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# Model for the calculation of the quantity of water evaporated during drying of olokoro clay

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**Abstract**

Model for the calculation of the quantity of water evaporated during drying of Olokoro clay has been derived. The model; $E = e^{(\ln t - 2.9206)}$ shows that the quantity of evaporated water during the drying process is dependent on the drying time, the evaporating surface being constant. The validity of the model is rooted in the expression $(\text{Log}\beta + \ln E)^N = \ln t$, since both sides of the expression are correspondingly almost equal. The respective deviation of the model-predicted quantity of evaporated water from the corresponding experimental value is less than 21% which is quite within the acceptable deviation range of experimental results, hence depicting the usefulness of the model. Evaporation rates evaluated from experimental and model-predicted results are $0.0575 gmin^{-1}$ and $0.0539 gmin^{-1}$ respectively, indicating proximate agreement.
*Keywords: Model, Water Evaporation, Drying, Clay.*

## 1. Introduction

Report from studies (Barsoum,1997a) carried out have shown that the contents of the basic clay materials are divided into three groups. The first group involves clays containing mainly the mineral kaolinite. The second groups are clays containing mineral rnontmorillorite, while the third group is clays which are intermediate product of disintegration of mica into kaolin. Unal (1986) reported that the structure of sinters and pellets may be divided into two parts viz, the mineral and the pores. It was stated that the properties of pellets and sinters are closely related to the mineral constituents.

Furnass (1928) reported that voids volume in packed dispersed powder depend on the ratio of smallest size (Ss) to largest size (Ls) particle as well as the percentage of constituent monosized particles. It was concluded that the smaller the (Ss/Ls) ratio, the more continuous the distribution and the lower the void volume of the system. Singer and Singer (1963) found that on heating dried clays, water is given off. With time, a hard but porous piece forms. A swollen appearance might occur during the release of some gases, but overall shrinkage must occur when verifications set in leading to a strong dense piece.

Nwoye (2003a) reported that chemical composition of the pellet, pelletisation parameters and firing conditions affect the shrinkage of clay pellets. He posited that the rate of chemical reaction is very much dependent on the gas-solid contact area, which is mostly governed by the porosity of the pellet. It was stated that shrinkage of clay is probably due to volume change resulting from evacuation of water from the voids, reduction of the size of the pores as well as decrease in the inter-particle separation.

It has been reported (Viewey and Larrly, 1978) that fine particles shrink more, are denser and exhibit excellent mechanical properties. Studies (Viewey and Larrly, 1978) carried out to investigate the relationship between particle size and size distribution with linear drying shrinkage, firing shrinkage and apparent porosity shows that no visible relationship exists between particle size and linear drying shrinkage. In this work (Viewey and Larrly, 1978) finer particles were found tend to shrink more. It was concluded that the finer the particle size, the lesser the apparent porosity and greater the bulk density.

The behaviour of ceramic products has been found (Arisa,2007) to be very dependent on their composition, grain size, grain distribution, structure of grain and pores. Nwoye (2003b) also posited that the grain size and grain distribution of the clays have significant effect on their physical and technological properties (binding ability, shrinkage and plasticity).

It has been reported (Barsoum,1997b) that pores are deleterious to the strength of ceramics not only because they reduce cross-sectioned area over which the load is applied but more importantly act as stress concentrators.

Pore deformation mechanism in shrinking Nigeria clays, was studied (Nwoye,2009) over a range of heating temperature from 1000 to $1300^0$C. The results of the study indicate that pores pre-existing before sintering deformed by the collapsing of the wall surrounding the pores. It was discovered (Nwoye,2009) that the wall surrounding the pre-existing pores collapsed as a result of the weakening of the clay-binder contact surface and loosening of the macro structure of the formed clays, occasioned by the response of the clay and binder to temperature increase. It was also found (Nwoye,2009) that binder burn-out which releases gases, elimination of gaseous product of decomposition and oxidation of some clay constituents as well as evaporation of free water between clay and binder particles, all played very vital roles in decreasing the pre-existing interparticle separation hence deforming the pores.

