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Model for Computational Analysis and Predictive Assessment of Bulk Density of Fired Bricks Based on Incurred Shrinkage *(pp. 74-82)*

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Abstract: A model has been derived for computational analysis and predictive assessment of bulk density of fired bricks based on incurred shrinkage. These clay materials were prepared using different grain sizes; <100μm, 100-300μm, 300-1000μm and their respective mixtures before firing. The values of bulk densities of fired clay were found to vary with double natural log of the shrinkage incurred during the firing process. These grain sizes of clay also vary with the magnitude of the bulk density. The established model; $\gamma = \ln(\ln[S^{1.1589}])$ indicates that the bulk density of bricks during firing was dependent on the incurred shrinkage. The validity of the model is rooted on the expression; $\mathrm{Exp}(e^{\gamma}) = S^{1.1589}$ where both sides of the expression are correspondingly almost equal. The maximum deviation of the model-predicted bulk density from the corresponding experimental values is less 7%.

Key words: Prediction, bulk density, bricks, shrinkage

1 INTRODUCTION

Studies carried out by Reed (1988) on shrinkage of clay during evaporation of water as drying is taking place indicate that at constant drying 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.

Similar work by Keey (1978) also suggested that at this stage, free water is removed between the particles, and the inter-particle separation decreases, resulting in shrinkage. The report by Keey (1978) indicates that during the decreasing rate, particles make contacts as water is removed, causing shrinkage to cease.

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

$$\theta = \gamma^3 - 3\gamma^2 + 3\gamma \tag{1}$$

indicating that the volume shrinkage is dependent on the linear dried shrinkage γ, experienced during air-drying of wet clays. The model was found to be third-order polynomial in nature. Results generated by the model confirm that Olokoro clay has 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.

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 1200^0C) was derived by Nwoye et al. (2008). Results from the derivation indicate that the overall volume shrinkage values predicted by the model are in agreement with those calculated using conventional equations. The model;

$$S_T = \alpha^3 + \gamma^3 - 3(\alpha^2 + \gamma^2) + 3(\alpha + \gamma) \tag{2}$$

shows that the overall volume shrinkage is dependent on the direct values of the dried γ and fired shrinkage α for its precision. It was discovered that overall volume shrinkage increases with increase in dried and fired shrinkages until overall volume shrinkage reaches maximum.

Several models derived (Nwoye, 2009a; Nwoye et al.,2009a and 2009b) to calculate the quantity of water evaporated during drying of wet clay, have shown that drying temperature and drying time play major roles in determining the magnitude of water removed during the drying process. This invariably determines the extent of shrinkage incurred in the clay.

The present work is to derive a model for computational analysis and predictive assessment of bulk density of fired bricks based on the shrinkage incurred in the bricks.

2 MODEL FORMULATION

Results of the experiment previously carried out were used for the model derivation (Nwoye, 2009b). These results as shown in Table 1 indicate that approximately;

$$Exp(e^\gamma) = (S)^n \tag{3}$$

$$(e^\gamma) = \ln[(S)^n] \tag{4}$$

By taking the natural logarithm of equation (4),

$$\gamma = \ln(\ln[(S)^n]) \tag{5}$$

By introducing the value of n into equation (5)

$$\gamma = \ln(\ln[(S)^{1.1589}]) \tag{6}$$

Where

n = 1.1589; Coefficient of shrinkage for Olokoro clay at 1200^0C (Nwoye, 2009b)

(γ) = Bulk density of the fired bricks (g/cm^3)

Equation (6) is the derived model

Table1: Variation of grain size with bulk density and volume shrinkage (Nwoye, 2009b)

Grain size (µm)	γ	S (%)
(A) <100	1.39	25.63
(B) 100-300	1.34	25.07
(C) 300-1000	1.32	24.82
A + B	1.32	25.35
A + C	1.31	25.24
B +C	1.32	24.96
A + B + C	1.32	25.17

3 BOUNDARY AND INITIAL CONDITIONS

A rectangular shaped brick of length 70mm, width 17mm, and breadth 9mm was firing 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, <100µm, 100-300µm, 300-1000µm and their respective mixtures. The drying temperature and drying time used are 1200^0C and 18hrs 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. These and other detailed process conditions are as stated in the experiment (Nwoye, 2009b).

4 MODEL VALIDATION

The model validation was carried out by comparing the model-predicted γ values and those from the experiment (Nwoye, 2009b) for equality or near equality. This revealed deviation between these two bulk density 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 γ value to that of the corresponding experimental value.

