

Determination of Fatigue Limit of Coir/CNT/Fly Ash Reinforced Epoxy Polymer Matrix Composite

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Abstract

In the quest of new material development, polymer matrix composite plays prominent role. Instead of reinforcing synthetic material in the polymer composite, an attempt is made in this work to reinforce green/recyclable/reusable materials in the polymer composite. Composite specimens are made with epoxy as matrix and coir/CNT/fly ash as reinforcements. The influences of wt.% of coir/CNT/fly ash on fatigue behavior of composite are determined. Response Surface Methodology (RSM), a Design of Experiments (DOE) approach is followed in specimen preparation and testing. ANOVA is used to find the influences of different parameters such as wt.% of coir/CNT/fly ash on fatigue behavior of composite. Optimized levels of parameters are also found out.

Keywords

polymer matrix composite, fatigue limit, Response Surface Methodology, Design of Experiments

1 Introduction

Increase in the innovation during the time of world wars in past century led us to the daunting situation in the present like increase in the amount of non-recyclable plastics on land and water murdering the flora and fauna, polluting every source of energy. Material like plastic or composite is needed which can fulfill our demands and that is also perishable in the environment without leaving hazardous waste. Consequently natural fibers come into the picture. These fibers are very ubiquitous to use that comes with economical cost, low density, environment friendly nature and CO₂ neutrality. These natural fiber composites can be used in distinct area where deduction in weight is highly required keeping ecology in mind.

Many investigations/studies are reported in the literature about use of Coir, Carbon Nano Tubes, Fly Ash and Sisal as reinforcements in polymer matrix composites. Coconut Fiber (Coir) is a natural fiber obtained from the outer covering of coconut. The coir fiber is relatively waterproof, and is one of the few natural fibers which offer resistant to damage by saltwater. The coir fiber is elastic enough to twist without breaking and it holds a curl as though permanently waved. Pandi et al. [1] concluded that the use of coir in the concrete increases compressive strength and split tensile strength as compared to the conventional

concrete. Ali and Chow [2] studied the viability of using coconut-fiber ropes as vertical reinforcement in mortar-free low cost housing in earth quake prone regions. The study concluded that the pull out energy increases with an increase in embedment length, rope diameter, cement and fiber content in the matrix. Ali et al. [3] studied the influences of 1 %, 2 %, 3 % and 5 % fiber contents at fiber lengths of 2.5, 5 and 7.5 cm on properties of concrete. For a proper analysis, the properties of plain cement concrete were used as reference by Ali et al. [3]. It was seen that damping of coir fiber reinforced concrete (CFRC) beams increases with the increase in fiber content. It was observed that CFRC with a fiber length of 5 cm and fiber content of 5 % produced the best results. Yousif and Ku [4] demonstrated the existence of high interfacial adhesion characteristics between coir fiber and polyester resin and hence proved the suitability of using such composites as liquid storage tanks. Karthikeyan and Balamurugan [5] concluded from their investigations that epoxy composite reinforced with coir fiber of length 30 mm shows better impact strength than other lengths. They also concluded that there is no significant increase in impact strength of alkali treated composite if the alkali concentrations exceed 6 %. Fu et al. [6] studied the elastic modulus of

hybrid particle/short fiber reinforced polymer matrix composites theoretically by considering the effects of absolute and relative reinforcement volume fractions, fiber elastic modulus, particle modulus, fiber length and orientation.

Bansal et al. [7] compared bamboo - jute polymer composite with bamboo - coir polymer composite pertaining to impact strength and hardness. Authors concluded that bamboo-coir epoxy polymer composite shows better results in impact strength and hardness when compared to the other two composites i.e. bamboo epoxy polymer composite and bamboo-jute epoxy polymer composite. Basiji et al. [8] dealt with the effect of fibre length and fibre loading level on modulus of rigidity, modulus of elasticity, tensile strength and impact strength. Ramesh et al. [9] found that the combination of banana fibre and epoxy resin in polymer matrix composite exhibits maximum result for both tensile strength and flexural strength. Hossain et al. [10] studied jute epoxy laminated composite and concluded that in longitudinal direction, tensile strength and stiffness are higher but found opposite in the transverse direction. Saradava et al. [11] improved the mechanical properties of coir fiber reinforced polymer composite by using red mud as the filler.

