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DEVELOPMENT OF MATHEMATICAL MODEL FOR THE PREDICTION OF THE BREAKDOWN VOLTAGE OF PARTICULATE CASSAVA CORTEX/EPOXY COMPOSITES

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ABSTRACT

This research determined the dielectric strength of composite materials developed from carbonized and uncarbonized cassava cortex. Carbonized cassava cortex (CCCtx) and uncarbonized cassava cortex (UCCtx) with 150–600µm sizes were varied from 40 – 60wt% in the cassava cortex/epoxy composite. The dielectric strength was determined and the effect of carbonization on the dielectric strength was also studied. The results show that smaller particles and weight percentage have the best properties. The significant factors (main and interaction) were identified by analysis of variance technique. The Cube and contour graphs show the estimated response surface for the composite property as a function of sample condition, wt%, and particle size. The predicted dielectric values were found to be close to the experimentally observed ones. The developed mathematical model can be used for optimization of the process parameters of the electrical insulation behaviour of cassava cortex epoxy particulate composites with respect to the breakdown voltage values.

KEY WORDS: Composites, Cassava Cortex, Carbonization, Epoxy, Mathematical Model.

1.0 INTRODUCTION

Every material has a unique set of electrical characteristics that are dependent on its dielectric properties. Accurate measurements of these properties can provide scientists and engineers with valuable information to properly incorporate the material into its intended application for more solid design and usage [1]. Furthermore, the measurement of properties of dielectric materials can provide critical design parameter information for many electronics applications. For example, the loss of a cable insulator, the impedance of a substrate, or the frequency of a dielectric resonator can be related to its dielectric properties. The information is also useful for improving ferrite, absorber, and packaging designs. More recent applications in the area of industrial microwave processing of food, rubber, plastics and ceramics have also been found to benefit from knowledge of dielectric properties [1].

A dielectric is an electrical insulator that can be polarized by an applied electric field. When a dielectric is placed in an electric field, electric charges do not flow through the material, as in a conductor, but only slightly shift from their average equilibrium positions causing dielectric polarization. Because of dielectric polarization, positive charges are displaced toward the field and negative charges shift in the opposite direction. This creates an internal electric field which reduces the overall field within the dielectric itself [2].

If a dielectric is composed of weakly bonded molecules, those molecules not only become polarized, but also reorient so that their symmetry axis aligns to the field. [2] When dielectrics are placed in an electric field, practically no current flows in them because, unlike metals, they have no loosely bound or free electrons that may drift through the material [2]. Dielectrics are not a narrow class of so-called insulators, but rather are the broad expanse of nonmetals considered from the standpoint of their interaction with electric, magnetic, or electromagnetic fields. Thus we are concerned with gases as well as with liquids and solids, and with the storage of electric and magnetic energy as well as its dissipation.

In recent research, it is commonly observed that due to the production advantage of particulate composites over fiber composites, researchers and industries like electronic, electrical, construction and automobile are gradually shifting to using particulates composites [3]. The cheapness of the agro-waste material generally lowers the overall cost of the product. Among the particulate materials in use, agro-waste materials are the cheapest thus, lowering the cost of production. Incorporating agro-waste materials into epoxy has been proved to decrease the composite density and improve the dielectric properties of the composites [4]. Natural particle-containing composites are more environmentally friendly, and are used in transportation (automobiles, railway coaches, aerospace), military applications, electrical/electronic industries, packaging, consumer products, etc. [5].

Cassava peel waste is increasingly generated annually in Nigeria. It is obtained from production of cassava tuber for human consumption, starch production and industrial uses [6].It is recorded in the literature that about 450,000 tons of cassava peels are generated annually in Nigeria as waste [7]. There are about three distinct regions in a cassava root: a central vascular core, the flesh, and the phelloderm (peels) which contains the cortex. As these peels are discarded as waste, they gradually heap up with time and constitute air and environmental pollution. The yield strength of the vegetation and soil around the cassava peel heaps also becomes affected due to the chemical reactions that take place between the fermenting peels, soil and the surrounding vegetation. [8].

Cassava cortex is used as reinforcement in this study so as to complement previous research efforts to reclaim agro-waste materials for other useful purposes. This work therefore presents the developed mathematical models of these composites based on the carbonization of CCtx, particle size and weight percent of the reinforcing particles. This work will add to the economic value of CCtx as an agricultural waste and as well control all the pollution caused by it. CCtx being a natural filler is expected to have good interfacial contact with the epoxy. To achieve this, the cassava cortex materials were carbonized at 550°C.

