Kinetic Study of the Rate of Retting of Empty Plantain Fruit Bunch Fibers

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Abstract— **Empty plantain fruit bunch fibers were extracted by means of water retting. The kinetics of the water retting process was critically studied based on the fluid-particle (shrinking-core) kinetic models. Four size categories of group of six bunch samples each were used for the experiment, and the fit of experimental data to proposed models were studied using MATLAB curve-fitting toolbox. Results for the water retting experiment showed that the retting is significantly enhanced by the addition of a load/weight on the retting bunch, while the analysis (curve-fitting of the models with experimental data) confirmed the diffusion of the retting fluid (water) through the layer of fiber bundles (ash-layer) as the controlling resistance. Statistical analysis produced similar results as those of the kinetic study, revealing an enhanced retting with longer retting period, smaller bunch sizes, together with addition of weight during retting. This is revealed by the obtained optimum (minimum) bunch diameter of 2.40cm with a bunch sample size of 4.0cm, when retted for a period of 16days by the addition of the greatest load of 5kg stone weight. The fiber extracted finds use in the manufacture of reinforced composite materials which are fast replacing the use of metallic and plastic materials, due to the quest for materials that are light and cheap, yet strong.**

Index Terms— **Empty plantain fruit bunch fiber, retting, kinetics, shrinking-core models, statistical model.**

I. Introduction

In recent years, people have placed high emphasis on forest preservation and rational use of forestry and agricultural residues. This trend is mainly motivated and accelerated by the dilemma of an ever-increasing consumption of wood fiber-based products despite the dwindling wood resources. Furthermore, the application of cellulose fiber has many advantages: it is environmentally sound, recyclable, and low in cost. In 2006, the annual global production of lingo-cellulose fibers for crops was about 4 billion tons, of which 60% came from agriculture and 40% from the forest. In comparison, the annual world production of steel was around 0.7 billion tons, and plastic was about 0.1 billion tons [1].

Natural fibers present important advantages such as low density, appropriate stiffness, mechanical properties, high disposability and renewability. Moreover, they are recyclable and biodegradable. Many of our technologies require materials with unusual combination of properties that cannot be met by the conventional metal alloys. This led to the discovery of composite materials with superior corrosion resistance, good temperature resistance and resistance to extreme wears.

Composites are naturally occurring or artificially made materials with significantly different physical or chemical properties which remain separate and distinct at macroscopic and microscopic scale within the finished structure. They comprise of strong load carrying material known as reinforcement which are imbedded in a weaker material known as matrix. The reinforcement provides strength and rigidity, helping to support structural load while the matrix or binder - which maybe organic or inorganic - maintains the position and orientation of the reinforcement. The reinforcement may be particles, platelets or fibers and are usually added to improve mechanical properties such as stiffness, strength and toughness of the matrix material. The mechanical properties of a natural fiber-reinforced composite depend on many parameters, such as fiber strength, modulus, fiber length, shear lag parameter, the fiber-matrix interfacial bond strength etc. A strong fiber-matrix interface bond is critical for high mechanical properties of composites. A good interfacial bond is required for effective stress transfer from the matrix to the fiber whereby maximum utilization of the fiber strength in the composite is achieved [2].

Nigeria is one of the largest plantain producing countries in the world {3, 4, 5]. Plantain fiber can be obtained easily from the plants which are left as waste after the fruits have ripened. So plantain fiber can be explored as a potential reinforcement. Many investigations have been made on the potential of the natural fibers as reinforcements for composites and in several cases the result have shown that the natural fiber composites own good in stiffness, but the composites do not reach the same level of strength as the glass fiber composite [6,7].

Even though many researchers have geared towards investigating the optimal techniques for the extraction of fibers from empty plantain fruit bunch, none have shown interest in understanding the kinetics of the decay process during water retting and/or extraction via other means [2, 8, 9, 10]. This research work hopes to bring insight into the aforementioned limitation.

