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Optimum Design of a Coir Fiber Biocomposite Tube Reinforced with Nano Silica and Nano Clay Powder

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ABSTRACT

Due to significant environmental advantages, biocomposites have recently received increasing attention. In the present research, strength of hat-shaped coir fiber biocomposites tubes reinforced with nano powder was evaluated experimentally under 3-point bending tests. The tubes were manufactured using hand lay-up technique and based on Taguchi design of experiment. The effects of different parameters including fiber loading, type of nano powder and its weight percentage and also weight percentage of NaOH in alkali treatment were analyzed. Optimization was also performed using Taguchi L8 orthogonal array. Moreover, analysis of variance (ANOVA) was conducted to determine the significance of the parameters. In this study, finite element model was also created in ABAQUS software to compare with the results obtained from the experiments to achieve validated finite element model. There was a good agreement between the results from experiments and those obtained in numerical simulations.

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1. INTRODUCTION

Biodegradable and eco-friendly materials have recently received increasing attention. Natural fiber is one of these materials which offer environmental and economic advantages like being strong, lightweight and cheap. Moreover, they are derived from biodegradable resources that are widely distributed in the world. Using these fibers as reinforcement for composites could reduce greenhouse gases and carbon emission into the atmosphere. Coir fiber can be used as a natural fiber in biocomposites since it is abundant in nature and has a minimal effect on the environment due to its biodegradable properties [1]. It also has high weather resistance because of higher amount of lignin and absorbs water to a lesser extent compared to other natural fibers due to its less cellulose content [2]. One of the major drawbacks of using coir as reinforcement material is its hydrophilic nature, which causes moisture absorption and consequent deformation of the product. Adhesion between the fiber and polymer is also one of the factors affecting the strength of manufactured composites. In order to prevent such problems coir fiber is chemically treated, which in turn improves the mechanical properties of the biocomposites [3].

Safety, weight and protecting the environment are important vehicle attributes that are affected by structural and material design of vehicle body. Due to favorable effects on the mentioned attributes, considerable growth has been seen in the use of biocomposites in the automotive components over the past decade. In order to increase cross sectional stiffness, automotive body components are usually thin-walled structural elements with large value of width to the thickness ratio [4]. Hat-shaped tubes are one of the most used automotive body structural components. Figure 1 depicts front floor cross members used for mounting of front seats on the automotive floor panel, which are hat shaped.

Common composites increasingly used in automotive industry can be replaced with the one reinforced with natural fibers. There are some studies conducted to replace synthetic fibers with natural ones.

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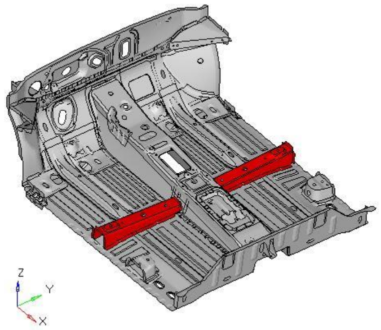


Figure 1. Hat-shaped tube used for seat mounting on the automobile floor

Premlal et al. and Yang et al. manufactured rice husk reinforced polypropylene composites and found better mechanical properties in their composites [5, 6]. Sapuan et al. [7] carried out experiments using tensile and flexural (three-point bending) tests of epoxy reinforced with banana fiber. Thwe and Liao [8] manufactured bamboo fiber reinforced polypropylene (PP) composites using compression molding; Maleic anhydride polypropylene (MAPP) was used as a compatibilizer to improve the adhesion between the reinforcements and the matrix. Based on the results, use of MAPP as coupling agent in the polypropylene matrix resulted in decreased saturated moisture absorption level and enhanced mechanical properties of the specimens. It was also shown that the durability of bamboo fiber reinforced polypropylene can be enhanced by hybridization with small amount of glass fibers. Park et al. [9] showed the potential of rice husk in reinforcing thermoplastic polymer. Better mechanical properties were also attained in rice husk reinforced polystyrene and polyvinyl chloride (PVC) composites [10, 11]. M. Habib et al. [12] studied the interfacial damage in biopolymer composite reinforced with hemp fibers. Their results showed that the finite element model is able to predict the behavior of these biocomposites. Deepak et al. [13] studied the influence of nano clay in polyester resin based composites reinforced with coir fibers. Their results showed improvement in the mechanical properties. Dong et al. [14] presented experimental results to quantify the effects of fiber content (5–30 wt%) and fiber treatment on surface morphology, tensile, flexural, thermal and biodegradable properties of Polylactic acid (PLA)/coir fiber biocomposites. Van Vuure et al. [15] studied compressive properties of 3 different natural fiber composites based on flax, bamboo and coir fiber and showed that coir fiber composites perform better in compression than in tension. Khan et al. [16] studied fracture behavior of bamboo fiber reinforced epoxy composites. Scanning electron microscope (SEM) results revealed that fiber breakage, matrix cracking, fiber matrix debonding and fiber pull out are major causes of failure of composite.

