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Experimental and Analytical Study of Water Diffusion in Palm Kernel Shell of Cameroon

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Abstract

Moisture diffusion during soaking of palm kernel shell (***Elaeis guineensis***) aggregate concerning DURA variety of Cameroon was studied. Parameters like percentage of water gain at the saturation point and the effective moisture diffusivity were the main purposes. The knowledge of the behavior of those shells in presence of the liquid during the realization of the composite materials is important. Gravimetric method with discontinuous control of the mass of sample after immersion at the ambient temperature was used. Palm kernel shell aggregate of two origins and two considerable sizes respectively in mm: Sizes ≥ 16 and 12.5 ≤ Sizes < 16 were used. The rate of water absorption was found to be [6.18% and 11.74%] respectively for Tombel PKS and Bafang PKS and moisture diffusivity of [5.19×10^{-8} and 7.90×10^{-9} m^2/s] was also determined according to their irregular shapes by fitted soaking data in Becker's model.

Keywords

Palm Kernel Shell (PKS), Absorption, Moisture, Diffusivity

1. Introduction

One of the successful methods to valorize green energies and fight against pollution is to transform agricultural biomass into raw materials. Cameroon is the third African country in oil palm production and the industrial and craftsmen transformation co-produce several residues among which we have palm kernel shell (PKS). The PKS has been regarded as waste from oil palm processing [1]. It has been shown in Nigeria, first African producer of oil palm that approximately 15 to 18 tonnes of fresh fruit bunches are produced per hectare per year and PKS comprises about 64% of the bunch mass [2]. In Cameroon, the sub-product PKS is either burned to supply energy at palm mills machines or left in piles to the air. The process of burning PKS releases significant volatiles and particulates which pose pollution concerns and generates greenhouse effect and his natural degradation is too slow. Also, PKS is pouring on road to improve vehicular traction along plantation farms where there are no tarred roads. Researches works have been carried out on PKS, among which the determination of physical and chemical characteristics of PKS [3], which are essential parameters in utilization, development of processing methods, and design of equipment, is related to their transformation [4]. Other researchers deal with the use of both charred and non-charred PKS for filtering effluent from sedimentation tanks of water treatment plant [5], and also as concrete reinforcement agent in substitution to conventional aggregates such as granite [6]. The use of PKS in the composites materials implies water diffusion phenomenon. Therefore, we are interested in the kinetics of water absorption in the shell. In the present study, objectives are: Determination of the rate of water absorption and moisture diffusivity in the PKS using hydration data in the Becker's model suitable for arbitrary shapes [7]. Palm kernels, even on the same cob, vary in their shape from oval to round enabling the use of standard relations of regular shape body for moisture diffusion.

2. Materials

Palm kernel shells used in this investigation were obtained from the production areas of the west and south-west region of Cameroon. One variety of shell (DURA) is concerned, and it is characterized by the considerable volume of the shell. PKS aggregate, **Figure 1** below obtained was made through mechanical method. The initial moisture content of selected sizes of PKS was within the interval of [6.18%; 11.74%] respectively Tombel PKS and Bafang PKS and was determined by oven drying method of the whole kernels at 105˚C for 6 h [8] and expressed as percentage dry basis (db). 20 samples were produced for this study *viz*. 10 per region.

Figure 1. PKS aggregate sample (source: authors).

3. Methods

3.1. Experimental Measurements

1) Granulometric analysis

After measuring the mass of PKS aggregate, we pour it into a set of sieves arranged in descending order of fineness. Thereafter it is taken to the automatic sieves shaker D407 for 15 min to achieve complete classification. At the end of sieving operation, according to the pre-selected sieves we have recorded three different sizes respectively in (mm): 12.5 ≤ Sizes < 16; Sizes ≥ 16 and Sizes < 12.5. This last size was not significant for us to carry experimentation.

2) Gravimetric method

Samples were dried in a standard drying oven of mark Memmert model UN 160 at 105˚C for 6 hours, until the mass of the samples doesn't vary any more [8]. PKS aggregate samples were conditioned in test bowl and then the test bowl was placed in an ambient temperature (23˚C) water bath for soaking experiments as described by [8]. During soaking experiments, the samples were removed at specific variable intervals of time and the soaked samples were quickly blotted with the paper towels (3 - 5 times) to remove hygroscopic surface moisture and weighed. The moisture gain was calculated from the variation in weight of the sample to an accuracy of 0.01 g using electronic precision scale. The saturation mass is reached when the mass of the PKS remains constant.