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

$$D_V = \left(\frac{\gamma_M - \gamma_{exp}}{\gamma_{exp}}\right) x\ 100 \qquad (7)$$

Where

γ_M = Bulk density of fired bricks as predicted by model

γ_{exp} = Bulk density of fired bricks as obtained from experiment (Nwoye,2009b)

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

$$C_f \quad = \quad -D_v \qquad (8)$$

Therefore

$$C_f = -100\left(\frac{\gamma_M - \gamma_{exp}}{\gamma_{exp}}\right) \qquad (9)$$

Introduction of the value of C_f from equation (9) into the model gives exactly the corresponding experimental value γ_{exp}.

5 RESULTS AND DISCUSSION

The model is equation (6). Computational analysis of the experimental results in Table 1 gave rise to Table 2.

The model indicates that the bulk density is dependent on the shrinkage incurred in the bricks during firing. The validity of the model was found to be rooted on the expression

$Exp\ (e^{\gamma}) = (S)^{1.1589}$ where both sides of the expression are correspondingly almost equal. Table 2 also agrees with equation (6) following comparison of the value $Exp\ (e^{\gamma})$ and $(S)^{1.1589}$ evaluated from Table 1 as a result of corresponding computational analysis.

Table 2: Variation of Exp (e^{γ}) with $(S)^{1.1589}$

(e^{γ})	$Exp\ (e^{\gamma})$	$(S)^{1.1589}$
4.0149	55.4178	42.9140
3.8190	45.5586	41.8292
3.7434	42.2414	41.3462
3.7434	42.4214	42.3711
3.7062	40.6989	42.1581
3.7434	42.2414	41.6166
3.7434	42.2414	42.0227

An ideal comparison of the bulk density 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 (coefficient of determination). The values of the correlation coefficient, R calculated from the equation;

$$R = \sqrt{R^2} \tag{10}$$

using the r-squared values (coefficient of determination) from Figs.1 and 2 show better correlations (0.9999) with model-predicted bulk density than that obtained from experiment (0.7336) (both relative to incurred shrinkage). This suggests that the model predicts more accurate, reliable and ideal bulk density than the actual experiment despite its deviations from the experimental values.

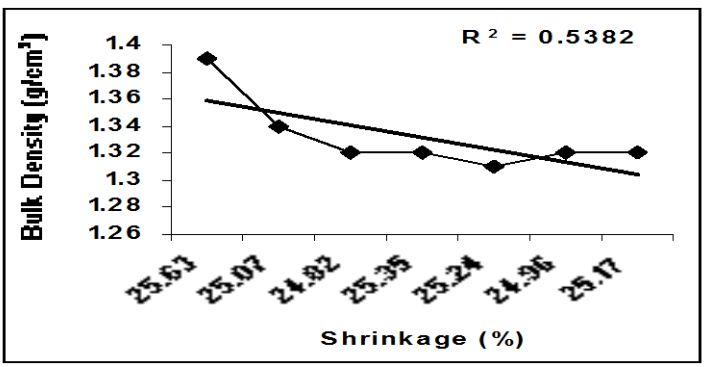

Figure 1: Effect of Shrinkage on the Bulk Density of Bricks as Obtained from Experiment (Nwoye, 2009b)

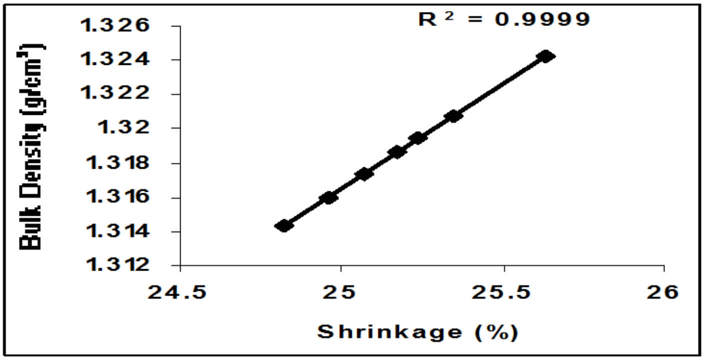

Figure 2: Effect of Shrinkage on the Bulk Density of Bricks as Predicted by Derived Model

Figure 3 shows very close alignment of the curves from model-predicted values of the bulk density ($M_O D$) and that from the corresponding experimental values ($E_X D$). The degree of alignment of these curves is indicative of the proximate agreement between both experimental and model-predicted bulk density.