Adding nano powders to a matrix could improve mechanical properties of a composite material. Because of the higher surface area of the nanoparticles, the interaction with other particles within the mixture is more and this increases the strength and also makes them suitable to replace metals in automotive and other applications [17]. There are many researches that investigate the effects of adding nano particles on the mechanical properties of the composite material [18-23]. Mosalman et al. [24] studied the effects of adding various percentages of TiO_2 (0.5, 1 and 2 wt%) to pure Poly methyl methacrylate (PMMA) on the mechanical properties of produced composite by performing several tests. Results illustrated that combination of TiO_2 nanoparticle with PMMA, improved the mechanical properties of composite. Abdellaoui et al. [25] manufactured and studied Jute/epoxy hybrid laminated biocomposite by using little clay particles at various contents (5 to 20 wt%). Their results showed that the mechanical properties increased with clay content, up to an optimum value at 15 wt%.

As a widely used technique in engineering optimization, Taguchi method has proved to be an efficient approach in engineering analyses to optimize the performance characteristics within the combination of design parameters. It can also be used to determine the importance of various factors involved in the process [26]. Analysis of variance (ANOVA) is also a technique which is used to analyze the results and identify the factors which have a significant effect on the output [27].

In the current work, optimum design of a biocomposite hat-shaped tube for being used as front floor cross member of automotive body structure for mounting front seats is carried out. Polyester, coir fiber, nano silica and nano clay powder are used as matrix, natural fiber and reinforcement, respectively. No investigation has been carried out on hat-shaped tube made from these materials before. Taguchi design of experimental technique was used to design the experiments and therefore eight hat-shaped tubes were fabricated using hand lay-up method based on Taguchi design of experiments. Three-point bending test is carried out on the specimens to evaluate the strength of the beams. Finally, optimization is done using Taguchi method, where the objective is to maximize the maximum withstanding force under the 3-point bending test. A discussion is made on the results using ANOVA and the importance of each design parameter is evaluated. Moreover, finite element model of the bending test is created with a commercial software ABAQUS to compare the results obtained from the experiment to arrive at meaningful results for validation.

2. EXPERIMENTAL PROCEDURE

2. 1. Materials In this study, the unsaturated polyester resin is used as the matrix. The natural fiber is coir fiber, which was extracted from the husk of coconut. Two kinds of nano powder (nano silica and nano clay) are also used as the reinforcing filler. Table 1 shows the properties of nano clay and nano silica. Additionally, chemical analysis of nano clay and nano silica is given in Tables 2 and 3, respectively.

2. 2. Treatment of Coir Fiber As it was mentioned before, one of the major problems of using coir fiber as reinforcement material is its hydrophilic nature, which causes moisture absorption and consequently deformation of the product. In order to minimize the factors like the lack of wettability and interfacial bonding between natural fibers and well known commercial polymers like polyester, alkali treatment was employed. Coir fiber extracted from coconut husk was cut into 2 mm size then it was soaked into NaOH solution for 5 hours followed by washing with distilled water. Then the fiber was dried in an oven at 90°C for 3 hours.