Nwoye (2008) studied the effect of porosity on the shrinkage behavior of clay pellets and briquettes of different porosities. The result of the investigation indicates that shrinkage which is a major cause of rupture in fired clay increased with decrease in porosity. It was also discovered (Nwoye,2008) that the porosity of pellet/briquette plays important role in controlling and determining the shrinkage index of the pellet.

Reed (1988) described firing as having three stages through which it proceeds; preliminary reactions which include binder burnout, elimination of gaseous product of decomposition and oxidation, sintering as well as cooling which may include thermal and chemical annealing.

Several works (Barsoum,1997a; Viewey and Larrly, 1978; Reed, 1988; Keey,1978) have been carried out on shrinkage of clay during drying. In all these works, porosity has been shown to influence the swelling and shrinkage behaviour of clay products of different geometry. It has been reported (Reed, 1988) that drying occurs in three stages; increasing rate, constant and decreasing rate. He pointed out that during the increasing rate; evaporation rate is higher than evaporating surface hence more water is lost. At constant rate, the evaporation rate and evaporation surface are constant. He posited that shrinkage occurs at this stage. Keey (1978) also in a similar study suggested that at this stage, free water is removed between the particles and the interparticle separation decreases, resulting in shrinkage. During the decreasing rate, particles make contacts as water is removed, which causes shrinkage to cease.

Model for calculating the volume shrinkage resulting from the initial air-drying of wet clay has been derived (Nwoye,2008). The model;

$$\theta = \gamma^3 - 3\gamma^2 + 3\gamma \qquad (1)$$

calculates the volume shrinkage $\theta$ when the value of dried shrinkage $\gamma$, experienced during air-drying of wet clays is known. The model was found to be third-order polynomial in nature. Olokoro clay was found to have the highest shrinkage during the air drying condition, followed by Ukpor clay while Otamiri clay has the lowest shrinkage. Volume shrinkage was discovered to increase with increase in dried shrinkage until maximum volume shrinkage was reached, hence a direct relationship.

Nwoye et al. (2008) derived a model for the evaluation of overall volume shrinkage in molded clay products (from initial air-drying stage to completion of firing at a temperature of $1200^0$C). It was observed that the overall volume shrinkage values predicted by the model were in agreement with those calculated using conventional equations. The model;

$$S_T = \alpha^3+\gamma^3-3(\alpha^2+\gamma^2)+3(\alpha+\gamma) \qquad (2)$$

depends on direct values of the dried $\gamma$ and fired shrinkage $\alpha$ for its precision. Overall volume shrinkage was found to increase with increase in dried and fired shrinkages until overall volume shrinkage reaches maximum.

Nwoye (2009) derived a model for calculating the quantity of water lost by evaporation during oven drying of clay at $90^0$C. The model;

$$\gamma = \exp[(\ln t)^{1.0638} - 2.9206] \qquad (3)$$

indicated that the quantity of evaporated water, $\gamma$ during the drying process is dependent on the drying time t, the evaporating surface being constant. The validity of the model was found to be rooted in the expression $(\text{Log}\beta + \ln\gamma)^N = \ln t$.

Model for predictive analysis of the quantity of water evaporated during the primary-stage processing of a bioceramic material sourced from kaolin was derived by Nwoye et al. (2009a).

The model;

$$\alpha = e^{(\ln t/2.1992)} \qquad (4)$$

shows that the quantity of water $\alpha$, evaporated at $110^0$C, during the drying process is also dependent on the drying time t, where the evaporating surface is constant. It was found that the validity of the model is rooted on the expression $(\ln t/\ln\alpha)^N = \text{Log}\beta$ where both sides of the expression are correspondingly approximately equal to 3. The respective deviation of the model-predicted quantity of evaporated water from the corresponding experimental value was found to be less than 22% which is quite within the acceptable deviation range of experimental results.

Model for quantifying the extent and magnitude of water evaporated during time dependent drying of clay has been derived (Nwoye et al., 2009b). The model;

$$\gamma = \exp((\ln t/2.9206)^{1.4}) \qquad (5)$$

indicates that the quantity of evaporated water $\gamma$ during the drying process (at $90^0$C) is dependent on the drying

time, t the evaporating surface being constant. It was found that the validity of the model is rooted in the expression $\ln\gamma = (\ln t/\text{Log}\beta)^N$ where both sides of the expression are correspondingly almost equal.

