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Response Surface Optimization of the Impact Strength of Plantain Fiber Reinforced Polyester for Application in Auto Body Works

(pp 505-520)

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Abstract: The impact strength of plantain fiber reinforced polyester composites (PFRP) was evaluated to assess the possibility of using it as a new material in engineering applications. The study considered the controlling factors (notch tip radius (A) and notch depth (B)) of different reinforcement combinations in the determination of impact strength of the composites. This property was determined for plantain empty fruit bunch (PEFBF) and plantain pseudo stem (PPS). Impact tests were conducted on the replicated samples of PEFB fiber reinforced polyester composite and PPS fiber reinforced polyester respectively using Archimedes principles in each case to determine the volume fraction of fibers. To obtain the optimum properties being investigated, Charpy impact tester was used to establish the actual control factor levels needed to optimize the mechanical properties being investigated. These control factor levels were then applied to optimize the mechanical properties of plantain fiber composites using response surface methodology (RSM) of Design – Expert 8 software. The impact strength of plantain fiber reinforced polyester was evaluated as 167.851 KJ/m^2 for optimum performance.

Key Words: composite matrix, plantain fiber, response surface methodology, notch, design-Expert 8

INTRODUCTION

Plantains (Musa spp., AAB genome) are plants producing fruits that remain starchy at maturity (Marriot and Lancaster, 1983; Robinson, 1996) and need processing before consumption. Plantain processing and production in Africa is estimated at more than 50% of worldwide production (FAO, 1990). Comestible fruit production from Musaceas plants is an important economical activity in developing countries like Nigeria such that it generates a large amount of agro-industrial residues. Some of these wastes are a potential resource of natural fibers, which can be used as reinforcement for composite materials (Gañán, Zuluaga, Restrepo, Labidi and Mondragon, 2012); Nigeria being one of the largest plantain producing countries in the world (FAO, 2006). Plantain fiber can be obtained easily from the plants which are rendered as waste after the fruits have ripened.

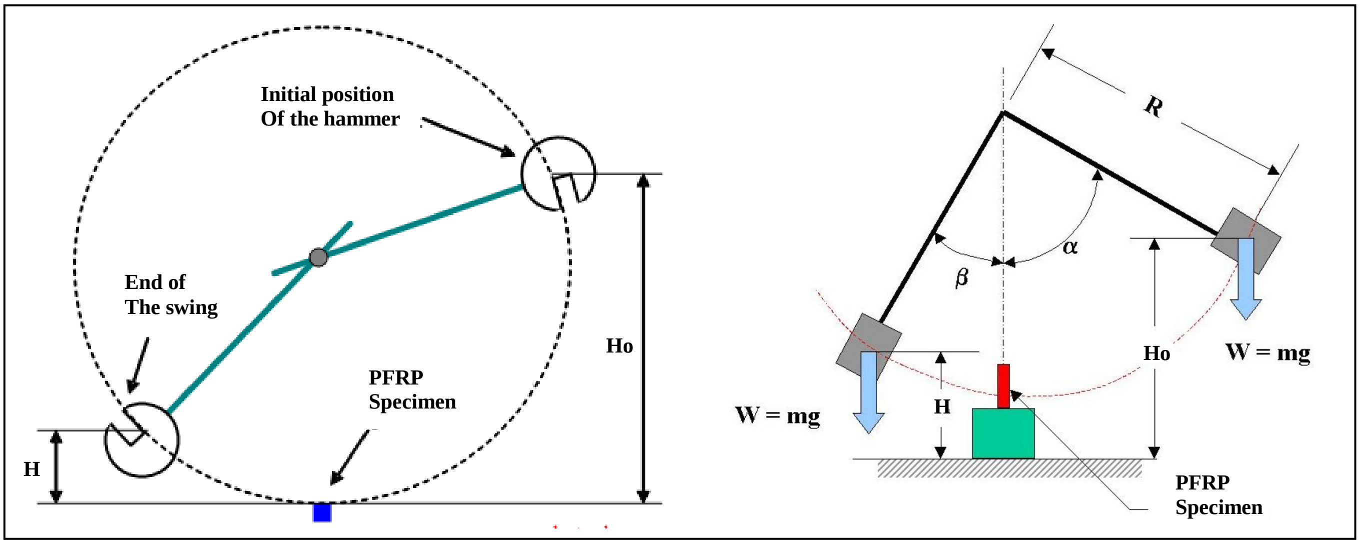
Impact strength is indicative of the toughness of the material, which is the ability of the material to absorb energy during plastic deformation. It is the resistance of a material to fracture under dynamic loads. Toughness therefore is an indication of the energy that a material can absorb before breaking and is usually measured by Izod and Charpy impact tests (Nielsen 1994). In a first order approximation, it can be said that notched impact energy is a measure of crack propagation and unnotched impact energy is a measure of both crack initiation and propagation. There are two standard methods to measure impact strength of materials. One is the Charpy impact test. Charpy V-notch tests are used to measure the fracture toughness of materials. The notched bar is subjected to an impact with a striker moving at about 5m/s.

