Prediction of Mechanical Properties of Natural Fibers Reinforced Polymer Composites

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Abstract

The objective of this present study is to assess and predict the mechanical properties of polymer composites reinforced with a natural ligno-cellulosic fiber extracted from cotton shell. The mechanical properties of Cotton Shell Fiber (CSF) reinforced epoxy composites, prepared with different CSF weight proportions and particle size, are experimentally evaluated and also the prediction of mechanical properties has been performed by using Multiple Regression Analysis. The required mechanical tests are conducted as per ASTM standards. The properties like, Tensile strength, Flexural strength and Hardness are enhanced with the addition of CSF particles and the reduction of the fiber size, whereas the impact strength decreases. The Analysis of variance (ANOVA) is also used to determine the design parameters which significantly influence the mechanical properties. The comparison of experimental and the predicted values show that both have good resemblance with each other.

Keywords: *Cotton Shell Fibres, Mechanical Properties, Regression analysis, ANOVA, Input parameters.*

1. Introduction

Composite materials are employed to generate special physical and mechanical property materials for various applications which are utilized to generate materials embedded with high strength and light weight. In fact, inquisitive investigators have spent a lot of sweat and blood on research for the purpose of ushering in diverse composite materials to evaluate the composite material applications.

Latest research reports of polymer based composite materials have established various approaches for polymer formulations and have permitted the production of innovative products with ideal properties for distinctive application [1]. During the past decade, natural fiber reinforced polymer composites are attaining most convenient applications in sea vehicles, various parts of automotive, medical devices, sporting goods and aerospace industry, due to their classical merits like lesser weight, minimum cost, resistance to corrosion and wear and elevated specific strength etc.[2]. The mechanical properties of natural hybrid fibers reinforced polyester composites are analysed according to their weight proportion and length of fibers [3]. Empirical models have been developed for assessing the mechanical properties and morphology of composites prepared by Recycled Low Density PolyEthylene (RLDPE) reinforced with snail shell particles of different weight percentages and sizes [4].

An empirical, statistical method and theoretical or analytical methods are followed in general for predicting the response parameters [5]. A study has been conducted to develop a statistical method for evaluating the value of cotton using High Volume Instrument (HVI) to calculate cotton fiber properties [6]. Prediction of surface roughness in drilling of Glass Fiber Reinforced Polymer (GFRP) composite materials has been done with fuzzy logic rule–based modelling and ANOVA [7]. Mechanical performance of Roselle Fiber-Reinforced Vinyl Ester (RFRVE) composites is investigated experimentally and after that, the optimization of process variables in accordance to mechanical properties of RFRVE composite is carried out by employing the grey based-Taguchi method [8].

A linear regression model has been suggested for computing correlated records and establishing the attribute values from huge materials databank. This procedure identifies the connection between two sub properties of mechanical property of various kinds of materials and also helps to forecast the properties of strange materials [9].

Using multiple linear regression analysis, the yarn parameters of ring spun cotton yarns are predicted and confirmed that yarn properties were affected by fiber properties, number of yarns, twist and roving properties [10]. The mechanical behaviour of the plain and woven fabric reinforced composites is examined and the reports exhibit that the weaving arrangement influences the tensile and impact properties of the composites [11]. Innovative mathematical models have been developed by using non-linear regression procedure for the estimation of concrete compressive strength at various age levels [12]. The new natural lignocellulosic CSF particles have much potential to manufacture polymer composites for interior and exterior automotive parts.

Authors published Comparative analysis of regression and ANN models for predicting the physical property of jute – banana fiber reinforced epoxy composites [13].

The investigations of mechanical properties of the Cotton Shell Fiber (CSF) particles reinforced with epoxy composites have not yet been performed as per the detailed literature review. The objective of the present study is to assess and predict the mechanical properties of polymer composites reinforced with a new natural lingo-cellulosic fiber extracted from cotton shell. The required tests are conducted as per ASTM standards. Also, in this investigation, a statistical model has been established to predict the mechanical properties of the composites using Multiple Regression Analysis.