2. 3. Design of Experiment In order to investigate how different parameters can affect the output parameter, Taguchi design of experiment (DOE) was used and the effects of 4 parameters in 2 levels have been studied. Table 4 shows the parameters and their levels. Table 5 displays the L8 (2^4) Taguchi design (orthogonal array), which contains 8 runs. It is noteworthy that if the full factorial design was used, it would have 16 runs. Factor levels are weighted equally across the entire design. The table columns represent the control factors, the table rows represent the runs (combination of factor levels), and each table cell represents the factor level for that run.

2. 4. Fabrication of Composite At first, polyester/nano clay or polyester/nano silica were prepared by mixing the desired amount of nano clay or nano silica with polyester in a suitable beaker. Then the mixture was placed in a high intensity ultra-sonicator for 30 min with pulse mode (15s on/15s off) [28].

TABLE 1. Properties of nano clay and nano silica

Kind of nano powder	Nano clay	Nano silica
Density (g/cm^3)	0.5-0.7	0.1
Particle size (nm)	1-2	20-30
Specific surface area (m^2/g)	220-270	180-600
Color	Pale yellow	white

TABLE 2. Chemical analysis of nano clay

Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	Fe_2O	LOI
0.98	3.29	19.60	50.95	0.86	1.97	0.62	5.62	15.45

TABLE 3. Chemical analysis of nano silica

SiO_2	**Ti** [ppm]	**Ca** [ppm]	**Na** [ppm]	**Fe** [ppm]
>99%	<120	<70	<50	<20

TABLE 4. Parameters and their levels for DOE

Level	Weight of fiber (g)	Kind of nano powder	Weight percent of nano powder (Wt %)	Weight percent of NaOH in alkali treatment (Wt %)
1	50	Nano clay	2	10
2	80	Nano silica	1	5

TABLE 5. Taguchi design of experiment

Run	Weight of fiber	Kind of nano powder	Weight percent of NaOH in alkali treatment	Weight percent of nano powder
1	1	1	1	1
2	1	1	2	2
3	1	2	1	2
4	1	2	2	1
5	2	1	1	2
6	2	1	2	1
7	2	2	1	1
8	2	2	2	2

Once the process completed, for better dispersion it was placed in mechanical mixer.

Treated coir fiber was weighted according to the required weight fraction determined by Taguchi design of experiment for each run. Sufficient amount of polyester/nano clay or polyester/nano silica was weighted and poured in a beaker. Mold surface was cleaned then the uniformly mixed fiber and matrix was taken into the die.

2. 6. Three Point Bending Test Bending tests were conducted using a Universal Testing Machine (SANTAM/STM-150). The test specimens and loading situations are shown in Figure 2. The test was performed at a crosshead speed of 5 mm/min and the support span was considered 300 mm. 8 specimens, which were manufactured based on the Taguchi design of experiment, were tested.

The dimensions of the specimens (hat shaped tubes) were: length of 400 mm, the cross section width of 70 mm and the cross section height of 50 mm. The width of the cross section flanges was 30 mm and the thickness of the tube was 7 mm. Figure 3 shows the cross-sectional dimensions of the tube model.

The experimental results of the force-deflection curve for three point bending tests are given in Figure 4 and Figure 5 for nano clay and nano silica, respectively.

Figure 2. Three point bending test, the specimen and loading situations

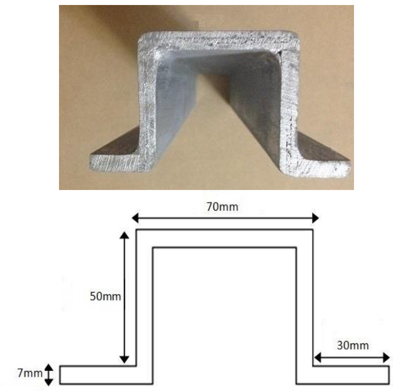


Figure 3. Cross section dimensions of the tube

Table 6 also shows the experimental values of ultimate load, maximum deflection and calculated stiffness for the specimens. As mentioned earlier, in this study hat-shaped tubes are designed to be used as automotive body front floor cross members. Primary function of these components is to mountain front seats. Structural requirement for front seats mounting system is to withstand 4000 N transverse load. Results reported in Table 6 show that higher strength were achieved comparing to the required value.
The value of stiffness for each specimen is derived from Equation (1).

