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Simulation of Ohiya Clay-Feldspar-Silica Mix for Refractory Applications

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Abstract
An empirical model for predicting refractoriness of Ohiya clay and a simulation for determining optimal framework for producing different qualities of refractory bricks as may be desired by end users were developed in this study to advance industrial utilization of this clay mineral in Abia State of Nigeria. The developed function and its optimization simulation revealed 1200°C as optimal firing temperature and 40:32:21 as the optimal mix of the clay, feldspar and silica for standard refractory bricks' production. The quality of refractory bricks developed with these optimal process parameters settings compared favourably with the model's predictions and NIS/ISO specifications (at $\alpha = 0.05$). The reddish colour of the bricks produced is in accordance with Fe_2O_3, CaO and MgO contents of Ohiya clay. Application of the developed simulation model in standard refractory bricks production yielded 16% profit. Therefore, its adoption for refractory products development from Ohiya clay is recommended to curb excessive importation of refractories in Nigeria.

Keywords: *Firing temperature, Material mix, Ohiya clay, Refractoriness, Simulation model*

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1. Introduction

The increasing rate of importing refractory materials for various metallurgical and process industries in Nigeria is worrisome despite the huge natural reserves of untapped kaolin and other minerals used for production of refractories in this country. Hence, the tremendous research efforts recently towards determining the suitability of the raw materials deposits of this nation for refractory applications in order to reduce production cost and create jobs in this sector as well as earn foreign exchange (Musa *et al*, 2012). Refractories are non-metallic materials typically composed of silicon and aluminium oxides with the functional ability to withstand both physical and chemical wear, possess high melting temperatures and maintain their structural properties at very high temperatures (Onwuachi, 2012). Cajetan *et al.* (2015) attributed outstanding position of refractory bricks in modern industries to their ability to withstand high temperatures without melting, inert, possession of reversible thermal expansion and resistance to thermal shocks. Refractory brick is used for extreme mechanical, chemical and thermal stresses applications while porous or kiln brick goes for less harsh situations such as in electric or natural gas-fire kiln (Avallone and Baumeister, 1996). According to Punmia and Jain (2003) dense refractory brick grades are for different maximum service temperatures range of 23 to 1260°C while silica refractory bricks withstand temperature up to 1648°C (3000°F). Thus, the intensive applications of silica refractory bricks for constructing furnaces, smelting vessels for holding and transporting metal and slag and flues or stacks through which hot gases are conducted (Abia *et al.,* 2006; Omotoyinbo and Oluwole, 2008; Oke *et al.*, 2015). This refractory brick is also very vital for processing materials at very high temperatures in glassmaking, cement and ceramic industries (Aramide and Oke, 2014). The widening applications of ceramic products coupled with the high population growth rate of Nigeria increased the demand for these products and subsequently the volume of refractory bricks for their production. Therefore, the high rate of external sourcing of kaolin to meet the demand despite the untapped ones in this country (Abubakar *et al.,* 2014; Folorunso, 2012; Olokode *et al.*, 2013).

Assessment of refractory potentials of natural kaolin deposits in Nigeria in order to curb its importation is not new. Nnuka and Agbo (2000), Abolarin *et al.* (2005), Mark and Onyemaobi (2009), Mark (2010), Mark *et al.* (2011), Amuda *et al.* (2005) and Kure (2011) reported viability of natural clay deposits at Otukpo, Barkin Ladi, Alkaleri Ibere, Oboro, Ohiya and some areas in South-West and North Central for refractory bricks production. However, Amuda *et al.* (2005), Azunna *et al*. (2017), Onyekuru *et al*. (2018) and Ikechukwu *et al.* (2020) sorted for blending of the local sourced clays to match the foreign ones because they are not precisely compatible with the imported one in their natural form. Thus, the report of Nwankwojike *et al.* (2020) that investors are scared of over 74.38 million metric tons of natural clay deposit at Ohiya in Umuahia, Abia State of Nigeria because of ceramic products made from it (using formulations designed based on the foreign clays) are often characterized by defects. Although, simulations for producing different porcelains from Ohiya clay were formulated using empirical functions of its modulus of rapture, cold compression strength, linear shrinkage and minimum apparent porosity developed by Ibeh *et al*. (2021), its blend for standard refractory brick production is lacking. This is because the refractoriness of this clay is not fitted along despite that it was experimentally assessed with these response parameters since it is a quality determinant of porcelain. Refractoriness of a clay mineral measures its fusibility or temperature at which it softens (Osarenmwinda and Abel, 2014). Since refractoriness of any clay mineral plays vital roles along with other responses in determining the quality of refractory bricks produced from it. This study developed a model for predicting refractoriness of Ohiya clay and applied it in determining optimal framework for its application in refractory brick production.

