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OPTIMIZING CERAMIC RAW MATERIALS FOR PRODUCTION OF HIGH VOLTAGE PORCELAIN INSULATOR

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ABSTRACT

Materials combination of ceramic raw materials for production of porcelain insulator has been trial and error approach. In this work, effects of these raw materials proportioning on the properties of high voltage porcelain insulator were investigated for the optimization of raw materials combination. This was carried out using response surface methodology (RSM), for mix design optimization (MDO) incorporated in the design of experimental tool version (6.0.6). Fourteen porcelain bodies were formulated from the experimental design output by varying materials combination of clay 40-60 %, feldspar 20-40 % and quartz 10-30 % body constituents (as variables). They were produced by dry pressing method at pressure of 5.0 MPa. Porosity, water absorption, bulk density, bending strength and dielectric strength were the responses investigated. Models for these properties were generated from the statistical analysis of variance (ANOVA) and optimized solutions generated. The optimized solution with highest desirability was characterized with 49.81 % clay, 40 % feldspar and 10.19 % quartz. The resulting predicted response values of porosity, water absorption, bulk density, bending strength and dielectric strength were 0.98 %, 0.47 %, 1.75 g/cm^3, 40.88 MPa and 49.82 kV/mm respectively.

Keywords: *materials combination, electrical porcelain insulator, porcelain properties.*

INTRODUCTION

Electrical insulators are materials possessing electrical insulating properties widely used in electrical and electronic industries for electrical power transmission and distribution at low and high voltages. Over the years, they are usually made from plastics, wood and glass (Onaji, 1984). Those made from plastics tend to put more pressure on the demand of petroleum as the major source of raw material; because it competes with other products made from petroleum. Development of insulators from wood have also encouraged deforestation activities which can trigger climatic change effects. More-so, insulators made from glass are fragile and cannot withstand mechanical stress (Ngayakamo and Park, 2018). These set back led to the discovery of ceramic raw materials clay, feldspar and quartz as potentials for electrical porcelain insulator development (Okojie, 1987; Jonathan, 1994; Oladiji *et al.*, 2010; Okolo *et al*., 2014; Okolo *et al*., 2016; Onaji, 2017; Yaya *et al*., 2017; Ngayakamo and Park, 2018; Merga *et al.*, 2019).

Generally, electrical porcelain insulators are glazed or unglazed vitreous ceramic materials produced from the blend of clay, feldspar and quartz in the right proportion to enhance the porcelain insulator with high mechanical and electrical properties (Okolo *et al.*, 2014; Ngayakamo and Park, 2018; Merga *et al.*, 2019). Porcelain insulator with high mechanical and electrical properties is known as high voltage porcelain insulator. High voltage porcelain insulator is an electrical insulator for high voltage applications. It possesses high dielectric strength and bending strength greater than 30 kV/mm and 35 MPa respectively. It is used in high voltage power transmission and distribution such as tension, post and hollow insulators.

These high voltage porcelain insulators have advantages over other insulating materials like plastics, glass and wood due to their high dielectric strength and bending strength; and abilities to retain these properties in any atmospheric weather condition (Ngayakamo and Park, 2018). They are produced in the right proportion of the materials combination because each material plays a specific role in porcelain structural properties. While clay [$Al_2Si_2O_5(OH)_4$] gives plasticity, quartz (SiO_2) maintains the shape of the ceramic structure during firing and feldspar [$K_xNa_{1-x}(AlSi_3)_8$] lowers the melting point and influence vitrification of the ceramic structure (Carty and Senapati, 1998; Olupot, 2006).

MATERIALS AND METHODOLOGY

Materials

Materials used in this work were beneficiated clay obtained from Ozanagogo in Delta State, feldspar and quartz were respectively obtained from Okene and Zariagi, both in Kogi State. Equipment used were digital weighing balance (02250kg/02551,11bs, Display type LCD), mixer machine (Ridsdale & CO limited, England, Model-89.2), electric hydraulic press (WEBBER-HYDROLIK, TYPE-Pi00EH, Capacity-100T, Serial No:38280), electric furnace (Naberthern 30-3000 ^{0}C), tensometric machine [TUF-C-1000kN (SERVO)], all available in Federal Institute of Industrial Research Oshodi (FIIRO) Lagos State and high voltage testing transformer kit [High Voltage (CONSOLE)] available in University of Lagos, Lagos State.