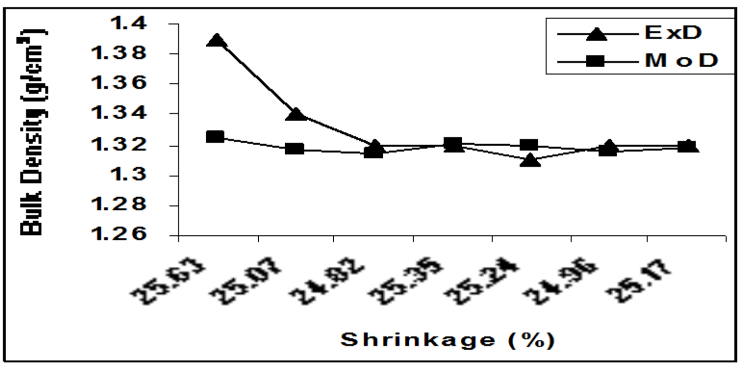

Figure 3: Comparison of the Bulk Density Resulting from Shrinkage of Bricks as Obtained from Experiment (Nwoye, 2009b) and Derived Model

It was also shown in Fig.4 that the maximum deviation of the model-predicted bulk density values from those of the experiment are less than 7% which is quite within the acceptable deviation limit of experimental results. The deviations (of the model-predicted bulk density) from the actual experimental values show a maximum value at 6.06% (Fig.4). This corresponds to a model-predicted bulk density of 1.3208 g/cm^3.

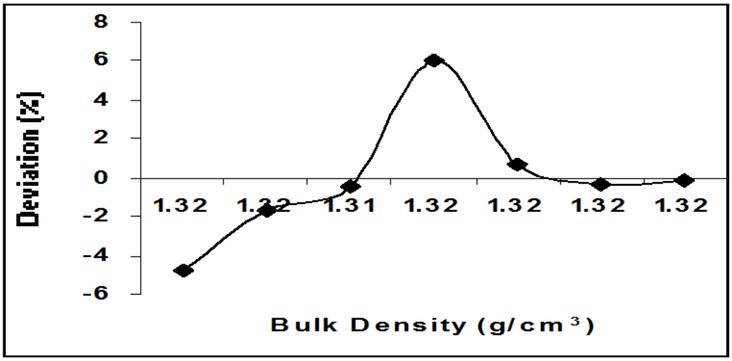

Figure 4: Variation of model-predicted bulk density with its associated deviation from experimental values (Nwoye, 2009b)

Correction factor to the model-predicted bulk density (shown in Fig.5) gives a corresponding value; -6.06% (negative) to the maximum deviation in Fig. 4. Furthermore, the orientation of this curve is opposite that of the deviation of model-predicted bulk density in Fig.4. This is because correction factor is the negative of the deviation as shown in eqns. (8) and (9). 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.

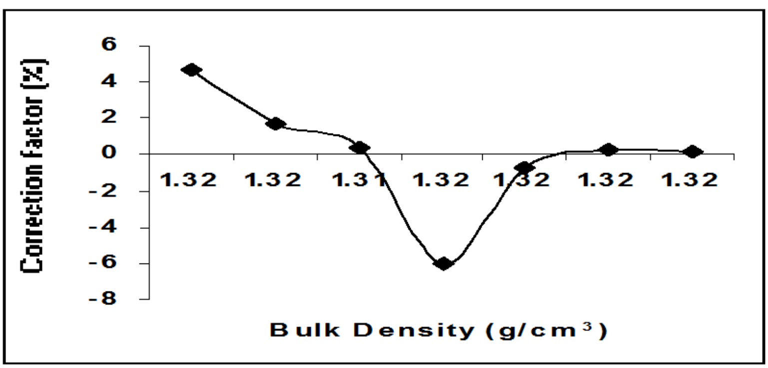

Figure 5: Variation of model-predicted bulk density with its associated correction factor

The model can be useful to engineers for carrying out failure or survival analysis of bricks used for building construction relative to change in the porosity of the bricks as a result of shrinkage sustained during service. This is because there is likelihood of swelling of the bricks when water absorbed by the material becomes excessive. It is strongly believed that excessive water absorption in clay materials can only occur when there is increased porosity in the material. Furthermore, increased porosity results from decreased bulk density of the material. Swelling which is the outcome of excessive water absorption in clay materials has been found (Nwoye,2010) to weaken the grain boundaries and also loosen the clay-binder interface leading to collapse of the microstructure of the clay material. This implies failure. Therefore the bulk density of the brick at any point in time (due to shrinkage) affects the porosity of the brick and invariably the structure.

6 CONCLUSION

The model computes and predicts the bulk density of fired bricks based on the shrinkage incurred. The validity of the model is rooted on the expression; $Exp\ (e^{\gamma}) = (S)^{1.1589}$ where both sides of the expression are correspondingly almost equal. The maximum deviation of the model-predicted bulk density from the corresponding experimental values is less 7%.

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