Response surface methodology (RSM) is a collection of statistical and mathematical techniques useful to develop, improve and optimize processes and products (Myers and Montgomery, 2002). The objective of RSM is the investigation of responses over the entire variation domain of independent variables and the localization of regions of interest, in which the responses are optimal or very close to the optimal ones (Deepak et al.,2008). RSM also quantifies the relationship between the controllable input parameters and the obtained response surfaces (Montgomery, 2009). An important assumption is that the independent variables are continuous and controllable by experiments with negligible errors. The task then is to find a suitable approximation for the true functional relationship between independent variables and the response surface (Montgomery, 2009). The first requirement for RSM involves the design of experiments to achieve adequate and reliable measurement of the response of interest. An effective alternative to factorial design is central composite design (CCD), originally developed by Box and Wilson (1951) and improved upon by (Box and Hunter, 1957). CCD gives almost as much information as a three-level factorial, requires many fewer tests than the full factorial design and has been shown to be sufficient to describe the majority of steady-state process responses. Hence in this study, it was decided to use CCD to design the experiments.

With the increasing use of natural fiber reinforced composites in structural engineering applications it is becoming essential to have as complete an understanding as possible of the failure mechanisms. The study of fracture surfaces can lead to an understanding of the source of the fracture and the relation between the mode of crack propagation and micro structure of the material. This study therefore aims to investigate the effect of notch dept, notch tip radius and stress concentration factor on impact strength of PFRP using response surface methodology and classical experimental procedures. Plantain fiber was chosen in terms of its abundant availability and because plantain grows to its mature size in only ten months, whereas wood takes a minimum of 10 years (Xiaoya, Qipeng and Yongli, 1998).

THEORETICAL BACKGROUNDS

Impact tests determine impact toughness, a material property, most commonly by measuring the work required to fracture a test specimen under impact. The test is useful in the analysis and prediction of the behaviour of different material under impact stresses or dynamic loading. Impact test is used for measuring toughness of materials and their capacity of resisting shock. However, impact tests cannot directly predict the reaction of a material to real life loading; instead, the results are used for comparison purposes. In this test the pendulum swings up to its starting position (height H_o) and then it is allowed to strike the notched specimen, fixed in a vice as shown in figure 1. The pendulum fractures the specimen, spending a part of its energy



From figure 1 it can be shown that the initial energy can be expressed as

$$E_i = WR(1 - cos\alpha) \quad (1)$$

and energy after fracture can be expressed as

$$E_r = WR(1 - cos\beta) \quad (2)$$

while energy absorbed by specimen can be expressed as

$$E_{abs} = W\,R\,(cos\,\beta - cos\,\alpha) \quad (3)$$

The linear elastic stress concentration factor k_t is given by

$$K_t = 1 + 2\left(\frac{a}{r}\right)^{1/2} \quad (4)$$

where: r = the notch radius (mm) and a = the notch dept (mm), K_t = stress concentration factor (SCF)(Crawford, 1998).

METHODOLOGY

The methodology of this study employs traditional experimental and response surface method to optimize the impact strength of plantain fiber reinforced polyester composite, the factor settings was based on the results of Ihueze et al.,

(2012) for which Taguchi robust design was used to determine the optimal parameter settings. The response surface method (RSM) was then applied to estimate the transfer functions at the optimal region. The estimated function is then used to optimize the responses. The quadratic model, linear regression and ANOVA are therefore the tools for data analysis used for RSM of this study. Two-way ANOVA was used to investigate the effect of notch tip radius and notch depth on impact strength of PFRP. Null hypothesis was that notch tip radius, notch depth, and interaction of two factors did not affect impact strength of PFRP. A p-value of less than 0.05 was deemed to be statistically significant for the effects.

Plantain fiber extraction and Chemical treatment

The plantain fibers were mechanically extracted from both stem and empty fruit bunch. The fibers were soaked in a 5% NaOH solution for 4 hours. Alkali treatment is a chemical method which can change the constituents of fibers. The fibers were further treated with a solution of water and methanol (Saline treatment) in the ratio of 4:6 and then neutralized with dilute acetic acid in the ratio of 100:10 and finally washed with water. The resultant fibers were dried at 30^{o}C for 72 hours before the examination of the tensile test.