II METHODOLOGY

Sample/Material Collection

Sampling of the materials used for the experiment took place within Eziobodo locality of Owerri West LGA of Imo State, Nigeria. The experimental materials were gathered to make them readily available for the work. The plantain bunches were assembled from the community central market on a major market day, from the local dealers after large sales were made. Twenty four (24) plastic bowls (for the water retting) were also provided for the experiment, alongside weighing scale, prepared stones(weights/loads) of different sizes and measuring rule. Sufficient borehole water was also provided for the work.

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Material Preparation

The empty plantain fruit bunches was assembled, cut into categorized sizes of close length, diameter and weight. The plastic bowls were arranged on the floor of an empty room (where the water retting experiment was carried out), and about three (3) liters of borehole water were poured into each of the 24 bowls for the bunch retting. Transparent measuring rule, writing pad and pen were provided, both for immediate and periodic recording of the experimental results.

Materials used for the Fiber Extraction were: Plantain Empty Fruit bunch of various sizes (by mass and diameter); Weights (Stones) of different masses; 5kg, 4kg, 3kg, 2kg and 1kg; Borehole water, wide plastic bowls, Measuring rule (plastic) and Weighing scale and Analytical balance.

Experimental Method

Procedure for the Water Retting:

1. Six(6) different group samples, each of four(4) different bunch size categories of 5.5cm, 5.0cm, 4.5cm and 4.0cm in diameter respectively were made available in its fresh state at the beginning of the experiment.
2. Five(5) hard stones of mass 5kg, 4kg, 3kg, 2kg and 1kg respectively were also made available in quadruplets for the experiment.
3. Twenty four (24) new flat and wide plastic bowls were arranged on the floor of an unoccupied room for the work.
4. Water was poured into each of the 24 bowls to an extent to accommodate the retting bunch, and the bunches in their order and categories were carefully immersed in water contained in the bowls.
5. The various weights/loads were then placed on the immersed bunches in the order of their classification, which are meant to enhance the retting process.
6. To each of the four categories of sizes, there was no load placed in one of the bowls, and the fiber obtained there-in served as the Control Samples.
7. The retting kinetics was then monitored in periods of four (4) days intervals. After every four (4) days, the wetted and retting bunches were removed from the stagnant water in the bowl, and the average diameter of the un-retted (unreacted) core region were measured with a transparent measuring rule and recorded. This was done for the entire twenty four bowls at the intervals and the results recorded accordingly.
8. At the end of sixteen (16) days, which is the period for the study, the retted bunches were removed and washed. The fiber obtained were weighed, dried and reweighed for the different categories. Also, the loading mass to un-retted core ratios and fiber yield were calculated for each of the categories.

However, the size characterization of the bunch used for the study also involved measurement of the bunch length, which is useful for the determination of the bunch volume, which was useful in the fluid-particle kinetic modeling of the water retting process.

Mathematical Methods

The shrinking unreacted-core models used herein are:

$$\frac{t}{\tau} = 1 - \left(\frac{r_c}{R}\right)^2 \qquad (1)$$

Case where liquid film diffusion controls

$$\frac{t}{\tau} = [\left(\frac{r_c}{R}\right)^2 \left(2\ln\frac{r_c}{R} - 1\right) + 1] \qquad (2)$$

Case where ash-layer diffusion controls

$$\frac{t}{\tau} = 1 - \left(\frac{r_c}{R}\right) \qquad (3)$$

Case where chemical reaction at the core surface controls

Kinetic Model Curve-Fitting with MATLAB

First, the MATLAB Curve fitting toolbox was employed in the fitting of the proposed kinetic shrinking core models of the retting process with the experimental results. For each of the categories of the water retting samples, the retting period and un-retted diameter data obtained from experiment were used to fit each of the models proposed to ascertain their tendency to control the resistance of the retting process. The model with the best goodness of fit (R^2) was taken as the actual controlling resistance for the retting.

MATLAB statistical toolbox was used in the Analysis of Variance, Regression Statistics analysis and surface response plots of experimental results.