2. Mechanical testing of CSF reinforced composites

The Epoxy resin and CSF particles composites have been developed by mixing Epoxy resin and CSF particles with different weight % combinations and different sizes of CSF particles. They are given in Table 1 and Table 2, respectively.

Different composites of various Epoxy resin and CSF contents by weight and particle size are prepared. The suitable dimensions of specimen are prepared according to the size and shape, as per ASTM Standards, using diamond cutter.

Table 1 Data variable of constituents

Sl.No.	Composite	Epoxy Resin % (wt)	CSF particles % (wt)
1	W1	90	10
2	W2	80	20
3	W3	70	30

Table 2 Data variable of CSF particles size

Sl.No.	Composite	Size of CSF particles (μm)
1	S1	180
2	S2	150
3	S3	125

3. Prediction of Mechanical Properties

The prediction of mechanical properties of CSF reinforced epoxy composites are explained.

3.1 Design of Experiments

A Taguchi based Design of Experiment (DOE) has been performed for the superior prediction of the mechanical properties in connection with the input variables. In this study, an L9 orthogonal array (2 parameters and 3 levels) type DOE is used. MINITAB 14 is used for conducting the DOE. The input and output parameter data matrix is exhibited in Table 3. An analysis of variance (ANOVA) has been carried out for identifying the correlation among the parameters and for verifying the statistical model.

3.2 Statistical Model

In social behavioural sciences and in the physical sciences, the widely used reliable statistical technique is the regression analysis. In order to state clearly the dependence of output variables on various independent constituent variables, the outstanding choice is the Multiple Linear Regression analysis. Statistical models have more fascination that once they have been formatted, they can be used to carry out predictions faster than other modeling techniques, and it is also quite easy to execute in software. Many research attempts have focused on using the Multivariable Regression model to enhance the preciseness of predictions [12].

Table 3 Data Matrix for Mechanical properties of different composites

Experiment				Experimental output parameters			
Sl. No.	Input parameter combination						
	Epoxy Resin Weight (E) %	CSF particles weight (W) %	Size of CSF particles (S) µm	Tensile Strength (MPa)	Flexural Strength (MPa)	Hardness (HB)	Impact Energy (J)
1	90	10	180	16.76	76.92	24	0.428
2	80	20	180	17.50	98.14	25	0.382
3	70	30	180	19.73	102.76	30	0.369
4	90	10	150	18.82	79.99	32	0.532
5	80	20	150	20.51	98.23	33	0.467
6	70	30	150	24.39	103.8	35	0.414
7	90	10	125	22.27	80.73	37	0.658
8	80	20	125	26.22	88.90	38	0.461
9	70	30	125	27.73	114.6	38	0.366

3.3 Linear Regression Model

The regression models with one dependent parameter and more than one independent parameter, is termed as multiple or multivariate regression analysis. The Multiple linear regression analysis has been conducted in MINITAB 14 for enhanced understanding of the influences of CSF parameters on the mechanical properties and regression equation is also established for the prediction of various mechanical properties.

3.4 Multiple Regression Analysis (MRA)

In this work, the MRA has been used for the prediction of various mechanical properties like tensile strength, flexural strength, hardness and impact strength. The developed regression equations (1), (2), (3) and (4) respectively, for the tensile strength, flexural strength, hardness and impact strength are as follows.

$$\text{Tensile strength} = 37.2 + 0.233 \times W - 0.134 \times C \quad (1)$$

S = 0.9657 R-Sq = 95.3% R-Sq(adj) = 93.8%

$$\text{Flexural Strength} = 71.9 + 1.39 \times W - 0.0391 \times C \quad (2)$$

S = 5.0383 R-Sq = 88.5% R-Sq(adj) = 84.6%

$$\text{Hardness} = 60.5 + 0.167 \times W - 0.207 \times C \quad (3)$$

S = 1.3335 R-Sq = 95.2% R-Sq(adj) = 93.6%

$$\text{Impact Energy} = 0.894 - 0.00782 \times W - 0.00188 \times C \quad (4)$$

S = 0.0542 R-Sq = 75.0% R-Sq(adj) = 66.6%

where

- W represents the CSF particle weight proportion in the composite system
- C represents the Size of the CSF particle in the composite system