Determination of fiber Volume Fraction through Archimedes principle

Calculations of volume fraction of plantain fiber is achieved following the derivations from rule of mixtures based on the procedures of (Jones, 1998; Barbero, 1998) and implementation of Archimedes procedures in the determination of volume of fiber.

$$M_c = M_f + M_m \tag{5}$$

$$V_f = \frac{M_f}{\rho_f} \tag{6}$$

$$V_m = \frac{M_m}{\rho_m} \tag{7}$$

$$V_c = V_f + V_m \tag{8}$$

$$V_{fr} = \frac{V_f}{V_c} \tag{9}$$

$$V_{fr} = \frac{V_f}{V_f + V_R} \tag{10}$$

$$V_R = \left(\frac{1 - V_{fr}}{V_{fr}}\right) v_f \tag{11}$$

$$V_m = \frac{V_m}{V_c} \tag{12}$$

where

M_c = Mass of composite specimen, (g); M_f = Mass of plantain fiber, (g); M_m = Mass of matrix, (g); ρ_f = Density of plantain fiber, (g/m^3); ρ_m = Density of matrix, (g/m^3); V_c = Volume of composite specimen, (cm^3); V_m =

Volume of matrix, (cm^3); V_m = Matrix volume fraction; V_R = volume of resin; V_{fr} = volume fraction of fiber; V_f = volume of plantain fiber (cm^3) determined using Archimedes principle that the volume of water displaced is equivalent to the volume of fiber.

Because the calculation of the volume of an irregular object (such plantain fiber) from its dimensions is a mirage by traditional method, such a volume can be accurately measured by placing the object into water based on steps below. It follows from the Archimedes principle that the volume of the displaced water is equal to the object volume (Acott, 1999). The following steps lead to the estimation of volume fraction of fibers:

Step 1: The mass of a sizable quantity of plantain fiber lump (m_f) sample is determined using digital METLER$^{(R)}$ balance (Precision: 0.0001g) and then a small container (C_s) for which its density and mass is known or previously determined, is used to contain the fiber ensuring that the small container is completely filled with plantain fiber.

Step 2: A graduated glass cylinder was then filled with about 100 ml of water.

Step 3: Errors due to parallax was avoided by viewing the meniscus from a 0/180 degree angle, that is hold it up to eyes and then take the water volume measurement from the base of the curved water meniscus.

Step 4: The water volume from Step 3 is recorded and denoted as (V_0)

Step 5: The object (small container + fiber) is then placed into the cylinder. The water level will rise, noting that the object must be completely covered with water.

Step 6: Step 3 is repeated and denoting the new water level as V_1.

Step 7: The volume V_0 (Step 4) is subtracted from V_1 (Step 6) to calculate the volume of the object, such that

Volume of object (small container + fiber) = V_1-V_0 (13)

But the volume of water displaced (V_d) = [volume of fiber (V_f)] + [volume of small container (C_s)]

Therefore

$$Volume\ of\ fiber = \left(volume\ displaced - \frac{mass\ of\ small\ container\ \ (C_s)}{density\ of\ small\ container\ \ (\rho_s)}\right) \quad (14)$$

Step 8: Finally the density of plantain fiber is determined by dividing the fiber mass (Step 1) by its volume (Step 7).

Sample formation and determination of impact strength

Flat unidirectional arrangements of the fibers were matted using polyvinyl acetate as the bonding agent. They were arranged to a thickness of 1.2mm and dried at room temperature for 72 hours. The composite manufacturing method adopted for is based on open molding Hand lay-up processing technology in which the plantain fiber reinforcement mat is saturated with resin, using manual rollout techniques of (Clyne and Hull, 1996) to consolidate the laminate and removing the trapped air. A mild steel mold of dimensions (130×110×10) mm was used for casting the composites. At the time of curing, a compressive pressure of 0.05MPa was applied on the mould and the composite specimens were cured for 24 hours.

Replicate samples of plantain fibers reinforced polyester matrix were then subjected to impact tests using Charpy tester. The plantain stem and empty fruit bunch fiber reinforced composites were prepared for impact tests in according to ISO-180 standard. For the impact tests, a pendulum impact test machine was employed. According to the ISO 180, impact specimens were cut to a standard size of 55×10×10mm. Three replicate samples each were produced in two different groups, one of the groups containing samples with reinforcement made from fibers extracted from plantain empty fruit bunch and the other from fibers extracted from plantain stem fibers.

In both groups, three different notch depths of the specimen were prepared to be 2, 1.295 and 1mm. Tests were made over the service temperature range (26^0C±5) and the notched bars had a 45^0 notch at varying notch-tip radius of 1, 1.5 and 2. The specimen was clamped into pendulum impact test fixture with the unnotched side facing the striking edge of the pendulum. The pendulum was released and allowed to strike through the specimen. Energy absorbed is expressed in J or ft-lb. Impact strength is calculated by dividing impact energy in Joule by the at the notch section of the specimen (Crawford, 1998). The test result was typically the average of the three specimens.