Methodology

Ranges of raw materials used were clay 40-60 %, feldspar 20-40 % and quartz 10-30 %; based on the previous works by Jonathan *et al*., (1994); Oladiji *et al.*, (2010); Okoro *et al*., (2016). Thus, the boundary input conditions for the independent variable raw materials as shown in Table 1.

Table 1: Design of experimental input details for raw materials.

Material	Unit	Low actual	High actual
Clay	%	40	60
Feldspar	%	20	40
Quartz	%	10	30

Formulation of porcelain bodies

From experimental design variable specified in the design interface as shown in Table 1 and selected properties of electrical porcelain insulator were used for mix design optimization (MDO), incorporated in the design of experiment (v6.0.6). The experimental design output containing the varied raw materials combination and the detail schedule generated is shown in Table 2.

Table 2: Experimental design output for porcelain formulations

Run	Clay wt%	Feldspar wt%	Quartz wt%	Porosity %	Water Abs. %	Bulk Density g/cm^3	Bending Strength N/m^2	Dielectric Strength kV/mm
1	60	30	10	tbd	tbd	tbd	tbd	tbd
2	50	30	20	tbd	tbd	tbd	tbd	tbd
3	60	30	10	tbd	tbd	tbd	tbd	tbd
4	40	40	20	tbd	tbd	tbd	tbd	tbd
5	45	25	30	tbd	tbd	tbd	tbd	tbd

6	40	30	30	tbd	tbd	tbd	tbd	tbd
7	50	20	30	tbd	tbd	tbd	tbd	tbd
8	40	35	25	tbd	tbd	tbd	tbd	tbd
9	50	40	10	tbd	tbd	tbd	tbd	tbd
10	60	20	20	tbd	tbd	tbd	tbd	tbd
11	50	30	20	tbd	tbd	tbd	tbd	tbd
12	60	20	20	tbd	tbd	tbd	tbd	tbd
13	50	40	10	tbd	tbd	tbd	tbd	tbd
14	60	25	15	tbd	tbd	tbd	tbd	tbd

Tbd = to be determined

Production of porcelain bodies

Three samples were produced from each materials combination of the fourteen formulations. They were produced by mixing the beneficiated powdered materials in the ratio as shown in Table 2. The mixtures were compacted at 5.0 MPa using electric hydraulic press. The molded cylindrical specimens were seasoned indoor at room temperature for 5 days, oven dried at temperature of 110 ^{0}C for 24 h and fired at temperature of 1200 ^{0}C for 3 h. The samples were left to cool to room temperature and the properties were determined.

Determination of physical, mechanical and electrical properties of porcelain bodies

Porosity, water absorption and bulk density were determined using standard method (ASTM). Bending strength was determined by a three-point testing method. The load was applied on porcelain samples until failure occurred and manometer readings were recorded in MPa. Dielectric strength was also measured by applying a voltage across the fired porcelain sample using two electrodes at the rate of 1 kV/mm until a cracking sound was heard from the porcelain sample and reading for each sample was recorded in kV/mm.

RESULTS AND DISCUSSION

Table 3: Properties of porcelain insulator analysis

Run	Clay wt%	Feldspar wt%	Quartz wt%	Porosity %	Water Abs. %	Bulk Density g/cm^3	Bending Strength N/m^2	Dielectric Strength kV/mm
1	60	30	10	1.000	1.400	1.96	25	25
2	50	30	20	0.997	0.500	1.74	45	50
3	60	30	10	1.180	1.300	1.89	30	25
4	40	40	20	0.868	0.700	1.68	30	50

5	45	25	30	1.733	1.200	1.52	50	65
6	40	30	30	0.663	0.500	1.75	40	45
7	50	20	30	1.624	0.700	1.52	45	60
8	40	35	25	0.989	0.500	1.78	40	45
9	50	40	10	0.938	0.500	1.79	42	50
10	60	20	20	1.693	1.900	1.52	25	30
11	50	30	20	0.988	0.600	1.73	40	45
12	60	20	20	1.653	1.800	1.45	30	35
13	50	40	10	0.889	0.400	1.76	40	50
14	60	25	15	1.859	1.200	1.99	35	40

