Model for Predictive Analysis of the Shrinkage Sustained in Fired Clay Materials Relative to the Resultant Fired Bulk Density

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Abstract: Model for predictive analysis of the shrinkage sustained in fired clay materials relative to its fired bulk density has been derived. These materials were prepared using different grain sizes; <100µm, 100-300µm, 300-1000 µm and their respective mixtures. The derived model;

$$S = \left[\exp(e^{\gamma}) \right]^{0.9615}$$

was found to be dependent on the resultant bulk density of the clay body following firing at a temperature of 1200^{0}C. The validity of the model is rooted on the expression; $\ln[(S)^{1.04}] = e^{\gamma}$ where both sides of the expression are correspondingly approximately equal to 3. The maximum deviation of the model-predicted shrinkage from the corresponding experimental values is 12% which is within the acceptable range of deviation limit for experimental results. [Researcher. 2009:1(5):85-88]. (ISSN: 1553-9865).

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1. Introduction

Firing of clay has been found to proceed in three stages; 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 (Reed,1988). Barsoum (1997), Viewey and Larrly(1978) and Keey (1978) studied the shrinkage of clay during drying. In all these works, porosity was shown to influence the swelling and shrinkage behaviour of clay products of different geometry. Reed (1988) posited 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. The researcher posited that shrinkage occurs at this stage. In a similar study, Keey (1978) suggested that at this stage, free water is removed between the particles and the inter-particle separation decreases, resulting in shrinkage. During the decreasing rate, particles make contacts as water is removed, which causes shrinkage to cease.

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

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

calculates the volume shrinkage when the value of dried shrinkage γ, 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.

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) has been derived by Nwoye et al. (2008). It was observed that the overall volume shrinkage values predicted by the model were in agreement with those calculated using conventional equations. The model;

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

depends on direct values of the dried γ and fired shrinkage α 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;

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

indicated that the quantity of evaporated water, γ 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 has been derived by Nwoye et al (2009a) .The model;

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

indicates that the quantity of water α, evaporated at 110^0C, 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;

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

indicates that the quantity of evaporated water γ during the drying process (at 90^0C) 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.

The present work is to derive a model for predictive analysis of the shrinkage sustained in fired clay materials (made from Otamiri clay) relative to the resultant fired bulk density.

2. Model Formulation

Results of the experiment previously carried out (Nwoye,2006) were used for the model derivation. These results as shown in Table 1 indicate that;

$$\ln\left(S^N\right) = e^{\gamma} \quad \text{(approximately)} \quad (6)$$

Introducing the value of N in to equation (6) and taking exponential of both sides reduced it to;

$$S^{1.04} = \left(\exp(e^{\gamma})\right) \quad (7)$$

Dividing the indices of both sides of equation (7) by 1.04 reduces it to;

$$S = \left(\exp(e^{\gamma})\right)^{1/1.04} \quad (8)$$

$$S = \left(\exp(e^{\gamma})\right)^{0.9615} \quad (9)$$

Where

N = 1.04; Particle packing index for Otamiri clay at 1200^0C (determined in the experiment (Nwoye,2006))

(γ) = Resultant fired bulk density of the clay material at 1200^0C (g/cm^2)

Equation (9) is the derived model

3. Boundary and Initial Conditions

Consider a rectangular shaped clay product of length 70mm, width 17mm, and breadth 9 mm exposed to drying in the furnace while it was in wet condition. Initially, atmospheric levels of oxygen are assumed. Atmospheric pressure was assumed to be acting on the clay samples during the drying process (since the furnace is not air-tight). The grain sizes for the clay materials used are, <100 μm, 100-300 μm, 300-1000 μm and their respective mixtures. Firing temperature; 1200^0C, exposure time of clay body during firing; 18hrs, range of apparent porosity and water content of the clay body following firing; 21.92-23.66% and 25.59-26.28% respectively. The boundary conditions are: atmospheric levels of oxygen at the top and bottom of the clay samples since they are 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 are taken to be symmetries.

4. Model Validation

The formulated model was validated by direct analysis and comparison of the model-predicted S values and those from the experiment (Nwoye, 2006) for equality or near equality.