Carbonization of CCtx therefore involves converting CCtx as an agricultural residue into elemental carbon and other chemical compounds by heating in the absence or limited amount of air to a temperature high enough to dry off volatile substances in the Cassava cortex[9]. CO_2, and some organic vapours are released during the carbonization process. The carbonization was aimed at reducing the volatile content of the CCtx and enhances its structural strength for better dielectric properties [10].This work thus investigated the dielectric strength of this agro-waste material (CCtx), modeled the results obtained in terms of its carbonization temperature, wt% and particle size so as to complement their existing areas of application and as well predict its dielectric behaviour in different areas of electrical/electronic applications. Few researchers have investigated the effect of carbonization on the electrical insulation of agro-waste materials. This work however presents the relevance of carbonization on agro-waste materials with respect to the breakdown voltage of the materials.

2.0 MATERIALS AND METHOD

2.1 Materials

Materials used in this work include: Epoxy LY556 (matrix) uncarbonized and carbonized CCtx, set of sieves (mesh sizes: 150, 300, and 600µm), hacksaw, vernier caliper, grinding machine, heat treatment furnace, a pair of thongs, digital weighing balance, Switch and Control Desk for high voltage 5RP0.5/5Trg etc.

2.2 Method

The agro-waste material (CCtx) was locally sourced from Oba town in Nsukka local government area. They were washed and sun dried for two weeks. The CCtx was carbonized at a temperature of 550°C for one hour soaking time in the absence of oxygen using a heat treatment furnace. See figure 1. The CCtx particles were milled after carbonization and sieved to particle sizes of 150, 300, and 600µm.

The prepared CCtx particulates, epoxy resin, and hardener were properly mixed and poured into the mould. The mixture was allowed to cure in the mould and was removed for test analysis. The composites were produced by varying the CCtx from 40 to 60wt%. See figure 2.


(a) (b) (c)

Fig.1.Photographs of the cassava cortex: (a) cassava cortex under sun drying (b) sieved uncarbonized cassava cortex (c) sieved carbonized cassava cortex.

The fabrication processes involved are classified into three steps: moulding, preparation of the composition and casting. Some cast samples of the composites are as shown in Figure 2

Fig.2: Cast samples of the composite.

3.0 STATISTICAL DESIGN ANALYSIS FOR THE MECHANICAL PROPERTIES OF CASSAVA CORTEX COMPOSITES.

The process parameters considered in this research are sample condition i.e. carbonization temperature (A), wt% filler loading (B) and particles size(C). The two levels for process parameters with their units and notations are given in Table 1.

Table 1: Low and High level of each factor.

Factors	Low level (−)	High level (+)
Sample Condition (A)	32^oC	550^oC
Weight % Filler Loading (B)	40wt%	60wt%
Particles Size(C)	150µm	600µm

Full factorial design is a statistical tool to analyze a set of results with minimum number of experiments [11]. The methods of designing such experiments are dealt within literature [12].Two level full factorial design was used in this study. The eight sets of coded conditions of experiments based on 2^3 full factorial designs are given in Table 2 [12]. The sum of squares for main and interaction effects was calculated using Yates algorithm. The significant factors (main and interaction) were identified by analysis of variance (ANOVA) technique.

3.1 Development of Mathematical Model

The model for the breakdown voltage behaviour of the composites was obtained by representing the dielectric strength values by D, the response function can be expressed by equation below:

$D=f(A,B, C)$ -------------------- (1)

Where A=Sample condition (carbonization temperature)
B=weight % filler loading
C = Particle size

The model selected includes the effects of main variables first-order and second-order interactions of all variables. Hence the general model is written as:

$D = a_o + a_1A + a_2B + a_3C + a_4AB + a_5AC + a_7BC + a_8 ABC$-------------------- (2)

Where a_o is the response variable at the base level and a_1, a_2, a_3, are coefficients associated with each variable A(Sample condition), B(weight percentage) and C(particles size) respectively; and a_4, a_5, a_6, a_7 anda$_8$ the interaction coefficient between A, Band C within the selected levels of each variable. The methodology for calculating the values for each regression coefficient, using the coded values A, Band C of each variable, is described elsewhere [13].Thus, the number of trial experiments, to be conducted for each material is 8 (i.e. 2^3=8). The eight sets of coded conditions of experiments based on 2^3 full factorial designs are given in Table 2 [12]. The standard order of sequence is shown in Table 2. The sum of squares for main and interaction effects was calculated using Yates algorithm.