By using Excel 2007 and Matlab R2014 b software with 95% rate of confidence, the solution of differential diffusion equation for arbitrary shapes provides by Becker was applied. The final mass is obtained when the mass of sample becomes constant. The duration of immersion is estimated about 28 days.

3) Percentage of water absorbed

The rate of absorption of water W compared to the dry matter of the samples is calculated starting from the drying mass M_0 and the equilibrium mass M_{eq} according to Equation (1).

$$w(\%)=\frac{M_{eq}-M_0}{M_0}*100 \quad (1)$$

The instantaneous humidity content $M(t)$ compared to the dry matter is computed by Equation (2).

$$M(t)=\frac{M_t-M_0}{M_0} \quad (2)$$

where M_0 and M_t are the mass at respectively initial time and the actual time.

3.2. Analytical Approach

In the literature several analytical models are proposed to describe the water diffusion kinetic of seeds and PKS can be ranged. Moisture ratio which is the equivalent without dimension of the instantaneous water content is given by Equation (3).

$$MR(t) = \frac{M_t - M_0}{M_{eq} - M_0} \tag{3}$$

The volume-surface area ratio (v/s) was calculated by dividing the equivalent volume of sphere by surface area of crushed palm kernel shell as

$$\frac{v}{s} = \frac{4\pi r^3}{3s} \Rightarrow \frac{v}{s} = \frac{r}{3}\left[\frac{4\pi r^2}{s}\right] \tag{4}$$

where r is equivalent radius. The factor ($4\pi r^2/s$) is the ratio of equivalent surface area of a sphere of equal volume to the surface area of the crushed palm kernel shell, and can be denoted as sphericity ϕ. Substituting ϕ, Equation (4) gets reduced to

$$\frac{v}{s} = \frac{r}{3}\phi \Rightarrow \frac{v}{s} = \frac{d}{6}\phi \tag{5}$$

where d is the equivalent diameter which can be expressed by a relationship as $d = (6v/\pi)^{1/3}$ from Equation (4). Substituting d, in Equation (5) and further simplifying, we get Equation (6) which describes the relationship between volume and surface area explicitly,

$$\frac{v}{s} = \left[\frac{6v}{\pi}\right]^{1/3} \frac{\phi}{6} \Rightarrow \frac{v}{s} = \frac{\phi v^{1/3}}{4.836} \tag{6}$$

Similar expression has also been reported by [7]. The sphericity of sample was therefore computed from Equation (7) as:

$$\phi = \frac{(LBT)^{1/3}}{L} \tag{7}$$

where ϕ is sphericity; L the length, mm; B the breadth, mm; and T thickness, mm [7].

Spatial dimensions, *viz.* length, breadth and thickness of 150 units, were measured using digital vernier caliper with 0.05 mm accuracy. These are the dimensions along the longest axis, across the axis perpendicular to the longest in the horizontal direction, and across the third axis perpendicular to both the first and second axis. Sphericity was averaged from 150 crushed palm kernels shells. The mean volume of sample was obtained through Equation (8).

$$v = \sum m/\rho n \tag{8}$$

where m is the mass of sample, ρ the solid density of palm kernel shell and n the number of sample.

Moisture diffusion of a liquid in a solid is primarily caused by concentration gradient. This gradient tends to move the water molecules to equalize concentration. The diffusion coefficient is defined by Fick's second law as Equation (9).

$$\frac{\partial c}{\partial t} = D_{eff}\left(\frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2} + \frac{\partial^2 c}{\partial z^2}\right) \tag{9}$$

where, D_{eff} is the diffusivity coefficient; c is the concentration of diffusing substance at a point in solid; x, y and z are Cartesian coordinates of the point under consideration; and t is the diffusion time. It has been demonstrated that Equation (9) can be integrated approximately through Equation (10) for diffusion in solids of arbitrary shape to correlate the moisture gain during soaking in water [7].

$$\frac{c-c_s}{c_0-c_s}=1-\frac{2}{\sqrt{\pi}}X+BX^2 \tag{10}$$

Subject to the following initial and boundary conditions

$$c=c_0 \quad at \quad t=0,$$

$$c=c_s \quad at \quad s=0 \quad and \quad t>0,$$

where s is a general coordinate with origin at bounding surface, c the average concentration, c_s the concentration at the bounding surface and c_0 the initial concentration and t the diffusion time. After replacing the concentration term (c) by the moisture content (m) the equation can be rewritten as:

$$MR=\frac{M_t-M_{eq}}{M_0-M_{eq}}=1-\frac{2}{\sqrt{\pi}}X+BX^2 \tag{11}$$

where MR is moisture ratio. M_t, M_0 and M_{eq} are average moisture contents at any given soaking duration, initial moisture content and moisture content at the equilibrium respectively. Equation (11) can be arranged by Equation (12) and Equation (13) as:

$$1-MR=\left(2/\sqrt{\pi}\right)X-BX^2 \tag{12}$$

where,

$$X=\left(s/v\right)\sqrt{Dt} \tag{13}$$

in which (s/v) is surface to volume ratio, D moisture diffusivity and t diffusion time. B is a parameter dependent of solid shape. Combining Equations (11)-(13), we get

$$M_t-M_0=\alpha\sqrt{t}-\mu t \tag{14}$$

where,

$$\alpha=\left(2/\sqrt{\pi}\right)\left(M_{eq}-M_0\right)\left(s/v\right)\sqrt{D} \tag{15}$$

and

$$\mu=B\left(M_{eq}-M_0\right)\left(s/v\right)^2 D \tag{16}$$

from Equation (15),

$$D=\left[\alpha\sqrt{\pi}/\left\{2\left(M_{eq}-M_0\right)\left(s/v\right)\right\}\right]^2 \tag{17}$$

In Equation (17), M_{eq} and M_0 are constants for a particular PKS sample and the ratio of volume-to-surface area (v/s) may be taken as constant irrespective of moisture content [7]. A plot of $\left(M_t-M_0\right)$ with $\sqrt{t}$ would give a polynomial curve of coefficients (α) and (μ), Equation (14). Moisture diffusivity, D, can be determined at ambient temperature using (α) values in Equation (17). The value of moisture content M_{eq} can be estimated by the method provided by [7] from absorption data. Since the quantities s/v, $\sqrt{D}$, M_{eq} and M_0 do not vary for a particular sample of PKS in Equation (17), Equation (14) can be then rewritten as:

$$M_t - M_0 = (\beta - \omega)(M_{eq} - M_0) \tag{18}$$

where,

$$\beta = \left(2/\sqrt{\pi}\right)(s/v)\sqrt{Dt}\ ;\ \ \omega = B(s/v)^2(Dt) \tag{19}$$

In Equation (18) we can easily see that if the diffusion time t is kept constant, then the quantity $(M_t - M_0)$ would be a linear function of M_0 with a slope of $(\beta - \omega)$ with $\omega > \beta$. On extending the plot to abscissa axis when $(M_t - M_0)$ = 0, the intercept can be designated as moisture content M_{eq}.

4. Results and Discussions

4.1. Water Absorbed

After evaluating the percentage of water gain by PKS aggregate for the different sizes using Equation (1), the summary of the results for the various samples is illustrated in **Table 1**.

We note that the percentage of water absorption of PKS aggregate of the two regions is approximately the same. **Table 2** represents some materials with the comparison of their water absorbed percentage. It is observed that PKS water absorption is close to coconut *nucifera* absorption.

Table 1. Percentage of water absorbed of PKS.

Water Absorption (d.b) (%)		
Sample of size 12.5 ≤ S < 16 (mm)		
Sample N°	BAFANG	TOMBEL
1	20.76	18.27
2	20.03	18.94
3	20.57	19.27
4	20.31	19.39
5	20.59	19.93
Average	**20.45**	**19.16**
S D	**0.28**	**0.61**
Sample of size S ≥ 16 (mm)		
1	16.16	17.60
2	15.39	17.97
3	16.49	17.49
4	15.68	17.99
5	15.97	18.97
Average	**15.94**	**18.00**
S D	**0.42**	**0.58**
PKS final absorption	**18.20**	**18.58**

Table 2. Comparison of water absorbed of some kernels.

	Types of materials	Water absorbed (%)	Soaking duration	T (˚C)	Ref
	Coconut *nucifera*	Speci 1: 17.32 Speci 2: 20.42	35 Days	23	[8]
Maize varieties	Abotem	59.16	3.5 h to 8 h	(30 - 60)	[12]
	Omankwa	57.67			
	Dorke	61.11			
	Akposoe	64.83			
	Abeleehi	59.38			
	Abrohemaa	60.04			
	Palm kernel shell	TO Speci: 18.58 BA Speci: 18.20	28 Days	23	Case study

4.2. Kinetic of Moisture Diffusion

Figure 2 presents the curves of experimental points of the variation of moisture gain $(M_t - M_0)$ according to the root square of time of PKS for different sizes. The experimental study of the phenomenon of water diffusion in PKS aggregate has two phases, namely a rapid (initial) absorption phase and a slow (final) absorption phase. This last phase has a low absorption rate of about 7% to 9% of the total absorption compared to the first phase, which is in a range of 91% to 93% of the total absorption of the samples, which express the approach of saturation. For this, the application of Equation (14) will be done over a period of 150 minutes.