Banerjee et al. [12] predicted the stress analysis of a single walled carbon nano tube using finite element method and also analyzed the changes in Young's modulus and thickness for the 3 phased composites. Ashrafi et al. [13] found few advantages like impact area reduction, increase in impact strength, mode I fracture toughness and mode II inter laminar fracture toughness with the addition of 0.1 % of single walled carbon nano tube in epoxy. Yokozeiki et al. [14] performed investigations on carbon fiber reinforced polymer composites with (5 wt.%) and without cup stacked carbon nano tubes (CSCNT) and quasi-isotropic laminates (with 0, 5 and 10 wt.% of CSCNT in epoxy) and found improvement of several properties and no adverse effects on mechanical properties due to cup stacked carbon nano tubes.

Fly ash is a waste product obtained from burning coal mainly in thermal power plant. It has awful effects on health of environment that's the reason reuse of fly ash is very important. Patil et al. [15] found that fly ash can be used in the small amount as an additive which improves the compressive strength of the concrete. Chen et al. [16] demonstrated that fly ash reinforced epoxy polymer composites with 15 % of fly ash exhibited significant improvement in impact strength, flexural strength and flexural modulus. They also concluded that the addition of fly ash

in epoxy polymer composites also resists crack propagation and improves fracture toughness. Deepthi et al. [17] reinforced fly ash cenospheres with high-density polyethylene to make lightweight composites to reduce weight, shrinkage, and water absorption. The result showed that there is a remarkable improvement in the mechanical and thermal stabilities of the composites. Nath et al. [18] experimented with unmodified and modified fly ash (surface of fly ash treated with sodium lauryl sulphate (SLS)) in the fabrication of composites with polyvinyl alcohol as matrix. The surface, modified with SLS, improved the tensile strength of the composites up to 33 % and 75 % higher than the unmodified fly ash. The study also proved that fly ash could be used to develop high performance biodegradable composites. Mahalingam et al. [19] investigated shear strength of CNT/coir/fly ash reinforced epoxy polymer composites. They arrived optimum combinations of CNT/coir/fly ash in composites to get maximum shear strength.

Purohit et al. [20] added fly ash as the filler in polymer composite to study tensile, flexural and impact strengths. Authors concluded that addition of fly ash increases the flexural strength up to 4 % fly ash in composites. Kumre et al. [21] concluded that addition of sisal fiber improves the mechanical properties in glass fiber reinforced polymer composites. Sunkara et al. [22] prepared polymer matrix composite with Nano fly ash as the filler which resulted in increase in tensile and impact strengths of the composite. D'Souza et al. [23] reviewed the mechanical properties of glass-epoxy composite with fly ash as the filler material. Authors concluded that tensile strength of composite reached to maximum of 77.2 MPa at 6 % fly ash. Also the specimen with 3 % filler has the least water absorption percentage compared to 6 % and 9 % filler. They also observed that specimen with 9 % fly ash filler has the maximum bending strength compared with 3 % and 6 % fly ash filler.

Akhil and Reddy [24] concluded that the mechanical strength of glass fiber reinforced polymer composite is increased by adding coal ash and fly ash powder as the filler material. Pattanaik et al. [25] studied dry sliding wear behavior of epoxy fly ash composite with the help of Taguchi method of design of experiment. Authors investigated that with least number of experiments, Taguchi L32 orthogonal array gives the most accurate result. Tiwari et al. [26] studied the mechanical and thermal properties of fly ash/epoxy composite and observed that even small content of nanofiller reduces the defects between fillers and polymer interface and enhances the mechanical properties of the composite. Singla and Chawla [27] concluded that by adding

fly ash in epoxy composite, the compressive strength can be increased. Ramakrishna et al. [28] analyzed that the tensile and damping properties of glass fiber epoxy composites are improved by adding 5 % fly ash as the filler. Mohan et al. [29] studied the mechanical properties of fly ash filled glass fiber reinforced polymer composite. The authors concluded that by addition of 2 % of fly ash in composite gives better strength than that of 5 % fly ash.