4.0 RESULTS AND DISCUSSION

The results of the research are given below.

Table 2: Standard Order of Test Sequence and Actual/Predicted Values Result

Experiment number		weight %(B)	Particle size(C) µm	DIELECTRIC STRENGTH (kV/mm)	
				ACTUAL VALUES	PREDICTED VALUES
1	Uncarbonized (-1)	10(-1)	150(-1)	510.84	506.31
2	Carbonized (+1)	10(-1)	150(-1)	217.96	250.31
3	Uncarbonized (-1)	60(+1)	150(-1)	458.67	438.78
4	Carbonized (+1)	60(+1)	150(-1)	190.71	182.78
5	Uncarbonized (-1)	10(-1)	600(+1)	476.77	454.64
6	Carbonized (+1)	10(-1)	600(+1)	204.33	198.64
7	Uncarbonized (-1)	60(+1)	600(+1)	340.56	387.11
8	Carbonized (+1)	60(+1)	600(+1)	149.85	131.12

Coded = -1(low level), +1(upper level)

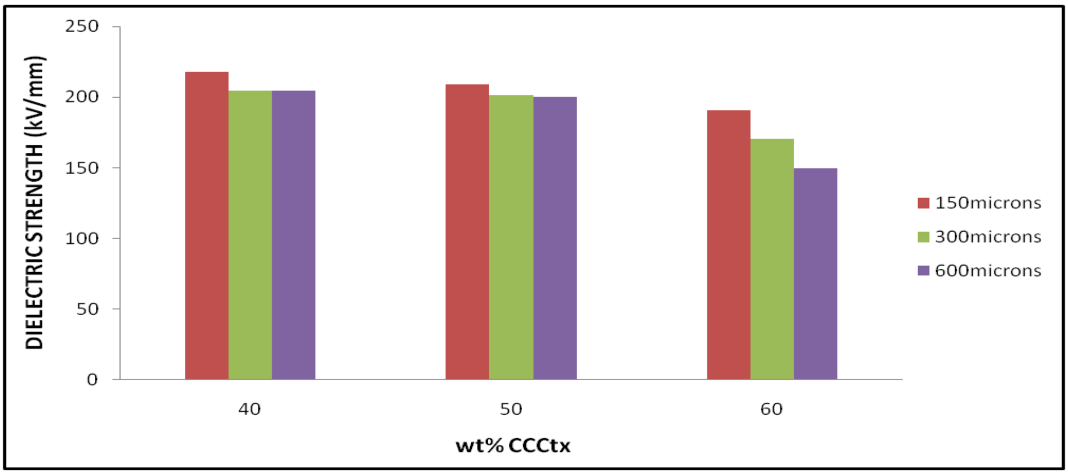

Fig. 3a: Dielectric Strength of CCCtx

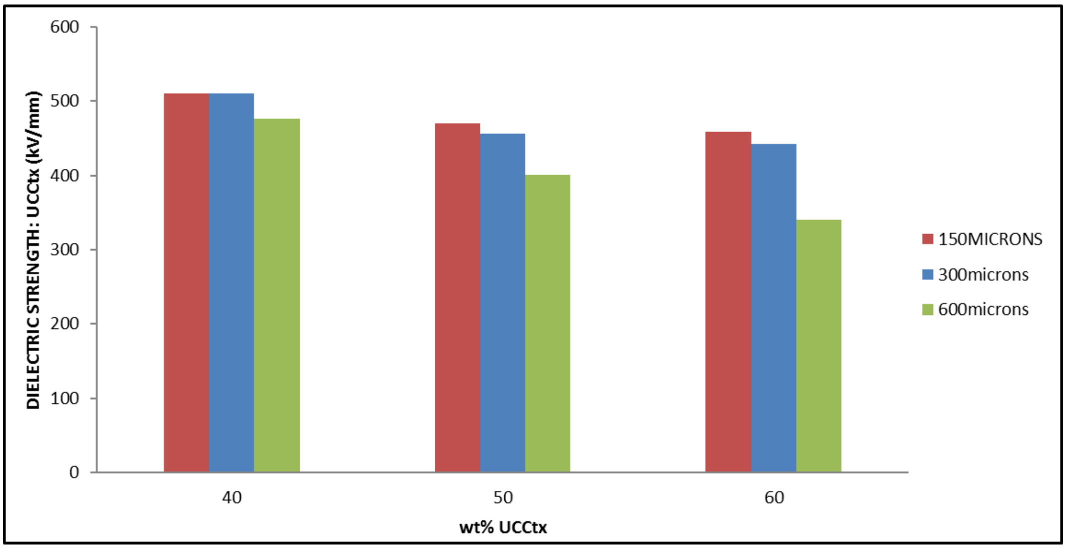

Fig. 3b: Dielectric Strength of UCCtx

Figures 3a and b show the Dielectric Strength of CCCtx and that of UCCtx. It was observed that the composite material with optimal strength is the one with lower wt% and smaller particle sizes. This is due to the fact that there is more interfacial contact between the smaller particle sizes and the epoxy resin than there is between the larger particles and the resin. This helps to minimize the presence of pores in the smaller particles than in the larger particles thereby enhancing the composite's dielectric strength.

It was also observed that the composite material with optimal strength is the uncarbonized ones. The same trend was observed at all the compositions and all the particle sizes. Thus, the composite material with optimal dielectric strength is the uncarbonized ones. This is because the carbon enhanced from the carbonization process caused a significant amount of micro-pore volume which then reduced the dielectric strength of the composites [14].Thus, high carbonization temperature causes the formation of micro-pores in the carbonized material which in turn reduced the dielectric strength of the composites. [14] Generally, researchers observed that as carbonization temperature increases, both the total micro-pore volume and the specific surface area also increase [15]e.g. several batches of chars were prepared