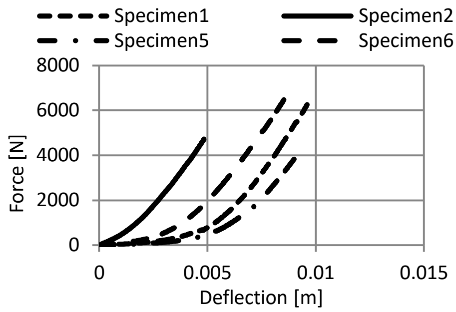


Figure 4. Force-deflection curves for three point bending test-nano clay

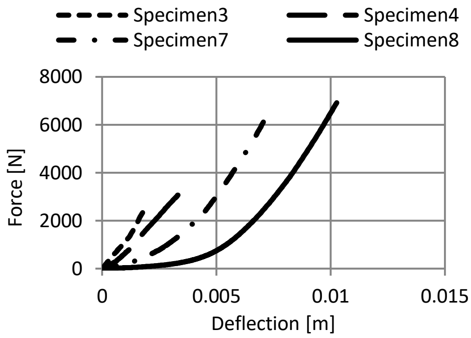


Figure 5. Force-deflection curves for three point bending test-nano silica

TABLE 6. Experimental results of three point bending test

Run	Ultimate load [N]	Maximum deflection [mm]	Young's modulus obtained by 3-point bending test [MPa]	Stiffness [N/mm]
1	6334.8	9.6484	1319.997	864.94
2	4719.8	4.8445	1958.709	1170.37
3	2387.5	1.7948	2674.376	1349.14
4	3075.4	3.3201	1862.283	1048.29
5	3881.1	9.038	863.3317	563.89
6	6474.6	8.5288	1526.231	993.39
7	6566.6	7.3187	1803.856	973.74
8	3903.2	8.2693	948.959	611.79

$$K=\frac{\textbf{\textit{Max Force}}}{\textbf{\textit{Max Deflection}}} \tag{1}$$

It should be noted that for calculating the stiffness the nonlinear section of the force-deflection curve, which is considered as experimental error, is omitted. As shown in Table 8, specimen3 has the highest stiffness while specimen 5 has the lowest stiffness. It should be noted that the stiffness is calculated based on the results of linear section of the force-deflection graph.

Based on 3 point bending test results, Young's modulus can be calculated by Equation (2), where F is force, L is the length of beam, δ is the deflection and I is the second moment of area.

$$E=\frac{FL^3}{48\delta I} \tag{2}$$

Table 6 shows the Young's modulus obtained from 3 point bending test results. The table depicts specimen 3 has the highest Young’s modulus while specimen 5 has the lowest Young’s modulus and about 68% improvement was obtained. The results of such tests can also be used for investigating the accuracy of the results obtained for elastic modulus from tensile test .The results show that there is a good agreement between Young’s modulus obtained by tensile and 3-point bending test that shows the accuracy of these tests. Based on the results shown in Tables 6 and 7, it is illustrated that an improvement of about 58% can be obtained by changing design parameters considered in this paper which are weight of fiber, kind of nano powder, weight percent of NaOH in alkali treatment and weight percent of nano powder.

3. FINITE ELEMENT SIMULATION

Three-point-bending test was simulated using finite element modeling (FEM) software ABAQUS 6.13. The loading cross head and supports were defined as cylindrical rigid body. Since coir fiber is randomly oriented, the biocomposite reinforced with nano powder is considered as an isotropic material and it was modeled based on the results obtained from tensile test. The tubes property was modeled as elastic with Young’s modulus obtained from results of the experiment for each run based on design of experiments using the Taguchi approach.

The connections between two supports, loading head and tube were defined as surface to surface contact using Coulomb friction coefficient 0.1. The mesh size was also set to 5.0 mm. Moreover, the loading was applied at the reference point of loading head as 0.01m displacement in the Y direction and reference points of the supports were fixed. Figure 6 shows the schematic illustration of the finite element model of 3-point bending test.