III RESULT ANALYSIS AND DISCUSSION

The three models were fit to experimental results, of the four bunch categories (sizes), with the retting of six samples each. It was observed that the model proposed for the ash-layer diffusion (equation 2) always had the best goodness of fit (R^2) in majority of the results obtained (Table 7 - Table 10). Evaluating the R^2 values for the twenty four comparative plots helped to conclude that the ash-layer penetration is the best fitting to control the retting resistance. Hence, the controlling resistance for the plantain bunch water retting is the penetration of the retting water through the bundles of the already released fiber, together with the lignin/gum on the surface of the fiber.

The experimental results of the retting of the four bunch categories, showed a consistency in all parameters measured. First, for all categories of bunch, it was clear that the added weight (to support/enhance retting) had a huge effect on the retting process, as seen in the increased reduction of the bunch fiber radii as the weight increased. This is truly a confirmation to the proposition made by extractors of fiber and some researchers in literature that loading may improve the retting process and possibly enhance fiber yield.

In the statistical analysis, from Table 5 (water retting – 'bunch diameter during retting' as response), based on the ANOVA, all of the three variables/factors (i.e weight added, initial bunch diameter and retting time) significantly contribute to the retting process (at 95% confidence), although the retting time is the most significant variable of the three judging by their F-values.

It can be observed from Table 6 that the model is adequate at 95% confidence based on the F-statistics, as the P-val is found to be less than 0.05. Based on the T-statistics, the most significant term is the interaction term between the weight added (X1) and the initial bunch diameter(X2) having the highest T-value of $|1.8972|$, which is close to $|2|$. On the P-val column, we also find this agreement that the interaction term aforementioned is the most significant with a

Table 1: Result for the water retted bunch CATEGORY A (Average Bunch Diameter (5.50cm), Average Bunch Mass (341.62g))

Sample Code	Bunch Diameter	Bunch Length	Bunch Mass (wet basis)	Weight Added	Bunch diameter After 4days	Bunch diameter After 8days	Bunch diameter After 12days	Bunch diameter After 16days	Mass of Fiber obtained (wet basis)	Fiber yield (wet basis)
A_i	$D_{A,cm}$	$L_{A,cm}$	$M_{A,g}$	$w_{i,kg}$	d - 4, cm	d - 8, cm	d -12,cm	d -16,cm	$m_{A,g}$	Y,%
A_5	5.50	15.0	381.56	5	3.80	3.60	3.30	3.00	251.41	65.89
A_4	5.40	14.0	363.42	4	3.80	3.70	3.50	3.20	183.24	50.42
A_3	5.50	15.6	352.31	3	3.90	3.80	3.60	3.30	150.37	42.68
A_2	5.40	12.8	280.94	2	4.40	4.00	3.70	3.30	129.74	46.18
A_1	5.40	12.9	296.08	1	4.70	4.30	3.80	3.50	137.47	46.43
A-CT	5.50	14.9	375.42	0	4.80	4.50	4.10	3.60	210.84	56.16
Mean	5.50	14.2	341.62	2.5	4.23	3.98	3.67	3.32	177.18	51.29

Table 2: Result for the water retted bunch CATEGORY B (Average Bunch Diameter (5.00cm), Average Bunch Mass (248.80g))

Sample Code	Bunch Diameter	Bunch Length	Bunch Mass (wet basis)	Weight Added	Bunch diameter After 4days	Bunch diameter After 8days	Bunch diameter After 12days	Bunch diameter After 16days	Mass of Fiber obtained (wet basis)	Fiber yield (wet basis)
B_i	$D_{B,cm}$	$L_{B,cm}$	$M_{B,g}$	$w_{i,kg}$	d - 4, cm	d - 8, cm	d -12,cm	d -16,cm	$m_{B,g}$	Y,%
B_5	4.90	14.2	240.65	5	3.50	3.20	3.00	2.80	185.01	76.88
B_4	5.00	13.2	244.21	4	3.70	3.40	3.10	3.00	153.00	62.65
B_3	5.00	13.6	249.16	3	3.90	3.70	3.30	3.10	151.74	60.90
B_2	5.10	13.9	247.13	2	4.20	3.90	3.50	3.20	148.03	59.90
B_1	4.90	12.2	221.06	1	4.30	4.10	3.60	3.40	130.78	59.16
B-CT	5.00	14.8	290.58	0	4.30	4.20	3.70	3.50	161.74	55.66
Mean	5.00	13.7	248.80	2.5	3.98	3.75	3.37	3.17	155.05	62.53