There are attempts reported in the literature regarding the reinforcements of CNT, coir and fly ash in epoxy polymer matrix composites separately or together. There are no attempts reported regarding the calculation of fatigue limit of such composites. The concept of fatigue limit for metallic substances has been known for many years but the limit of resources and the fight to make everything better open a new aspect for the of fatigue limit for the composite materials. Hence calculation of fatigue limit of CNT/coir/fly ash reinforced epoxy polymer matrix composite is tried in this work.

2 Methodology

In this work, material properties found by Venkatachalam et al. [30] are used to calculate fatigue limit. Polymer matrix composite is made with epoxy resin [LY556] as matrix and Coir fiber (in powder form)/CNT/fly ash as reinforcements. Samples are prepared based on Response Surface Methodology (RSM), a Design of Experiments (DOE) tool. The Central Composite Design (CCD) in RSM is used to arrive the different combinations of samples. The input parameters are wt.% of coir, CNT and fly ash. Table 1 shows that wt.% of coir and fly ash are from 0 % to 2 % and that of CNT is from 0 % to 1 %. The different levels of wt.% and its actual values are given in Table 2.

Table 3 shows the values of yield stress in MPa taken from Venkatachalam et al. [30]. Fatigue limit is calculated using Soderberg's equation based on yield stress value.

Table 1 Different levels and wt.% of Coir, CNT and Fly ash [30]

Variables	Parameters	Levels	-2	-1	0	1	2
A	Coir	wt.% of materials in composite	0 (0)	0.5 (0.09)	1 (0.182)	1.5 (0.273)	2 (0.364)
B	CNT	(actual wt. in gram is given in bracket)	0 (0)	0.25 (0.045)	0.5 (0.091)	0.75 (0.136)	1 (0.182)
C	Fly-ash		0 (0)	0.5 (0.091)	1 (0.182)	1.5 (0.273)	2 (0.364)

Table 2 Different combinations of Tensile test specimens based on CCD of RSM [30]

Exp. No.	Coir		CNT		Fly-Ash	
	Coded	Actual	Coded	Actual	Coded	Actual
1	-1	0.091	1	0.1365	-1	0.091
2	0	0.182	0	0.091	0	0.182
3	1	0.273	-1	0.0455	-1	0.091
4	0	0.182	0	0.091	0	0.182
5	1	0.273	1	0.1365	1	0.273
6	-1	0.091	-1	0.0455	1	0.273
7	0	0.182	0	0.091	0	0.182
8	0	0.182	0	0.091	2	0.364
9	-2	0	0	0.091	0	0.182
10	0	0.182	0	0.091	-2	0
11	0	0.182	2	0.182	0	0.182
12	0	0.182	-2	0	0	0.182
13	2	0.364	0	0.091	0	0.182
14	0	0.182	0	0.091	0	0.182
15	0	0.182	0	0.091	0	0.182
16	0	0.182	0	0.091	0	0.182
17	1	0.273	-1	0.0455	1	0.273
18	-1	0.091	1	0.1365	1	0.273
19	-1	0.091	-1	0.0455	-1	0.091
20	1	0.273	1	0.1365	-1	0.091

Table 3 Values of Yield Stress of 20 samples [30]

Sample Number	Yield Stress
1	12.75
2	10.86
3	10.94
4	10.86
5	11.82
6	11.42
7	10.86
8	11.04
9	11.02
10	11.17
11	14.61
12	13.18
13	11.10
14	10.86
15	10.86
16	10.86
17	12.01
18	11.55
19	11.13
20	12.23