Analysis and comparison between these S values reveal deviations of model-predicted S from those of the experimental values. This is 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 expected to have played vital role during the evaporation of water were not considered during the model formulation. This necessitated the introduction of correction factor, to bring the model-predicted S value to that of the corresponding experimental value.

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

$$Dv = \left(\frac{S_M - S_{exp}}{S_{exp}} \right) \times 100 \qquad (10)$$

Where

S_M = Shrinkage sustained in clay body as predicted by derived model
S_{exp}= Shrinkage sustained in clay body as obtained from experiment (Nwoye,2006)

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

$$Cf = -Dv \qquad (12)$$

Therefore

$$Cf = -100 \left(\frac{S_M - S_{exp}}{S_{exp}} \right) \qquad (13)$$

Introduction of the value of Cf from equation (13) into the model gives exactly the corresponding experimental value S_{exp}.

5. Results and discussions

The model is equation (9). It was found that the model is dependent on the resultant bulk density of the fired clay materials. The validity of the model was found to be rooted on the expression; $\ln[(S)^{1.04}] = e^{\gamma}$ where both sides of the expression are correspondingly approximately equal to 3. Table 2 also agrees with equation (6) following the values of $\ln[(S)^{1.04}]$ and e^{γ} evaluated from Table 1 as a result of corresponding computational analysis. Fig. 1 shows appreciable close alignment of the curves from model-predicted values of shrinkage (Smod) and that from the corresponding experimental values (Sexp). It is strongly believed that the degree of alignment of these curves is indicative of the proximate agreement between both experimental and model-predicted shrinkages sustained in the clay material. Table 3 shows that the maximum deviation of the model-predicted shrinkage from the corresponding experimental values is less than 12% which is within the acceptable range of deviation limit for experimental results.

Conclusion

The model predicts the shrinkage sustained in fired clay materials relative to its resultant fired bulk density. The model is dependent on the fired bulk density, which resulted from the firing of the clay material. The validity of the model is rooted on the expression; $\ln[(S)^{1.04}] = e^{\gamma}$ where both sides of the expression are correspondingly approximately equal to 3. The maximum deviation of the model-predicted shrinkage from the corresponding experimental values is less than 12% which is within the acceptable range of deviation limit for experimental results.

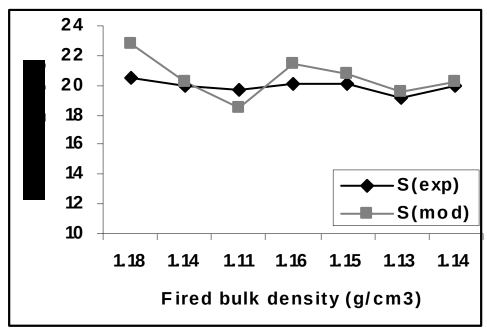

Fig.1: Comparison of the shrinkages sustained in the clay body as obtained from experiment (Nwoye, 2006) and derived model.

Table1: Variation of fired bulk density and volume shrinkage with grain size of Otamiri clay fired at 1200^{0}C. (Nwoye, 2006).

Grain size (µm)	γ	S (%)
(A) <100	1.18	20.52
(B) 100-300	1.14	19.93
(C) 300-1000	1.11	19.63
A + B	1.16	20.16
A + C	1.15	20.08
B +C	1.13	19.17

Table 2: Variation of $\ln[(S)^{1.04}]$ with e^{γ}

$S^{1.04}$	$\ln[S^{1.04}]$	e^{γ}
23.1560	3.1423	3.2544
22.4640	3.1119	3.1268
22.1125	3.0961	3.0344
22.7337	3.1238	3.1899
22.6399	3.1197	3.1582
21.5738	3.0715	3.0957
22.5109	3.1140	3.1268

Table 3: Deviations (from experimental values) of model-predicted volume shrinkage and the associated correction factors

Dv (%)	Cf (%)
+11.37	-11.37
+1.43	-1.43
-5.77	+5.77
+6.54	-6.54
+3.76	-3.76
+2.34	-2.34
+1.23	-1.23

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