Table 3: Result for the water retted bunch CATEGORY C (Average Bunch Diameter (4.50cm), Average Bunch Mass (230.05g))

Sample Code	Bunch Diameter	Bunch Length	Bunch Mass (wet basis)	Weight Added	Bunch diameter After 4days	Bunch diameter After 8days	Bunch diameter After 12days	Bunch diameter After 16days	Mass of Fiber obtained (wet basis)	Fiber yield (wet basis)
C_i	$D_{C,cm}$	$L_{C,cm}$	$M_{C,g}$	$w_{i,kg}$	d - 4, cm	d - 8, cm	d -12,cm	d -16,cm	$m_{C,g}$	Y,%
C_5	4.50	13.5	210.00	5	3.20	3.10	2.80	2.60	139.94	66.64
C_4	4.50	16.8	237.57	4	3.40	3.30	3.00	2.90	175.52	73.88
C_3	4.50	15.1	258.75	3	3.70	3.50	3.20	3.00	179.55	69.39
C_2	4.50	14.7	237.51	2	3.90	3.70	3.30	3.00	172.50	72.63
C_1	4.40	14.2	204.03	1	4.00	3.80	3.30	3.10	134.44	65.89
C-CT	4.55	13.5	232.41	0	4.10	3.80	3.40	3.20	144.44	62.15
Mean	4.50	14.6	230.05	2.5	3.72	3.53	3.17	2.97	157.73	68.43

Table 4: Result for the water retted bunch CATEGORY D (Average Bunch Diameter (4.00cm, Average Bunch Mass (176.20g))

Sample Code	Bunch Diameter	Bunch Length	Bunch Mass (wet basis)	Weight Added	Bunch diameter After 4days	Bunch diameter After 8days	Bunch diameter After 12days	Bunch diameter After 16days	Mass of Fiber obtained (wet basis)	Fiber yield (wet basis)
D_i	$D_{D,cm}$	$L_{D,cm}$	$M_{D,g}$	$w_{i,kg}$	d - 4, cm	d - 8, cm	d -12,cm	d -16,cm	$m_{D,g}$	Y,%
D_5	3.95	14.7	186.09	5	3.00	2.50	2.40	2.20	138.88	74.63
D_4	3.90	15.4	178.73	4	3.10	2.70	2.60	2.50	128.92	72.13
D_3	3.80	12.4	162.66	3	3.40	3.00	2.80	2.60	119.36	73.38
D_2	4.10	15.6	200.86	2	3.50	3.20	2.90	2.60	130.86	65.15
D_1	4.00	11.3	148.94	1	3.50	3.30	3.00	2.80	105.21	70.64
D-CT	4.00	15.1	179.94	0	3.60	3.30	3.10	2.90	121.71	67.64
Mean	4.00	14.1	176.20	2.5	3.35	3.00	2.80	2.60	124.16	70.60

Table 5: Analysis of variance result for water retting – 'bunch diameter during retting' as response

Source	Sum Sq.	d.f	Mean Sq.	F	Prob>F
X_1	5.7212	5	1.14425	12.33	5.6474e-009
X_2	7.1271	3	2.37569	25.6	7.4003e-012
X_3	10.2521	3	3.41736	36.82	2.7756e-015
Error	7.7958	84	0.09281		
Total	30.8962	95			

Table 6: Numerical results for model fit to experimental data for water retting – 'bunch diameter during retting' as response