The coefficient of determinations (R^2 value) attained for tensile, flexural, hardness and impact strength are 0.953, 0.885, 0.952 and 0.750, respectively. R^2 value is a statistical measure of confirmation of closeness between experimental and predicted data.In other words, the deduced models have greater correlation with the experimental values. Apart from impact strength, the other R^2 values point out that the less amount of deviation is perceived in the acquired data. The suitability of the established model is verified by residual analysis. The normal probability graph of residuals for tensile strength is presented in Figure 1 (a). It also reveals the comparison of data sets and normal distribution. Further, this graph verifies the normality assumptions and exhibits a lesser degree of variability in the tensile strength values obtained from the experiments. Another graph of residuals against the fitted values (predicted response values) is presented in Figure 1 (b), which promises the appropriateness of the deduced model for tensile strength.

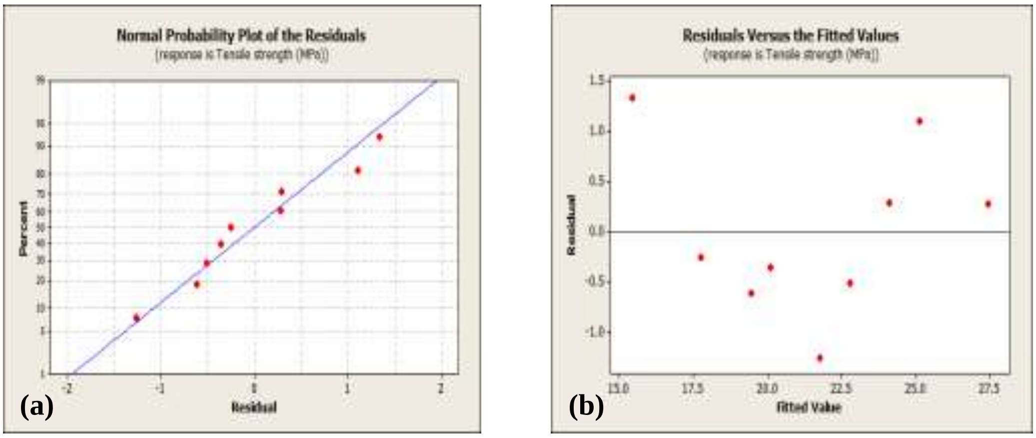

Figure 1 Residual analysis in tensile strength (a) normal probability plot of the residuals, and (b) the residuals versus the fitted (predicted response) values

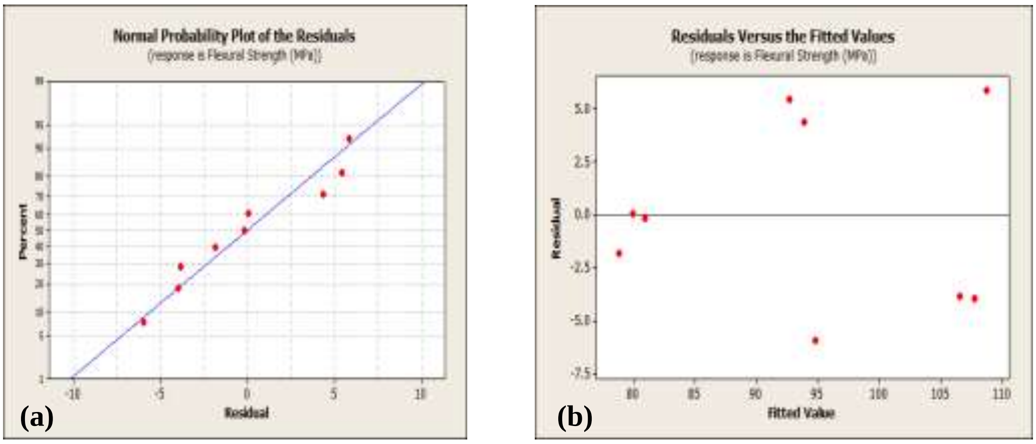

Figure 2 Residual analysis in flexural strength (a) normal probability plot of the residuals, and (b) the residuals versus the fitted (predicted response) values