2. Materials and methods

This study involves the development of empirical model for predicting refractoriness of Ohiya clay and determination of optimal firing temperature and mix of it with feldspar and silica for standard refractory brick production. The model predictors include variants of quantity of Ohiya clay *(Q_c)*, feldspar *(Q_f)*, silica (Q_s) and firing temperature *(T)*. The data (Table 1) used for fitting the functional relationship between these predictors and the clay refractoriness (R) were obtained from experimental records of Ibeh *et al*. (2021). The refractoriness function was fitted using iterative backward elimination based least square method. The criteria adopted in selecting the best fit model of this response are that the normal probability and histograms of good functions' residuals must approximate straight line and dumb-bell plots while their residuals versus run order and residuals versus fitted response plots remain structureless (scatter feature). The prediction accuracy of each best fit response function was further confirmed by comparing their predictions with six experimental records not used for the models' fitting at α = 0.05 significant level. Thereafter, the desirability simulation model for producing different qualities of refractory bricks as desired by end users was developed with multiobjectives of apparent porosity and linear shrinkage minimization and maximization of modulus of rapture, cold compression strength and refractoriness at specific targets of water absorption rate and apparent density. The following functions of apparent porosity (P_a), linear shrinkage(L_s) modulus of rapture (H) and cold compression strength (CCS) of Ohiya clay given by Ibeh *et al*. (2021) were used in the formulation of the simulation.

$$Pa = 12.38 + 0.11Q_c - 5.51 \times 10^{-2}Q_f - 2.91 \times 10^{-3}T + 0.11Q_S + 1.28 \times 10^{-4}Q_c^2 - 3 \times 10^{-6}Q_cT - 4.05 \times 10^{-3}Q_cQ_s + 7.6 \times 10^{-5}Q_ST \quad (1)$$

$$Ls = -5.1 + 0.21Q_c - 1.64 \times 10^{-2}Q_f + 6.27 \times 10^{-3}T + 2.6 \times 10^{-4}Q_S + 6.67 \times 10^{-4}Q_cQ_s - 1.5 \times 10^{-5}Q_fT - 8 \times 10^{-6}Q_sT \quad (2)$$

$$H = 28.72 - 0.2Q_c + 0.22Q_f + 1.41 \times 10^{-2}T - 3.26 \times 10^{-2}Q_S + 1 \times 10^{-6}T^2 - 1.75 \times 10^{-4}Q_fT + 5.17 \times 10^{-3}Q_fQ_s - 1.02 \times 10^{-4}Q_sT \quad (3)$$

$$CSS = -19.53 + 0.71Q_c + 0.99Q_f + 1.51 \times 10^{-3}T - 0.14Q_S - 1.14 \times 10^{-2}Q_c^2 - 1.14 \times 10^{-2}Q_f^2 - 3 \times 10^{-6}T^2 - 6.165 \times 10^{-3}Q_s^2 + 2.24 \times 10^{-4}Q_cT + 8.54 \times 10^{-3}Q_cQ_s - 2.15 \times 10^{-4}Q_fT - 8.1 \times 10^{-5}Q_sT \quad (4)$$

