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The physical properties and strength characteristics of kenaf plants

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Abstract: This article reports some physical properties and strength characteristics of two kenaf (*Hibiscus cannabinus*) varieties in Nigeria at critical stages of harvest with a view of understanding the plant material reaction to the load and deformation. The kenaf samples were subjected to a uniaxial compression test between two parallel plates at a loading rate of 20 mm·min^{-1} and a uniaxial bending test between two supports on each end at a loading rate of 50 mm·min^{-1} using a Universal Instron Testing Machine (Instron, USA). The results of the parameters studied revealed that Tianung 1 gave the higher stem height, stem diameter, compressive stress, bending stress, rupture load, rupture energy, Young's modulus, and toughness, which were 293.10 cm, 18.45 mm, 8.70 MPa, 44.86 MPa, 191.51 N, 3.43 J·mm^{-2}, 350.81 MPa, and 6.85 N·mm^{-1}, respectively, at four months after planting. The parameters studied significantly increased with maturity for the two kenaf varieties. However, the moisture content significantly reduced with maturity.

Keywords: yield strength; bending stress; rupture load; rupture energy; Young's modulus

Kenaf has a single, straight, unbranched stem consisting of two parts; the bark fibre and the core fibre (Joshi et al. 2004) which matures between the ages of three and four months after planting (Webber et al. 2002). Kenaf can grow under a wide range of weather conditions, to a height of more than 3 m and a stem diameter of 1–5 cm (Dauda et al. 2014). Kenaf is comprised of 35–40% bark fibres and 60–65% core fibres by weight of the kenaf stalk. Kenaf contains approximately 65.7% cellulose, 21.6% lignin and pectin and other compositions (Shakhes et al. 2011). Kenaf has gained commercial interest because of the search for an alternative to the consumption of wood-based products which has resulted in a decrease in forest resources (Solomon et al. 2013; Dauda et al. 2014; Karimi et al. 2014). Kenaf is economically important as a source of cellulosic fibre with high CO_2 fixation ability (Lam et al. 2003; Scordia et al. 2013). Thus, it is essential to understand the many different aspects of kenaf and have reliance on a systematic approach that will integrate the production, harvesting, processing, and utilisation of the plant. Researchers have evaluated some properties of various plants in order to establish relevant information for the design of machinery. Nazari et al. (2008) reported that the tensile strength of the lower region of alfalfa stem varied between 28.80–32.75 MPa. Chattopadhyay and Pandey (1999) reported that the bending stress for sorghum stalks at the seed stage and forage stage were 40.53 and 45.65 MPa, respectively. Dauda et al. (2014) reported that the maximum cutting force and rupture energy of the Malaysian kenaf variety V36 at the bottom region was 1584.55 N and 8.75 J, respectively, for a 35% moisture content,

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while it was 694.86 N and 3.50 J, respectively, for a 72% moisture content. However, all the parameters studied in the previous research do not account for the strength characteristics of the kenaf stem at the stages of harvest.

This article provides some physical properties and strength characteristics of two varieties of kenaf plants in Nigeria. These properties include; the stem length, stem diameter, cross-sectional area, moisture content, compressive yield stress, toughness, and bending stress at two significant stages of harvest. The results are relevant for the design of the appropriate processing and handling machines such as a harvester and a decorticator. They are also the relevant properties that determine the use of kenaf as a composite material in various applications such as a bio-composite in glass fibre and building construction materials (Anuar, Zuraida 2011)

MATERIAL AND METHODS

Physical properties. In this research, the physical properties, namely the stem length, stem diameter, and cross-sectional area of two kenaf varieties named Ifeken 100 and Tianung 1, were studied. These properties were determined with 40 randomly selected kenaf stem samples obtained from the Teaching and Research Farms, Obafemi Awolowo University, Ile-Ife. All the samples studied were matured for three and four months. The two maturity stages were selected because kenaf is harvested for its quality fibre at three months old and harvested for seed purposes at four months old. The stem length was measured from the soil surface to the tip of the stem using a metre rule with 0.1 cm accuracy. The stem diameter of the kenaf plant decreased towards the top of the plant. Dauda et al. (2014) studied three regions of a Malaysian kenaf variety V36, and the result showed that the bottom region has the greater stem diameter; hence, the more significant rupture energy and rupture force. However, the bottom region of the plant at the above-ground level was studied in this research. The stem diameter was measured with a digital calliper with an accuracy of 0.01 mm (Kayembe 2015). The cross-sectional area of the stem was calculated from the corresponding stem diameter. To determine the average moisture content of the kenaf stem at the date of harvest, the samples cut to an average length of 20 cm from the bottom region were weighed and dried in a laboratory oven (Uniscope, England) at 104 ^{0}C for 24 hrs (ASABE, 2012) by replicating the experiment three times for each kenaf variety.