Similarly, Figures 2 (a) and (b), 3 (a) and (b) and 4 (a) and (b) show the normal probability graph of residuals and the graph of residuals against the fitted values (predicted response values) for flexural, hardness and impact energy, respectively.

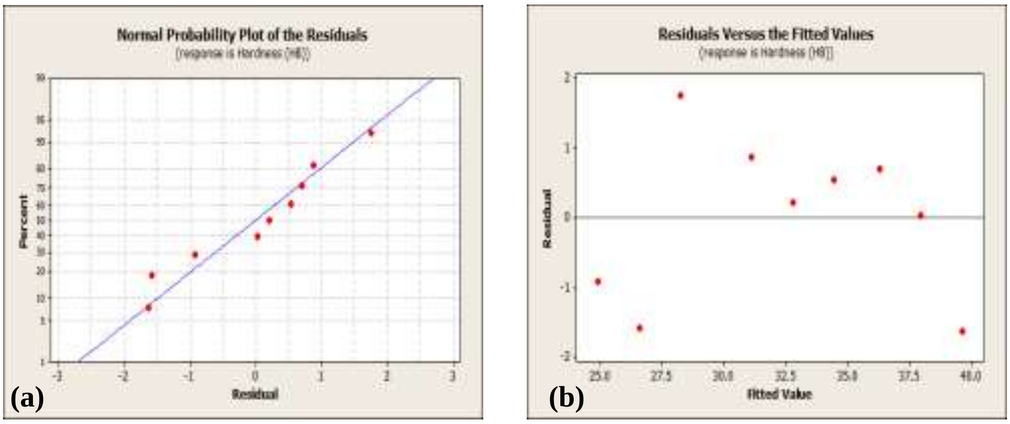

Figure 3 Residual analysis in hardness (a) normal probability plot of the residuals, And (b) the residuals versus the fitted (predicted response) values

The CSF particle weight percentage has the positive effect for the tensile strength, flexural strength and hardness but for impact strength, both CSF particle weight percentage and size have negative effect. The values of the mechanical properties recorded from the conducted experiments and those estimated from the linear regression equations are charted in Figures 5 to 8, for tensile, flexural, hardness and impact energy respectively. Based on the graph, it can be perceived that there is no much variation among the experimental values and the predicted values obtained from linear regression model.

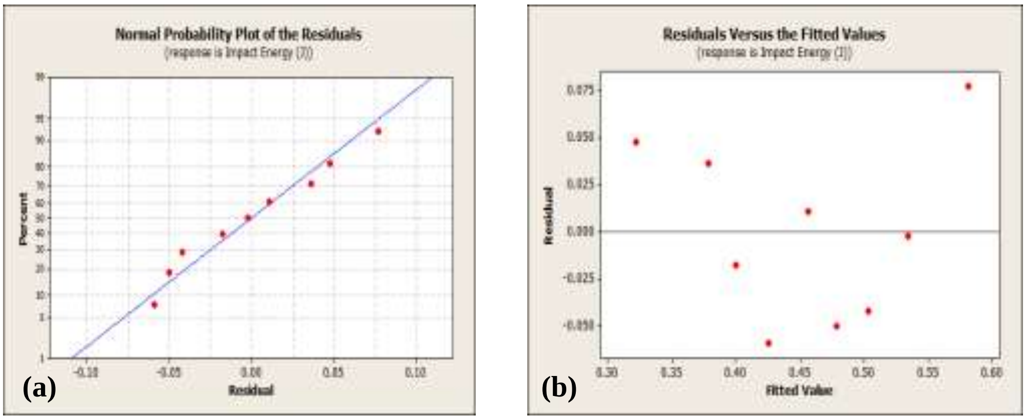

Figure 4 Residual analysis in impact energy (a) normal probability plot of the residuals, and (b) the residuals versus the fitted (predicted response) values