Nwoye et al., (2009c) derived a model for predicting the quantity of water evaporated during drying of clay at a temperature range 80-110$^0$C. The model;

$$E = \exp[0.3424(\text{Log}T)^{2.3529}] \quad (6)$$

indicates that the quantity of evaporated water during the drying process is dependent on the drying temperature, the evaporating surface being constant. The validity of the model is rooted in the expression $(\ln E \times \text{Log}\ \beta)^N = \text{Log}\ T$ since both sides of the expression are correspondingly approximately equal to 2. The respective deviation of the model-predicted quantity of evaporated water from the corresponding experimental value is less than 20% which is quite within the acceptable deviation range of experimental results, hence depicting the usefulness of the model. Water evaporation per unit rise in the drying temperature evaluated from experimental and model-predicted results are 0.078 and 0.0502g/$^0$C respectively, indicating proximate agreement.

Model for predicting the quantity of water evaporated during the primary-stage processing of a bioceramic material sourced from kaolin has been derived (Nwoye et al.,2010). The model;

$$E = \text{Exp}[0.3424(\text{Log}T)^{2.439}] \quad (7)$$

| *lnt* | *Logβ* | *lnE* | *(Logβ + lnE)$^N$* |
|---|---|---|---|
| 3.4012 | 2.9206 | 0.4700 | 3.3906 |
| 3.9120 | 2.9206 | 1.0296 | 3.9502 |
| 4.2485 | 2.9206 | 1.2528 | 4.1734 |
| 4.4998 | 2.9206 | 1.6487 | 4.5693 |
| 4.7005 | 2.9206 | 1.8245 | 4.7451 |
| 4.8675 | 2.9206 | 2.1748 | 5.0954 |

shows that the quantity of evaporated water during the drying process is dependent on the drying temperature, the evaporating surface being constant. It was found that the validity of the model is rooted on the expression $(\text{Log}\beta \times \ln E)^N = \text{Log}T$ where both sides of the expression are correspondingly approximately equal to 2. The respective deviation of the model-predicted quantity of evaporated water from the corresponding experimental value was found to be less than 19% which is quite within the acceptable deviation range of experimental results, hence depicting the usefulness of the model.

The present work is to derive a model for the calculation of the quantity of water evaporated during drying of Olokoro (Nigeria) clay at 80$^0$C.

## 2. Experimentation and method

Olokoro clay was prepared, moulded and dried at a temperature of 80$^0$C through a drying time range; 30-130mins. The raw material used was Olokoro clay mined from south-eastern part of Nigeria. The clay sample was crushed to particle size of 425μm and homogenized separately; mixing thoroughly with 10g bentonite (binder) and 6% water (of total weight). A mould of surface area 833mm$^2$ was used to make a rectangular shape of the clay. The moulded clay was then dried in an electric oven to enhance loss of water through evaporation (Nwoye, 2007).

## 2. Model formulation

Model formulation was achieved using experimental data derived in previous work (Nwoye, 2007) as shown in Table 1.Computational analysis of these data (Nwoye,2007), gave rise to Table 2 which indicate that;

$$(\text{Log}\ \beta + \ln\gamma)^N = \ln t \quad \text{(approximately)} \quad (8)$$

Introducing the value of N into equation (8) and evaluating further

$$\text{Log}\ \beta + \ln E = \ln t \quad (9)$$

$$\ln E = \ln t - \text{Log}\ \beta \quad (10)$$

$$E = e^{(\ln t - \text{Log}\ \beta)} \quad (11)$$

Introducing the value of β into equation (11) reduces it to;

$$E = e^{(\ln t - 2.9206)} \quad (12)$$

Where

E = Weight of water lost by evaporation during the drying process (g)
(β) = Area of evaporating surface (mm$^2$)
N = 1.0; (Collapsibility coefficient of binder-clay particle boundary at the drying temperature of 80$^0$C) determined in the experiment (Nwoye,2007).
t = Drying time (mins.).