Bafang PKS has slow rate for bigger particles compared to others and also has low absorption compared to Tombel PKS. This could be because of the microstructure of Bafang PKS with poor porosity and weak void index according to their geography zone of production.

4.3. Evaluation of Moisture Content Surface M_{eq}

The surface moisture content (M_{eq}) was evaluated to determine the moisture diffusivity using Equation (16). The experimental data of moisture gain in PKS for a soaking time of 150 min were plotted against diverse initial moisture contents of PKS ranging from 0.045 to 0.07 g/g (db) for Tombel and 0.098 to 0.139 g/g (db) for Bafang at ambient water soaking temperatures as shown in Figure 3.

For Tombel PKS, M_{eq} was 0.092 g/g and 0.082 g/g at ambient temperature and For Bafang PKS, M_{eq} was 0.18 g/g and 0.143 g/g respectively for the two different sizes. Coefficients of soaking curves were determined from Figure 2, surface moisture content from Figure 3 and they are reported in Table 3.

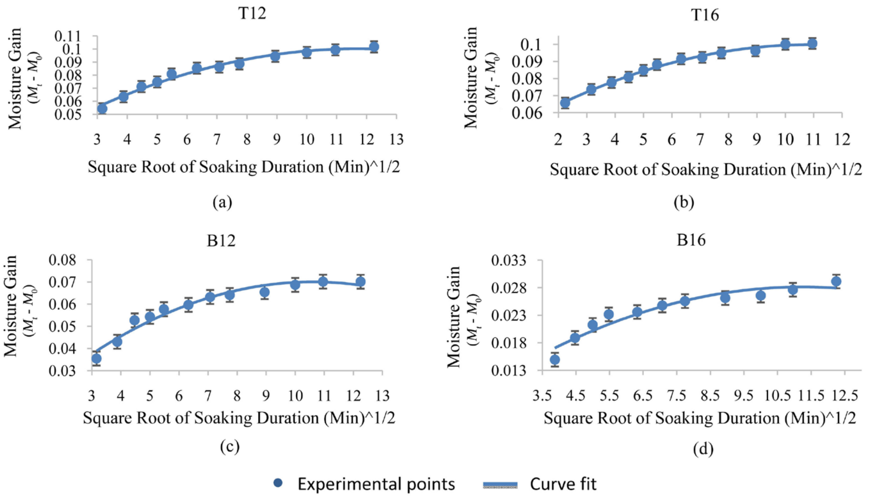

Figure 2. Relation between the moisture gain and square root of the soaking time. (a) Tombel PKS of size 12.5 ≤ S < 16 (mm); (b) Tombel PKS of size S ≥ 16 (mm); (c) Bafang PKS of size 12.5 ≤ S < 16 (mm); (d) Bafang PKS of size S ≥ 16 (mm).

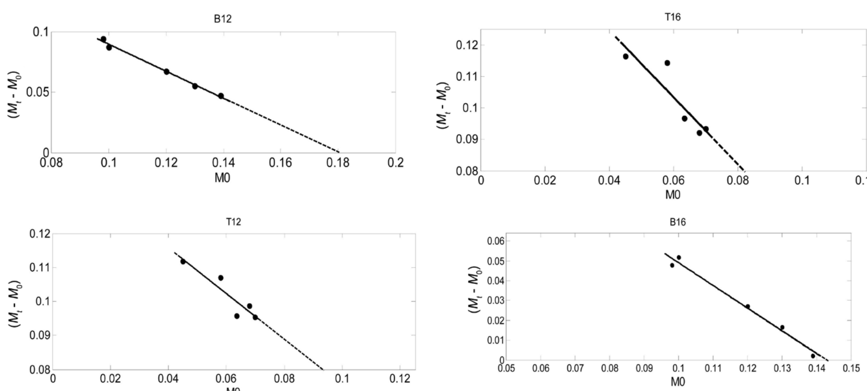

Figure 3. Extrapolation of $(M_t - M_0)$ as a function of M_0 to obtain the surface moisture content.

Table 3. Surface moisture content, coefficients of soaking curves of PKS and pertinent statistics parameters.