from palm shell by carbonization in a flow of nitrogen using a fixed-bed reactor at temperatures of 500, 600, 700, 800 and 900 °C for 1 h to study the effects of carbonization temperature on char yield and its porosity. The results show that carbonization temperature has a significant effect on the micro- and meso-pore volumes [16]. The lower dielectric strength of the CCCtx therefore is the adverse effect of the high carbonization temperature on the particulates of the samples.

From the result of factorial design in Table3, the sample condition, wt% and particle size of cassava cortex appear to be the most important variable with main effect of (-256), (-67.53) and (-51.67). This implies that carbonizing the cassava cortex decreased the dielectric strength by 256, increasing the wt% of cassava cortex from 40wt% to 60wt% decreased the dielectric strength by 67.53 and increasing the particle size from 150µm to 600µm decreased the dielectric strength by 51.67. It can also be seen that the interaction of AB(26.66), AC(24.42) and ABC(14.20) have positive effects on the dielectric strength of the composites i.e. they tend to increase the dielectric strength of the composites; while the interaction of BC(-27.82) has a negative effect; thus, it decreased the dielectric strength of the composites. The cube graph, half normal plot and contour graph show the estimated response surface for dielectric strength as a function of sample condition, wt% and particle size. The graphs show that the dielectric strength were highly influenced by the sample condition(A), wt%(B) and particle sizes of cassava cortex.

The developed model equation for the dielectric strength of the composites can be expressed as:

$$D=+318.71-(128.00*A)-(33.76*B)-(25.83*C) \quad (3)$$

Substituting the coded values of the variables for any experimental condition in Equation 3, the dielectric strength for the composites can be calculated.

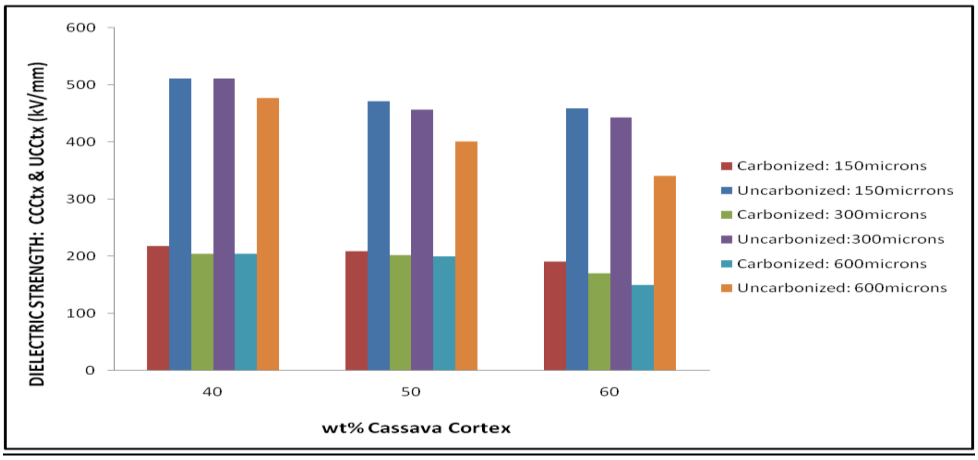

Fig. 3c: Dielectric Strength of CCCtx and UCCtx

MODEL FOR PREDICTION OF THE DIELECTRIC STRENGTH OF CASSAVA CORTEX COMPOSITES

Table3: Expanded Plan Matrix for Factorial Design of the Dielectric strength of the composites[17].