Table 1: Variation of quantity of evaporated water with drying time

| *(t)* | *(β)* | *E* |
|---|---|---|
| 30 | 833 | 1.60 |
| 50 | 833 | 2.80 |
| 70 | 833 | 3.50 |
| 90 | 833 | 5.20 |
| 110 | 833 | 6.20 |
| 130 | 833 | 8.80 |

Source:- (Nwoye,2007)

Table 2: Variation of lnt with $(\text{Log}\beta + \ln E)^N$

## 3. Boundary and Initial Conditions

A rectangular shaped clay product of length 49mm, width 17mm, and breadth 9mm exposed to drying in the furnace while it was in wet condition was considered. Initially, atmospheric levels of oxygen are assumed.

Atmospheric pressure were assumed to be acting on the clay samples during the drying process (since the furnace was not air-tight). The grain size of clay particles used was 425μm, weight of clay and binder (bentonite) used (for each rectangular product); 100g and 10g respectively, quantity of water used for mixing; 6% (of total weight), drying temperature used; $80^0$C, area of evaporating surface;833mm$^2$ and range of drying time used; (30-130 mins.).

The boundary conditions were: atmospheric levels of oxygen at the top and bottom of the clay samples since they were dried under the atmospheric condition. No external force due to compression or tension was applied to the drying clays. The sides of the particles and the rectangular shaped clay products were taken to be symmetries.

## 4. Model Validation

The formulated model was validated by direct analysis and comparison of the model-predicted E values and those from the experiment for equality or near equality.

Analysis and comparison between these E values revealed deviations of model-predicted E from those of the experimental values. This was believed to be due to the fact that the surface properties of the clay and the physiochemical interactions between the clay and binder, which were found to have played vital role during the evaporation process were not considered during the model formulation. This necessitated the introduction of correction factor, to bring the model-predicted E value to that of the corresponding experimental value.

Deviation (Dv) (%) of model-predicted E values from the experimental E values is given by

$$Dv = \left(\frac{Pw - Ew}{Ew}\right) \times 100 \qquad (13)$$

Where

Pw = Quantity of water evaporated as predicted by model (g)

Ew = Quantity of water evaporated as obtained from experiment (g) (Nwoye,2007)

Correction factor (Cf) is the negative of the deviation i.e

$$Cf = -Dv \qquad (14)$$

Introduction of the value of Cf from equation (8) into the model gives exactly the corresponding experimental value of E (Nwoye,2007).

## 5. Results and Discussion

The quantities of water evaporated during this drying period are as presented in Table 1.

The derived model is equation (12). Comparison of Figs. 1, 2 and 4 indicate that values of E obtained. This suggests that the model predicts more accurate, reliable and from the experiment and those from the model show minimum deviations, hence depicting the reliability and validity of the model. The respective deviation of the model-predicted quantity of evaporated water from the corresponding experimental value is less than 21% which is quite within the acceptable deviation range of experimental results, hence depicting the usefulness of the model. It was found that the validity of the model is rooted in the expression $(Log\beta + lnE)^N = lnt$ where both sides of the equation are correspondingly almost equal. Table 2 also agrees with equation (8) following the values of $(Log\beta + lnE)^N$ and lnt evaluated from Table 1 as a result of corresponding computational analysis. Therefore

$$Cf = -100\left(\frac{Pw - Ew}{Ew}\right) \qquad (15)$$

An ideal comparison of the quantity of water evaporated as obtained from experiment and as predicted by the model for the purpose of testing the validity of the model is achieved by considering the $R^2$ values. The values of the correlation coefficient, R calculated from the equation;

$$R = \sqrt{R^2} \qquad (16)$$

using the r-squared values (coefficient of determination) from Figs.1 and 2 show a better correlation (1.0000) with model-predicted quantity of water evaporated than that obtained from experiment (0.9649).