Response surface methodology (RSM) and optimization of results

The design expert8 software was used to apply response surface methodology (RSM). The central composite design (CCD) of RSM was used to obtain the second order regression polynomial that optimizes the impact strength response of PFRP. RSM tries to fit a polynomial function of

$$y = \beta_o + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 \quad (15)$$

to data, where $\beta_1,\ \beta_2,\ \beta_n = main\ effects\ of\ associated\ factor\ factors, \beta_{12}, \dots \beta_{23} = iteraction\ effects\ of\ associated\ factors$

RESULTS AND DISCUSSIONS

The Charpy impact tester results are presented in tables 1 and 2.
The relevant data for implementation of RSM are presented in tables 3 and 4 where the response 1 of table 4 is obtained by performing multilinear regression analysis with experimental results to obtain the multilinear regression model of the form

IMPACT strength = 130 + 52.5 Notch tip radius - 72.9 Notch depth

The Coefficient of determination (R^2) of the Regression model is 1 establishing a perfect fit of the linear model to experimental data.

This equation is used with different factor combinations of table 4 to evaluate response 1 of table 4 of CCD.

Table 1: Experimental results of impact tests on empty fruit bunch fiber composite

Expt. No	Notch depth (mm)	crosshead Height (m)	Impactor weight [m kg)	Impact energy (joules)	impact angle (β)	Mean Impact strength (kJ/m^2)	Velocity (2 g a)$^{1/2}$ (m/s)	impact time (sec)	impact force (N)
1	1	1.55	3.94	86.61476	111.6	157.4374	5.567764	1.09	39.4
2	1	1.75	6.03	55.27597	124	100.4578	5.91608	1.30	60.3
3	1	1.93	9.97	8.267773	151	14.98831	6.21289	2.01	99.7
4	1.5	1.55	6.03	86.92972	110	158.01	5.567764	1.01	60.3
5	1.5	1.75	9.97	55.59093	122.5	101.0304	5.91608	1.04	99.7
6	1.5	1.93	3.94	8.503995	151.5	15.41781	6.21289	2.71	39.4
7	2	1.55	9.97	86.85098	110.3	157.8669	5.567764	1.03	99.7
8	2	1.75	3.94	55.27597	124	100.4578	5.91608	1.33	39.4
9	2	1.93	6.03	8.031551	151.6	14.55882	6.21289	2.64	60.3

Table 2: Experimental results of impact tests on pseudo stem fiber composite

Expt. No	Notch depth (mm)	crosshead Height (m)	Impactor weight (kg)	Impact energy (J)	impact angle (β)	Mean Impact strength (kJ/m^2)	Velocity (2 g a)$^{1/2}$ (m/s)	impact time (sec)	impact force (N)
1	1	1.55	3.94	86.92972	110	158.01	5.567764	1.09	39.4
2	1	1.75	6.03	55.66967	124.5	101.1736	5.91608	1.33	60.3
3	1	1.93	9.97	8.031551	150.02	14.55882	6.21289	2.41	99.7
4	1.5	1.55	6.03	86.77224	111	157.7237	5.567764	1.00	60.3
5	1.5	1.75	9.97	62.99255	121.9	114.4879	5.91608	1.01	99.7
6	1.5	1.93	3.94	8.267773	150.9	14.98831	6.21289	2.51	39.4

7	2	1.55	9.97	86.81161	110.8	157.7953	5.567764	1.03	99.7
8	2	1.75	3.94	55.74841	122	101.3167	5.91608	1.33	39.4
9	2	1.93	6.03	7.874069	151	14.27249	6.21289	2.64	60.3

Table 3: Factor Settings for a two factor experiment

Factor	Name	Units	Minimum	Maximum	Coded Values	Mean	Std. Dev.
A	Notch tip Radius	mm	0.792893	2.207107	-1.000=1.00 1.000=2.00	1.5	0.377964
B	Notch Depth	mm	0.73284	2.03816	-1.000=0.92 1.000=1.85	1.3855	0.348861

Table 4: Central composite design(CCD)Matrix and Results

Std	Run	Block	Factor 1	Factor 2	Response 1
			A:Notch tip Radius Mm	B:Notch Depth mm	Impact Strength KJ/m2
2	1	Day 1	2	0.924	167.8509
6	2	Day 1	1.5	1.3855	107.9383
4	3	Day 1	2	1.847	100.5384
5	4	Day 1	1.5	1.3855	107.9383
3	5	Day 1	1	1.847	48.02568
7	6	Day 1	1.5	1.3855	107.9383
1	7	Day 1	1	0.924	115.3382
10	8	Day 2	1.5	0.73284	155.5355
14	9	Day 2	1.5	1.3855	107.9383
11	10	Day 2	1.5	2.03816	60.34115
9	11	Day 2	2.207107	1.3855	145.0704
12	12	Day 2	1.5	1.3855	107.9383
13	13	Day 2	1.5	1.3855	107.9383
8	14	Day 2	0.792893	1.3855	70.80622

The CCD has been applied using Design expert8 software to optimize the impact strenght of PFRP and the accuracy of the model obtained is very acceptable. From the ANOVA table of table 5, the Lack of Fit test gave a relatively large F-value (63660000), this means that the model fits the data well. The Lack of Fit residual is the estimation of the variations of the terms that are not included in the model. If its amount is close to the pure error, which is the within-run variation, it can be treated as part of the noise. Another way to check the model accuracy is to check the residual plots (figure 5).