Table 1: Experimental analysis of Ohiya clay's refractoriness

Std Order	Run Order	Q_c(kg)	Q_f(kg)	T (°C)	Q_s(kg)	R (°C)
27	1	40	25	850	30	1500
5	2	30	15	1300	15	1560
30	3	40	25	850	30	1500
25	4	40	25	850	30	1492
17	5	20	25	850	30	1370
19	6	40	5	850	30	1530
14	7	50	15	1300	45	1470
1	8	30	15	400	15	1570
3	9	30	35	400	15	1550
18	10	60	25	850	30	1480
24	11	40	25	850	30	1272
23	12	40	25	850	0	1697
29	13	40	25	850	30	1490
13	14	30	15	1300	45	1345
2	15	50	15	400	15	1623
6	16	50	15	1300	15	1630
22	17	40	25	1750	30	1523
9	18	30	15	400	45	1365
20	19	40	45	850	30	1427
21	20	40	25		30	1487
7	21	30	35	1300	15	1580
10	22	50	15	400	45	1457
26	23	40	25	850	30	1492
8	24	50	35	1300	15	1595
12	25	50	35	400	45	1326
16	26	50	35	1300	45	1375
11	27	30	35	400	45	1290
4	28	50	35	400	15	1540
15	29	30	35	1300	45	1320
28	30	40	25	850	30	1490

The optimal settings of Ohiya clay, feldspar, silica and firing temperature for standard refractory bricks production were determined by solving the developed simulation using response optimizer of MINITAB 17 software with International Organization for Standardization/Nigerian Industrial Standard (ISO/NIS) specifications as set targets. The prediction accuracy of the simulation was confirmed experimentally by comparing the feature of refractory bricks produced based predicted optimal settings with ISO/NIS set standards at $\alpha = 0.05$ significant level. The cost and savings involved in the application of the developed Ohiya clay simulation for refractory bricks production were evaluated based on the standard bricks produced with it using the prevailing average market prices in Umuahia, Nigeria between January and June, 2021.

3. Results and discussion

Statistical and experimental evaluation of residuals associated with best fit function of Ohiya clay's refractoriness (Equation 5) developed in this study indicated that it is apt for further analysis since its residual plots (Fig.1) exhibited the expected straight line, dumb-bell plot and structureless profiles. In addition, the profile of its prediction and experimental values comparison shown in Fig. 2 depicts over 95% prediction accuracy which implies non violation of constant variance assumption expected of a good model.

$$R = 1322.9 + 16.8Q_c + 5.75Q_f - 1.17\times10^{-1}T - 7.35Q_S - 1.7\times10^{-1}Q_c^2 - 3.63\times10^{-2}Q_f^2 + 1.5\times10^{-5}T^2 - 9.48\times10^{-3}Q_S^2 - 1.525\times10^{-1}Q_cQ_f + 1.31\times10^{-3}Q_cT + 7.5\times10^{-2}Q_cQ_s + 2.41\times10^{-3}Q_fT - 8.67\times10^{-2}Q_fQ_s \quad (5)$$