Strength characteristics. To determine the strength characteristics (compressive yield stress, bending stress, Young's modulus, toughness, rupture load, and energy) of the kenaf stems, 40 samples of Ifeken 100 and Tianung 1 were subjected to two tests using a universal Instron testing machine (Instron, USA). The compressive yield strength was determined using 10 samples each of the two kenaf varieties. Each sample, a 30 mm long stem, was subjected to a uniaxial compression test between two parallel plates. The objective of the test is to draw the force-deformation diagram of the samples between the two parallel plates. The loading speed was set at 20 mm·min^{-1}. Also, to determine the bending strength of the kenaf stem, 10 samples each of the two kenaf varieties were used. The samples were placed on two anvils 65 mm apart. A sliding plate moving at 50 mm·min^{-1} strikes the specimen at the middle. The force-deformation, rupture load, and energy of the samples were displayed on the monitor connected with the universal testing machine. Young's modulus was determined from the slope of the stress-strain curve while the toughness of the specimen was calculated from the area under the force-deformation curve. The analysis of the measured data was accomplished using a Data Analysis Toolkit on Microsoft Excel Professional (version 2016).

RESULTS AND DISCUSSION

Evaluation of the physical properties

The kenaf varieties studied at two different stages of maturity on the experimental field had similar physical properties. Table 1 shows the results of the measurements of the stem height, diameter, and cross-sectional area of the kenaf stems at the two different stages of maturity. According to Table 1, the standard deviation of the stem height, diameter, and cross-sectional area of the two determined kenaf varieties showed less dispersion at the early age of maturity as it revealed that the maturity of the plant

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Table 1. The physical properties of the kenaf variety stem with a plant age of 3 and 4 months

	Ifeken 100			Tianung 1		
	mean (SD)	max	min	mean (SD)	max	min
3 months						
Height (cm)	137.60 (28.37)	188.10	103.00	225.63 (27.29)	272.35	183.88
Diameter (mm)	9.64 (0.77)	10.80	8.66	12.07 (1.60)	16.55	10.59
Cross-sectional area (mm^2)	73.43 (11.75)	91.64	58.91	116.46 (33.55)	215.21	88.14
4 months						
Height (cm)	173.95 (38.83)	233.00	110.00	235.84 (29.45)	293.10	197.70
Diameter (mm)	10.20 (1.57)	12.33	8.17	13.32 (1.96)	16.55	10.64
Cross-sectional area (mm^2)	83.66 (25.56)	119.50	52.45	142.22 (45.59)	215.12	88.91

all the parameters studies were significant at a level of 0.05%, SD – standard deviation; max – maximum; min – minimum

significantly affected the physical properties of the plant. Tianung 1 has a more significant stem height and diameter than Ifeken 100, hence a higher cross-sectional area. Although both varieties had a significant increase in height and diameter when concerned with the maturity. The cross-sectional area is significant in determining the effect of the physical properties of the plant on the compressive yield strength, bending stress, rupture load, and energy. Kenaf with a thicker stem requires considerably more energy to shear the stem during harvest (Dauda et al. 2014).

The average moisture level of the Ifeken 100 and Tianung 1 kenaf stems determined three months after planting were 57.55 and 61.48%, respectively; the corresponding values at four months after planting were 30.73 and 32.55%, respectively, as shown in Fig 1. The moisture content level of both varieties significantly reduced with the level of maturity.