Table 3 showed the effects of materials combination on the properties of produced porcelain insulators. The materials combination of 50, 40 and 10 wt% clay, feldspar and quartz respectively; as shown in Run 13 exhibited the best results with the values of porosity, water absorption, bulk density, bending strength and dielectric strength to be 0.889 %, 0.400 %, 1.79 g/cm^3, 40 MPa and 50 kV/mm respectively. The same trend was also obtained in Run 9 except water absorption which was exactly 0.5 %; though, theoretically standard value of water absorption is less than 0.5 %. Therefore, within the limit of experimental error, the results were in agreement with the standard values according to ISO-13006.

Mixture contained high percentage of clay (> 50 wt%), low percentage of feldspar (< 40 wt%) and low percentage of quartz (exactly 10 wt%) showed high porosity, water absorption and bulk density; and low bending strength and dielectric strength. Mixture contained high amount of clay (50 wt%) with high amount of feldspar (40 wt%) and low amount of quartz (10 wt%) exhibited low porosity, water absorption and bulk density, high bending strength and dielectric strength.

Generally, the results showed that higher amount of clay with feldspar and lower amount of quartz decreased porosity, water absorption and bulk density but increased bending strength and dielectric strength of porcelain insulator.

Model Developed for Porcelain Properties

ANOVA results of the developed model for porcelain properties are significant because their probabilities (0.0001) are less than F-values (0.05). Also, lack of fit values of the porcelain properties are not significant because they are greater than 0.05. Therefore, these models are good enough to represent the variable combinations, because the significant models and insignificant lack of fits recorded are respectively desirable as shown in Table 4.

Table 4: ANOVA results of the models developed for the properties of porcelain insulator

Source	Sum of Square	Degree of Freedom, DF	Mean Square	F Value	Prob. > *F*	Remarks
POROSITY						
Model	0.87	5	0.17	1138.96	<0.0001	Significant
AB	0.13	1	0.13	856.40	<0.0001	
AC	0.16	1	0.16	1069.79	<0.0001	
BC	0.23	1	0.23	1486.30	<0.0001	
Residual	0.001228	8	0.000154	-	-	
Lack of fit	0.0004477	4	0.0001194	0.64	0.6636	Not significant
WATER ABSORPTION						
Model	0.15	5	0.030	74.40	<0.0001	Significant
AB	0.006116	1	0.006116	14.93	<0.0001	
AC	0.0007162	1	0.0007162	1.75	<0.0001	
BC	0.00003169	1	0.00003169	0.077	<0.0001	
Residual	0.003278	8	0.0004097	-	-	
Lack of fit	0.002377	4	0.0005.944	2.64	0.1848	Not significant
BULK DENSITY						
Model	0.24	5	0.048	196.68	<0.0001	Significant
AB	0.025	1	0.025	103.65	<0.0001	
AC	0.16	1	0.16	635.84	<0.0001	
BC	0.098	1	0.098	400.24	<0.0001	
Residual	1.966E-003	8	2.457E-004	-	-	
Lack of fit	1.066E-003	4	2.665E-004	1.18	0.4368	Not significant

BENDING STRENGTH						
Model	307.21	5	61.44	35544.03	<0.0001	Significant
Linear mixture	192.44	2	96.22	55662.38	<0.0001	
AB	20.52	1	20.52	11872.73	<0.0001	
AC	0.079	1	0.079	45.71	0.0001	
BC	19.08	1	19.08	11038.54	<0.0001	
Residual	0.014	8	1.729E-003	-	-	
Lack of fit	0.012	4	2.957E-003	5.91	0.0567	Not significant
DIELECTRIC STRENGTH						
Model	1003.19	5	200.64	2715.28	<0.0001	Significant
Linear mixture	807.77	2	403.88	5465.84	<0.0001	
AB	4.01	1	4.01	54.31	<0.0001	
AC	13.32	1	13.32	180.31	<0.0001	
BC	134.82	1	134.82	1824.60	<0.0001	
Residual	0.58	8	0.074	-	-	
Lack of fit	0.13	4	0.032	0.27	0.8807	Not significant

Equations 1 to 5 presented the models developed for properties of porcelain. All the equations followed quadratic order, where "A" represents clay, "B" for feldspar and "C" represents quartz. The equations also showed the numerical combinations of the independent variables, whose properties (responses) can be validated experimentally.