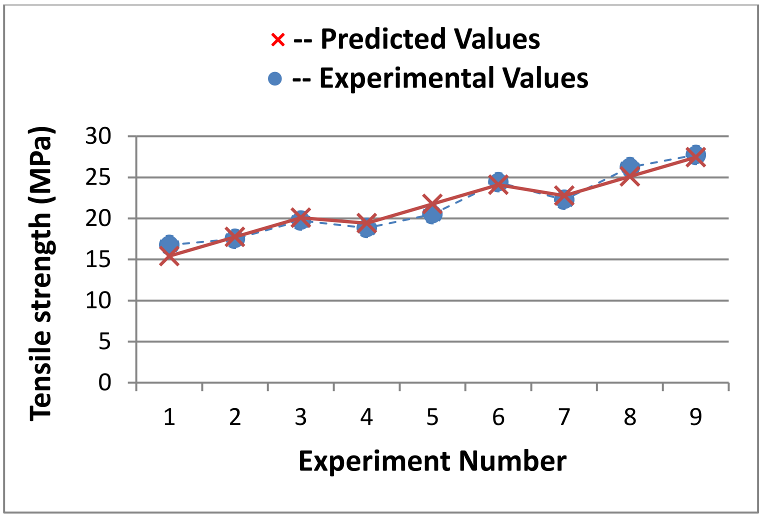

Figure 5 Comparison of tensile strength values

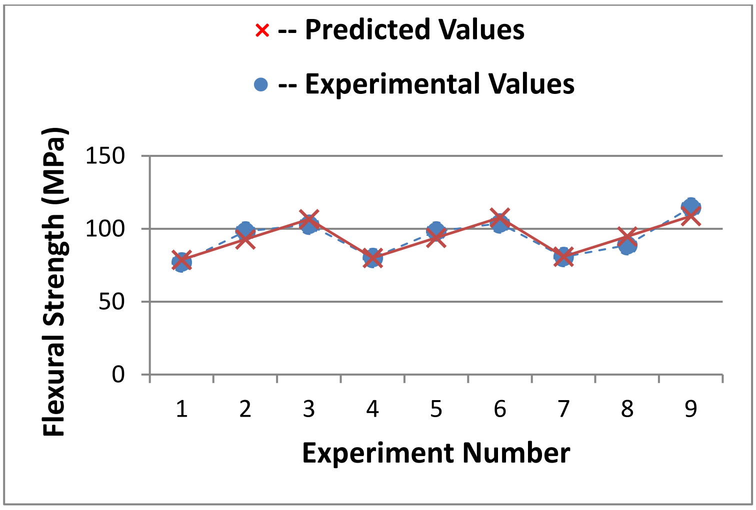

Figure 6 Comparison of flexural strength values

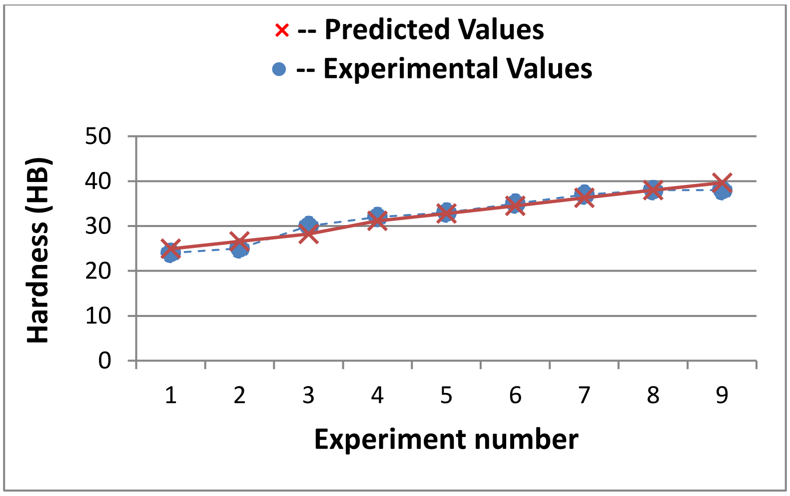

Figure 7 Comparison of hardness values

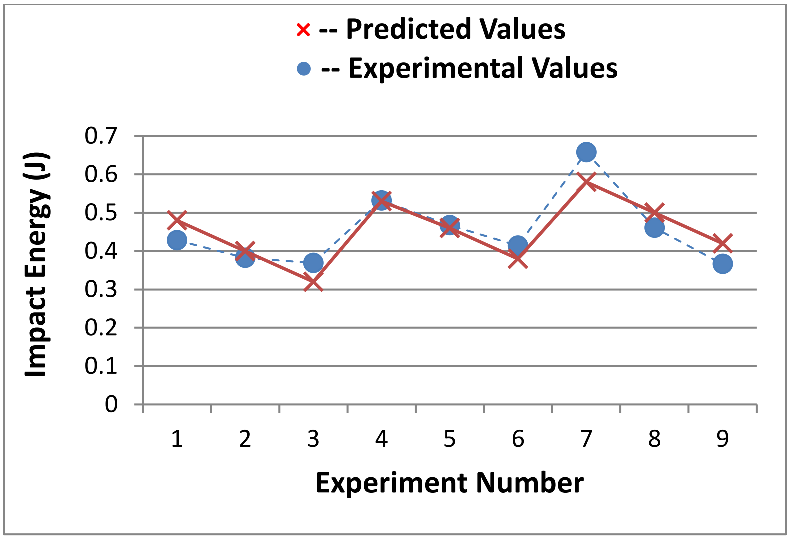

Figure 8 Comparison of impact energy values

4. Analysis of Variance

The Analysis of variance is used to determine the design parameters which significantly influence the tensile, flexural, hardness and impact strengths. They are exhibited in Tables 4, 5, 6 and 7, respectively. The analysis is evaluated at confidence level of 95 %, that is the significance level is α=0.05. The last columns of the Tables 4 to 7 show the contribution (P) of each parameter on the response, and it implies the degree of influence on the results. Since the difference between the experimental and predicted values is less, the predicted model is much significant [14]. Positive coefficient of input parameter indicates that if their magnitude elevates, the corresponding dependent parameter will also enhance whereas the negative coefficient of the input parameter imparts the reverse effect on the dependent parameter.

4.1 Influence of Input Parameters

The influence of the input parameters, CSF particle content and size of the particle, on the mechanical properties of CSF reinforced epoxy composites are determined and exhibited in the respective graphs.

Table 4 ANOVA table for Tensile strength

Source	DF	Seq SS	Adj SS	Adj MS	F	P
CSF particle weight proportion(W)	2	5.19	5.19	2.6	21.77	0.007
Size of CSF particle (S)	2	13.33	13.33	6.66	55.88	0.001
Error	4	0.48	0.48	0.12		
Total	8	18.99				

The influence of input parameters while carrying out the tensile test of CSF reinforced composite are given in Figure 9, and from the graph it is evident that the CSF particle size influence more in progressing the tensile strength than the CSF particle content.