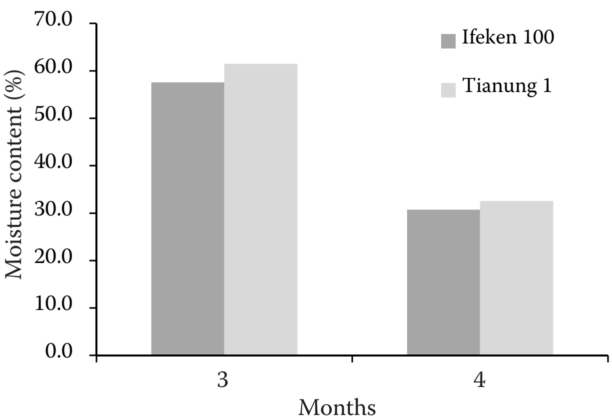

Fig. 1. The moisture content of the kenaf stem

Evaluation of the strength characteristics

Both kenaf varieties exhibit similar behaviour under loading. Table 2 shows the compressive strength characteristics of the kenaf stem. At the plant age of three months, the compressive yield stresses were 3.75 and 6.54 MPa for Ifeken 100 and Tianung 1, respectively. While, at the plant age of four months, the compressive yield stresses were 6.18 and 8.70 MPa for Ifeken 100 and Tianung 1, respectively. This result is similar to that obtained by Dauda et al. (2014) who reported a compressive yield strength of 4.82 and 9.24 MPa for the lower region of the stem of the Malaysian kenaf variety V36 at a moisture level of 55 and 35% (Wb), respectively. The plant maturity and moisture content level had a significant effect on the compressive yield stress. The trend is the same for the maximum load and energy at the rupture of the stem. Tianung 1 has a higher load and energy at the rupture with the corresponding values of 775.41 N and 5.39 $J \cdot mm^{-2}$, respectively. The stem gained strength from the bark fibre, which resisted the internal force that caused a crack in the core fibre. However, a higher level of moisture resulted in lower compressive yield stress, load, and energy at rupture. Table 3 shows the regression analysis of the load and energy at the rupture based on the stem diameter at three and four months after planting. The models can be used to predict the load and energy at the rupture of the stem at three and four months after planting, respectively, when the diameter of the lower region is known. The load and energy at the rupture are relevant parameters for the design of

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Table 2. The compression properties of the kenaf variety stem with a plant age of 3 and 4 months

	Ifeken 100			Tianung 1		
	mean	SD	SE	mean	SD	SE
3 months						
Cross-sectional area (mm^2)	61.41	3.19	1.01	88.55	7.86	2.49
Compressive yield stress (MPa)	3.75	0.50	0.16	6.54	0.93	0.29
Load at rupture (N)	351.44	239.92	75.67	766.95	127.61	40.36
Energy at rupture (J·mm^{-2})	2.52	0.59	0.19	3.79	1.70	0.54
4 months						
Cross-sectional area (mm^2)	92.79	12.52	3.96	96.59	4.31	1.36
Compressive yield stress (MPa)	6.18	1.20	0.38	8.70	2.53	0.79
Load at rupture (N)	420.98	92.39	29.21	775.41	113.41	35.86
Energy at rupture (J·mm^{-2})	3.31	1.75	0.55	5.39	2.74	0.87

All the parameters studies were significant at a level of 0.05%; SD – standard deviation; SE – standard error

Table 3. The models and constant values for the load and energy based on the stem diameter at 3 and 4 months after planting

Regression model	Constant value		R^2
	b_0	b_1	
3 months			
$L_{i\,max} = b_o d_i + b_1$	1011.100	–8586.900	0.9390
$L_{t\,max} = b_o d_t + b_1$	267.560	–2071.200	0.9920
$E_{i\,max} = b_o d_i + b_1$	2.543	–19.966	0.9896
$E_{t\,max} = b_o d_t + b_1$	3.165	–29.789	0.7837
4 months			
$L_{i\,max} = b_o d_i + b_1$	119.170	–872.040	0.9344
$L_{t\,max} = b_o d_t + b_1$	883.090	–9015.900	0.7609
$E_{i\,max} = b_o d_i + b_1$	2.767	–26.719	0.8725
$E_{t\,max} = b_o d_t + b_1$	9.054	–95.004	0.6678

$L_{i\,max}$ – the maximum load imposed on the Ifeken 100 stem at rupture (N); b_0, b_1 – the curve fitting parameters which are different in each equation; d_i – the diameter of the Ifeken 100 stem (mm); d_t – the diameter of the Tianung 1 stem (mm); $L_{t\,max}$ – the maximum load imposed on the Tianung 1 stem at rupture (N); $E_{i\,max}$ – the maximum energy of the Ifeken 100 stem at rupture (J·mm^{-2}); $E_{t\,max}$ – the maximum energy of the Tianung 1 stem at rupture (J·mm^{-2}); R^2 –the coefficient of determination

the appropriate processing and handling machines. Also, these properties are relevant for the selection of the fibres for the production of a bio-degradable sack for packaging purposes (Nishino et al. 2003; Akil et al. 2011).

The flexural tests determine the bending stress, Young's modulus, toughness, rupture load, and energy of the kenaf stem. The results are shown in Table 4. A similar trend of deformation was observed in both kenaf varieties. The results of the parameters studied gave significantly different values when concerned with the varieties, cross-sectional area, and maturity of the stems. The Tianung 1 kenaf variety at four months after planting has a more substantial bending stress, rupture load, rupture energy, Young's modulus, and toughness with the corresponding values of 44.86 MPa, 191.51 N, 3.43 J·mm^{-2}, 350.81 MPa, and 6.85 N·mm^{-1}, respectively. The trend is similar to the results reported by Nazari et al. (2008) for the alfalfa stem, Tavakoli et al. (2009) on the wheat straw, Ghahraei et al. (2011) and Dauda et al. (2014) for the kenaf stem. During loading, the stem tends to withstand the load as a result of the bast fibre, which behaves like an elastic material. The behaviour is a result of the accumulation of the fibre and moisture level reduction as the plant matured. Accumulation of the fibre results in lignification, which makes the cell wall thicker, and increases the stem rigidity, thereby causing the stem to resist any force imposed on it. Therefore, an increase in the cross-sectional area of the stem was responsible for the increased toughness of the stem when it is fully matured. The regression analysis of the effect of the stem diameter on the rupture load and rupture energy concerning maturity gave the linear functions shown in Table 5. All the indexes are significant at a level of 95%. The parameters studied provide the relevant information needed in designing the machinery and equipment used during the harvesting and post-harvesting operations of a kenaf