Variables	Coefficients	Standard error	T -stat	P-val	F-stat
Constant	0.1262	2.8856	0.0437	0.9652	Sse = 8.2341
X_1	0.1864	0.1732	1.0758	0.2850	Dfe = 89
X_2	1.1450	1.1962	0.9572	0.3412	Dfr = 6
X_3	-0.0343	0.0720	-0.4757	0.6355	Ssr = 22.6621
X_1X_2	-0.0620	0.0327	-1.8972	0.0612	F = 40.8246
X_1X_3	0.0040	0.0041	0.9705	0.3345	Pval = 0
X_2X_3	-0.0028	0.0125	-0.2270	0.8209	
X_1^2	-0.0137	0.0125	-1.0976	0.2755	
X_2^2	-0.0500	0.1248	-0.4007	0.6897	
X_3^2	-0.0017	0.0019	-0.8681	0.3878	
	R^2=0.7399	Adj. R^2 = 0.7127			

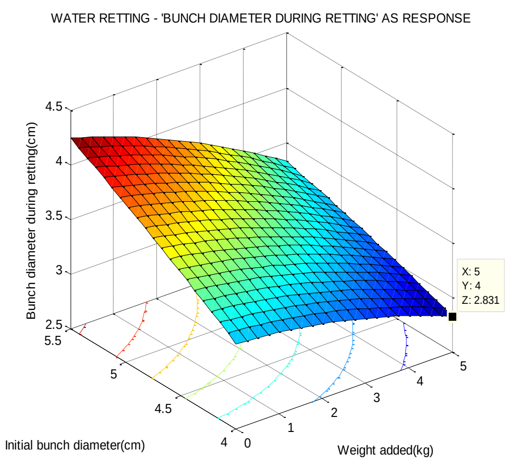

Fig.1: Initial Bunch Diameter vs. Weight Added

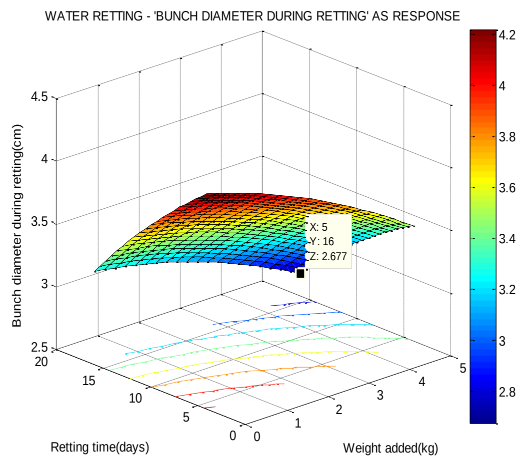

Fig. 2: Retting time vs. Weight Added

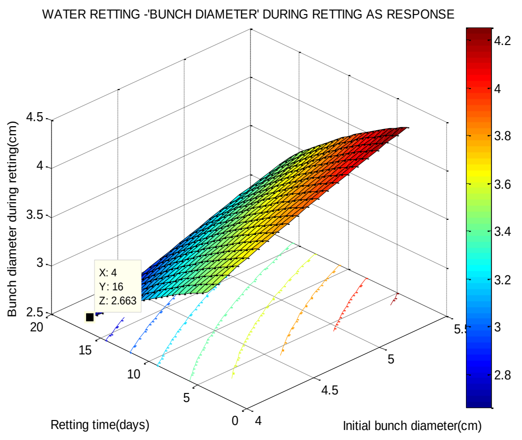

Fig. 3: Retting time vs Initial Bunch Diameter

Table 7: R-squared values for Category A Bunch

Model Category	1 Diffusion control	2 Ash Layer Control	3 Chemical Reaction
A-CT	0.5748	0.8491	0.7867
A1	0.5865	0.8486	0.8168
A2	0.6072	0.8348	0.8067
A3	0.6818	0.9022	0.8456
A4	0.5757	0.8397	0.7588
A5	0.5874	0.8449	0.7656