	PKS Bafang						PKS Tombel					
Size	N°	M_{eq} (g/g)	(a) (×10^{-2})	(μ) (×10^{-3})	R^2	*RMSE*	N°	M_{eq} (g/g)	(a) (×10^{-2})	(μ) (×10^{-3})	R^2	*RMSE*
12.5 To <16	1						1					
	2						2					
	3	0.18	1.191	0.562	0.969	0.0024	3	0.092	1.387	0.5951	0.983	0.0022
	4						4					
	5						5					
S ≥ 16	1						1					
	2						2					
	3	0.143	0.4627	0.2068	0.930	0.0013	3	0.082	1.051	0.4584	0.984	0.0015
	4						4					
	5						5					
	Average	**0.1615**	**0.8268**	**0.3844**	**0.955**	**0.0018**	**Average**	**0.087**	**1.219**	**0.5267**	**0.9835**	**0.0018**

4.4. Sphericity of Palm Kernel Shell Aggregate

Sphericity of PKS aggregate was computed from [7] equation. Average sphericity for 150 broken palm kernels shells has been found to be 0.477 (47.7%). Sphericity of non-broken Palm kernel shells of 70% has also been reported by [9], 80% by [10] and 78% by Mijinyawa and Omokhoje in 2005 in the determination of some physical properties of palm kernel, presented in the Proceedings of the Nigerian Institution of Agricultural Engineering.

4.5. Moisture Diffusivity

To determine the different moisture diffusivity, we used Becker's Model [7] expressed by Equations (10)-(17). Experimental absorption data recorded allow us to determine moisture contents at any given soaking duration and moisture content at the equilibrium respectively to be plotted. Results are reported in **Table 4**.

By looking at the different values presented in **Table 5**, it is observed that, moisture diffusivity in the case study approach Okra fibre and rice grain. The little difference between diffusivity coefficients of PKS for the two regions is due to their initial moisture content.

5. Conclusions

Palm kernel shell aggregate of Cameroon dried in oven to obtain initial moisture content within the interval of [6.18%; 11.74%] was studied with an objective to assess the effective coefficient of diffusion through the phenomenon of water absorption by the shells. Samples were immersed in the distilled water at the ambient temperature of 23˚C and total moisture equilibrium balance of samples is reached after a period of approximately 28 days in water. The rate of water

Table 4. Moisture diffusivity of palm kernel shell.

	PKS Bafang		PKS Tombel	
Size	N˚	D eff (cm^2/s) *Average value*	N˚	D eff (cm^2/s) *Average value*
12.5 To <16	1		1	
	2		2	
	3	8.76×10^{-5}	3	4.94×10^{-4}
	4		4	
	5		5	
S ≥ 16	1		1	
	2		2	
	3	7.04×10^{-5}	3	5.45×10^{-4}
	4		4	
	5		5	
	Average	**7.90×10^{-5}**	**Average**	**5.19×10^{-4}**

Table 5. Comparison of the effective coefficients of diffusion during absorption at constant temperature (23˚C).

Materials	Temp (23˚C)	D_{eff} (m^2/s) Initial phase	Final phase	Ref
Coconut shell Specie 1		$1.10 \pm 0.23 \times 10^{-10}$	$1.90 \pm 0.35 \times 10^{-12}$	[8]
Coconut shell Specie 2		$1.04 \pm 0.21 \times 10^{-10}$	$2.08 \pm 0.31 \times 10^{-12}$	
Afra wood		1.38×10^{-3}		[8]
Ojamlesh wood		3.71×10^{-4}		[11]
Roosi wood		4.88×10^{-4}		[12]
Date pits		9.98×10^{-12}		[12] [13]
Rice grain		7×10^{-10}		[8]
Pasta		5.69×10^{-11}	4.20×10^{-11}	[12]
Raphia vinifera fibre		(7.12×10^{-11} - 2.36×10^{-10})	(2.87×10^{-14} - 6.73×10^{-14})	[14]
Okra fibre		5.40×10^{-10}		[8]-[15]
Betel nut fibre		2.80×10^{-10}		[16]
Jute fiber		2.33×10^{-12}	2.30×10^{-13}	
flax fiber		2.11×10^{-12}	2.11×10^{-13}	[8]-[15]
fiber of sisal		4.00×10^{-12}	4.38×10^{-13}	
PKS Tombel		5.19×10^{-8}		Present work
PKS Bafang		7.90×10^{-9}		

absorption percentage is found to be 18.20% and 18.58% respectively for Bafang and Tombel PKS aggregate. Experimental moisture gain following Becker's equation with the square root of soaking time of 150 min has been plotted. Moisture diffusivity of 5.19×10^{-8} and 7.90×10^{-9} m^2/s was respectively determined for Tombel and Bafang PKS.

The knowledge of moisture diffusion phenomenon through PKS allows mastering the behaviour of composite in their elaboration process, above all total liquid soil that can influence cohesion energies within composite material.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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