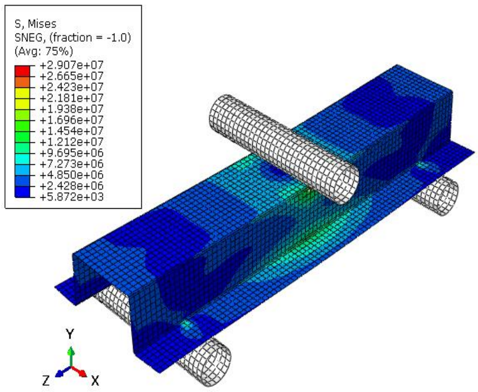
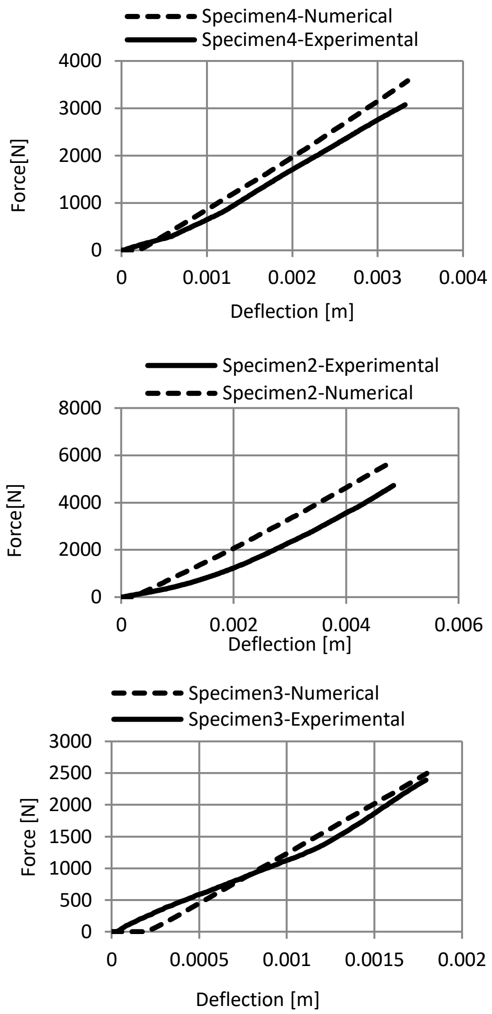


Figure 6. Schematic illustration of the finite element model of three point bending test

Figure 7 shows the comparison of the force-deflection curves obtained from experiments and numerical analysis for 4 specimens.



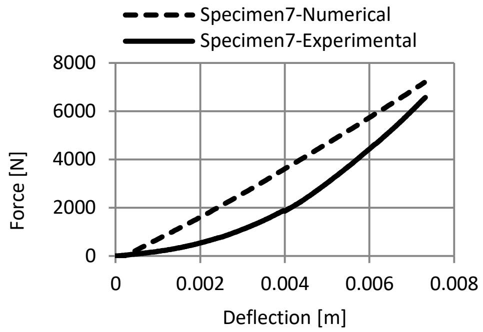


Figure 7. Comparison of the force-deflection curves obtained from experiments and numerical analysis

It can be seen that there is a good agreement between the results from experiments and numerical simulations. The values of stiffness obtained from numerical simulations and experimental tests are shown in Table 7.

TABLE 7. Numerical and experimental stiffness

Run	Numerical stiffness [N/mm]	Experimental stiffness [N/mm]	Error
1	887.58	864.94	2.61%
2	1191.87	1170.37	1.84%
3	1385.43	1349.14	2.69%
4	1068.49	1048.29	1.93%
5	575.36	563.89	2.03%
6	1008.88	993.39	1.56%
7	984.73	973.74	1.13%
8	611.79	624.43	2.07%

4. S/N RATIO ANALYSIS

Signal-to-noise (S/N) ratio is a measure used in science and engineering that compares the level of a desired signal to the level of background noise. In the present investigation, maximum force in three point bending test, which is as the output parameter, has to be maximized and therefore the larger the better approach has been used based on Equation (3) for calculating S/N ratio:

$$\text{S/N ratio} = -10\, \boldsymbol{log_{10}}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (3)$$

where, y denotes the value of each objective function, and n represents the number of repetition of each experiment. Each level providing the largest S/N ratio would be considered as the optimum one. Furthermore, results corresponding to S/N ratio response of outputs are tabulated in Tables 8 and 9 along with Figure 8.