Figure 3 shows that the maximum standard error of design is about 0.8 and it occurs when the actual control factors are at their maximum setting.

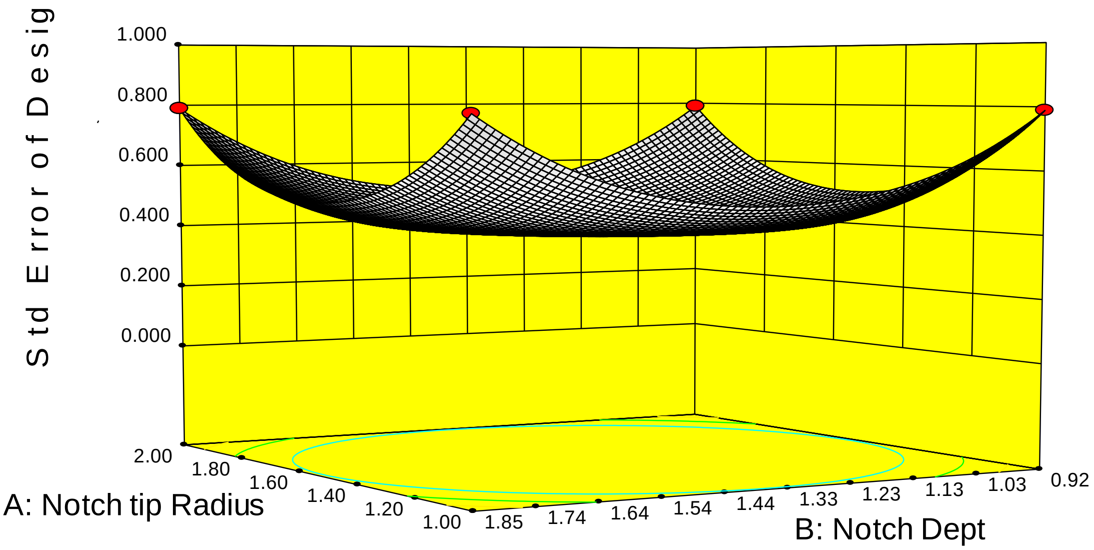


Figure 3: Design- expert8 response surface depiction of standard error of design as a function of Notch tip radius (A) and Notch depth (B).

Table 5: ANOVA table for response surface model results

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Block	0	1	0			
Model	14577.12	5	2915.425	63660000	< 0.0001	Significant
A-Notch tip Radius	5515.167	1	5515.167	63660000	< 0.0001	
B-Notch Dept	9061.957	1	9061.957	63660000	< 0.0001	
AB	0	1	0			
A^2	0	1	0			
B^2	0	1	0			

Residual	0	7	0
Lack of Fit	0	3	0
Pure Error	0	4	0
Cor Total	14577.12	13	

The Model F-value of 63660000.00 shown in the ANOVA of table 5 implies the model is significant, There is only about 0.01% 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 A, B, AB, A^2, B^2 are significant model terms. The residuals of the model are approximately normally distributed and the variance of the residuals is homoscedastic (i.e. they lie between two parallel lines). The regression model, in terms of the coded and actual factors, is as presented in equations 16 and 17. The "Pred R-Squared" of 1.0000 is in reasonable agreement with the "Adj R-Squared" of 1.0000.

The RSM model in terms of coded and actual factors are given respectively in equation (16) and (17) as

Impact Strenght = $107.94+26.26A-33.66B+0.000AB+0.000A^2+0.000B^2$ (16)

Impact Strenght = $130.21100+52.51270A-72.92800B+1.62658E-013AB-1.83458E-012A^2-6.62562E-014B^2$ (17)

The two models show that the impact strength increases with notch tip radius and decreases with increasing notch depth. Neglible interaction effects are also shown by the coefficient of AB in the models. The coeffient of A in the model representing the main effects of A shows that factor A has the highest influence on impact strength.

The plot of the predicted versus actual values, shown in Figure 4, indicates the very good agreement between the response surface model and the actual values. The residuals from the least squares fit play an important role in judging model adequacy (Myers and Montgomery, 2002).

Figure 5 shows response surface plot of probability of residuals as a function of internally studentized residuals. It shows that error measurement between actual value and model predicted values are zero and constant. It is also an indication normally distribution.