3 Results and discussion

In order to ensure more safety, Soderberg equation is chosen ahead of Goodman criterion and Gerber criterion. Soderberg equation, an equation used to quantify the interaction of mean and alternating stresses on the fatigue life of a material, is used to calculate the fatigue limit. The equation is typically presented as a linear curve of mean stress vs. alternating stress that provides the maximum number of alternating stress cycles a material will withstand before failing from fatigue. Line joining σ_{yt} (yield strength of the material) on mean stress axis and σ_e (fatigue limit of the component) on stress amplitude axis is called as Soderberg line. Based on the guidelines [31], σ_{max} and σ_{min} are considered as 80 % and 40 % of the yield stress respectively. Equation 1 represents Soderberg equation:

$$\frac{\sigma_m}{\sigma_{yt}} + \frac{\sigma_a}{\sigma_e} = 1, \tag{1}$$

where

$$\sigma_m - \text{Mean Stress} = \frac{\sigma_{max} + \sigma_{min}}{2},$$

σ_{yt} – Yield Stress,

$$\sigma_a - \text{Stress Amplitude} = \frac{\sigma_{max} - \sigma_{min}}{2},$$

σ_e – Fatigue Limit,

σ_{min} – Minimum Stress,

σ_{max} – Maximum Stress.

Table 4 represents the values of fatigue limit of the different samples taken from the Table 2 and calculated using the Soderberg equation. Analysis of variance (ANOVA) is performed to find the influences of wt.% of coir, CNT and fly ash using MINITAB software. Regression equation is obtained to know the influences of these input parameters on fatigue limit. Equation (2) is the regression equation obtained from ANOVA. Equation (2) is the 2nd order polynomial equation. A comparison is also carried out between the fatigue limit values presented in Table 4 and fatigue limit values obtained from regression equation. Table 5 presents the comparison between fatigue limit values obtained from Soderberg equation and regression equation. The error is less than 10 % except for two samples. Hence the regression model obtained from ANOVA can be used for further reference.

$$\begin{aligned} \text{Fatigue Limit} = & 6.31606 - 0.41632A - 3.55513B \\ & + 0.08400C + 0.09833A \times A + 6.05332B \times B \\ & + 0.11833C \times C - 0.30275A \times B \\ & + 0.39138A \times C - 1.48725B \times C \end{aligned} \tag{2}$$

Where,

A = Coir: % of coir used in the sample,

B = CNT: % of CNT used in the sample,

C = Fly Ash: % of fly ash used in the sample.

Table 4 Fatigue limit calculated based on Soderberg equation

Sample No.	Fatigue Limit (MPa)
1	6.3745
2	5.4323
3	5.4681
4	5.4323
5	5.9082
6	5.7123
7	5.4323
8	5.5216
9	5.5122
10	5.5847
11	7.3035
12	6.5919
13	5.5478
14	5.4323
15	5.4323
16	5.4323
17	6.0050
18	5.7745
19	5.5662
20	6.1174

Table 5 Error analysis between calculated fatigue limit values and regression equation fatigue limit values

Sample No.	Fatigue Limit in MPa (calculated from Soderberg eqn.)	Fatigue Limit in MPa (calculated from regression eqn.)	Error %
1	6.3745	6.4152	-0.64
2	5.4323	5.2339	3.65
3	5.4681	5.2204	4.53
4	5.4323	5.2339	3.65
5	5.9082	5.4673	7.46
6	5.7123	5.5625	2.62
7	5.4323	5.2339	3.65
8	5.5216	5.1249	7.18
9	5.5122	5.7032	-3.47
10	5.5847	5.5795	0.09
11	7.3035	7.2970	0.09
12	6.5919	6.1974	5.98
13	5.5478	4.9612	10.57
14	5.4323	5.2339	3.65
15	5.4323	5.2339	3.65
16	5.4323	5.2339	3.65
17	6.0050	5.2671	12.29
18	5.7745	5.5158	4.48
19	5.5662	5.9140	-6.25
20	6.1174	5.9685	2.43