Porosity = 0.99(A) + 1.33(B) + 0.063(C) + 2.95(AB) + 3.35(AC) + 3.81(BC)-1

Water absorption = 0.82(A) + 1.07(B) + 0.73(C) + 0.64(AB) + 0.22(AC) + 0.045(BC) -----------2

Bulk density = 1.08(A) + 1.59(B) + 0.57(C) + 1.30(AB) + 3.27(AC) + 2.50(BC)...-------3

Bending strength = 22.65(A) + 37.05(B) + 62.62(C) + 36.84(AB) – 2.32(AC) – 34.84(BC) ----- 4

Dielectric strength = 32.62(A) + 63.85(B) + 92.76(C) – 16.29(AB) – 30.18(AC) – 92.62(BC) ---5

Equations 1 to 3 showed that higher amount of clay with feldspar and lower amount of quartz decreases the values of porosity, water absorption and bulk density while Equations 4 and 5 showed that higher amount of clay with feldspar and lower amount of quartz increases the values of bending strength and dielectric strength. This is desirable as shown in Table 3.

Adequacy tests of the porcelain property models

The models developed were checked for consistency; considering their R^2-values, adjusted R^2 and adequate precisions as shown in Table 5.

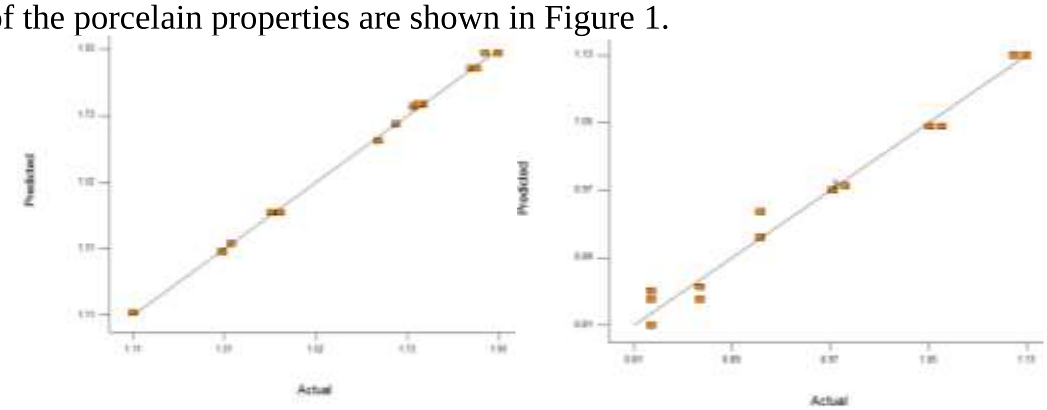
Table 5: Model adequacy parameters for the properties of porcelain insulator

Parameter	Porosity	Water absorption	Bulk density	Bending strength	Dielectric strength
R^2	0.9986	0.9789	0.9919	1.0000	0.9994
Adjusted R^2	0.9977	0.9658	0.9868	0.9999	0.9990
Predicted R^2	0.9950	0.9452	0.9748	0.9998	0.9983
Adequate precision	98.651	24.453	38.967	521.728	149.481
Error (%)	0.09	0.01	0.51	0.01	0.04

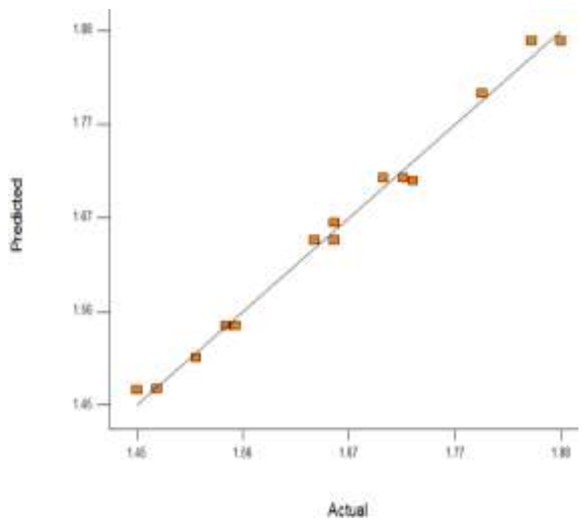
Table 5 has its R^2 values close to unity or unity as desirable. Error, the difference between R^2 and R^2 adjusted proved that, the models are consistent. The adequate precision values of all the porcelain properties were reasonable and therefore showed that the models are consistent.