Based on Table 9 as well as Figure 8, it is evident that weight percent of nano powder, kind of nano powder, weight of fiber and weight percent of NaOH in alkali treatment are ranked as the 1^{st} to 4^{th} dominant factor in determining output, respectively. Additionally, Figure 9 depicts mean response graph variation of output with different process parameters, respectively. It must be pointed out that in these curves, the sharper the slope of the line, the more effective that particular design parameter is on output parameters. Taking into account the sharpest linear slope in Figure 9, it can be deduced that the weight percent of nano powder is the most significant factor for output.

Additionally, the optimum design considering this quality becomes $WF_2NP_1AT_1WNP_1$ that means the optimum setting can be obtained when parameter WF (weight of fiber) is in the second level or 80g (WF_2), parameter NP (kind of nano powder) is in the first level or nano clay (NP_1), parameter AT (weight percent of NaOH in alkali treatment) is selected in the first level or 10 wt% (AT_1) and finally, parameter WNP (weight percent of nano powder) is in the first level or 2 wt% (WNP_1).

TABLE 8. Orthogonal matrix employed for evaluation of maximum force in 3point bending test

Run	Weight of fiber	Kind of nano powder	Weight percent of NaOH in alkali treatment	Weight percent of nano powder	Maximum force in 3 point bending test [N]	S/N ratio of result
1	1	1	1	1	6334.8	76.03
2	1	1	2	2	4719.8	73.48
3	1	2	1	2	2387.5	67.56
4	1	2	2	1	3075.4	69.66
5	2	1	1	2	3881.1	71.78
6	2	1	2	1	6474.6	76.22
7	2	2	1	1	6566.6	76.35
8	2	2	2	2	3903.2	71.83

TABLE 9. Response results of S/N ratio for output

Level	Weight of fiber	Kind of nano powder	Weight percent of NaOH in alkali treatment	Weight percent of nano powder
1	71.71	74.38	72.93	74.59
2	74.04	71.37	72.82	71.16
Delta	2.34	3.01	0.11	3.43
Rank	3	2	4	1
Optimum level	2	1	1	1

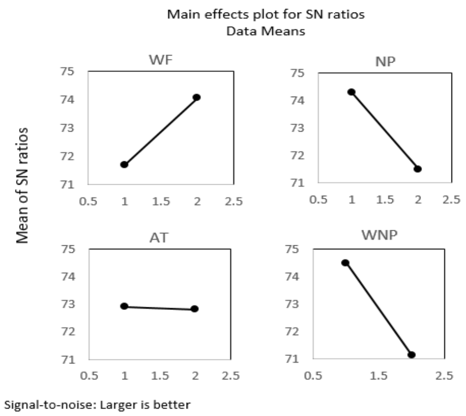


Figure 8. S/N ratio response graph-variation of output with different process parameters

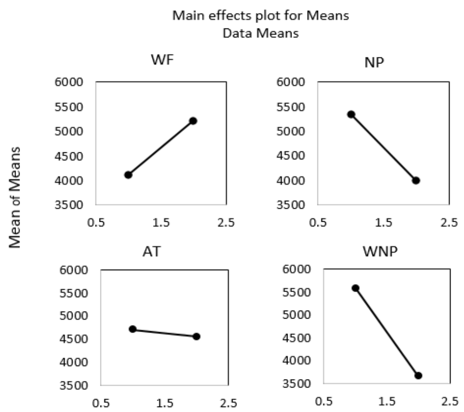


Figure 9. Mean response graph-variation of output with different process parameters

Taguchi predicts the maximum force of the optimum condition (F_{opt}) based on Equation (4).

$$F_{opt} = WF_2 + NP_1 + AT_1 + WNP_1 - 3*T/N \quad (4)$$

where WF2 , NP1, AT1, WNP1 denote the average effect of each factor in optimum level and T represents the grand total of all results and N is number of experiments and therefore the maximum force of the optimum condition would be 6960.68N.