By constructing a normal probability plot of the residuals, a check was made for the normality assumption. The normality assumption was satisfied as the residual plot approximated along a straight line, so we conclude that the empirical model is adequate to describe the impact behavior of PFRP by response surface.

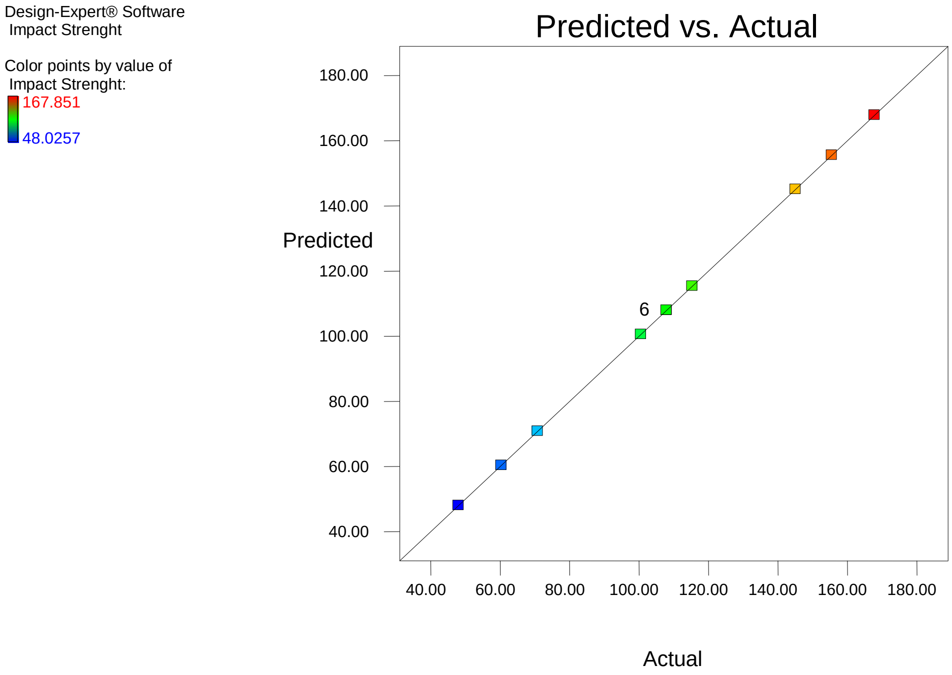


Figure 4: Response surface method depiction of model predicted values and the value of actual factor

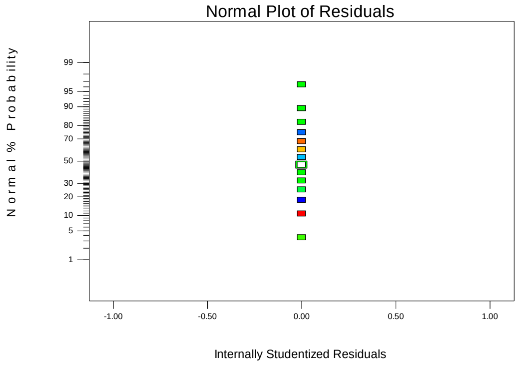


Figure 5: Design- expert8 response surface plot of probability of residuals as a function of internally studentized residuals

Figures 6 is the response surface contour plots of impact strength in terms of actual factors A and B showing occurrence of maximum tensile strength with table 4 at maximum setting of notch tip radius 2 and minimum setting of notch depth of 0.92 as 167.851 KJ/m^2 and a mean response of about 107.9383KJ/m^2.

The response surface plot of figure 7 is a clear depiction that the notch depth influences the impact strength, and the strength is at maximum when the notch depth is set at 0.92 and notch radius at 2. Also impact strength was found to increase with notch tip radius and decreases with notch depth.