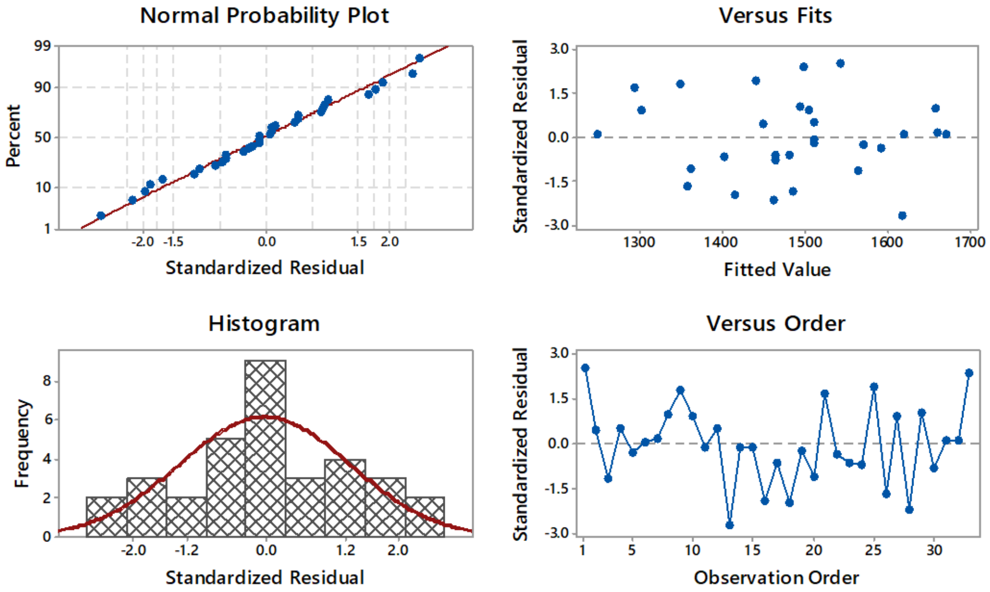

Fig. 1: Residual plots of the developed Ohiya clay's refractoriness function

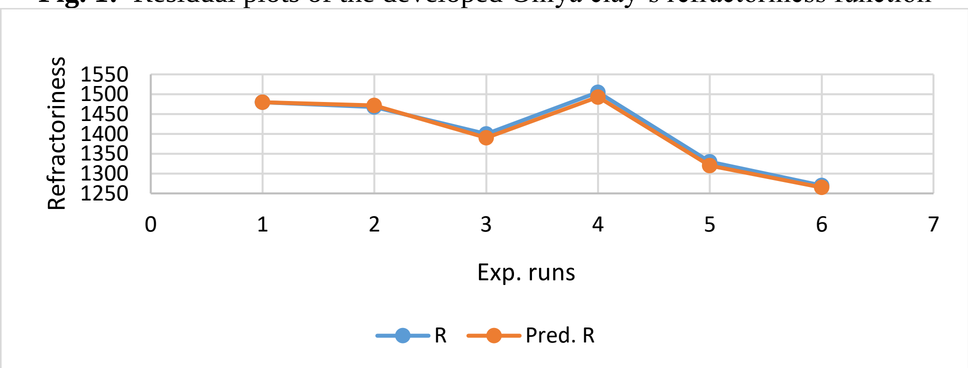

Fig. 2: Experimental confirmation of the developed Ohiya clay's refractoriness function

The developed simulation predicted 0.327, 1.9434, 0.5573 and -0.30 as optimal coded settings of Ohiya clay, feldspar, temperature and silica respectively (Fig. 3) which implies the optimal clay, feldspar and silica mix of 40:32:21 at a firing temperature of 1200°C. The quality settings of refractory bricks (Fig. 4) developed based on this simulated optimal temperature and materials mix compared favourably with the model's predictions and conformed to NIS/ISO specifications (Table 2). The reddish colour of the bricks produced is in accord with Ibeh *et al*. (2021) and Ikechukwu *et al.* (2020) which confirmed Fe_2O_3, CaO, and MgO contents of Ohiya clay and Kreimeyer (1987) which revealed that these elements can appreciably modify the colour of the fired clay. Cost analysis of standard refractory brick produced from Ohiya clay shown in Table 3 revealed three hundred and eighty-seven naira (₦387) as the cost 230×110mm fire clay brick against the market price of four hundred and fifty naira (₦450). Hence, the production of refractory bricks at the optimal settings can save about sixty-three naira (₦63), which translates to 16% in profit.