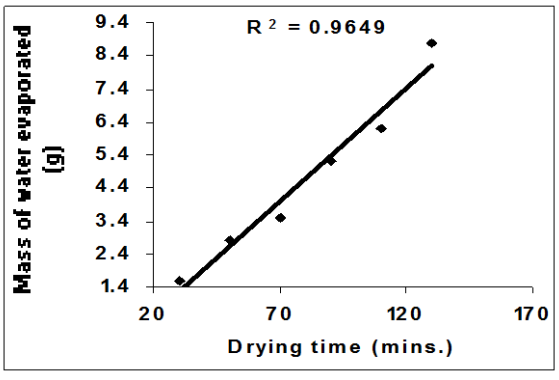


Fig. 1: Variation of mass of water evaporated with drying time (as obtained from experiment (Nwoye,2007)

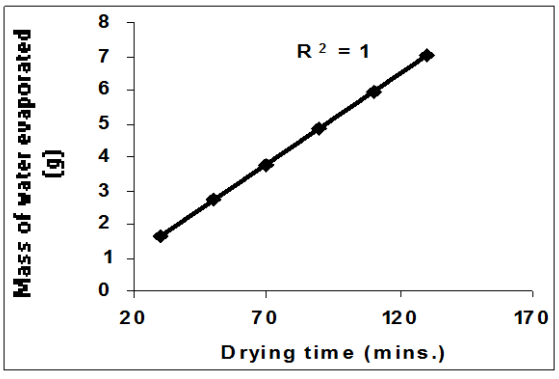


Fig. 2: Variation of mass of water evaporated with drying time (as predicted by model)

This suggests that the model predicts more accurate, reliable and ideal quantity of evaporated water than the

actual experiment despite its deviations from the experimental values. Fig. 3 involving a plot of lnE against lnt was culled from equation (11) which directly forms the model. Here the correlation was also found to be better than that obtained from experimental results. This also indicates the validity of the model.

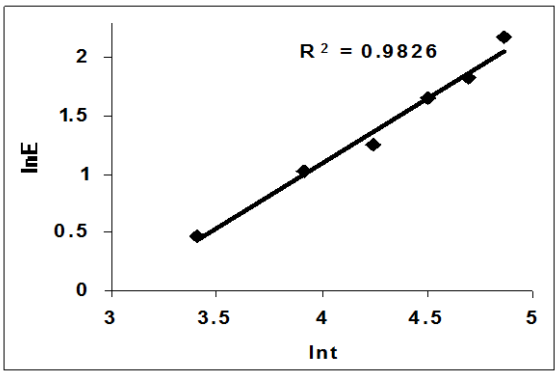


Fig. 3: Variation of lnE with lnt

Based on the foregoing, the model is believed to be very valid as a predictive tool. The positive and negative deviations (of the model-predicted quantity of water evaporated) from actual experimental values show undulating relationship (as in Fig. 4) with the mass of water evaporated.

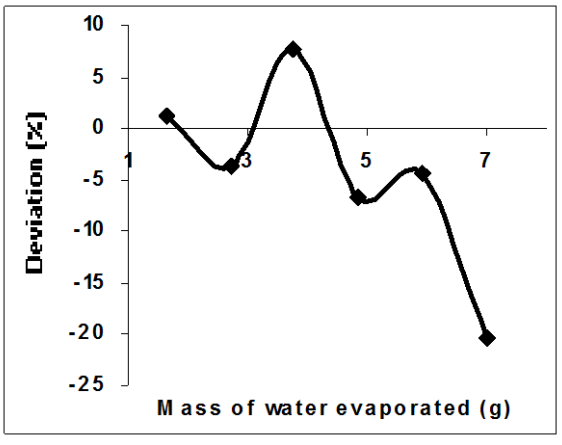


Fig. 4 Variation of model-predicted mass of evaporated water with its associated deviation

This curve indicates that the highest and least deviations are -20.34 and 7.71% respectively recorded against 7.01 and 3.77g of water evaporated respectively. Correction factor for the model-predicted quantity of water evaporated (shown in Fig. 5) also shows an indulating relationship with mass of water evaporated. However, comparison of Figs. 4 and 5 shows that the orientation of the curve of the correction factor against mass of water evaporated is opposite that of the deviation against mass of water evaporated.