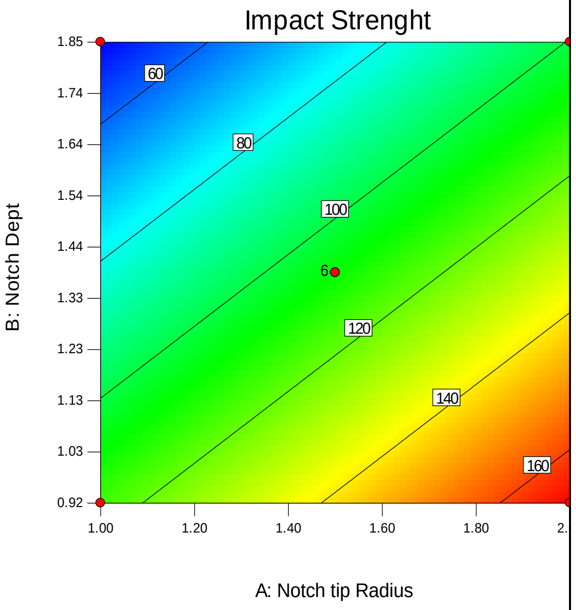


Figure 6: Design expert8 Contour plot presentation of PFRP impact results

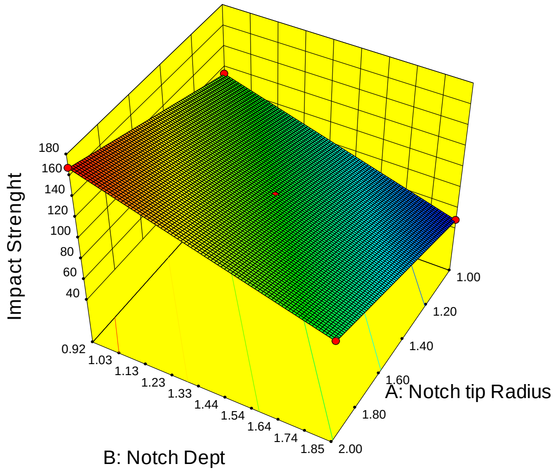
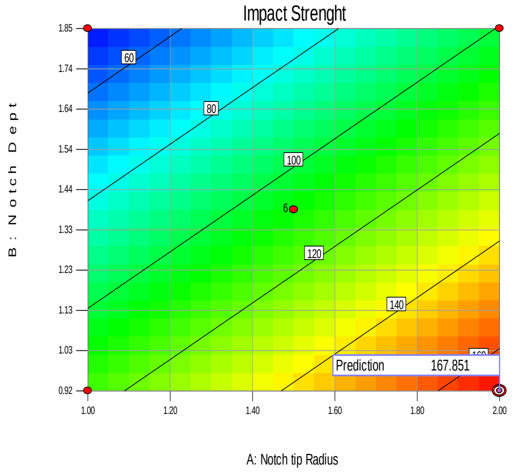


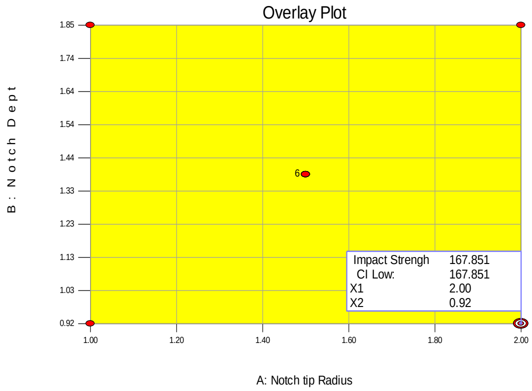
Figure 7: Design expert8 3D Surface plot of factor interaction effects on impact strength.

OPTIMIZATION OF PLANTAIN FIBER REINFORCED POLYESTER COMPOSITES IMPACT STRENGTH

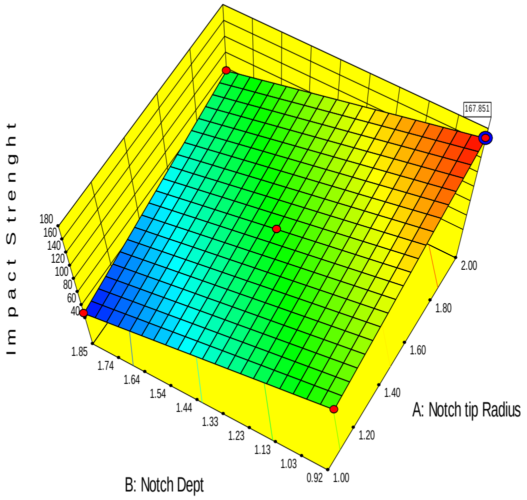
The overlay plot of figure 8a, contour plot of figure 8b and 3D plot of figure 8c of design expert8 optimum design output on impact strength of PPFRP show that the impact strength increases with notch tip radius, the impact strength decreases with notch depth. Also shown are optimum notch tip radius of 2mm, notch depth of 0.92mm and impact strength of 167.851KG/mm^2.



(a)



(b)



(c)

Figure 8: Design expert8 optimum design responses

Figure 9 and figure 10 show the effect of the notch depth and the notch tip radius on impact strength of various reinforcement combinations of PFRP (volume fractions of 45%, 50%, 55% and 60%). The impact strength also was found to increase with increasing notch tip radius and to decrease with increasing notch depth. This assertion was obeyed by most composites except that with 60% volume fraction, with composite of 50% volume fraction showing highest strength.