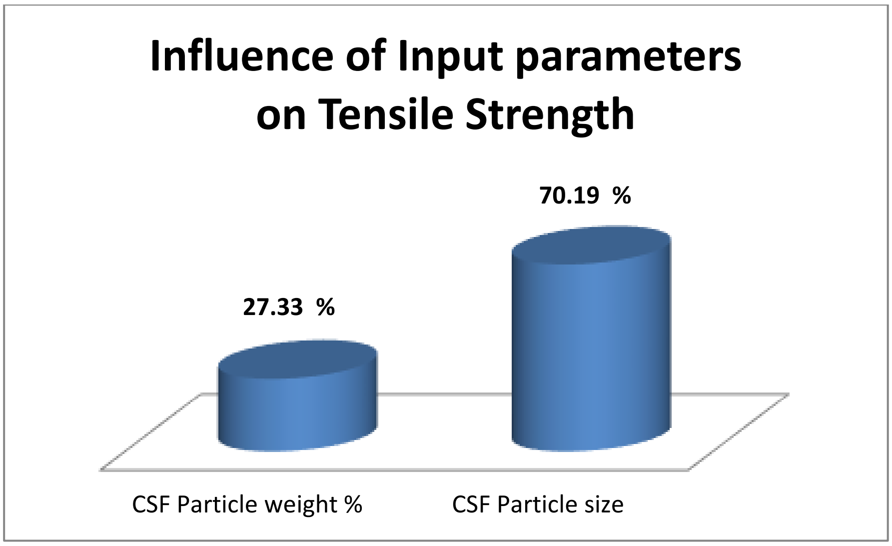

Figure 9 Influence of Input parameters on tensile strength

The influence of input parameters while carrying out the flexural test of CSF reinforced composite are given in Figure 10, and from the graph it is evident that the CSF particle weight content influence more in augmenting the flexural strength compared to CSF particle size.

Table 5 - ANOVA table for Flexural strength

Source	DF	Seq SS	Adj SS	Adj MS	F	P
CSF particle weight proportion(W)	2	10.35	10.35	5.18	18.93	0.009
Size of CSF particle (S)	2	0.05	0.05	0.03	0.09	0.914
Error	4	1.09	1.09	0.27		
Total	8	11.49				

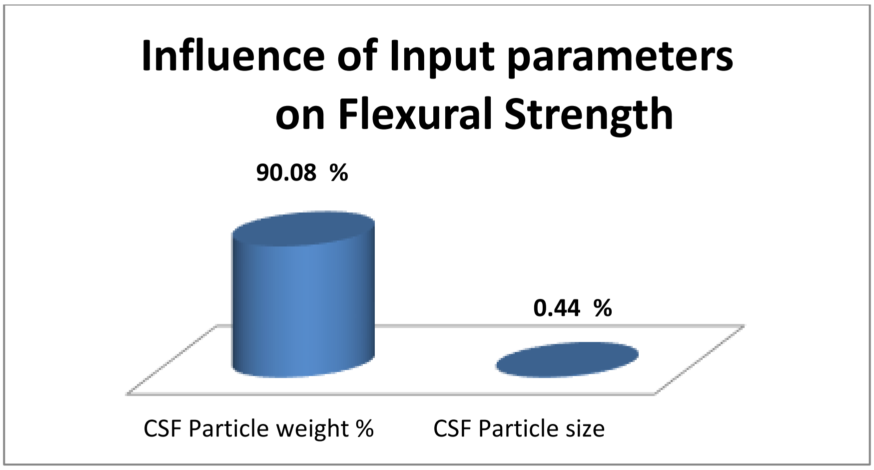

Figure 10 Influence of Input parameters on flexural strength

The influence of input parameters while carrying out the hardness test of CSF reinforced composite are given in Figure 11, and from the graph it is evident that the CSF particle size influence more in enhancing the hardness value than the CSF particle content.