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Table 4. The flexural stress properties of the kenaf variety stem with a plant age of 3 and 4 months

	Ifeken 100			Tianung 1		
	mean	SD	SE	mean	SD	SE
3 months						
Cross-sectional area (mm^2)	69.26	31.93	10.10	170.92	60.83	19.24
Bending stress (MPa)	8.58	2.84	0.89	20.57	2.64	0.84
Rupture load (N)	64.49	18.62	5.89	161.25	77.37	24.47
Rupture energy ($J \cdot mm^{-2}$)	1.71	0.41	0.13	3.12	0.54	0.17
Young modulus (MPa)	131.24	106.49	33.67	144.20	60.03	18.98
Toughness ($N \cdot mm^{-1}$)	1.19	0.42	0.13	2.63	1.20	0.38
4 months						
Cross-sectional area (mm^2)	90.91	42.39	13.41	164.12	43.16	13.71
Bending stress (MPa)	11.58	3.14	0.99	44.86	1.87	0.59
Rupture load (N)	70.08	23.13	7.31	191.51	12.68	4.01
Rupture energy ($J \cdot mm^{-2}$)	1.78	0.23	0.07	3.43	1.58	0.50
Young modulus (MPa)	231.29	106.19	33.58	350.81	124.65	39.42
Toughness ($N \cdot mm^{-1}$)	2.93	0.38	0.12	6.85	3.90	1.23

All the parameters studies were significant at a level of 0.05%; SD – standard deviation; SE – standard error

plant in order to reduce fibre damage and seed loss. Young's modulus and the toughness are two of the parameters that measure the fibre plant tissue hardness. These properties are relevant for the selection of the kenaf fibre as a structural material. The higher the Young's modulus and toughness of the fibre plant is, the higher the resistance to failure is.

Table 5. The models and constant values for the load and energy based on the stem diameter at 3 and 4 months after planting

Regression model	Constant value b_0	b_1	R^2
3 months			
$L_{i\,max} = b_o d_i + b_1$	9.1046	–19.489	0.9978
$L_{t\,max} = b_o d_t + b_1$	37.2650	–370.240	0.8487
$E_{i\,max} = b_o d_i + b_1$	0.1862	–0.0121	0.8562
$E_{t\,max} = b_o d_t + b_1$	0.2688	–0.7129	0.9194
4 months			
$L_{i\,max} = b_o d_i + b_1$	8.3241	–17.435	0.8928
$L_{t\,max} = b_o d_t + b_1$	4.9040	–119.980	0.9751
$E_{i\,max} = b_o d_i + b_1$	0.1542	–0.153	0.9210
$E_{t\,max} = b_o d_t + b_1$	0.6154	–5.539	0.9776

$L_{i\,max}$ – the maximum rupture load imposed on the Ifeken 100 stem at rupture (N); b_0, b_1 – the curve fitting parameters which are different in each equation; d_i – the diameter of the Ifeken 100 stem (mm); d_t – the diameter of the Tianung 1 stem (mm); $L_{t\,max}$ – the maximum rupture load imposed on the Tianung 1 stem at rupture (N); $E_{i\,max}$ – the maximum rupture energy of the Ifeken 100 stem at rupture ($J \cdot mm^{-2}$); $E_{t\,max}$ – the maximum rupture energy of the Tianung 1 stem at rupture ($J \cdot mm^{-2}$); R^2 – the coefficient of determination

CONCLUSION

The evaluation of the physical properties of the two kenaf varieties revealed that the plant height and cross-sectional area of the stem has a direct relationship with the plant maturity while the moisture content has an inverse relationship with the plant maturity. The maximum height for Ifeken 100 was 233.00 cm, and Tianung 1 was 293.10 cm at four months after planting, respectively. Further growth of the stem from three months to four months led to a decrease in the moisture content. At the early stage of maturity, the fibre separation is more natural when the moisture content of the stem is high, while more significant seed loss and fibre damage resulted from the further decrease in the moisture content during the harvest. The bending stress, rupture load, rupture energy, Young's modulus, and toughness of the two kenaf varieties increased with maturity; hence, the energy required to process the stem increased as a result of the increase in the toughness of the stem. These results have implications in the usage of kenaf as a structural material and the development of a kenaf stem processing machine, and such a machine

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would be adaptable for processing wheat straw, alfalfa stems, and other identical kenaf varieties.

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