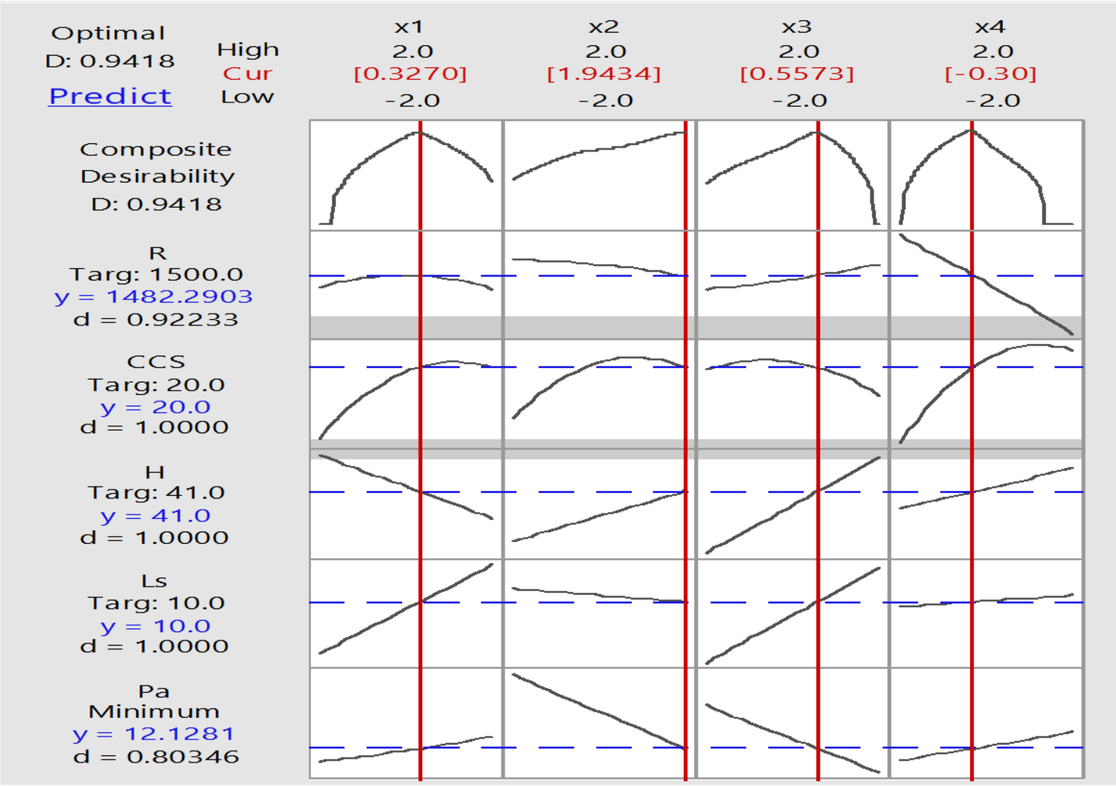

Fig. 3: Optimal refractoriness simulator for Ohiya clay**.**

Fig. 4: Standard fireclay brick developed from Ohiya clay

Table 2: Comparative analysis of standard refractory bricks from ohiya clay

Responses	**Predicted**	**Actual**	**% Error**	**Set standard**
Modulus of Rupture (kg/cm^2)	41.00	40.67	0.80	≥21 kg/cm^2
Apparent Porosity (%)	12.10	11.93	0.60	9-30%
Linear Shrinkage (%)	10.00	9.93	0.70	5-11%
Compressive Strength (mPa)	20.00	20.67	3.20	≥10mPa
Refractoriness (^{o}C)	1482	1493	0.70	≥1200^{o}C

Table 3: Cost Analysis of standard refractory brick from ohiya clay

Description	Unit Price (₦/Kg)	Quantity (Kg)	Amount(₦)
Ohiya Clay	15	1.40	21
Feldspar	100	1.12	112
Silica	100	0.74	74
Labour Cost	-	-	80
Miscellaneous	-	-	100
Total			**387**

4. Conclusions

An empirical model for predicting refractoriness of Ohiya clay and a simulation determining optimal framework for producing different qualities of refractory products as may be desired by end users with over 96% prediction accuracy were developed in this study to advance industrial utilization of this clay mineral in Abia State of Nigeria. Refractory bricks produced based on the model's prediction of 1200^{o}C as optimal firing temperature and 40:32:21 as the optimal mix of the clay, feldspar and silica conformed to NIS/ISO specifications with 16% savings. Thus, the developed simulation should be adopted for refractory products development from Ohiya clay to curb excessive importation of refractories in Nigeria.

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