Relationships between predicted and experimental parameters for porcelain properties.

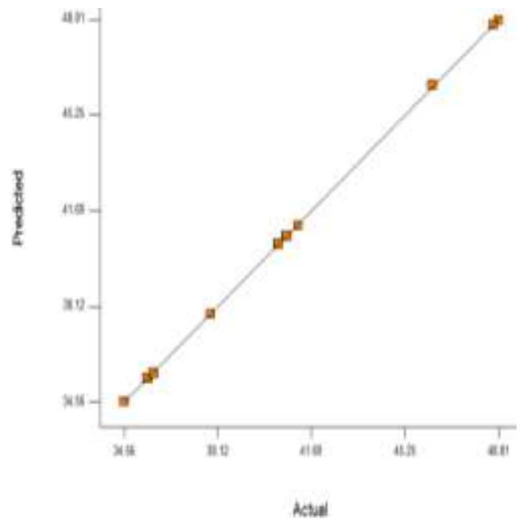
Relationships between the predicted data and that of experimental parameters of the porcelain properties are shown in Figure 1.



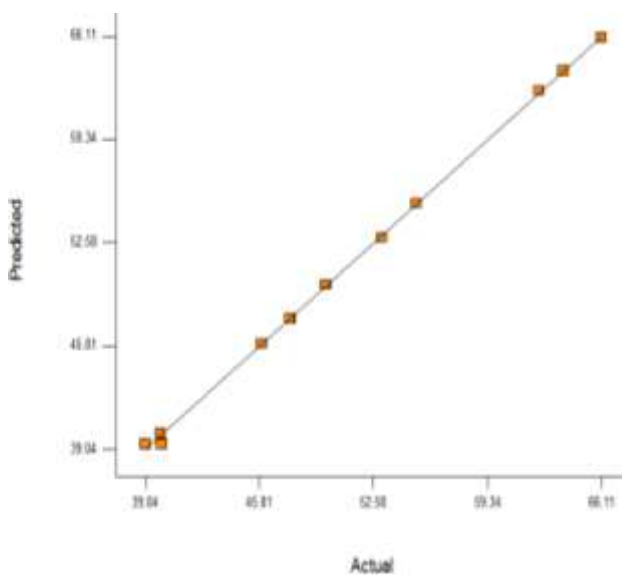
(i) (ii)



(iii)



(iv)



(v)

Figure 1: Parity plots of the experimental and predicted data of the porcelain properties.
(i) porosity, (ii) water absorption, (iii) bulk density, (iv) bending strength (v) dielectric strength

The experimental data are in good agreement with the predicted data, because the data points fall close to the regression lines without outlier.

Three-dimensional (3D) plots of the independent variable against porcelain properties