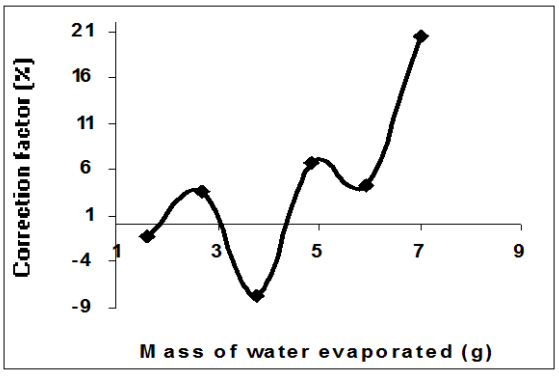


Fig. 5 Variation of model-predicted mass of evaporated water with its associated correction factor

This is attributed to the fact that correction factor is the negative of the deviation as shown in eqns. (14) and (15). It is believed that the correction factor takes care of the effects of the surface properties of the clay and the physiochemical interaction between the clay and the binder which (affected experimental results) were not considered during the model formulation.

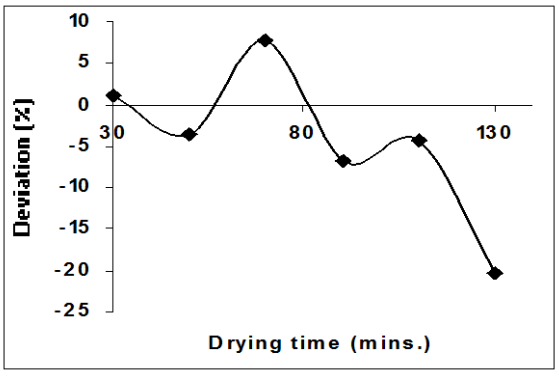


Fig. 6 Variation of deviation (of model-predicted mass evaporated water) with drying time

Fig.6 shows that the relationship between deviation of model-predicted quantity of water evaporated and the drying time is also undulating, indicating same orientation as in Fig.4. Comparison of Figs. 4 and 6 indicates that this relationship is due to the fact that the same values for the least and highest deviations obtained in Fig. 4 are also tenable in Fig.6 for drying times 70 and 130 mins. respectively.

The water evaporation rate resulting from drying of Olokoro clay at $80^0$C was determined following comparison of the evaporation rates obtained by calculations involving experimental results, and model-predicted results obtained directly from the model.

Evaporation rate, Er ($gmin^{-1}$) is calculated from the equation;

$$Er = E/t \qquad (17)$$

Therefore, a plot of mass of water evaporated E against drying time, t (as in Fig. 1) using experimental results gives a slope, S at points (30,1.6) and (110, 6.2) following their substitution into the mathematical expression;

$$S = \Delta E/\Delta t \qquad (18)$$

Eqn. (18) is detailed as

$$S = E_2 - E_1/ t_2 - t_1 \qquad (19)$$

Where

$\Delta E$ = Change in the quantities of water evaporated $E_2$, $E_1$ at two drying time values $t_2$, $t_1$. Considering the points (30, 1.6) and (110, 6.2) for ($E_1$, $t_1$) and ($E_2$, $t_2$) respectively, and substituting them into eqn. (19), gives the slope as $0.0575 gmin^{-1}$ which is the evaporation rate during experimental drying of the clay. Also similar plot (as in Fig. 2) using model-predicted results gives a slope. Considering points (30, 1.62) and (110, 5.93) for ($E_1$, $t_1$) and ($E_2$, $t_2$) respectively and substituting them into eqn. (19) gives the value of slope, S as $0.0539 gmin^{-1}$. This is the evaporation rate predicted by the model during the drying of the clay. A comparison of these two values of water evaporation rates shows proximate agreement. This indicates a very high degree of validity for the model as a reliable tool for predicting the quantity of water evaporated as well as the evaporation rate during drying of Olokoro clay at $80^0$C.

## 6. Conclusion

The model calculates the quantity of water lost by evaporation during drying of Olokoro (Nigeria) clay at $80^0$C. It was found that the validity of the model is rooted in the expression $(\text{Log } \beta + \ln\gamma)^N = \ln t$ where both sides of the expression are correspondingly almost equal. The respective deviation of the model-predicted quantity of evaporated water from the corresponding experimental value is less than 21% which is quite within the acceptable deviation range of experimental results. Evaporation rates evaluated from experimental and model-predicted results are 0,0575 and $0.0539 gmin^{-1}$ respectively, indicating proximate agreement.

Further works should incorporate more process parameters into the model with the aim of reducing the deviations of the model-predicted E values from those of the experimental.

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