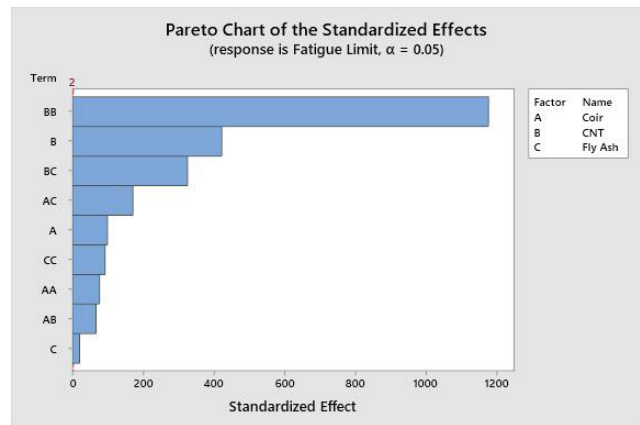


Fig. 1 Effect of constituents on fatigue limit

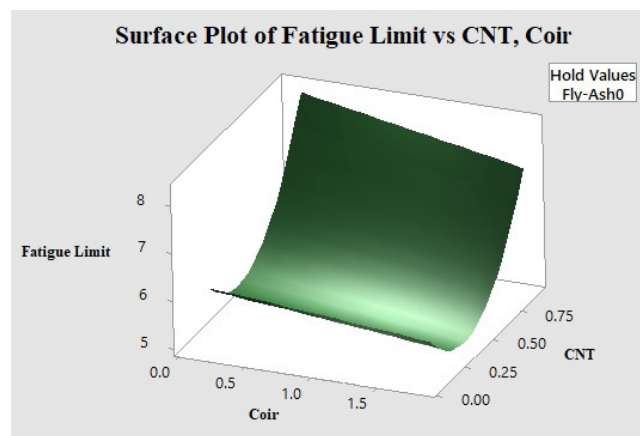


Fig. 2 Surface plot of fatigue limit vs. CNT/Coir

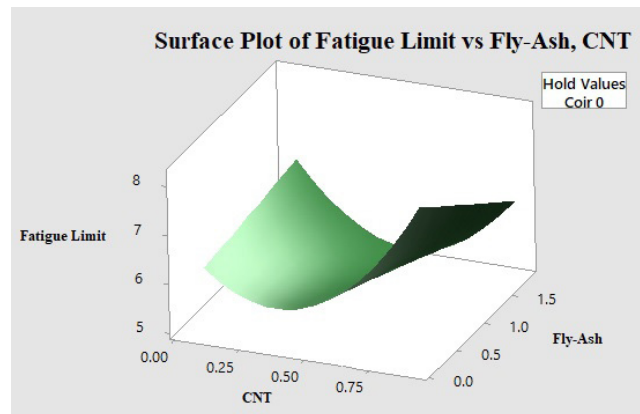


Fig. 3 Surface plot of fatigue limit vs. fly-ash, CNT

Fig. 1 shows the effect of different constituents of the regression equation on the fatigue limit. In Fig. 1, where *A*, *B* and *C* represent wt.% of Coir in the samples, wt.% of CNT in the samples and wt.% of Fly Ash in the samples respectively. From the Fig. 1, one can understand that the influence of CNT is maximum on the value of fatigue limit. The influence of fly ash is negligible as compared to CNT and coir.

Fig. 2 represents the surface plot between fatigue limit vs. CNT and coir. It is concluded from the Fig. 2 that adding 0.5 to 1 % of CNT makes huge effect on the fatigue limit while effect of coir decreases as increase in the amount till 2 %. Addition of Coir helps to increase the green content of the samples but its effect on the fatigue limit is very less.

Fig. 3 illustrates the surface plot of fatigue limit vs. CNT and fly ash. Fig. 3 helps to understand the effect of both CNT and fly ash on the fatigue limit. It is understood that combination of 1 % CNT and 0 % fly ash results in the maximum amount of the fatigue limit but increase in the wt.% of fly ash tends to decrease the fatigue limit.

Fig. 4 explains the interaction among the coir and fly ash on fatigue limit. From Fig. 4, it is evident that the increasing fly ash and coir wt.% increases fatigue limit till 2 % of both fly ash and coir.