Table 8: R-squared values for Category B Bunch

Model Category	1 Diffusion control	2 Ash Layer Control	3 Chemical Reaction
B-CT	0.6794	0.8257	0.8094
B1	0.6680	0.8242	0.8054
B2	0.5925	0.8690	0.7968
B3	0.5877	0.8643	0.7952
B4	0.5579	0.8594	0.7847
B5	0.5687	0.8587	0.7866

Table 9: R-squared values for Category C Bunch

Model Category	1 Diffusion control	2 Ash Layer Control	3 Chemical Reaction
C-CT	0.6875	0.8693	0.8352
C1	0.7278	0.8585	0.8269
C2	0.6884	0.8546	0.8288
C3	0.6477	0.8660	0.8352
C4	0.5964	0.8619	0.8296
C5	0.6176	0.8746	0.8254

Table 10: R-squared values for Category D Bunch

Model Category	1 Diffusion control	2 Ash Layer Control	3 Chemical Reaction
D-CT	0.7578	0.8549	0.8266
D1	0.7364	0.8675	0.8486
D2	0.6247	0.8707	0.8536
D3	0.6470	0.8741	0.8556
D4	0.5694	0.9098	0.8326
D5	0.5672	0.8544	0.8163

p-value of 0.0612 which is significant at 90% confidence interval. The model explains about 74% of the variability observed in the experimental data.

The surface response plot of Fig. 1 produced a minimum response (bunch diameter during retting) of 2.83cm, when the weight added and the initial bunch diameter are used as factors, showing some interaction between the factors as seen on the contour lines of the plot. The nature of the minimum response indicates that retting will be faster if more weight is added and/or a lower initial bunch diameter is used. The plot also reveals an almost linear relationship between weights added and bunch diameter during retting and between initial bunch diameter and bunch diameter during retting, with initial bunch diameter having a more significant effect as can be seen in the colour variation along its axis indicating extent of change in the response. The ANOVA p-value corroborates this observation.

Fig. 2 had a minimum response of 2.67cm, when the bunch diameter during retting is weighed against the weight added and the retting time as the factors, and the contour lines showed no clear interaction between the factors. The plot reveals an almost curvilinear relationship between the weight added and bunch diameter during retting and between retting time and bunch diameter during retting, although the retting time have shown to have a more significant effect as evident in the colour variation along its axis which indicate the extent of change in the response. Again, the ANOVA p-value corroborates the aforementioned observation.

Fig. 3 produced a minimum value of 2.66cm for the bunch diameter during retting against the initial bunch diameter and the retting time as factors, also having no clear interactive contours on the plot. The plot further reveals a linear relationship between the initial bunch diameter and the bunch diameter during retting and a slightly curvilinear relationship between retting time and bunch diameter during retting, however the retting time proving to be the more significant factor as seen in the colour variation along the retting time axis indicating the extent of change in the response. The ANOVA p-value is in clear agreement with this observation.

However, when the MATLAB optimization toolbox was used for the optimization of the response, a 'bunch diameter during retting' value of 2.40cm was obtained against the weight added, initial bunch diameter and retting time values of 5kg, 4.0cm and 16days respectively, explaining that a minimum retting diameter of 2.40cm is obtained when a load of 5kg is placed on the smallest bunch size of 4.0cm and retted for the maximum retting period of 16days.

IV CONCLUSION

In this research, empty plantain fruit bunch fibers were extracted via stagnant water retting. As this was done, important experimental parameters such as retting time, bunch size and retting load were measured. The fiber extraction process was studied kinetically, using the shrinking unreacted-core model and statistically, using surface response methodology. Results obtained from the water retting reveal that there is enhanced retting when increased weights are placed on the empty fruit bunch.

The computer analysis established the fact that the kinetics of the retting process is controlled by the diffusion of the water through the binding lignin/gum and already released fiber (ash-layer diffusion), as its curve-fitted kinetic model always took the closest shape of that for the experimental data.

Finally, since the results of both the kinetic and statistical study are in very good agreement, reliable inferences have been drawn as regards the variability observed in the experimental data.

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