S/n	x0	A	B	C	AB	AC	BC	ABC	Dielectric Strength (kV/mm)
1	1	-1	-1	-1	+1	+1	+1	-1	510.84
2	1	1	-1	-1	-1	-1	+1	+1	217.96
3	1	-1	1	-1	-1	1	-1	+1	458.67
4	1	+1	+1	-1	+1	-1	-1	-1	190.71
5	1	-1	-1	+1	+1	-1	-1	+1	476.77
6	1	+1	-1	+1	-1	+1	-1	-1	204.33
7	1	-1	+1	+1	-1	-1	+1	-1	340.56
8	1	1	1	1	1	1	1	1	149.85
Effects	318.71	-256	-67.53	-51.67	26.66	24.42	-27.82	14.20	

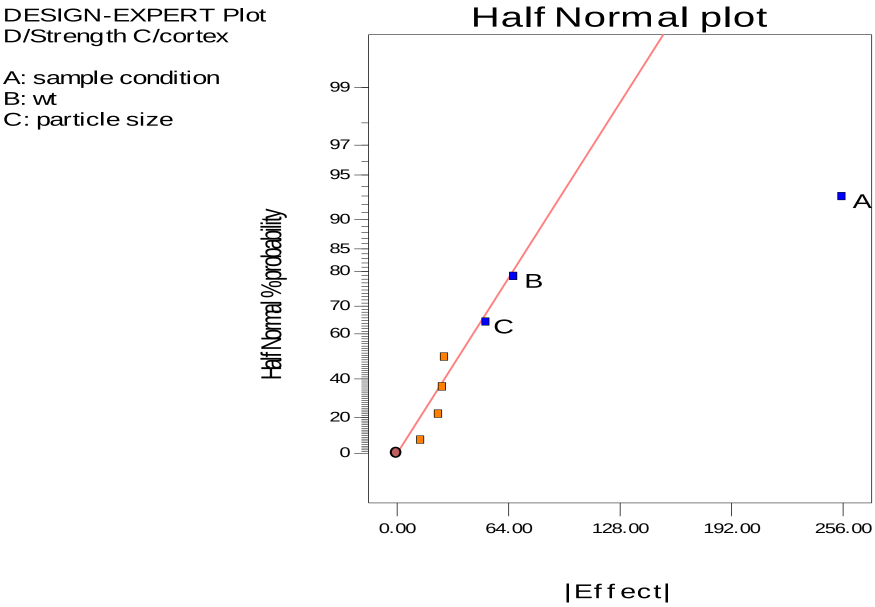

Fig. 4a: Variation of half probability with effects

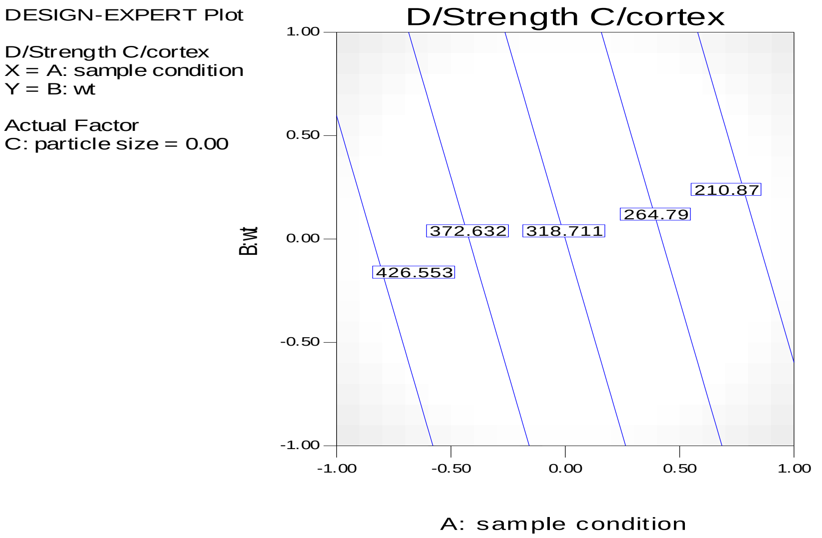

Fig. 4b: Contour surface plot of the effect of dielectric strength of Cassava Cortex.