Fig. 5 presents main effect plot for fatigue limit in terms of coir, CNT and fly ash. Main effect plot shows the individual performance of the reinforcements on the fatigue limit. It is palpable from Fig. 5 that coir and fly ash increase the fatigue limit in the range of 0.5 % to 1.5 % whereas CNT increases the fatigue limit in the range of 0.75 % to 1 %. Optimization of parameters is carried to find the optimum values of parameters to get maximum fatigue limit. There are two cases considered in the analysis. Tables 6 and 7 explain the optimum

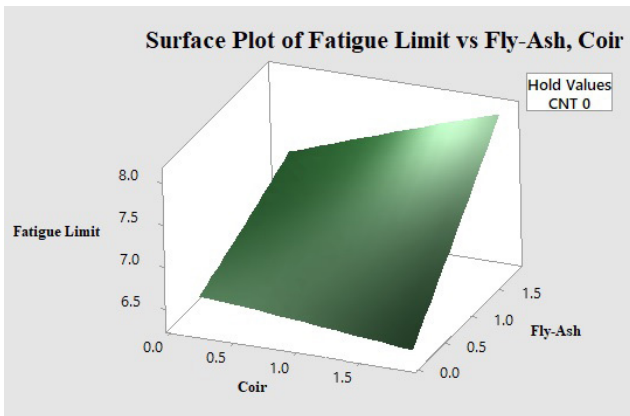


Fig. 4 Surface plot of fatigue limit vs. fly-ash, Coir

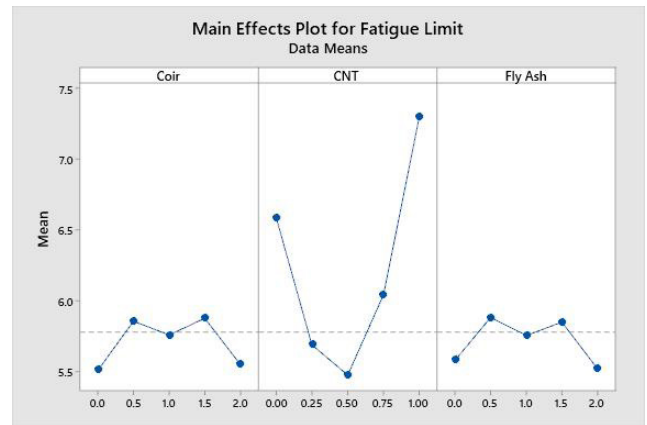


Fig. 5 Main effects plot for fatigue limit

parameters and maximum value of fatigue limit. In both cases composite desirability is maintained at 1. Among the two cases, case (I) gives maximum value of fatigue limit (8.81 MPa) with zero wt.% of coir and fly ash. If the objective is to increase the green/waste material content in the composite, the case (II) is the right option. In that scenario, 90 % of fatigue limit of case (I) is maintained with the addition of green/waste material content.

4 Conclusion

Fatigue limit of coir/CNT/fly ash reinforced epoxy polymer matrix composite is determined using Soderberg equation. In order to explore the influences of wt.% of coir, CNT and fly ash on fatigue limit of polymer composite, Response Surface Methodology is employed. After the calculating fatigue limit of all samples, ANOVA is applied to understand the influences of wt.% of coir, CNT and fly

ash on fatigue limit of polymer composite. Mean effects plot, surface plots and regression equation are obtained. Fatigue limit values, predicted using Regression equation, are in good agreement with that of Soderberg equation. Results from ANOVA analysis reveal that wt.% of CNT has more influence than coir and fly ash. Two cases are considered in the optimization section. It is suggested from the optimization analysis to consider the case (II) as it has green/waste materials presence with 90 % of fatigue limit value of case (I) which has no green/waste material presence. Combination of coir (0.55 wt.%), CNT (1 wt.%) and fly ash (0.55 wt.%) gives fatigue limit of 7.84 MPa.

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Table 6 Parameters and solution for optimization case (I)

Parameters						
Response	Goal	Lower	Target	Upper	Weight	Importance
Fatigue Limit	Maximum	5.43225	7.3		1	1
Solution						
Solution	Coir	CNT	Fly Ash	Fatigue Fit	Composite Desirability	
1	0	1	0	8.81	1	

Table 7 Parameters and solution for optimization case (II)

Parameters						
Response	Goal	Lower	Target	Upper	Weight	Importance
Fatigue Limit	Maximum	5.4323	7.301		1	1
Solution						
Solution	Coir	CNT	Fly Ash	Fatigue Fit	Composite Desirability	
1	0.55	1	0.55	7.84	1	

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