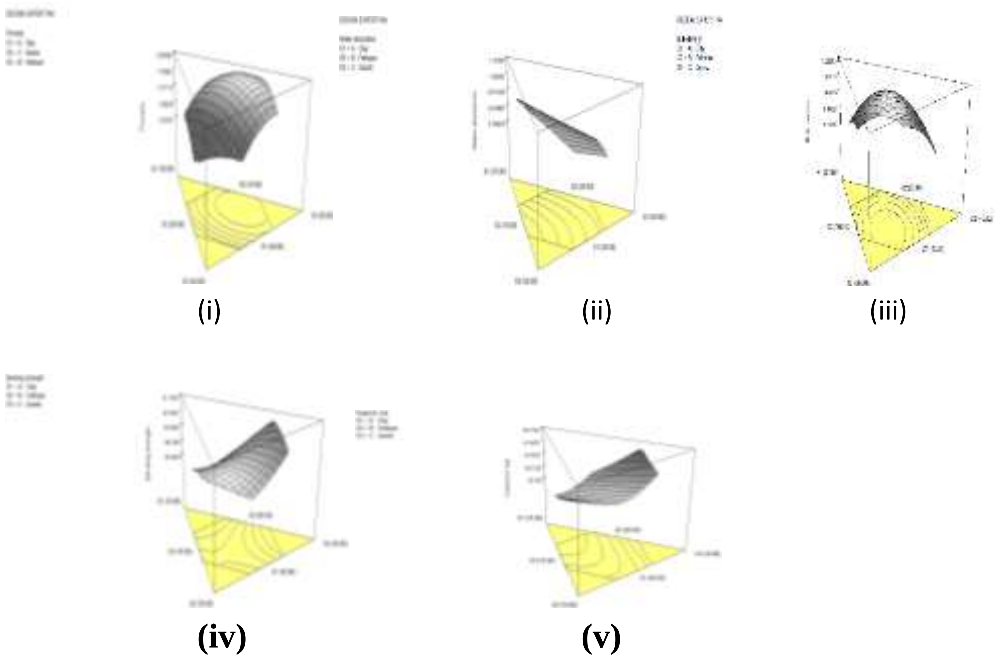


Figure 2: 3D plots of the models developed for porcelain properties: (i) porosity, (ii) water absorption, (iii) bulk density, (iv) bending strength (v) dielectric strength

The elliptical nature of the 3D-plots as shown in Figure 2 confirmed that the models are significant. More-so, figures (i), (ii) and (iii) showed that increase in the amount of clay with feldspar and lower amount of quartz decrease the porosity, water absorption and bulk density of the porcelain respectively. Whereas an increase in amount of clay with feldspar and lower amount of quartz increase the bending strength and dielectric strength as shown in figures (iv) and (v) respectively.

Optimum Materials Combination Solutions

Two optimized solutions for the materials combination were obtained from the models developed for the properties of porcelain insulator as shown in Table 6.

Table 6: Optimized solutions developed for the materials combination

Variable Parameter and Responses								Desirability %
Clay %	Feldspar %	Quartz %	P %	WA %	BD g/cm^3	BS MPa	DS kV/mm	
49.81	40.00	10.19	0.89	0.47	1.75	49.82	40.88	0.599
49.22	30.84	19.94	1.93	0.98	1.87	47.86	40.79	0.566

Table 6 presents clay, feldspar and quartz as variable parameters and porosity, P, water absorption, WA, bulk density, BD, bending strength, BS and dielectric strength, DS as dependent variables (responses). The two optimized solutions developed for the materials combination have desirability of 0.599 % for the first solution and desirability of 0.566 % for the second solution. The first solution was chosen for validation because it has the higher desirability when compared to the second solution.

Comparison of Standard with Experimental Values of Electrical Porcelain Insulator

The experimental values were compared with the standard values of electrical porcelain insulator as shown in Table 7.

Table 7: Comparison of standard values with experimental values of porcelain insulator

Property	Standard value	Experimental value
Porosity, P	**Less than 1 %**	**0.98 %**
Water absorption, WA	**Less than 0.5 %**	**0.47**
Bulk density, BD	**Between 1.71 – 2.1 g/cm^3**	**1.75 g/cm^3**
Bending strength, BS	**Greater than 35 MPa**	**40.88 MPa**
Dielectric strength, DS	**Greater than 30 kV/mm**	**49.82 kV/mm**

Source: Oladiji *et al*., 2010; Nwachukwu and Lawal, 2018; Ngayakamo and Park, 2018;
Merga *et al*; 2019.

Table 7 showed that the experimental values of the chosen optimized solution fall within the range of standard values. According to ISO-13006, the results obtained were in agreement with the standard values.

CONCLUSIONS

On the basis of our analyses, the conclusions could be drawn that the first solution is much more suitable than the second solution for the optimization of materials combination for the production of high voltage porcelain insulator at pressure of 5.0 MPa using dry pressing method. The optimized solution was found to be 49.81 % clay, 40 % feldspar and 10.19 % quartz and the resulting response values vis-a-vis porosity, water absorption, bulk density, bending strength and dielectric strength were 0.98 %, 0.47 %, 1.75 g/cm^3, 40.88 MPa and 49.82 kV/mm respectively.

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