Table 4: ANOVA for Selected Factorial Model of the dielectric strength value

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	1.455E+005	3	48509.48	42.50	0.0017	**significant**
A	1.311E+005		11.311E+005	114.83	0.0004	**significant**
B	9119.93	1	9119.93	7.99	0.0475	**significant**
C	5339.06	1	5339.06	4.68	0.0966	
Residual	4565.74	4	1141.44			
Cor Total	1.501E+005	7				

Figure 4a: shows the plot of three significant model terms A, B and C that significantly influenced the dielectric strength of the cassava cortex. The contour graph shows the two major factors: sample condition (A), and wt%(B) with these effects:(-256) and (-67.53).See table3. The contour graph reveals that as you navigate on the wt% axis from 0.00 to -1.00 there is increase in the dielectric strength of the Cassava cortex, but as you navigate from 0.00 to +1.00 there is a decrease in the dielectric strength. Thus, increased wt% reduced the dielectric strength of CCtx composites, while decreased wt% enhanced their dielectric strength. Moreso, as you move towards +1.00 of A axis, the dielectric strength decreased, while it increased towards -1.00; which implies that uncarbonized samples enhanced the dielectric strength of the cassava cortex more than the carbonized samples.

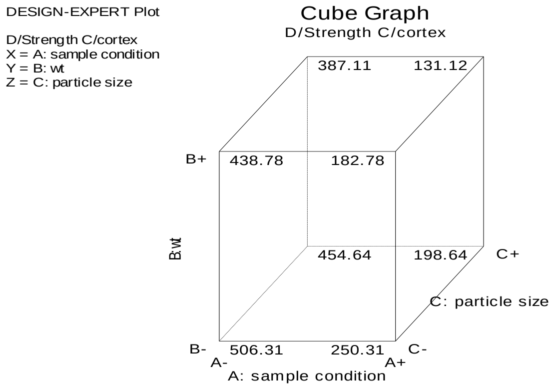

Fig. 4c: Cube plot of the effect of various parameters on Dielectric Strength of cassava cortex – epoxy composite [17].

Figure 4c: is the cube plot showing the three factors: Sample Condition (A), wt% (B) and Particle Size(C). The Dielectric strength of the CCtx was enhanced as you move from the +ve end (i.e. carbonized) to the –ve end (i.e. uncarbonized) of the A axis and as you move from the +ve end (i.e. 60wt %) to the –ve end (i.e. 40wt %)

of the B axis. This shows that the uncarbonized particles and the 40wt% reinforcement significantly improved the dielectric strength of the composite than the carbonized particles and 60wt% reinforcement. From the +ve end (i.e. 600microns) to the –ve end (i.e. 150microns) of the C axis, there was an increase in the dielectric strength of the samples, showing that smaller particle size has a significant effect on the dielectric strength of the cassava cortex. [17]

Table 2: shows the predicted values along with the actual experimental values in different experimental conditions. It is evident from the table that the actual experimental values are in close proximity with the predicted values.

ANOVA was used to determine the design parameters significantly influencing the dielectric strength. The ANOVA table revealed that the Model F-value of 42.50 implies the model is significant. There is only a 0.17% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case (sample condition)A and(wt%)B are the significant model terms (see Table 4) The "Pred R-Squared" of 0.8783 is in reasonable agreement with the "Adj R-Squared" of 0.9468 with a standard devation of 33.79and mean of 318.71.

5.0 CONCLUSION

A dielectric strength test was done on the formed composites and the following conclusions were made from the experimental analysis, modelling of results and discussions of our investigations:

1. Cassava cortex can be used as reinforcement into epoxy matrix for polymer composites production.
2. Increasing the filler fraction of CCtx particles from 40wt% to 60wt% decreased the dielectric strength of the composite.
3. Enhanced dielectric strength was obtained as the particle size additions decreased from 600µmto 150µm.
4. Enhanced dielectric strength was also obtained from the uncarbonized composites.
5. The main and the interaction effects of model parameters within the range of investigation ofCCtx epoxy composite can be studied effectively by factorial design technique.
6. Thedevelopedmathematicalmodelcanbeusedtopredictthedielectricstrengthintermsof the effect of carbonization, particle size and filler loading (wt%).
7. The results of the modeling are in good agreement with the experimental findings.

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