5. ANALYSIS OF VARIANCE (ANOVA)

The aim of ANOVA in this study is evaluation of the significance of each design parameter on output. Table 10 lists the ANOVA results. In Table 10, parameter f denotes degree of freedom (DOF) and there is also a parameter called F (variance ratio) that shows which design parameters has a significant effect on the quality characteristic. Usually when F>4, it means that the change of the design parameter has a significant effect on the quality characteristics. Evidently for maximum force as an output, weight of nano powder has a major effect. Based on the percentage of contribution in Table 11, weight of nano powder has the most dominant effect on output, while kind of nano powder, weight of fiber and weight percent of NaOH in alkali treatment are ranked 2^{nd} to 4^{th}, respectively.

Apparently, complete agreement can be observed between the results corresponding to order of parameter significance obtained from S/N ratio analysis and ANOVA results.

TABLE 10. Results of ANOVA analysis

Factor	f (DOF)	S (Total variance of each factor)	V (Variance)	F (Variance ratio)	S (Pure sum of squares)	P (Percent contribution)
WF	1	2319858	2319858	1.325094855	569147.105	12.47867701
NP	1	3750512.72	3750512.72	2.142279877	1999801.825	20.17426793
AT	1	124251.125	124251.125	0.070971812	-1626459.77	0.668355415
WNP	1	7143822.005	7143822.005	4.080526388	5393111.11	38.42711382
Total	7	18590576.54				
Error	3	5252132.685	1750710.895	1		

6. CONCLUSION

In the present research, hat-shaped coir fiber biocomposites tubes reinforced with nano powder as filler were manufactured based on Taguchi design of experiment and subjected to three-point bending test. Results showed that for the hat-shaped tubes as front seats mounting system, higher strength was achieved comparing to the required value.

Finite element model of the three-point bending test was created to be compared with the experimental results to achieve validated FE model. Comparison of the predictions from FEA and experimental results for the tubes stiffness shows that there is a good agreement between results.

To determine the importance of each studied factor, Taguchi method and ANOVA technique were used when maximum force in three-point bending test was considered as an output. The results showed that weight of nano powder has the most dominant effect on output while kind of nano powder, weight of fiber and weight percent of NaOH in alkali treatment are ranked 2^{nd} to 4^{th}, respectively. Additionally, based on Taguchi technique the optimum setting can be obtained when weight of fiber is 80 g, kind of nano powder is nano clay, weight percent of NaOH in alkali treatment is 10 wt% and weight percent of nano powder is 2 wt% and the maximum force at optimum condition is predicted to be 6960.68N. This study also showed that an improvement of about 58% can be obtained by changing design parameters.

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Optimum Design of a Coir Fiber Biocomposite Tube Reinforced with Nano Silica and Nano Clay Powder

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چکیده

اخیرا استفاده از مواد بیوکامپوزیت به دلیل مزایای فراوان زیست‌محیطی ، مورد توجه بسیاری از محققان قرار گرفته‌است. در این بررسی، استحکام تیوب کلاهی شکل از جنس بیوکامپوزیت الیاف نارگیل تقویت شده با نانوپودر مورد ارزیابی تجربی تحت تست خمش ۳ نقطه قرار گرفته‌است. تیوب با استفاده از تکنیک لایه‌چینی دستی و با توجه به طراحی آزمایش به روش تاگوچی ساخته شده‌است. تاثیر پارامترهای متفاوت شامل حجم الیاف، نوع نانوپودر و درصد وزنی آن و همچنین درصد وزنی NaOH در فرآیند بهبود قلیایی الیاف مورد بررسی قرار گرفت. بهینه‌سازی با استفاده از تاگوچی انجام شد. همچنین آنالیز واریانس به منظور تعیین اهمیت هر یک از پارامترها صورت گرفت. در این بررسی، مدل اجزامحدود به منظور حل عددی مسئله در نرم‌افزار آباکوس، مدل‌سازی شد و نتایج آن با نتایج حاصل از تست تجربی با هدف دستیابی به مدل عددی قابل اطمینان، مقایسه گردید و مطابقت خوبی بین نتایج تجربی و نتایج تئوری به‌دست آمد.

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