Table 6 - ANOVA table for Hardness

Source	DF	Seq SS	Adj SS	Adj MS	F	P
CSF particle weight proportion(W)	2	1.53	1.53	0.77	3.25	0.145
Size of CSF particle (S)	2	15.40	15.40	7.70	32.61	0.003
Error	4	0.94	0.94	0.24		
Total	8	17.88				

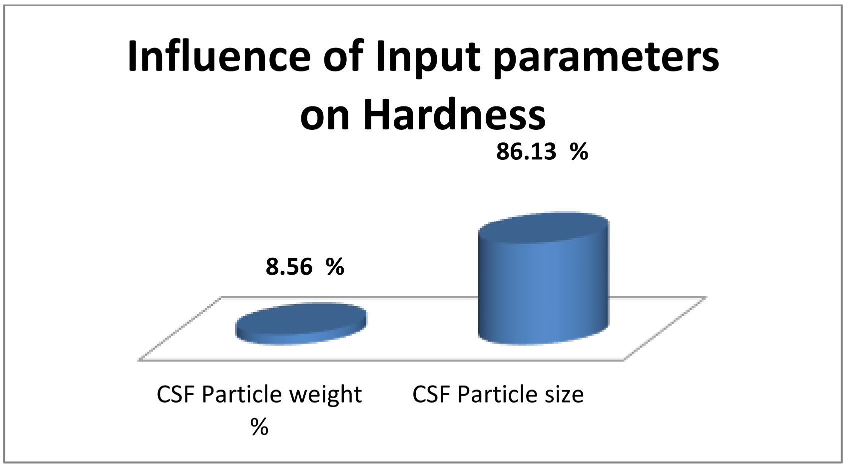

Figure 11 Influence of Input parameters on hardness

The influence of input parameters while carrying out the impact test of CSF reinforced composite are given in Figure 12, and from the graph it is evident that the CSF particle weight content influence almost twice in decreasing the impact energy compared to CSF particle size.

Table 7 ANOVA table for Impact energy

Source	DF	Seq SS	Adj SS	Adj MS	F	P
CSF particle weight proportion(W)	2	12.41	12.41	6.20	6.13	0.061
Size of CSF particle (S)	2	5.55	5.55	2.78	2.74	0.178
Error	4	4.05	4.05	1.01		
Total	8	22.01				

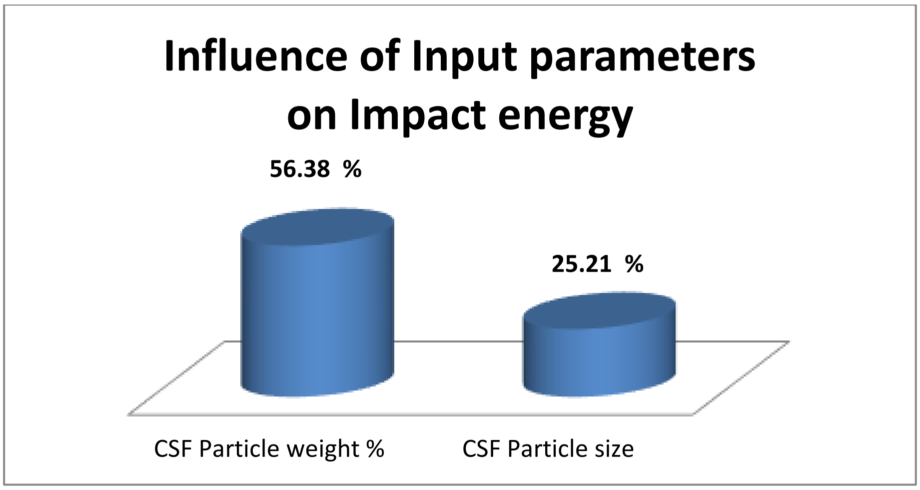

Figure 12 Influence of Input parameters on impact energy

5. Conclusions

The effects of cotton shell particles reinforced epoxy composites have been investigated as a function of CSF particles loading and size. They confirm that the tensile strength, flexural strength and hardness, increase with the increase of fiber content and the reduction in fiber size. But, the impact strength decreases with the addition of fiber content and the fiber size is reduced. This means that tensile, flexural and hardness are dependent on the content and size of the CSF particles, but impact strength is independent of content and size of the CSF particles. The developed linear regression model has proved that it is a decent potential to model the mechanical properties of CSF particles reinforced polymer composites. The resemblance between the experimental and predicted values exhibits that they are in positive concord.

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