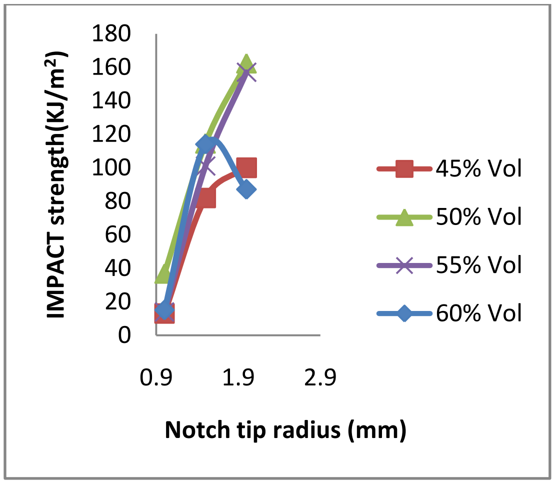


Figure 9: Variation of impact strength with notch tip radius for different fiber loading

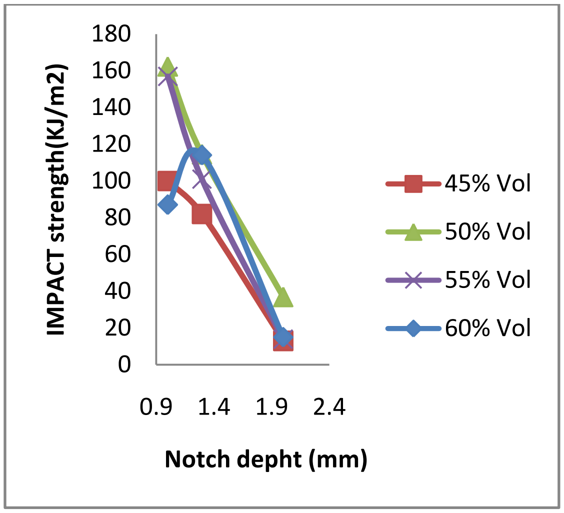


Figure 10: Variation of impact strength with notch depth

The influence of impact angle on impact strength is exhibited in figure 10.

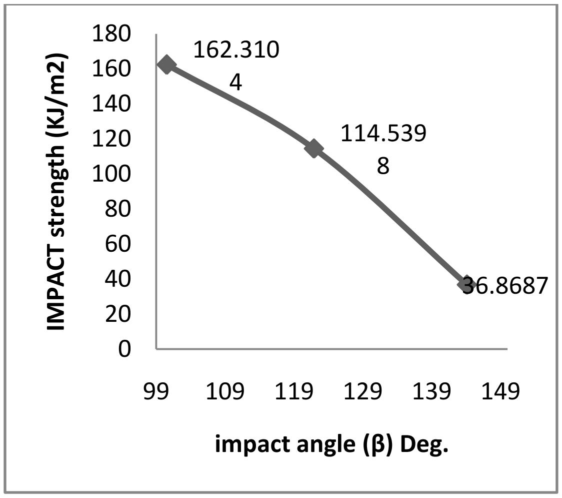


Figure 11: Variation of impact strength with impact angle

Three different notch lengths were converted to stress concentration factor using Equation (10) and stress concentration factor was found to have a linear relationship with impact strength and break energy of PFRP. Figure 12 shows that as stress concentration factor increases, impact strength and break energy of PFRP decreased.

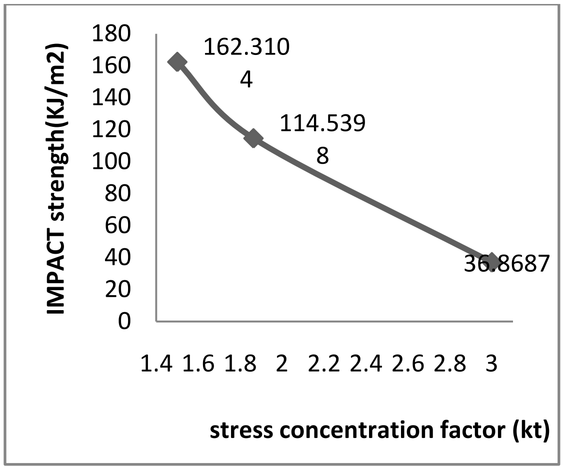


Figure 12: Variation of impact strength with stress concentration factor

CONCLUSIONS

The following deductions follow:

1. The impact strength of plantain fiber reinforced polyester matrix composite (PFRP) have been extensively studied and was found to increase with increasing notch tip radius and decreasing notch depth.
2. It was also found that an optimum value of impact strength occurs at notch tip radius of 2mm, notch depth of 0.92mm when the volume fraction of fibers is 50%.
3. Impact strength decreases with increasing stress concentration.
4. The quadratic response model of the impact strength response established showed negligible interaction effects of the factors within the model.
5. The impact strengths of plantain fiber reinforced polyester were evaluated as 167.851 KJ/m^2 for optimal response respectively for PEFBF and PPSF.
6. The impact strength model of PFRP is of the form

$$y = \beta_o + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3$$

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