breaking length respectively (Table 5), when fibre length was excluded from step-wise regression analysis. But for burst factor, the only dominant predictor was flexibility ratio which accounted for 33.2% of the total variation. The tearing strength and stretch at this stage was governed by fibre length and wall rigidity. The prediction equation in

Table 6: Multiple regression for pulp-sheet properties at 75^{OSR} of freeness

Equations		Predictors	Standard co-efficients	Individual variance R^2	Multiple R^2	Standard error
		Breaking length				
A		Constant	a. 2246.301			
	X_1	Flexibility ratio (d/D)	b_1 0.314	0.090		
	X_2	Reciprocal of wall thickness (1/2w)	b_2-0.259	0.013	0.025	104.173
B		Burst factor				
		Constant	a. 69.324			
	X_1	Flexibility ratio (d/D)	b_1-3.555	0.431		
	X_2	Slenderness ratio (L/D)	b_2-2.789	0.333		
	X_3	L^2 x (1/2w)	b_3 3.836	0.255	0.372	0.7322
C		Tear factor				
		Constant	a. 204.994			
	X_1	Fibre length	b_1 10.194	0.049		
	X_2	Square of fibre length (L^2)	b_2-10.277	0.077		
	X_3	Runkel ratio	b_3.0.066	0.053	0.291	10.2603
D		Stretch				
		Constant	a.-3.444			
	X_1	Fibre length (L)	b_1 0.537	0.541		
	X_2	Reciprocal of cell-wall thickness) (1/2w)	b_2-0.297	0.195		
	X_3	Flexibility ratio (d/D)	b_3.0.793	0.466	0.603	0.2052

Equation type: $y = a+b_1x_1 + b_2x_2 \dots b_nx_n$. where y = Pulp property desired and $x_1, x_2 \dots x_n$ = Independent variables (Fibre characteristic)

Table 5 showed that fibre length and wall rigidity accounted for 22.5 and 25.8% variation in tear factor respectively while 26.7, 35.5 and 24.5% variation in stretch was attributed to fibre length, wall rigidity and slenderness ratio in that order. Beating increases the number of bonding sites and enhanced inter-fibre bonding therefore, it is possible that the extensibility of a given bonding site will not be controlled primarily by the respective fibre characteristics, but the extent of fibre-to-fibre bond formation is necessitated by the bruising and fibrillation of fibre as beating progresses [4].

When beating was further increased to 75^{OSR} of freeness, the breaking length was 2672.4m (Table 3). At this stage, lumen-to-diameter (flexibility) ratio accounted for 9.0% variation in breaking length. Multiple regression analysis for this variable together with reciprocal of cell-wall thickness accounted for only 1.3% of the total variation with standard error estimate of 104.17. Burst factor was governed by the flexibility and slenderness of the fibre with R^2 of 43.1 and 33.3% respectively (Table 6). The product of fibre length and reciprocal of cell-wall thickness accounted for 25.5% of the observed variation. Tear factor was 140.6 at this level of freeness and was largely influenced by fibre length and Runkel ratio. Multiple regressions involving these variables accounted for 29.1% with error estimate of 10.260. However, the controlling factors on stretch at this level are fibre length flexibility of the fibre with R^2 of 54.1% and 46.6% respectively. Multiple regression analysis of these variables with the reciprocal of cell-wall thickness accounted for 60.3% of the total variation with error estimate of 0.2052. This means that increased beating time has helped the fibres to reach a stage where bonding with adjacent fibres is enhanced. Thus, the cohesive force between the fibres tends to be higher. Also, the relative importance of the observed fibre morphology at this stage corroborated the earlier observation that strength properties of pulp sheet is influenced by the amount of bonding sites made available by fibrillation or the number of bonds per cubic centimeter. Therefore, the influence of bonding increases with increased beating time. Hence, fibre length as a function of the total length available for

June 30, 2007bonding and cell-wall thickness as a function of slenderness, flexibility and rigidity of the fibre (which provide the mass at any given point along the length of the fibre) became important, [4, 5, 22].

CONCLUSION

The result of this work showed that fibre characteristics and their morphologies significantly influenced the strength properties of the pulp sheet of *Leucaena leucocephala.* It is not possible to fully categorize the performance of the pulp base on a single morphological factor. However cell-wall thickness and fibre length had the greatest influence on the strength properties of the unbeaten pulp. Although this influence was less after beating as evident from the regression analyses, nevertheless, they remained important factors. After beating, rigidity, flexibility and slenderness significantly influenced the breaking length, burst, tear and stretch of the pulp sheets. Fibre length was important in as much as minimum length is required for bonding distribution once beating commences.

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